Assessment of biofuel feedstock production in South Africa:

Technical report on the field-based measurement, modelling and mapping of water use in biofuel crops (Volume 2)

Report to the
WATER RESEARCH COMMISSION

on the project entitled
"Water use of cropping systems adapted to bio-climatic regions in South Africa and suitable for biofuel production"

by

RP Kunz[1], MG Mengistu[1], JM Steyn[3], IA Doidge[2], MB Gush[4], ES du Toit[3], NS Davis[5], GPW Jewitt[1] & CS Everson[1]

[1]Centre for Water Resources Research (CWRR), [2]African Centre for Crop Improvement (ACCI), School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa
[3]Department of Plant Production and Soil Science, Faculty of Natural and Agricultural Sciences, University of Pretoria, Pretoria, South Africa
[4]Natual Resources and the Environment, CSIR, Stellenbosch, South Africa
[5]Isikhungusethu Environmental Services, Pietermaritzburg, South Africa

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Water Research Commission
Private Bag X03
Gezina, 0031

orders@wrc.org.za or download from www.wrc.org.za

This report (**Volume 2**) is part of a three-volume series. **Volume 1** is a synthesis report which focuses on the key findings of the project. **Volume 2** provides more detail regarding the field work as well as the mapping and modelling components of the project. **Volume 3** presents the biofuel atlas and assessment utility, a copy of which appears on the CD enclosed at the back of Volume 1.

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EXECUTIVE SUMMARY

BACKGROUND AND MOTIVATION

South Africa is following the international trend of liquid biofuel production, as noted in the South African Biofuels Industrial Strategy of 2007. This strategy highlighted the benefits of biofuel production in terms of alleviating poverty in rural areas, promoting rural economic development and stimulating agricultural production. A 2% blend of biofuels in the national liquid fuel supply, equivalent to an annual production of approximately 400 million litres of biofuel, was proposed by the former Department of Minerals and Energy. To ensure sustainable biofuel production, South Africa plans to grow feedstock on currently under-utilised arable land and preferably under rainfed conditions.

In 2006, the task team that developed the biofuels strategy urged the government to determine the impacts of biofuel feedstock production on both water quality and water quantity. The Water Research Commission (WRC) responded to this request and funded a two-year (2007-2009) scoping study on the water use of biofuel feedstocks. The main aims of the scoping study were to 1) identify suitable feedstock for the production of biofuel, 2) map areas climatically suited to feedstock cultivation, 3) determine the available knowledge on feedstock water use, 4) model the water requirements of selected feedstock, and 5) identify existing knowledge gaps.

The scoping study report concluded that both sugarcane and sweet sorghum show potential to use more water than the natural vegetation they may replace, whilst other crops (e.g. sugarbeet, canola, soybean & sunflower) do not. However, the scoping study highlighted that for the emerging feedstocks (e.g. sugarbeet & sweet sorghum), parameter values were gleaned from the international literature. The literature also provided conflicting water use figures for certain feedstocks (in particular sweet sorghum) and that knowledge is surprisingly limited for certain crops (e.g. canola). The scoping study recommended a need to better understand the water use and yield of biofuel feedstocks. In addition, a more detailed mapping approach was required to identify feedstock growth areas that considered additional site factors (not just rainfall and temperature). Based on these recommendations, the WRC initiated and funded a six-year (i.e. more comprehensive) follow-up study.

This six-year solicited project began in April 2009 and was led by the University of KwaZulu-Natal, in close collaboration with the CSIR (Natural Resources & Environment) and the University of Pretoria (Department of Plant Production & Soil Science). The aims of the follow-up study were broadly similar to those of the scoping study, except for the need to estimate crop yield and biofuel yield.

PROJECT OBJECTIVE AND AIMS

The overall objective of this project was to determine the water use of selected biofuel feedstocks deemed suitable for bioethanol and biodiesel production in selected high and low potential bio-climatic regions of South Africa. The specific aims of the project were as follows:

AIM 1 - To specify and prioritise currently grown and potential alternative first and second generation crops and cropping systems including both annual and perennial crops/trees with attention to, amongst others:

- Crops and crop rotations for food and forage production,
- Crops and crop rotations for biofuel production,
- Multiple use systems e.g. food, fodder and fuel crop combinations,
- Monoculture high density crop production systems,
- Tree feedstocks in plantations, agro-forestry or alley cropping systems, and
- Cellulosic feedstocks.

AIM 2 - To review and characterise crop parameters, water use and yield (biomass, biofuel and by-products) of crops based on existing knowledge or estimation thereof by applying existing tools with reference to those prioritised in South Africa and those which have potential as alternative biofuel crops as identified above.

AIM 3 - To identify and describe bio-climatic regions suitable for these priority crop/tree systems for biofuel production with reference to, amongst others:

- Rainfall average and variability,
- Surface and underground water resources,
- Temperature average and extremes,
- Soil properties,
- Known pests and diseases, and
- Topography.

AIM 4 - To determine crop parameters and model water use of specific crops/trees for biofuel that have potential but insufficient knowledge exists in South Africa to promote effective production.

AIM 5 - To determine the biofuel yield potential of crops in the respective bio-climatic regions under rainfed and/or irrigated conditions.

AIM 6 - To estimate or quantify the water use efficiency of these crops with reference to, amongst others, the following parameters:

- Biomass yield per m^3 water over the full productive cycle, and
- Biofuel yield per m^3 water over the full productive cycle.

AIM 7 - To assess the impact of land use changes on the water balance, within selected key catchments of the specified bio-climatic regions and at appropriate scales, with introduction of crops suitable for biofuel production.

AIM 8 - To develop a user-friendly, map-based software utility for the planning and management of biofuels in South Africa, drawing on findings from the specific aims listed above.

AIM 9 - To provide training opportunities for one post doctorate, two full-time PhD and five full-time MSc students. The principal researcher was also encouraged to obtain a PhD degree (part-time).

METHODOLOGY

With reference to **AIM 1** (to specify and prioritise feedstocks), the project was largely governed by the revised national biofuels industrial strategy, which was published by the former Department of Minerals and Energy in 2007. This strategy recommended two bioethanol feedstocks (i.e. sugarcane & sugarbeet) and three biodiesel feedstocks (i.e. soybean, canola & sunflower) for biofuel production. An inaugural symposium and workshop was held on 10th and 11th February 2010 respectively. One of the main objectives of the workshop was to identify key feedstocks for further investigation by the project team. Two feedstocks, namely sugarbeet and sweet sorghum, were highlighted for field-based research. These two crops were also recommended for further investigation in the biofuels scoping study report published in November 2009. From 2011 onwards, two potential biofuel manufacturers (i.e. Mabele Fuels & Arengo 316) expressed interest in grain sorghum. At a biofuels technical meeting held on 17th July 2012, the decision was made to measure the water use and yield of grain sorghum. Thus, the final list of prioritised crops was sugarcane, sugarbeet, sweet sorghum, grain sorghum, soybean and canola. Sunflower was not included and was replaced with grain sorghum, as agreed to at the reference group meeting on 23rd July 2014.

With reference to **AIM 2** (to evaluate and characterise feedstocks), information pertaining to, *inter alia*, crop parameters, water use and yield of the prioritised crops was gleaned from the field-based research as well as a thorough review of available literature (refer to Volume 2). The task highlighted the lack of information available for emerging feedstocks such as sugarbeet and sweet sorghum. Furthermore, surprisingly little information is also known about canola production in South Africa, which was unexpected.

AIM 3 is referred to as the mapping component of the project, with the modelling component involving **AIM 4** (water use modelling) and **AIM 5** (crop yield modelling). In order to derive parameters for certain feedstocks, field-based research was conducted at a number of research farms. The output from the modelling component of this project largely addressed **AIM 6** (estimation of water use efficiency) and **AIM 7** (hydrological impact of feedstock cultivation). In order to meet **AIM 8**, a software program called the Biofuels Assessment Utility was developed. Lastly, a number of students from the University of KwaZulu-Natal and the University of Pretoria worked on the project over its six-year time span (**AIM 9**). The methodology developed for each of these project components is summarised next.

Field work

Based on recommendations from the scoping study and the inaugural workshop, initial field work focused on the emerging feedstocks, in particular sugarbeet and sweet sorghum. Thus, field trials were established in the 2010/11 season to measure the water use and yield under optimal (i.e. no stressed) conditions of a) sweet sorghum at the Ukulinga (University of KwaZulu-Natal) and Hatfield (University of Pretoria) research farms, and b) sugarbeet (Ukulinga only).

The trials were repeated in 2011/12 to obtain two seasons of water use and yield data. In 2012/13, a third sugarbeet trial was undertaken at Ukulinga as well as research on grain sorghum (at Ukulinga and Hatfield). In the final season (2013/14), the grain sorghum trial at

Ukulinga was repeated and cost over R134 100, thus highlighting the expense of field work. Water use and yield data for soybean and yellow maize was derived by another WRC-funded project (No. K5/2066). A summary of the crop coefficients used to parameterise a hydrological model is provided in this report. The model was then used to assess the hydrological impact on downstream water availability that may result from biofuel feedstock cultivation.

Model selection

In this study, the *ACRU* agrohydrological modelling system was selected and used to estimate the water use of selected biofuel feedstocks. This daily time-step, process-based model was used to simulate runoff response for different land covers, as the sum of both storm flow and base flow. The *ACRU* model was selected to ensure compatibility with previous studies. Furthermore, the simulated runoff response from different land covers has been widely verified against observed runoff from different catchments.

In order to estimate the yield of each prioritised feedstock, the *AQUACROP* model was used. This model, developed by the FAO based in Rome (Italy), was selected because of its sensitivity to water stress. *AQUACROP* has already been parameterised for a number of biofuel feedstocks, including sugarcane, sugarbeet, grain sorghum, soybean and sunflower. In addition, a plug-in version exists which facilitates multiple (i.e. iterative) runs for estimating regional crop yield.

AQUACROP is ideally suited to assessing the impact of water availability on crop production for both irrigated and rainfed agriculture. Daily transpiration is multiplied by a water productivity parameter (which differentiates C_3 from C_4 plants) in order to calculate biomass production, which is then accumulated over the growing season. Crop yield is calculated as the product of accumulated biomass and the harvest index. Finally, nutrient deficiencies and salinity effects are simulated indirectly by moderating canopy cover development over the season, and by reducing, *inter alia*, crop transpiration.

Quinary sub-catchments

For operational decision making, the former Department of Water Affairs delineated South Africa into 22 primary drainage basins, each of which has been sub-divided into interlinked secondary, tertiary and quaternary (i.e. 4^{th} level) catchments. In total, 1 946 quaternary level catchments make up the contiguous area of southern Africa (i.e. RSA, Lesotho & Swaziland). Each quaternary has been assigned a single rainfall driver station deemed representative of the entire catchment area.

However, considerable physiographic heterogeneity exists within many of the quaternaries. For this reason, each catchment has been further sub-divided into three sub-catchments, according to altitude criteria. The upper, middle and lower quinaries of unequal area (but of similar topography) were sub-delineated according to “natural breaks”' in altitude by applying the Jenks optimisation procedure. This resulted in 5 838 quinary sub-catchments deemed to be more homogeneous than the quaternary catchments, in terms of their altitudinal range. In this study, the quinary sub-catchment (and not the quaternary catchment) was selected as the modelling and mapping unit. The quinary sub-catchments soils database contains soils information derived from land types developed by the former Soils and Irrigation Institute. The land types identified in each quinary were area weighted in order to derive one set of soils attributes (e.g. soil water retention parameters and soil depth) deemed to be presentative of the entire sub-catchment.

All model simulations were performed using the quinary sub-catchment climate database. This database contains 50 years (1950 to 1999) of daily climate data (rainfall, maximum temperature, minimum temperature & reference evaporation) deemed representative of each hydrological sub-catchment. The same rainfall station selected to drive each quaternary catchment was used to represent each of the three quinary sub-catchments. However, monthly adjustment factors were derived for each quinary and then applied to the daily rainfall record obtained from each quaternary rainfall driver station. In this way, a unique 50-year daily rainfall record was created for each of the 5 838 quinaries. The multiplicative adjustment factors were derived by first calculating spatial averages of all the one arc minute gridded median monthly rainfall values located within each quinary sub-catchment boundary. The ratio of these spatially averaged monthly rainfall totals to the driver station's median monthly rainfalls was then calculated to arrive at the 12 monthly adjustment factors.

A representative grid point location was chosen for each quinary sub-catchment. This was done by first calculating the mean altitude of each quinary from a 200 m Digital Elevation Model. Grid points located within a sub-catchment boundary at an altitude similar to the sub-catchment mean were then identified. From these, the grid point closest to the sub-catchment centroid was then selected to represent the quinary.

For each selected grid point, an algorithm was used to derive daily maximum and minimum temperature data from the two nearest temperature stations. A monthly lapse rate adjustment was applied to account for altitude differences between the nearest temperature stations and the altitude of the selected grid point. Daily data from each temperature station was weighted according to distance (i.e. from the grid point to each station). Daily temperature data generated for the selected grid point was then used to estimate solar radiation and relative humidity. From this, daily estimates of reference evaporation (Penman-Monteith or FAO56 equivalent) were derived assuming a default wind speed of 1.6 m s^{-1}.

Since *ACRU* uses the A-pan evaporimeter as its reference, FAO56-based reference evaporation was adjusted to A-pan equivalent evaporation using a monthly multiplicative factor which ranged from 1.17 to 1.37 (i.e. A-pan evaporation exceeds FAO56 evaporation by 17 to 37%). This adjustment was derived from the reciprocal of a pan factor, which was calculated for a green fetch of 200 m and an average daily wind speed was 1.6 m s^{-1}. The pan factor varied monthly according to mean monthly relative humidity estimates.

Revised climate database

In this study, the daily temperature dataset deemed representative of each quinary centroid was revised. The algorithm used to select two representative temperature stations for each grid point was modified. The improved algorithm considered both the distance and altitude difference between the neighbouring temperature stations. This modification allowed for the selection of stations slightly further away, but required a smaller altitude adjustment of temperature. The weighting factor was corrected to assign more influence to the "best" (but not necessarily the closest) station. Daily reference (FAO56) evaporation estimates were then calculated from the revised temperatures values. In addition, a different technique was used to calculate monthly adjustment factors to derive unscreened A-pan equivalent evaporation from FAO56-based reference evaporation. The technique was based on a modified version of the so-called "*PENPAN*" equation, which recently has been successfully applied in Australia to estimate A-pan equivalent evaporation. The adjustments suggest that A-pan equivalent evaporation exceeds FAO56 evaporation by a factor ranging from 17 to 51% for southern Africa. Hence, the revised quinary sub-catchment climate database contains improved temperature and evaporation estimates.

Water use modelling

The same methodology that has been established (and accepted) in South Africa to determine the potential impact of a land use change from natural vegetation on downstream water availability, was used in this study. In essence, the *ACRU* hydrological model was parameterised for natural vegetation and used to determine long-term mean annual runoff response for baseline (i.e. historical) conditions (MAR_{base}). The Acocks Veld Type map is used to represent natural vegetation or pristine conditions.

The *ACRU* model was then parameterised for each prioritised feedstock and used to estimate the runoff response for a 100% land cover change (MAR_{crop}). Model parameter values were gleaned from 1) field work undertaken as part of this study, and 2) an extensive review of available literature.

Hydrological impacts of land use change

The relative reduction in annual runoff (MAR_{redn}) that may result from the intended land use change was calculated as (MAR_{base} - MAR_{crop})/MAR_{base}, which was expressed as a percentage change. Positive MAR_{redn} values suggest that the intended land use change may result in less water being available to downstream users. An annual reduction of 10% or more was considered significant and used to identify feedstocks that may need to be declared as Stream Flow Reduction Activities or SFRAs.

Of more concern is the impact of land use change on stream flow during the low flow period. The start of the driest three-month period (or driest quartile) was determined using the monthly stream flow estimates produced by *ACRU* for the baseline (i.e. natural vegetation). This reduction in monthly runoff over driest quartile was then determined and expressed as a percentage relative to the baseline. If this percentage exceeded 25%, the land use change may also be considered a considered a SFRA.

Biofuels assessment utility

A PC-based software utility was developed to 1) disseminate stream flow output from the *ACRU* model, and 2) assess the impact on a land use change to feedstock cultivation on downstream water availability. This utility will mainly be used by the Department of Water and Sanitation to assess a feedstock's stream flow reduction potential in any quinary sub-catchment.

Crop yield modelling

Previous work on national yield modelling involved the use of simple empirically-based yield models, which could not account for, *inter alia*, the so-called “CO_2 fertilisation effect”. For example, the yield models developed by Barry Smith utilise monthly rainfall and temperature data to derive crop yield estimates. In this study, a unique approach was adopted which involved the use of a more complex, deterministic-based model to simulate crop yield at the national scale.

Due to the conservative nature of most of *AQUACROP*’s parameters, the model requires the “fine-tuning” of only a few parameters in order to provide realistic estimates of crop yield. For this project, the model was well calibrated for both sugarcane and sugarbeet, in order to better represent local growing conditions. Similarly, research conducted as part of another WRC Project (K5/2066) assisted with the calibration of soybean and yellow maize. For grain sorghum, the default crop parameter file was mainly used. Where possible, the calibrated model was validated using datasets for other locations that were not used in the calibration process.

The use of *AQUACROP* to derive estimates of crop yield at the national level involved linking the model to the quinary sub-catchment climate and soils database. Over 5 000 lines of computer code were written to facilitate and automate this process. Typical planting dates for each feedstock were obtained from a literature review. The model was used to estimate yield for each prioritised feedstock (some with two different planting dates) across all 5 838 quinary sub-catchments. This meant the model was run for areas not suited to crop growth (i.e. too cold and/or too dry), which caused *AQUACROP* to “crash”. The automation process was specifically designed to re-start the model run if such an event occurred.

A variety of maps were produced from output simulated by *AQUACROP* at the quinary sub-catchment scale for three bioethanol crops (sugarcane, sugarbeet & grain sorghum) and two biodiesel crops (canola & soybean). These maps included the mean and median seasonal yield as well as the inter-seasonal variation in yield. Similar maps were produced for crop water use efficiency. Other maps which show the number of years of simulated yield data and the risk of crop failure were also produced. Yield and water use efficiency derived using *AQUACROP* was then compared to that derived using the Soil Water Balance (*SWB*) model for certain quinaries located in the Western Cape.

Biofuel yield potential

The theoretical biofuel yield was estimated from the sugar, starch and seed oil content of feedstocks studied in the field. However, the stoichiometric yield of bioethanol or biodiesel is also dependent on the crop yield. To simply this calculation, the biofuel yield was also estimated from the product of the crop yield and the extraction rate. A table of biofuel extraction rates for selected feedstocks is presented in this report.

Land suitability mapping

For the biofuels scoping study, a literature review was undertaken to glean climate criteria for optimum crop growth. A geographic information system was then used to map areas climatically suited to optimum feedstock cultivation. This was achieved by applying the climatic thresholds to spatial datasets of rainfall and temperature. These spatial datasets were obtained from the South African Atlas of Climatology and Agrohydrology.

In this study, the literature review was expanded to include new reference material not used in the scoping study to glean growth criteria for each crop. In addition, three additional site criteria were considered for mapping. For example, relative humidity was incorporated as an index of disease incidence. Soil depth and slope were used to eliminate shallow soils and steep slopes, which are not deemed suitable for crop production. Each site factor was weighted accordingly to indicate its overall influence on crop survival, with rainfall deemed twice as important as temperature and slope (and four times more important than relative humidity and soil depth).

A number of improvements were made to the mapping approach used in the scoping study. For example, a unique method was used to consider the timing of monthly rainfall across the growing season. The water use coefficient was used to determine in which month the crop's water requirement peaks. Similarly, more weighting was assigned to relative humidity criteria in the months where disease outbreak is more probable. The mapping approach also considered existing land use and land cover, in order to eliminate "no-go" crop cultivation areas (i.e. urban areas, water bodies and areas formally protected for their high biodiversity value).

RESULTS AND DISCUSSION

From the field work component of this project, the following information was generated for selected bioethanol feedstocks:

- Water use over the growing season, defined as accumulated total evaporation (i.e. actual evapotranspiration) measured under stress-free growing conditions.
- Final crop yield and sugar content of sugarbeet and sweet sorghum.
- Final crop yield and starch content of grain sorghum.
- Theoretical bioethanol yield derived from crop yield and sugar/starch content.
- Water use efficiency, defined as crop yield per unit water use.
- Biofuel use efficiency, or the theoretical biofuel yield per unit water use.

From WRC Project No. K5/2066, the above information was included for soybean and yellow maize. Using the available information, this list of feedstocks were ranked in terms of water use efficiency and biofuel use efficiency. The results show that sugarbeet is most water use efficient in terms of producing "more crop per drop", whilst grain sorghum is least efficient. However, in terms of biofuel use efficiency, yellow maize is the most efficient at producing more biofuel per unit of water consumed by the crop, with soybean regarded as the least efficient.

The primary outputs generated from the modelling of water use, and thus available for each of the 5 838 quinary sub-catchments, include the following:

- Estimates of daily, monthly and annual stream flow response from natural vegetation.
- Estimates of daily, monthly and annual stream flow response from a land cover of selected biofuel feedstocks.

- Maps highlighting quinaries in which a reduction in mean annual runoff of 10% or more may occur for selected feedstocks.
- Maps highlighting quinaries where a 25% or larger reduction in monthly runoff may occur during the low flow period.
- The shift in low flow period that may result from a land cover change from natural vegetation to the intended feedstock.

Based on *ACRU*'s simulated runoff output, canola is least likely to cause a significant (i.e. ≥ 10%) reduction in water available to downstream users, whereas sugarcane exhibits the highest SFR potential (i.e. highest crop water use). Few quinaries were flagged where a significant (i.e. ≥ 25%) reduction in monthly runoff accumulated over the low flow period may occur. However, all feedstock crops have the potential to shift the start of the low flow quartile (i.e. driest three months of the year), when compared to that for natural vegetated conditions. Hence, the reduction in flow flows may be exacerbated by this shift in "seasonality".

From the crop yield modelling, the following information is available for each of the 5 838 quinary sub-catchments for rainfed conditions:

- seasonal estimates of yield and water use efficiency for selected feedstocks,
- long term attainable yield and water use efficiency (mean and median),
- inter-seasonal variation in crop yield and water use efficiency,
- risk of crop failure, defined as the probability of a seasonal yield of zero dry tons per hectare,
- number of seasons of simulated yield and water use efficiency data, and
- length of the growing season.

The maps show that sugarcane is most water use efficient when produced along the coastal areas of KwaZulu-Natal and the Eastern Cape. Similarly, canola is most water use efficient when grown in the Western Cape region. Using the average crop yield estimate for a particular quinary, the biofuel yield potential can be determined using representative extraction rates. The results indicate that bioethanol feedstocks require much less arable land than biodiesel feedstocks to produce 1 000 m^3 of biofuel.

Land suitability maps were produced for sugarcane, sugarbeet, grain sorghum, soybean and canola. For certain feedstocks, the areas highlighted as highly suitable for crop production do not necessarily correspond to quinary sub-catchments exhibiting high crop yields. The results show a significant (i.e. ≈50%) reduction in the area considered suitable for soybean production when compared to the map published in the scoping study report. The cultivation of sugarbeet planted in winter will likely require supplemental irrigation. The canola map does not identify suitable production areas in the Free State, where cultivation is possible under rainfed conditions during the winter months.

INTERPRETATION OF RESULTS

With regard to assessing the stream flow reduction potential of a particular feedstock, the mean and not median runoff statistic should be used. In terms of quantifying the long-term attainable yield for a particular location, the median statistic is recommended and not the mean.

Although WUE is highly influenced by environmental factors that affect crop growth (e.g. cultivar choice, planting date, plant density etc.), the metric shows potential for highlighting optimum *vs*. sub-optimum growing areas. However, if used as a standalone metric, it can be easily misinterpreted. Hence, it is recommended that WUE is considered in relation to the expected yield for a particular location.

CONCLUSIONS

It is important to note that research priorities changed over the project's duration due to, *inter alia*, policy amendments and new developments pertaining to South Africa's biofuels industry. For example, field work and modelling efforts shifted focus to grain sorghum, which was not considered a prioritised feedstock at the outset of the project. Nevertheless, the project contributed to the generation of new knowledge as follows:

- Monthly crop coefficients were derived for prioritised feedstocks that are deemed representative of local conditions.
- These crop coefficients were used to improve estimates of the hydrological impact of feedstock production on downstream water availability.
- The crop coefficients were also used to determine the optimum distribution of monthly rainfall over the growing season.
- A land use change to feedstock cultivation may cause a possible shift in the low flow period, which was highlighted as another potential impact on downstream water users.
- The land suitability maps provide more realistic estimates of the total land area deemed suitable for feedstock cultivation.
- The use of a deterministic-type crop model to derive estimates of attainable yield and water use efficiency at a national scale represents a major contribution to the existing knowledge base on agricultural production potential.
- Thus, the mapping and crop yield modelling approaches developed for this project are considered unique and innovative.

Using a hydrological simulation model, the potential impact on catchment water resources of large scale land use change to feedstock cultivation was assessed. In addition, a crop water productivity model was used to provide estimates of attainable yield for selected feedstock crops at the national scale. Water use efficiency (WUE = yield per unit of crop water use) was then calculated for each hydrological sub-catchment across the country. It is envisaged that the project outcomes will benefit end-users in the following manner:

- The Department of Water and Sanitation will utilise the large database of monthly and annual runoff simulations to assess the stream flow reduction potential of selected feedstocks in any quinary sub-catchment.
- The biofuel manufacturers will utilise the land suitability and crop yield maps to identify and target areas where feedstock should be cultivated.
- Agricultural extension officers will also find the crop yield maps useful for advising emerging farmers on which crop is best suited to their location.
- The Department of Energy could utilise the information to revise the country's biofuel production potential.
- WUE estimates for each biofuel feedstock may assist land use planners in striving towards the most beneficial use of available water resources.

Crop water use is incorporated into most standards that have been developed to measure agriculture sustainability. However, various metrics are used to assess this. In general, water use in agriculture usually means the total volume of rain water consumed by the crop (i.e. green water component of the "water footprint" concept), or the volume of surface water or ground water applied as irrigation (i.e. blue water component).

The results from this study highlight the diverse range in feedstocks when ranked according to their biofuel yield potential per unit land area (i.e. "land footprint") or per unit water use (i.e. "water footprint"). The output from this comprehensive six-year study has confirmed that water availability and not land availability, will limit South Africa's biofuel production potential. The environmental impact of biofuel feedstock production depends on the mix of feedstocks used to meet the volume targets set by the mandatory blending rates.

RECOMMENDATIONS FOR FUTURE RESEARCH

Owing to the high cost of field experimentation, the study of emerging crops, where best agronomic practices aren't well established, is not recommended. The variability in seasonal estimates of water use efficiency derived from measurements for both sugarbeet and sweet sorghum highlight this point.

The threshold of 25% currently used to assess a significant reduction in monthly runoff over the low flow period may be too high and needs to be re-assessed. The shift in low flow period is cause for concern and should be factored into the assessment of a feedstock's potential to be declared a stream flow reduction activity.

Considerable effort is required to develop a land suitability map for a particular feedstock. Output (in particular yield and WUE) from the crop modelling component should be used as input for the mapping approach in order to improve the assessment of land suitability.

Canola was incorrectly identified as a feedstock where sufficient knowledge exists for modelling feedstock water use and yield. It is recommended that the water use and yield of canola is measured in the field to improve the current lack of knowledge pertaining to this crop. Furthermore, canola's land suitability map should be revised by modifying the rainfall thresholds in an attempt to identify suitable growing areas in the eastern parts of the Free State.

It is recommended that the stream flow database required by the biofuels assessment utility is distributed to end-users on DVDs. However, updates should be distributed via the internet using SAEON's data portal.

It is envisaged that a number of end-users will request output in a GIS-compatible format. To facilitate such requests, it is recommended that such data are made available for download via the internet from SAEON's data portal.

It is envisaged that the recommendations for future work which emanated from this project, will guide a follow-up study that was initiated and funded by the WRC. This five-year project (No. K5/2491 titled "Water use of strategic biofuel crops") began in April 2015 and will terminate in March 2020.

EXTENT TO WHICH OBJECTIVES WERE MET

The project was required to specify and prioritise currently grown and potential alternative first and second generation crops (**AIM 1**). In this study, no research effort was focused towards 2nd generation feedstocks. Although Napier grass was initially flagged as a potential second generation feedstock, it would be prohibited for use in biofuel production if draft regulations pertaining to alien invasive plants are promulgated. With reference to **AIM 2** (i.e. to evaluate and characterise feedstocks), information pertaining to, *inter alia*, crop parameters, water use and yield of the prioritised crops was gleaned from the field-based research as well as a thorough review of the available literature.

The terms of reference of this project required the estimation of water use of feedstocks suitable for bioethanol and biodiesel production in selected high and low potential bio-climatic regions of South Africa. For example, **AIM 7** required the impact of land use change on the water balance of selected key catchments to be assessed. In this study, feedstock water use was modelled for all regions across South Africa. The approach taken to run the models for all quinaries and not a subset of quinaries where the crop may grow (i.e. based on the land suitability map) provides the following advantages:

- The national yield maps can be used to validate and improve the land suitability maps, especially since the latter maps differentiate low from high potential production areas.
- It avoids the scenario where additional model runs may be required in the future to generate data for "missing" quinaries, which were not highlighted as suitable growing areas for a particular feedstock.

Two simulation models were used to provide estimates of crop water use (**AIM 4**) and yield (**AIM 5**) at the national scale, for multiple feedstocks and planting dates. The time and effort required to complete this computationally complex task meant that the following specific aims were not met:

- The biofuel yield potential of crops in the respective bio-climatic regions (**AIM 5**) was not mapped.
- Similarly, the biofuel yield per unit of water used over the full productive cycle (**AIM 6**) was not mapped.
- The modelling was undertaken for rainfed conditions and thus, no work was conducted for irrigated crops (**AIM 5**).

With reference to **AIM 6**, water use efficiency was defined as the utilisable crop yield (and not the biomass yield) per unit of water utilised over the full productive cycle. With reference to **AIM 3**, the availability of groundwater resources was considered in the mapping approach to identify suitable crop production areas.

Regarding **AIM 8**, a map-based software utility originally developed in 2009 to assess the stream flow reduction potential of commercial afforestation (called the SFRA Assessment Utility), was modified to meet the needs of this project. Significant improvements were made to the utility, with additional functionality added.

AIM 9 refers to capacity building which is discussed further in the section that follows. In summary, the project did not meet the envisaged target of graduating five MSc and two PhD students.

CAPACITY BUILDING AND TECHNOLOGY TRANSFER

Finally, at the outset of this project, it was envisaged that two full-time PhD and five full-time MSc students would obtain their degrees through this project. To date, only two MSc students have graduated. However, two part-time students (one MSc and a PhD) are currently in the process of finalising their write-ups.

Over the six-year project duration, numerous presentations were given to both local and international audiences. The project benefitted from the knowledge gained at the Bioenergy Australia conference in 2011. In addition, the project gained exposure at the World Biofuels Markets conference at Rotterdam in 2013.

A poster was presented at SANCIAHS in 2012 and a paper at SANCIAHS in 2014. A paper was also presented at the World Soybean Research Conference in 2013 and at the SASTA Congress in 2014. Presentations were also given at the WRC research symposiums in 2011, 2013 and 2015.

Two symposiums and workshops were also organised as part of the project. The inaugural symposium and workshop took place in February 2010, with a follow-up symposium and workshop held in January 2013. The latter resulted in two popular articles which appeared in the Farmers Weekly and Landbou Weekblad magazines in February and March 2013 respectively. A popular article was published in the Water Wheel in the March/April 2014 edition as well as an online article on Engineering News in May 2014. The project was also mentioned in an article published in the Mercury newspaper on 27th March 2014. Finally, a paper emanating from the project on the water use efficiency of sweet sorghum was published in Water SA in January 2016.

DATA AND TOOLS

The project has generated over 1 000 gigabytes (Gb) of compressed model output pertaining to the national water use and crop yield simulations. In addition, high frequency measurements of air temperature used to estimate crop water use via the surface renewal method was also generated. The biofuels assessment utility will be used to disseminate a large database (i.e. ≈43.3 Gb) of daily stream flow simulations for natural vegetation as well as selected feedstocks. All raw and processed data is stored and archived on a fileserver located in the ICS Server Room on the main campus of the University of KwaZulu-Natal in Pietermaritzburg. All project-related data and information was backed up to an external hard drive to be stored for the next five years. Contact person: Richard Kunz (kunzr@ukzn.ac.za).

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LIST OF ABBREVIATIONS

ACCI	African Centre for Crop Improvement
ACRU	Agricultural Catchments Research Institute
AgMIP	Agricultural Model Intercomparison and Improvement Project
AET	Actual EvapoTranspiration
APAN	USWB Class A evaporimeter
ARC	Agricultural Research Council
ARDA	Agrarian Research and Development Agency
ASCE	American Society of Civil Engineers
AWS	Automatic Weather Station
B5	5% biodiesel blend
BEEH	Bioresources Engineering and Environmental Hydrology (former)
CEC	Crop Estimates Committee
CARA	Conservation of Agricultural Resources Act
CGI	Crop Grains Institute or the ARC
CN	Curve Number
CNW	CaNola Winter
CO_2/CO2	Carbon Dioxide concentration
COMPETE	Competence Platform on Energy Crop and Agroforestry Systems for Arid and Semi-arid Ecosystems
cpl	cents per litre
CRBD	Completely Randomised Block Design
CSIR	Council for Scientific and Industrial Research
CSV	Comma Separated Values
CWRR	Centre for Water Resources Research
DAFF	Department of Agriculture, Forestry and Fisheries
DAP	Days After Planting
DDGS	Distiller's Dried Grains and Solubles
DoA	Department of Agriculture (former)
DoE	Department of Energy
DEAT	Department of Environmental Affairs and Tourism
DRDLR	Department of Rural Development and Land Reform
DME	Department of Minerals and Energy (former)
DST	Department of Science and Technology
DUL	Drained Upper Limit
DWA	Department of Water Affairs (former)
DWAF	Department of Water Affairs and Forestry (former)
DWS	Department of Water and Sanitation
E2	2% bioethanol blend
E3	3% bioethanol blend
E8	8% bioethanol blend
E10	10% bioethanol blend
EMA	Expectation Maximisation Algorithm
ESRI	Environmental Systems Research Institute
ET	EvapoTranspiration

EVS	Early Vegetative Stage
EWRI	Environmental and Water Resources Institute
FAO	Food and Agriculture Organisation of the United Nations
FAO56	Food and Agriculture Organisation, Paper No. 56
FAOSTAT	FAO STATistics
GAIN	Global Agricultural Information Network
GDD	Growing Degree Day
GDP	Gross Domestic Product
FC	Field Capacity
GTZ	German Technical Cooperation
FDR	Frequency Domain Reflectometry
GIS	Geographic Information System
GRS	GRain Sorghum
HI	Harvest Index
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
INTSORMIL	INTernational SORghum and MILlet Collaborative Research Support Program
IDC	Industrial Development Corporation
IoA	Index of Agreement
ISCW	Institute for Soil, Climate and Water
LAI	Leaf Area Index
LFR	Low Flow Runoff
LVS	Late Vegetative Stage
MAE	Mean Absolute Error
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff (or stream flow)
MdAR	Median Annual Runoff (or stream flow)
masl	metres above sea level
MAT	Mean Annual Temperature
NLC	National Land Cover
NDA	National Department of Agriculture
NPAES	National Protected Area Expansion Strategy
NWA	National Water Act
OEM	Original Equipment Manufacturer
PAR	Photosynthetically Active Radiation
PAW	Plant Available Water
PENPAN	Penman-type equation to estimate A-pan equivalent evaporation
PWP	Permanent Wilting Point
RCBD	Randomised Complete Block Design
REW	Readily Evaporable Water
RISKMAN	Risk Manager
RMSE	Root Mean Square Error
RUE	Radiation Use Efficiency
SAAMIIP	Southern Africa Agricultural Model Intercomparison and Improvement Project

SACU	Southern African Customs Union
SADC	South African Development Community
SAEON	South African Environmental Observation Network
SANBI	South African National Biodiversity Institute
SANCID	South African National Committee on Irrigation and Drainage
SAPIA	South African Petroleum Industry Association
SAS	Statistical Analysis System (Institute)
SASA	South African Sugar Association
SASRI	South African Sugarcane Research Institute
SAT	Semi-Arid Tropics
SBS	SugarBeet Summer
SBW	SugarBeet Winter
SCA	SugarCAane
SCWG	Soil Classification Working Group
SFR	Stream Flow Reduction
SFRA	Stream Flow Reduction Activity
SIRI	Soil and Irrigation Research Institute (former)
SLA	Specific Leaf Area
SLS	Surface Layer Scintillometry
SMRI	Sugar Milling Research Institute
SPH	Stems Per Hectare
SSH	Sweet Sorghum Hatfield
SSU	Sweet Sorghum Ukulinga
SNF	SuNFlower
SWB	Soil Water Balance
SYB	SoYBean
TAW	Total Available Water
TC	ThermoCouple
TDR	Time Domain Reflectometry
TFS	Total Fermentable Sugars
TPO	Total POrosity
UKZN	University of KwaZulu-Natal
UP	University of Pretoria
USA	United States of America
USDA	United States Department of Agriculture
USDoE	United States Department of Energy
USGS	United States Geological Survey
USWB	United States Weather Bureau
VEGMAP	National Vegetation Map of South Africa Project
VPD	Vapour Pressure Deficit
WAS	Water Administration System
WBGU	German Advisory Council on Global Change
WGS	World Geodetic System
WP	Water Productivity
WRC	Water Research Commission
WUE	Water Use Efficiency

LIST OF SYMBOLS

Roman Symbols (lowercase)

a	constant in *PENPAN* equation (2.4)
a	amplitude used in calculation of sensible heat H
c	velocity of the electromagnetic signal in free space (m s^{-1})
c_p	specific heat capacity of air (J kg^{-1} $^oC^{-1}$)
c_s	specific heat capacity of soil (J kg^{-1} $^oC^{-1}$)
c_{ds}	specific heat capacity of dry soil (J kg^{-1} $^oC^{-1}$)
c_w	specific heat capacity of water (J kg^{-1} $^oC^{-1}$)
d	root depth (cm)
e_a	actual vapour pressure (kPa)
e_s	saturated vapour pressure (kPa)
e_s - e_a	vapour pressure deficit (kPa)
k	thermal diffusivity of the wood (cm^2 s^{-1})
l_{ij}	length of the soil material between ports i and j (cm)
p	depletion fraction
r^2	coefficient of determination
r_s	surface resistance (s m^{-1})
u	daily averaged wind speed at height 2 m (m s^{-1})
u_2	daily averaged wind speed at height 2 m (m s^{-1})
u_*	wind friction velocity (m s^{-1})
v_1	increases in temperature of downstream probe (^oC)
v_2	increases in temperature of upstream probe (^oC)
w'	fluctuation from the mean of the vertical wind speed (m s^{-1})
x	distance between the heater and either temperature probe (cm)
z	measurement height of sonic anemometer (m)
z	elevation in masl

Roman Symbols (uppercase)

A	altitude (degrees decimal; always positive)
A	total cross-sectional area of the column (cm^2)
ALTF	altitude factor (m)
C	cloudiness (oktas)
D	Index of Agreement
D	vapour pressure deficit (kPa)
D	drainage (mm)
DSTF	distance factor (minutes of a degree)
E	total evaporation (mm day^{-1})
E_a	aerodynamic term of Penman-type equation (mm $month^{-1}$)
E_p	unscreened A-pan equivalent evaporation using *PENPAN* method (mm $month^{-1}$)
E_{pp}	screened A-pan equivalent evaporation (mm $month^{-1}$)
E_m	maximum evaporation (mm day^{-1})
E_r	reference evaporation (mm day^{-1})

E_{sm}	maximum soil water evaporation (mm)
E_{tm}	maximum crop transpiration (mm)
ET	actual evapotranspiration (mm) accumulated over growing season
ET_a	actual evapotranspiration (mm day^{-1})
ET_c	crop evapotranspiration (mm day^{-1})
ET_m	maximum evapotranspiration (mm day^{-1})
ET_o	reference crop (grass) evaporation using FAO56 method (mm day^{-1})
ET_p	potential evapotranspiration (mm day^{-1})
ET_r	reference crop (alfalfa) evaporation using ASCE-EWRI method (mm day^{-1})
F	term used to calculate H
FE	fermentation efficiency (%)
FI_{PAR}	fraction of photosynthetically active radiation intercepted by the canopy
FD	fetch distance (m)
G	soil heat flux density (MJ m^{-2} day^{-1})
G_{plate}	energy flux measured using the soil heat flux plates (MJ m^{-2} day^{-1})
G_{store}	energy flux stored in soil above heat flux plates (MJ m^{-2} day^{-1})
GDD	growing degree days (day ºC)
H	Linacre's augmentation radiation term
H	sensible heat flux (W m^{-2})
H_i	total hydraulic head at port i (cm)
H_j	total hydraulic head at port j (cm)
I	irrigation (mm)
K_a	apparent dielectric constant
K_c	crop coefficient (or water use coefficient)
$K_{c\ end}$	end-season crop coefficient
$K_{c\ ini}$	initial-season crop coefficient
$K_{c\ mid}$	mid-season crop coefficient
K_{cb}	basal crop coefficient
K_p	pan coefficient (or pan factor)
Ks_{ij}	saturated hydraulic conductivity of the soil between port i and j (cm s^{-1})
L	waveguide or probe length (m)
L_{dev}	length of the crop development stage (fraction)
L_{end}	length of the end-season stage (fraction)
L_{ini}	length of the initial-season stage (fraction)
L_{mid}	length of the mid-season stage (fraction)
L_a	apparent probe length (m)
M_s	dry mass of soil core (g)
MAE	mean absolute error (%)
MAR	mean annual runoff (mm day^{-1} or mm month^{-1})
MAR_{base}	mean annual runoff from the baseline land cover (mm day^{-1} or mm month^{-1})
MAR_{crop}	mean annual runoff from the crop surface (mm day^{-1} or mm month^{-1})
MAR_{org}	mean annual runoff determined using original quinary climate database (mm day^{-1} or mm month^{-1})
MAR_{rev}	mean annual runoff determined using revised quinary climate database (mm day^{-1} or mm month^{-1})
$MdAR$	median annual runoff (mm day^{-1} or mm month^{-1})
N	number of observations or measurements

P	atmospheric pressure (kPa)
P	precipitation (mm)
P	term used to calculate H
PAW	plant available water (m m^{-1} or vol %)
Q	volumetric outflow rate (cm^3 s^{-1})
R	runoff (mm)
R^2	coefficient of determination
R_a	extra-terrestrial solar radiation (MJ m^{-2} day^{-1})
R_{max}	total seasonal rainfall threshold (mm), above which the crop dies
R_{min}	total seasonal rainfall threshold (mm), below which the crop dies
R_{np}	net energy available to an A-pan (W m^{-2})
R_{nr}	net energy available to a short grass surface (W m^{-2})
R_{ns}	net solar radiation (MJ m^{-2} day^{-1})
R_s	incoming solar radiation (MJ m^{-2} day^{-1})
R_{so}	clear-sky solar radiation (MJ m^{-2} day^{-1})
R_n	net radiation (MJ m^{-2} day^{-1})
R_{nl}	net longwave radiation (MJ m^{-2} day^{-1})
$RANK$	temperature station ranking (fraction)
RH_{ave}	mean monthly relative humidity (%)
RH_{max}	daily maximum relative humidity (%)
RH_{min}	daily minimum relative humidity (%)
RMSE	root mean square error
RMSEs	systematic RMSE
RMSEu	unsystematic RMSE
S	soil water storage (mm)
T	daily air temperature (°C)
T_{ave}	average air temperature (°C)
T_{bse}	crop base temperature (°C), i.e. lower threshold temperature when crop development ceases
T_{upp}	upper threshold temperature when crop development ceases (°C)
T_a'	fluctuation of air temperature from the mean (°C)
T_s	soil temperature (°C)
T_c	crop transpiration (mm day^{-1})
T_d	daily dew point temperature (°C)
T_{dew}	monthly dew point temperature (°C)
T_{max}	daily maximum air temperature (°C)
T_{min}	daily minimum air temperature (°C)
T_*	temperature scale of turbulence (°C)
V_h	heat pulse velocity (cm hr^{-1})
V_s	volume of each soil core (cm^3)
WUE_{obs}	observed waster use efficiency (kg m^{-3})
WUE_{sim}	simulated waster use efficiency (kg m^{-3})
Y	root fraction
Y	crop yield (dry kg ha^{-1})
Y_a	actual crop yield (dry kg ha^{-1})
Y_m	maximum crop yield (dry kg ha^{-1})

Greek Symbols

α	correction or weighting factor
α	albedo of evaporating surface (fraction)
α_s	albedo of surface surrounding the A-pan (fraction)
Δ	slope of the vapour pressure curve (kPa °C^{-1})
γ	psychrometric "constant" (kPa °C^{-1})
λ	latent heat of vapourisation (MJ kg^{-1} or MJ kg^{-1})
λ	inverse of the slope of the logarithmic tension-moisture curve
λE	latent energy flux λE (W m^{-2} or J s^{-1} m^{-2})
Φ	porosity of the soil (fraction)
ρ_a	density of air (kg m^{-3})
ρ_b	bulk density of the soil (kg m^{-3})
ρ_s	bulk density of the soil (kg m^{-3})
ρ_w	density of water (kg m^{-3})
τ	inverse ramp frequency used in calculation of sensible heat *H*
θ_{DUL}	soil water content at the drained upper limit (m m^{-1} or vol %)
θ_{PWP}	soil water content at the permanent wilting point (m m^{-1} or vol %)
θ_{TPO}	soil water content at total porosity, i.e. saturation (m m^{-1} or vol %)
θ_v	volumetric soil water content (m^3 m^{-3})

***ACRU* parameters and variables**

CAY	monthly crop coefficient (K_c)
CELRUN	stream flow generated from the sub-catchment, including the contribution from all upstream sub-catchments (mm day^{-1} or mm $month^{-1}$)
COFRU	base flow recession constant (set to 0.009)
COIAM	coefficient of initial abstraction
COLON	monthly fraction of root colonisation of the B-horizon
CONST	fraction of plant available water at which total evaporation is assumed to drop below maximum evaporation (i.e. the onset of plant water stress)
CORPPT	monthly precipitation adjustment factors (e.g. to account for differences in monthly rainfall between the selected driver station and spatially averaged estimates for the sub-catchment)
CORPAN	monthly APAN adjustment factors (e.g. to adjust Penman-Monteith evaporation estimates to APAN equivalent evaporation)
EFRDEP	effective soil depth for colonisation by plant roots
EVTR	determines whether transpiration and soil water evaporation are calculated as separate components (*EVTR*=2) or combined (*EVTR*=1)
IRUN	determines if base flow contributes to stream flow
PCSUCO	monthly fractions (expressed as a %) of the soil surface covered by crop residue
ROOTA	monthly fraction of roots in the A-horizon
RUNCO	base flow store (mm)
SIMSQ	stream flow generated from the sub-catchment (mm day^{-1} or mm $month^{-1}$)
SMDDEP	effective soil depth (in m) from which storm flow generation takes place (set to topsoil depth)
QFRESP	storm flow response fraction for the catchment (set to 0.30)

VEGINT	monthly interception loss (mm rainday^{-1})

AQUACROP parameters and variables

B	biomass production (kg m^{-2})
BIO	above-ground biomass produced (t ha^{-1})
CC_o	initial canopy cover at emergence (%)
CC_{pot}	potential canopy cover under non-limited growing conditions (%)
CC_x	maximum canopy cover reached (%)
CN	curve number
CFA	number of crop failures
CO2	monthly ambient CO_2 concentration (ppm)
CYC	length of crop cycle from germination to peak yield (days)
DRA	amount of water drained out of the soil profile (mm)
E	soil water evaporation (mm)
ETC	total amount of water evapotranspired from the crop (mm)
ETR	monthly reference evaporation (mm)
D_r	root zone depletion (mm)
GDD	growing degree days accumulated for month (°C day)
GRO	length of growing season (days)
HI	harvest index
HI_o	reference harvest index
HID	harvest index (%)
INF	amount of water infiltrated into the soil profile (mm)
IRR	amount of water applied as irrigation (mm)
K_s	stress coefficient
K_y	yield response factor
K_{SAT}	saturated hydraulic conductivity (mm h^{-1} or mm d^{-1})
PGDP	Provincial Growth and Development Plan
PMS	potential maximum storage (mm)
RAI	monthly rainfall (mm)
REW	readily evaporable water (mm)
RUN	amount of water lost to surface runoff (mm)
SEA	total number of seasons simulated by the model
SOI	amount of water evaporated from the soil surface (mm)
StExp	level of water stress that reduces leaf expansion (%)
Tn	daily minimum air temperature (ºC)
Tr	transpiration (mm)
TRA	amount of water transpired from the crop surface (mm)
Tx	daily maximum air temperature (ºC)
UPF	amount of water moved upward by capillary rise (mm)
W_r	equivalent water depth (m)
WP	water productivity parameter (kg m^{-2} mm^{-1})
*WP**	normalised water productivity (kg m^{-2})
WPM	water use efficiency at maturity (kg m^{-3})
WPY	water use efficiency when yield peaks (kg m^{-3})
YLD	dry crop yield (t ha^{-1})

Z_{eff}	effective rooting depth (m)
Z_{min}	minimum rooting depth (m)
Z_{max}	maximum rooting depth (m)

SWB parameters and variables

CDM	canopy dry matter yield (kg m^{-2} or t ha^{-1})
DM	dry matter production (g m^{-2})
DWR	dry matter water ratio (Pa)
E_c	radiation conversion efficiency (MJ^{-1})
FI or FI_s	fraction of intercepted solar radiation
H_c	mean maximum plant height during the period of calculation (m)
$K_{c\ max}$	maximum crop coefficient value following rain or irrigation
K_s	canopy radiation extinction coefficient for solar radiation
HDM	harvestable dry matter yield (kg m^{-2} or t ha^{-1})
LAI	leaf area index (m^2 m^{-2})
PT	potential transpiration (mm)
LDM	leaf dry matter yield (kg m^{-2})
R_s	daily total solar radiation (MJ m^{-2})
SDM	stem dry matter yield (kg m^{-2})
SLA	specific leaf area (m^2 m^{-2})
TDM	total dry matter yield (kg m^{-2} or t ha^{-1})
VPD	vapour pressure deficit (Pa)

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1 INTRODUCTION

1.1 Background and Rationale

South Africa is following the international trend of liquid biofuel production, as noted in the South African Biofuels Industrial Strategy of 2007 (DME, 2007a). This strategy highlighted the benefits of biofuel production in terms of alleviating poverty in rural areas, promoting rural economic development and stimulating agricultural production. A 2% blend of biofuels in the national liquid fuel supply, equivalent to an annual production of approximately 400 million litres of biofuel, was proposed by the former Department of Minerals and Energy (DME, 2007a). The strategy aimed to replace 240 million litres of petrol with bioethanol made from sugarcane and sugarbeet (Mbohwa and Myaka, 2011), as well as the production of 160 million litres of biodiesel from sunflower, canola and soybean. To ensure sustainable biofuel production, South Africa plans to grow feedstock on currently under-utilised arable land and preferably under rainfed conditions.

In 2006, the task team that developed the biofuels strategy urged the government to determine the impacts of biofuel feedstock production on both water quality and water quantity (DME, 2006a). The Water Research Commission (WRC) responded to this request and funded a two-year (2007-2009) scoping study on the water use of biofuel feedstocks. The study was conducted by the former School of Bioresources Engineering and Environmental Hydrology (BEEH), based at the University of KwaZulu-Natal (UKZN) in Pietermaritzburg. The main aims of the scoping study were to 1) identify suitable feedstock for the production of biofuel, 2) map areas climatically suited to feedstock cultivation, 3) determine the available knowledge on feedstock water use, 4) model the water requirements of selected feedstock, and 5) identify existing knowledge gaps around feedstocks.

In November 2009, the WRC published the scoping study report on the water use of potential biofuel feedstocks (Jewitt *et al*., 2009a). The report identified 20 crops which may be utilised for biofuel production in South Africa. The water use of selected feedstocks was then simulated using the *ACRU* hydrological model developed by Schulze (1995). Of these, two feedstocks (sweet sorghum and sugarcane) may have the potential to use substantially more water than the reference natural vegetation. However, the scoping study highlighted that for the emerging feedstocks (e.g. sugarbeet & sweet sorghum), parameter values were gleaned from the international literature. The literature also provided conflicting water use figures for certain feedstocks (in particular sweet sorghum) and that knowledge is surprisingly limited for certain crops (e.g. canola). The scoping study recommended a need to better understand the water use and yield of biofuel feedstocks. In addition, a more detailed mapping approach was required to identify feedstock growth areas that considered additional site factors, i.e. not just rainfall and temperature feedstocks (Jewitt *et al*., 2009a). Based on these recommendations, the WRC initiated and funded a six-year (i.e. more comprehensive) follow-up study (WRC, 2010).

In November 2008, the WRC initiated and funded a second, more detailed project entitled: "Water use of cropping systems adapted to bio-climatic regions in South Africa and suitable for biofuel production". This funding totalled R7.4 million and the project commenced in April 2009, with termination in March 2015. The This six-year solicited project was awarded to the Centre for Water Resources Research (CWRR; previously called BEEH) at UKZN, who partnered with the University of Pretoria (UP) and the Council for Scientific and Industrial Research (CSIR). The aims of this follow-up study were broadly similar to those of the scoping study, except for the need to estimate crop yield and biofuel yield.

1.2 Project Objective and Aims

The overall objective of this project was to determine the water use of selected biofuel feedstocks deemed suitable for bioethanol and biodiesel production in selected high and low potential bio-climatic regions of South Africa. The specific aims of the project were as follows:

AIM 1 - To specify and prioritise currently grown and potential alternative first and second generation crops and cropping systems including both annual and perennial crops/trees with attention to, amongst others:

- Crops and crop rotations for food and forage production,
- Crops and crop rotations for biofuel production,
- Multiple use systems e.g. food, fodder and fuel crop combinations,
- Monoculture high density crop production systems,
- Tree feedstocks in plantations, agro-forestry or alley cropping systems, and
- Cellulosic feedstocks.

AIM 2 - To review and characterise crop parameters, water use and yield (biomass, biofuel and by-products) of crops based on existing knowledge or estimation thereof by applying existing tools with reference to those prioritised in South Africa and those which have potential as alternative biofuel crops as identified above.

AIM 3 - To identify and describe bio-climatic regions suitable for these priority crop/tree systems for biofuel production with reference to, amongst others:

- Rainfall average and variability,
- Surface and underground water resources,
- Temperature average and extremes,
- Soil properties,
- Known pests and diseases, and
- Topography.

AIM 4 - To determine crop parameters and model water use of specific crops/trees for biofuel that have potential but insufficient knowledge exists in South Africa to promote effective production.

AIM 5 - To determine the biofuel yield potential of crops in the respective bio-climatic regions under rainfed and/or irrigated conditions.

AIM 6 - To estimate or quantify the water use efficiency of these crops with reference to, amongst others, the following parameters:

- Biomass yield per m^3 water over the full productive cycle, and
- Biofuel yield per m^3 water over the full productive cycle.

AIM 7 - To assess the impact of land use changes on the water balance, within selected key catchments of the specified bio-climatic regions and at appropriate scales, with introduction of crops suitable for biofuel production.

AIM 8 - To develop a user-friendly, map-based software utility for the planning and management of biofuels in South Africa, drawing on findings from the specific aims listed above.

AIM 9 - To provide training opportunities for one post doctorate, two full-time PhD and five full-time MSc students. The principal researcher was also encouraged to obtain a PhD degree (part-time).

1.3 Approach

With reference to **AIM 1** (to specify and prioritise feedstocks), the project was largely governed by the revised national biofuels industrial strategy (DME, 2007a). This strategy recommended two bioethanol feedstocks (i.e. sugarcane & sugarbeet) and three biodiesel feedstocks (i.e. soybean, canola & sunflower) for biofuel production. The final list of prioritised feedstocks considered in this study was also influenced by the recommendations in the biofuels scoping study report (Jewitt *et al*., 2009a). In addition, an inaugural symposium and workshop was held on 10th and 11th February 2010 respectively. One of the main objectives of the workshop was to identify key feedstocks for further investigation by the project team. Finally, a biofuels technical meeting was held on 17th July 2012 to discuss whether grain sorghum should be included in the list of prioritised feedstocks.

With reference to **AIM 2** (to evaluate and characterise feedstocks), information pertaining to, *inter alia*, crop parameters, water use and yield of the prioritised crops was gleaned from the field-based research as well as a thorough review of available literature. **AIM 3** is referred to as the mapping component of the project, with the modelling component involving **AIM 4** (water use modelling) and **AIM 5** (crop yield modelling). In order to derive parameters for certain feedstocks, field-based research was conducted at a number of research farms. The output from the modelling component of this project largely addressed **AIM 6** (estimation of water use efficiency) and **AIM 7** (hydrological impact of feedstock cultivation). In order to meet **AIM 8**, a software program called the Biofuels Assessment Utility was developed. Lastly, a number of students from the University of KwaZulu-Natal and the University of Pretoria worked on the project over its six-year time span (**AIM 9**).

1.4 Structure of Report

Over the six-year project, a total of 21 deliverables were produced for the WRC which addressed the various project aims. These deliverables were combined into a final report consisting of three volumes. It is important to note that the majority of the research pertaining to crop yield and water use efficiency (WUE) modelling was conducted in 2015 and thus, was not previously reported.

Volume 1 is a synthesis report which contains the key findings of the project. Hence, this volume is intended for a wider audience, including decision-makers. **Volume 2** (this document) represents the technical report which provides the necessary detail regarding the field-based research, as well as the methodology used for the mapping and modelling components. Hence, this volume is intended for those (i.e. scientists) requiring more detail on the methodology. **Volume 3** represents the biofuel atlas and assessment utility. It provides the output (as maps, tables, tools etc.) from the modelling and mapping work.

Volume 1 is essentially a summarised version of **Volume 2** (this document). Thus, the chapter headings are identical in each document, which allows the reader to easily find and peruse the detailed methodology given in **Volume 2**. In **Volume 1**, each chapter contains a synthesised description of the methodology (c.f. sub-section "**Approach**"), which should suffice for the reader that doesn't require the necessary detail (which is included in **Volume 2**).

Chapter 2 provides a detailed review of each prioritised feedstock, which is required to fulfil **AIM 01** and **AIM 02**. **Chapter 3** pertains to the field-based research undertaken by the project. It also includes information on soybean and yellow maize, which formed part of WRC project K5/2066. **Chapter 4** summarises the parameters used for both the modelling component, which were obtained from field-based research and gleaned from the available literature. The mapping (i.e. land suitability) component of the study is presented in **Chapter 7**, with the water use and yield modelling component provided in **Chapter 5** and **Chapter 6** respectively. Finally, the main conclusions drawn from the study are listed in **Chapter 8** in **Volume 1**.

2 PRIORITISATION AND REVIEW OF FEEDSTOCKS

In this section, a detailed review of local and international literature is provided. The appraisal provides guidance for the methodology developed to shortlist, motivate and prioritise selected biofuel feedstocks deemed suitable for biofuel production in South Africa. An overview of world trends in biofuel production is provided, as well as an appraisal of the country's petroleum industry, the recently released mandatory blending rates and an overview of agricultural production are discussed.

2.1 Background

2.1.1 Definition of biofuels

Bioenergy is defined as energy in the form of electricity and heat produced from organic matter on a renewable basis (Watson *et al*., 2008). Biofuels are defined as gas, solid and liquid fuels produced from biomass (Watson *et al*., 2008). Hence, a variety of fuels can be produced from biological feedstocks, including liquid (such as bioethanol and biodiesel) and gaseous (e.g. hydrogen and methane). Although biofuels are seen as a sustainable fuel source, they cannot completely substitute fossil fuels. This is mainly due to the significant cropping area and water required to produce sufficient biofuel feedstocks in order to meet the demand for liquid transportation fuel. However, biofuels can contribute to reduce the overall consumption of fossil-based fuels (Duke *et al*., 2013).

2.1.2 Benefits of biofuel production

South Africa began phasing out the use of lead as an octane booster in petrol in 2006. Methyl tertiary butyl ether (MTBE) is another octane booster which was banned in 2000. Bioethanol can be used as an octane booster to replace harmful boosters such as lead and MTBE. In addition, biofuel production may increase agricultural production and improve food security. The demand for biofuel feedstocks is intended to bring fallow land in the former homeland areas back into agricultural production. This would require additional infrastructure (in particular roads) in rural areas in order to improve market access. A major spin-off of the biofuel industry is therefore job creation. Other benefits include improved energy security as well as contributing to South Africa's Cleaner Fuel Policy and thus its green economy.

2.1.3 Feedstock classification

2.1.3.1 First generation feedstocks

Bioethanol production is currently based on plants capable of producing starches and sugars. Currently, the global biofuels industry makes extensive use of these two agricultural products that are also primarily used in human food and farm animal feed. Thus, sugar from sugarcane underpins the Brazilian bioethanol production. Brazil is the world's largest producer of sugar and bioethanol. Brazil accounts for approximately 40% of world sugar trade and over half of the global bioethanol trade (Worldwatch Institute, 2006). Starch from maize underpins a significant proportion of US biofuels targets. Similarly, maize currently underpins fuel bioethanol production in China (IEA, 2004).

Oil plants manufacture oils which is stored in their seeds as nutritional reserves to support the growth of new seedlings after germination. Soybean is the major crop in both the US and South America, whilst canola (rapeseed) underpins the European market. Palm oil is the major crop in Indonesia and Malaysia (Worldwatch Institute, 2006). It should be noted that the lowest cost biodiesel is currently produced from recycled cooking oil and waste animal grease (Royal Society, 2008).

2.1.3.2 Second generation feedstocks

Biofuel production from lignocellulosic feedstocks has considerable potential, given the amount of energy stored in the biomass and the extent of biomass availability. Sources of lignocellulose include residues, co-products and waste generated by many different sectors such as agriculture, horticulture, forestry, paper and pulp as well as food processing. Globally, there are major research efforts to develop and optimise technologies for producing biofuels from lignocellulosic feedstocks. The world's largest demonstration facility (2.5 ML capacity) of lignocellulose bioethanol (from wheat, barley straw & corn stover) was first established by the Iogen Corporation in Ottawa, Canada.

Attention (particularly in the US) is focused mainly on switchgrass and miscanthus, although comparisons have shown that miscanthus produces more than twice the biomass yield of switchgrass (Heaton *et al.,* 2004; cited in Royal Society, 2008). The use of miscanthus raises concerns regarding the narrow gene pool currently available and its invasive characteristics. In the UK, a sterile triploid hybrid *Miscanthus x giganteus* (a cross of *M. sinensis* and *M. sacchariflorus*) is under cultivation, but is regarded principally as an energy crop for combustion, rather than for biofuel production. Although the grass can be cultivated with low inputs on marginal land, biomass yield is linked to agricultural input. Issues which still need to be addressed include an improved understanding of its agronomy and optimisation of harvesting processes (Royal Society, 2008).

2.1.4 Biofuel production

2.1.4.1 Sugar-to-bioethanol conversion

The conversion of biomass containing soluble sugars to bioethanol is illustrated in **Figure 1** for sugarcane. However, the process is similar for sugarbeet and sweet sorghum. The fermentation step is similar to that described in **Section 2.1.4.2**. It is cheaper and more efficient to convert sugar crops to bioethanol than compared to starch crops. This is because the starch must first be hydrolysed using enzymes, before the fermentation process can begin using yeast (or bacteria). A by-product from the conversion process is bagasse, which is burnt to generate the energy needed in the processing plant (known as co-generation), and excess energy enables the production of electricity for the national grid. This is compared to the starch-to-bioethanol process which requires the input of fossil fuel energy (typically coal fired boilers).

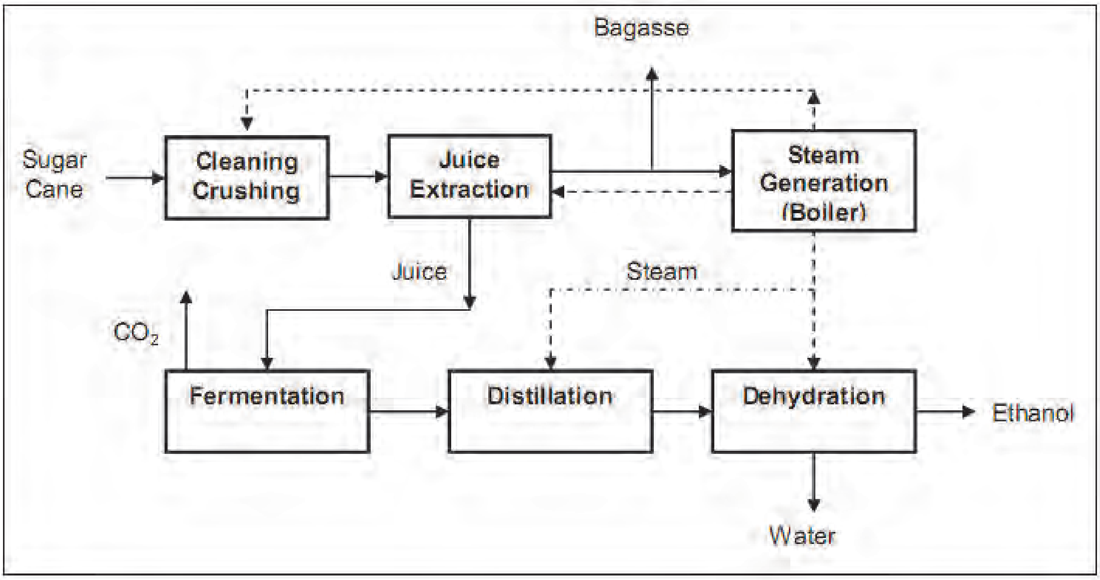


Figure 1 Production flowchart for producing bioethanol from sugarcane or other feedstocks containing fermentable sugars (DME, 2006a)

2.1.4.2 Starch-to-bioethanol conversion

The following information was extracted from Mabele Fuels' website[1]. Vogelbusch GmbH, a leading Austrian bioethanol process design company, has been subcontracted by Mabele Fuels to design the Bothaville bioethanol plant. There are four important steps in producing bioethanol from starch feedstocks as shown in **Figure 2**.

Grain milling: Sorghum (or maize) is milled (i.e. a size-reduction step) to make it easier to handle the feedstock and the bioethanol production process more efficient. Agricultural residues go through a grinding process to achieve a uniform particle size. This passes through a control process and on to the starch conversion process. Dust from the different steps is collected in a filter system.

Biomass conversion: A chemical reaction called hydrolysis occurs when dilute sulphuric acid is mixed with the milled feedstock. In this hydrolysis reaction, the complex hemicellulose sugars are converted to a mix of soluble (i.e. liquefied) five-carbon (pentose) and six-carbon (glucose) sugars. The cellulose fraction of the feedstock is hydrolysed using cellulose enzymes to produce glucose. The cellulose hydrolysis step is called cellulose saccharification because it produces sugars (i.e. pentose and glucose).

Fermentation: The sugars are then converted to bioethanol through a process called fermentation. The fermentation reaction is caused by yeast or bacteria, which feed on the sugars to produce bioethanol and carbon dioxide. Fermentation produces bioethanol broth, from which bioethanol is separated out (i.e. bioethanol recovery step) from the other components. A final dehydration step removes any remaining water from the bioethanol.

Distillation: The processing plant consists of a multi-pressure distillation system, making more economic use of heat energy and thus reducing steam consumption. There are a

[1] http://www.mabelefuels.com/products-services/ethanol-production/

number of different columns which operate at different pressure levels, so that one column can be heated with the overhead vapours of another.

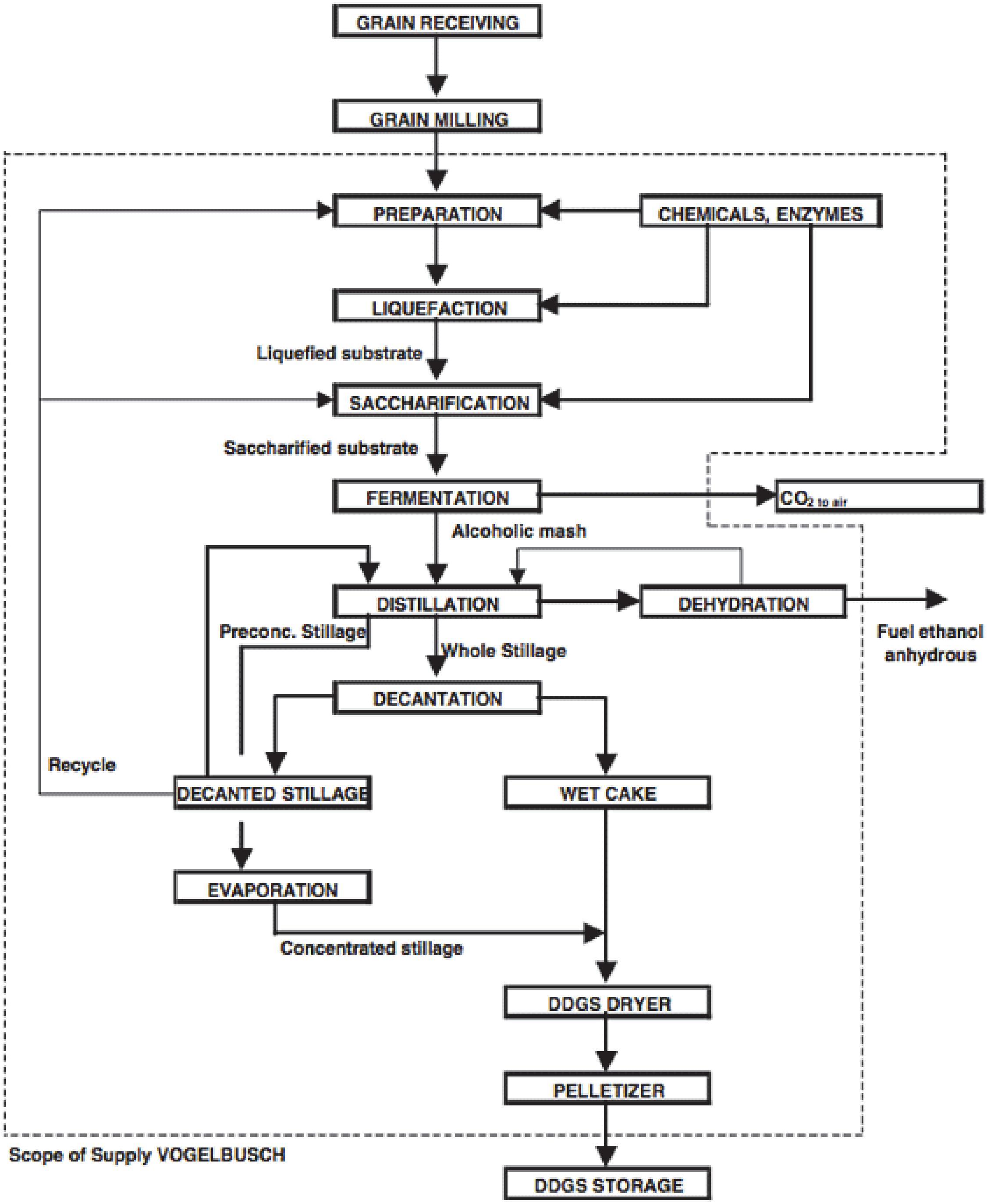


Figure 2 Basic process of converting starch into bioethanol (Source: Mabele Fuels website)

In summary, the technology for the conversion of grain to bioethanol is well established and summarised as follows: “The grain is pre-cleaned and stored. From storage the grain is transported to the jet cooking and liquefaction section of the Plant to produce cooked grain mash. The cooked grain mash is sent to the fermentation section of the Plant and then pumped to the distillery where the bioethanol is distilled. The bioethanol is then dried using molecular sieve technology” (IDC, 2013).

Hot silage is stored in an intermediate storage tank, from where it is pumped to decanters for removal of solids. Solids leaving the decanters are premixed with concentrated silage and fed by the mixing system to the drier. Drying of decanter cake and concentrated silage is done in a rotary drum dryer driven by natural gas. The dried product is transported by a conveyor system to the storage area or to the pelletizer. Distiller's dried grains and solubles (DDGS) is then conditioned with steam and water in the DDGS humidifiers and after intensive mixing the humid DDGS is pressed to pellets. After the pellets have been cooled, they are stored for future consumption.

2.1.4.3 Vegetable oil-to-biodiesel conversion

Biodiesel is made by the trans-esterification of vegetable oil with an alcohol, such as methanol (**Figure 3**). Various non-woody plant sources of oil include sunflower, soybean, and canola. Woody shrubs and trees can also be used to produce oil (e.g. African oil palm, Jatropha and Moringa). Other sources of biodiesel include animal fats, marine and algal oils (Tait, 2005).

A by-product of oilseed pressing is protein-rich oilcake that is used in animal feeds, as well as glycerine. Glycerine has many uses in the food and beverage industry as well as in pharmaceutical and personal care products. Glycerine is also used to produce nitro-glycerine, which is an essential ingredient of gunpowder and various explosives such as dynamite, gelignite and propellants like cordite.

The energy input required to convert soybean feedstock to biodiesel is much less than the energy to produce bioethanol from maize. According to Hill *et al.* (2006), soybeans create long-chain triglycerides that are easily extracted from seeds. A soybean processing plant which produces biodiesel is more than four times cheaper to build than an bioethanol plant utilising maize (DME, 2006a).

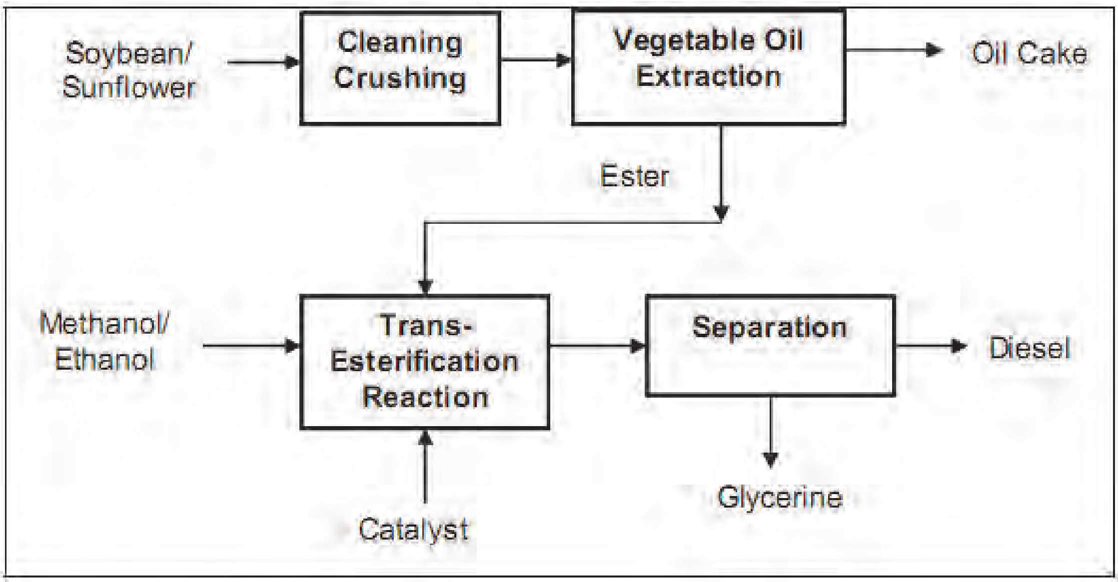


Figure 3 Production flowchart for producing biodiesel from vegetable oil such as soybean or sunflower (DME, 2006b)

2.1.5 Biofuel by-products

In general, two by-products generated by the above processes are suitable for animal feed and can be sold back to the agriculture sector. This applies to the DDGS from grain sorghum or maize, as well as the oilcake from soybeans or sunflower. However, sugarbeet and sweet sorghum processing also produce animal feed, but to a lesser extent. Bagasse from sugarcane or sweet sorghum processing can be used as a heating fuel or pulp for paper manufacture. Glycerine, another by-product from biodiesel production, is sold into a variety of markets for soap and resin manufacture, urethane foams, drugs and cosmetics as well as explosives. CO_2 is produced by all processing plants and may be sold as a compressed gas product required in specialised markets (DME, 2006a).

The 90-million litre capacity bioethanol production facility at Cradock will produce fuel grade bioethanol from grain sorghum, with by-products being DDGS, carbon dioxide and fly ash. Bricks will be made from the fly ash, a waste product from the burning of coal used by the factory to generate heat. The bricks will be used to create two roads in the Cradock district, thus providing additional employment opportunities (DRDLR, 2013).

As mentioned previously, DDGS is a by-product of starch-to-bioethanol conversion is used as animal feed (or fodder). DDGS has about three times the protein content and the same energy levels as the original grain feedstock. Consequently, it receives a price in the animal feeds market of between 0.80 and 1.2 times the maize (corn) price. The South African animal feed market comprises approximately 7.3 million tons per annum. DDGS is typically used to replace yellow maize and soya meal in the animal diet. Kotze (2012b) also reported that DDGS is a medium protein component of animal feed and will reduce the country's need to import soya oilcake.

Rainbow Nation Renewable Fuels (c.f. **Section 2.2.8**) plan to establish a soybean crushing facility alongside its own biodiesel refinery. The company argues that the main product is soybean meal used in animal feed, which is deemed more valuable than the biodiesel and glycerine (i.e. the by-products).

2.1.6 Estimating the biofuel demand

2.1.6.1 The petroleum industry

South Africa's economy is highly dependent on crude oil imports. According to the Department of Energy's website[2], imported crude oil supplies about 64% of South Africa's petroleum needs and the remaining 36% is made from syncrude i.e. coal and natural gas. According to the biofuels feasibility study (DME, 2006a) which accompanied the draft biofuels strategy report (DME, 2006b), South Africa spends about R120 billion each year (R300 million per day) on liquid fuels, representing almost 8% of the 2006 GDP. Crude oil imports (20% of total imports) cost about R45 billion per year. Liquid fuels constitute about 30% of South Africa's energy use and account for 70% of South Africa's total energy expenditure. The combined crude oil and syncrude refining capacity in South Africa is currently insufficient to satisfy the demand for liquid fuel products. The deficit in supply is replenished with imported petrol and diesel. The demand for liquid fuel imports was

[2] http://www.energy.gov.za/files/petroleum_frame.html

expected to increase by 3 to 5% per annum over the next five years, i.e. 2006 to 2010 (DME, 2006a).

According to the South African Petroleum Industry Association (SAPIA) website[3], South Africa has six refineries (four coastal and two inland; **Figure 4**), of which four process crude oil and two process syncrude (gas and/or coal). The refining capacity in 2010 was 10 567 and 9 301 million litres for petrol and diesel respectively (SAPIA, 2012). However, consumption in 2010 totalled 11 874 and 9 298 million litres of petrol and diesel respectively (SAPIA, 2012). Hence, in order to address the petroleum shortfall in 2010, South Africa imported 1 571 and 2 163 thousand tons of petrol and diesel respectively (SAPIA, 2012).

Figure 4 Location of South Africa's refineries (SAPIA, 2009a)

The growing dependence on imported petroleum products is unfavourable. In response to this issue, PetroSA plans to build a crude oil refinery at Coega in the Eastern Cape. The Coega refinery will have a capacity of producing 400 000 barrels per day. The refinery will alleviate the country's dependency on imports as well as providing a blending facility for the future production of bioethanol and biodiesel in the Eastern Cape (SAPIA, 2009a).

2.1.6.2 Fuel supply *vs*. demand

The consumption of petrol and diesel in South Africa from 1991 to 2010 is given in **APPENDIX A**. Based on the latest available figures, consumption in 2010 totalled 11 874 and 9 298 million litres of petrol and diesel respectively (SAPIA, 2012). In 2009 (**Table 1**), Gauteng was the largest consumer of petrol (36.5%) and diesel (23.4%).

[3] http://www.sapia.org//industry-overview/fuel-industry.html

Table 1 Consumption of petroleum productions in 2009 by Province (Source: SAPIA website[4])

Province	Petroleum consumption in 2009	
	Petrol (%)	Diesel (%)
Gauteng	36.5	23.4
Western Cape	15.8	15.3
KwaZulu-Natal	15.4	17.8
Mpumalanga	7.8	13.1
Eastern Cape	7.3	6.3
Free State	5.6	8.7
North West	5.5	6.7
Limpopo	4.5	5.0
Northern Cape	1.7	3.7

The latest available figures show that 20 172 million litres of petroleum (petrol + diesel) was consumed in 2010 (SAPIA, 2012). Based on petroleum consumption from 1991 to 2010 (i.e. 20 years as shown in **Figure 5** and **APPENDIX A**, a linear regression model [y = 398.27(x - 1990) + 13313; R^2 = 0.95] was developed to estimate the petroleum demand (y in million litres) from 2011 to 2016 (x = year).

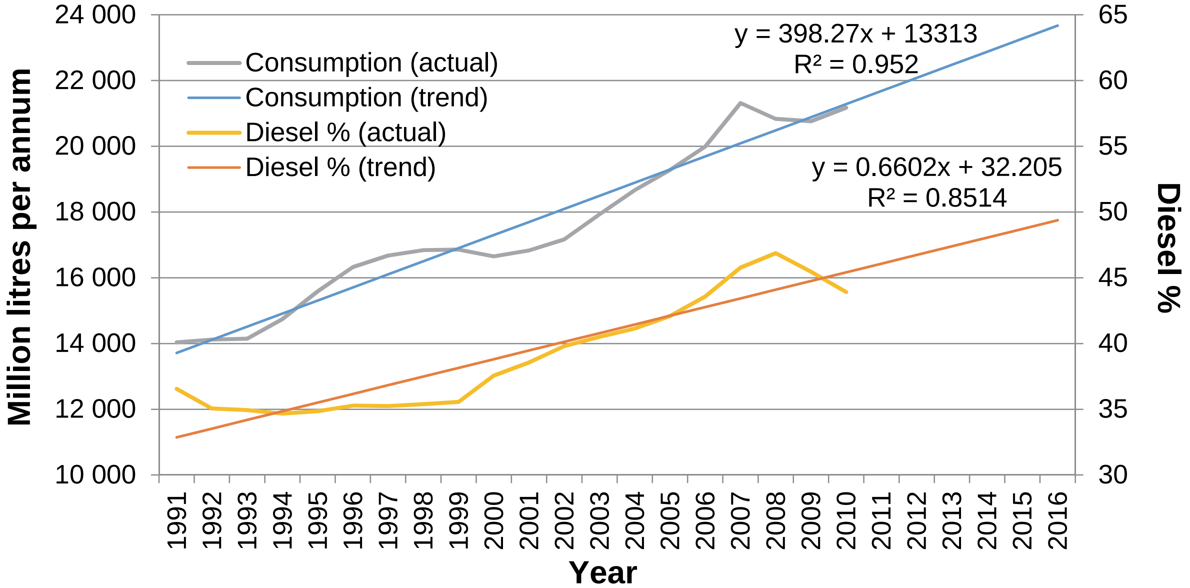


Figure 5 Petroleum consumption in South Africa from 1991 to 2010 (SAPIA, 2012), together with the diesel portion. Projected increases in demand from 2011 to 2016 are shown as linear trend lines

Since the mandatory blending rates take effect on the 1st April 2015, the estimated demand for petroleum in 2016 is therefore 23 668 million litres (i.e. 11.79% increase over the next 6 years). The portion of petroleum consumed as diesel increased from 36.55% in 1990 to 43.92% in 2010. A linear regression model [y = 0.6602(x - 1990) + 32.205; R^2 = 0.85] was developed to estimate the diesel percentage (y) from 2011 to 2016 (x = year). Hence, the diesel fraction is projected to increase to 49.37% in 2016 (**Figure 5** and **APPENDIX A**).

[4] http://www.sapia.org//industry-overview/fuel-industry.html

2.1.6.3 Logistics of biofuel blending

Bioethanol used in energy programmes around the world is currently denatured to render it non-palatable for human consumption. Hence, the feasibility study (DME, 2006a) recommended that in order to avoid fuel alcohol illegally entering the potable market, it must be denatured onsite and stored with a bittering agent and a suitable level of denaturant (such as 5% petrol). This practice must be developed with and agreed upon by stakeholders.

According to SAPIA (SAPIA, 2009b), the initial biodiesel blending rate should be limited to B5 to avoid vehicle warranty issues with original equipment manufacturers (OEMs). After due consideration of the technical requirements of existing diesel-engine vehicles, OEMs should support higher blending rates in the future. SAPIA (2009b) also mentioned that bioethanol could be accommodated in all grades of petrol with a blending up to 8% (E8) at the coast and 10% (E10) inland. Bioethanol blends in excess of E10 often require vehicle modifications.

SAPIA (2009b) criticised the government's biofuels strategy of 2007, stating that it is a very broad framework that does not provide the necessary details for practical implementation. The use of bioethanol and biodiesel presents challenges in blending, storage, distribution and usage, with biodiesel being much less complicated than bioethanol (due mainly to bioethanol's affinity to absorb water i.e. its hygroscopic nature). The movement of petrol (even with only a 2% bioethanol content) by pipeline which also transports jet fuel is also not permitted. This relates to the pipeline transportation by Transnet from Durban to OR Tambo International Airport. According to Njobeni (2012), SAPIA has suggested that the Department of Energy establishes a working group to deal with "practical issues" related to the uptake of biofuels. SAPIA does not want the uptake of biofuels to affect negatively the supply of fuels.

SAPIA (2009b) stated that: "A 2% (E2) blend could be produced at existing fuel depots and could be relatively easily implemented with some infrastructure changes. Capital expenditure would be required, especially for tankage, but significant investment would be needed for higher blend levels. Blending at refineries at 2% and higher levels is feasible and would also require capital investment".

In March 2012, a study was conducted to determine the investment required by the petroleum companies to purchase capital equipment necessary to blend biofuels with the fuel supply. According to Van der Westhuizen (2013), a capital investment of R278 million is required for blending at refineries and R459 million for blending at depots.

Since the blending of more than 2% bioethanol with fossil-based petrol should be done at refineries, a preliminary study conducted by Makenete *et al.* (2007) showed that Sasolburg emerged as the lowest-cost siting for a maize-to-bioethanol plant due to its proximity to the Sasol refinery. Secunda was rated as the next best location, again due to its proximity to the petroleum refinery. A sugarcane-to-bioethanol plant should ideally be located in Durban, in close proximity to the Sapref and Enref refineries.

2.2 Issues Influencing Feedstock Selection

Global bioethanol production is currently based on feedstocks capable of producing starches or sugars. Sugar extracted from sugarcane underpins the Brazilian bioethanol industry. Brazil is the world's largest producer of sugar and bioethanol. Starch from maize underpins a significant proportion of US biofuels targets. Similarly, maize currently underpins fuel bioethanol production in China (Royal Society, 2008). Canola is the predominant feedstock used in Europe (e.g. Germany) for biodiesel production (Swart, 2012). Hence, sugarcane, maize and canola are important feedstocks in the global biofuels industry. This section provides a timeline of publications and events which have helped shortlist or select biofuel feedstocks deemed suitable for the South African biofuels industry.

2.2.1 National biofuels industrial strategy (December 2007)

The revised national biofuel strategy (DME, 2007a) set a 5-year target for producing 400 million litres of biofuel. By 2013, this conservative target has yet to be realised. The reason is mainly due to the lack of incentives provided by local government to encourage biofuel production and uptake. In 2006, the chairman of the Protein Research Foundation of South Africa (Gerhard Scholtemeijer) remarked that nowhere in the world had a biofuel industry been established without a government presence (van Burick, 2006; cited by Swart, 2012). This translates into tax incentives, subsidies and policy changes to stimulate the establishment of a local biofuels industry.

The National Biofuels Task Team recommended two bioethanol feedstocks (sugarcane & sugarbeet) and three biodiesel feedstocks (soybean, sunflower & canola) for use in biofuel production. Maize is currently excluded due to food security concerns and as well as Jatropha for its possible alien invasive threat (DME, 2007a).

2.2.2 Inaugural biofuels workshop (February 2010)

The second deliverable of the biofuels project provided a synthesis of the main outcomes of the inaugural biofuels workshop held in February 2010. One of the workshop objectives was to recommend a list of key feedstocks for further investigation by the project. The following is a summary of the recommendations made from the workshop.

Two emerging feedstocks were highlighted for field experimentation, namely sugarbeet and sweet sorghum. Other crops identified for field work included Napier grass. Tree crops which cannot grow to full production during the project's 6-year period were rejected. This decision excluded the Chinese tallow tree from further investigation as well as two indigenous plums namely sour plum and jacket plum, originally highlighted in the biofuels feasibility study (DME, 2006a). In addition, feedstocks recognised as aggressive invaders in other parts of the world were also rejected. This excluded the Chinese tallow tree as well as switch grass from further study.

Crops where sufficient knowledge exists in South Africa, from which their water use can be modelled (and not derived from field work), include maize, sugarcane and sunflower. Other feedstocks with limited knowledge that should also be investigated include soybean, canola, cassava, Jatropha and Moringa. The latter two tree feedstocks were also highlighted in the biofuels feasibility study (DME, 2006a). The above recommendations include all the crops listed in the revised biofuels industrial strategy of South Africa (c.f. **Section 2.2.1**).

2.2.3 Biofuel technical meeting (July 2012)

On 17th July 2012, a biofuels technical meeting was held at UKZN in Pietermaritzburg to discuss which feedstocks exhibited sufficient knowledge to facilitate the estimation of water use and yield using appropriate simulation models. A summary of the decisions made at the meeting is shown in **Table 89** (**APPENDIX C**).

Feedstocks where insufficient knowledge currently exists to model water use and yield include sugarbeet, sweet sorghum, grain sorghum, soybean, Jatropha and Moringa. Hence, these feedstocks require further investigation involving field trials. However, due to budget constraints, the decision was made to stop monitoring the water use and oil seed yield of the Jatropha and Moringa plantations at Ukulinga and Hatfield respectively. It was agreed that an additional season of monitoring would not add to the existing knowledge base regarding these two biodiesel feedstocks.

The water use and yield of sugarcane was modelled. Other feedstocks that were modelled include soybean, canola and sunflower. However, feedback from the 2012 SANCID symposium suggested that canola is not a well-understood crop in South African growing conditions. Maize was not considered as it is currently excluded as a potential feedstock due to food security concerns. Similarly, Napier grass and Jatropha were not modelled due to their alien invasive threat.

2.2.4 Proposed mandatory blending rates (August 2012)

Biofuel mandates set a minimum volume of liquid biofuels to be blended with traditional fossil-based fuels for transport. The draft blending rates were released on 16th September 2011 by the Department of Energy (DoE) for public comment on or before 18th November 2011 (DoE, 2011). The draft regulations stipulated a minimum B5 (i.e. 5% biodiesel v/v) and a minimum E2 (i.e. 2% bioethanol v/v) blending ratio. On 23rd August 2012, the Department of Energy published regulations regarding the mandatory blending of biofuels in the Government Gazette (DoE, 2012b). The mandatory biodiesel blending was unchanged at B5. However, the mandatory bioethanol blending was modified to a permitted range of E2 up to E10.

In 2010, a total of 11 874 million litres of petrol was consumed (SAPIA, 2012). A minimum blending ratio of E2 requires an annual production of at least 237.5 million litres of bioethanol. However, the projected demand for petrol in 2016 is 11 983 million litres. Therefore, an E2 blend requires at least 239.7 million litres of bioethanol to be manufactured in 2016 (**Table 87** in **APPENDIX A**).

South Africa's diesel consumption was 9 298 million litres in 2010 (SAPIA, 2012). In order to achieve a minimum 5% biodiesel blend, approximately 465 million litres of biodiesel is required. However, the projected demand for diesel in 2016 is 11 685 million litres, assuming that 49.37% of the estimated petroleum demand (23 668 million litres) is for diesel (**Figure**

5). The biodiesel demand in 2016 would then increase to 584 million litres (**Table 87** in **APPENDIX A**).

2.2.5 Follow-up biofuels workshop (January 2013)

With regard to the shortlisting and prioritisation of potential feedstocks, the workshop highlighted the following:

- Future biofuel-related policy should clearly identify the specific feedstocks to be used, taking into consideration developing *vs*. commercial farmers, the required blending rates and volume targets, as well as the type of biofuel to be produced.

- Consideration should be given to feedstocks with multiple uses (i.e. food, feed and/or fuel). In other words, priority should be given to biofuel feedstocks that contribute to, rather than compete with, food security. Sweet sorghum is an example of a multi-use feedstock, capable of producing food, feed/fodder, fuel and fertiliser.

- Research is urgently required that quantifies the impacts of land use change to biofuel feedstock production, which should provide guidelines and boundaries for land use planners.

- In April 2009, draft regulations dictate that Napier grass (and other high biomass grasses) may be declared an alien invasive. However, this grass shows potential as a 2nd generation bioenergy feedstock.

- A list of criteria was suggested to guide the decision making process with regard to feedstock selection. All of the suggested criteria are mentioned in this report. However, as highlighted in **Section 2.2.8**, the proposed biofuel manufacturers can strongly influence the list of viable feedstocks.

- The role of the farmer needs to be adequately addressed. Important issues are the feedstock's suitability to marginal sites, the ease and cost of cultivation and the farmer's attitude to, and familiarity with, the feedstock.

The workshop also highlighted that there are 21 policies which affect biofuel feedstock production. Furthermore, a significant disconnect between research and policy exists i.e. is policy informing research or is research informing policy? In addition, there is confusion caused by contradictions which exist between National *vs*. Provincial policies. The workshop concluded that the way forward is to focus on the opportunities associated with a viable biofuels industry.

2.2.6 Presentation by DoE (August 2013)

On 13th August 2013, Mr Mkhize (Chief Director: Hydrocarbons Policy) from DoE presented an update on the biofuels industrial strategy to the Portfolio Committee on Energy. The presentation[5] highlighted grain sorghum and sugarcane as the most appropriate commercial feedstocks for bioethanol production. Similarly, the most appropriate feedstocks for

[5] http://www.agbiz.co.za/LinkClick.aspx?fileticket=rWJOh6S%2BiMY%3D&tabid=357

commercial biodiesel production are soybean and sunflower. Mr Mkhize also mentioned that no information exists in the public domain on the economic feasibility of growing sugarbeet.

2.2.7 Draft biofuels regulatory framework (January 2014)

2.2.7.1 Background

It is responsibility of the Department of Energy (DoE) to determine biofuel prices that offer “reasonable” returns for biofuel producers. This is the price that the petroleum companies will need to pay the licensed biofuel manufacturers (as listed in **Section 2.2.8**). In February 2012, the DoE appointed consultants to determine the selling price of bioethanol and biodiesel. A workshop was held in February 2012 to discuss the break-even prices as well as the blending rates that optimise the fuel octane value.

The pricing framework highlighted grain sorghum as the reference feedstock to represent the production of bioethanol from starch. Similarly, soybean was selected as the reference feedstock to represent the production of biodiesel from vegetable oil. The recommended pricing is designed to guarantee as 15% return on asset investments.

This legislation is necessary because the petroleum companies will not voluntarily blend the biofuel, as it will increase the cost of fuel (both petrol and diesel). It is expected that government will increase the fuel levy by 4 to 5c per litre, thus recouping the incentive from the public which will then be paid to the petroleum industry (Van der Westhuizen, 2013).

2.2.7.2 Overview of the framework

The Department of Energy (DoE) released its draft position paper on the biofuels regulatory framework on 15th January 2014 (DoE, 2014). The framework proposed a two-phase approach to biofuel manufacturing. In phase one, an E2 bioethanol blend is considered. Phase two would consider blends up to E10, based on a cost-benefit analysis undertaken by government. The optimum blending rate is determined by the petrol’s oxygenate and volatility specifications.

The two proposed bioethanol plants will produce sufficient bioethanol (≈240 million litres) from grain sorghum (≈600 000 tons) to satisfy the E2 blending rate, provided both plants operate at full capacity. The immediate question that is raised is how does the sugar industry contribute to phase one of the approach? The sugar industry is hoping the biofuel (and bioenergy) demand will bring existing farms back into production.

At present, only four bioethanol and four biodiesel manufacturing licenses have been granted by the Office of the Controller of Petroleum Products. Of these, only one company (Ubuhle Renewable Energy) intends to produce 50 million litres of bioethanol from sugarcane at Jozini. Capital investment is required to modify the sugar mills to ferment bioethanol from sugarcane. This becomes economically viable if the blending rate is E10 according to the South African Cane Grower’s Association (Viljoen, 2014). At present, it is more profitable for the sugar industry to sell their bioethanol to the white rum distillers (Viljoen, 2014).

Capital investment is also required to modify the petroleum depots and refineries to accommodate the blending of biofuel into the fuel supply chain. The proposed E2 blend can be done at depots, thus reducing the cost of transporting biofuel to each of the country's six refineries. It also reduces the initial investment required by the petroleum industry, before October 2015, to manage the challenges created by bioethanol's hygroscopic (i.e. affinity to absorb water) nature.

The draft position paper focuses on the economics of biofuel production. Firstly, biofuel manufacturers will be subsidised by Treasury from funds acquired from the General Fuel Levy. The framework proposed a levy ranging from 3.5 to 4.5 cents per litre (cpl) on page 9, yet 4.5 to 6.5 cpl on page 23. The awarding of the subsidy is also dependent on the biofuel manufacturer meeting, *inter alia,* the following requirements:

- source at least 10% of its feedstock from smallholder/emerging farmers within four years of start-up (for rural upliftment),
- obtain written consent from the land owner to grow biofuel feedstocks (for protection of land rights),
- ensure that feedstock is not grown on currently productive commercial farms (for protection of food security),
- safeguard against the clearing of trees (particular indigenous) for feedstock production, unless agreed upon by relevant authorities (for protection of natural resources),
- obtain written permission from the DWA to use irrigation water for feedstock production, and
- provide detailed motivation for feedstock irrigation and that the country's water resources are not be negatively impacted.

A letter from DAFF is also required that confirms feedstock was planted in "designated areas". However, it does not apply to land acquired through the land reform process (i.e. land purchased by the Department of Rural Development and Land Reform, for example, in the Cradock region). The eligibility criteria stipulated above does affect the mapping component of the biofuels project and therefore should be taken into consideration.

The subsidy is based on each biofuel manufacturer producing 158 and 113.6 million litres of bioethanol and biodiesel respectively. These "caps" were imposed to accommodate as many players as possible into the industry. In other words, a biofuel manufacturer will only be subsidised up to these volume "caps", irrespective of the plant's total capacity.

According to the DoE (2014; Table 1 on page 8), Arengo 316 is planning a second phase of the Cradock bioethanol plant which will produce a further 90 million litres. It is believed that sugarbeet will be the preferred feedstock when the plant's capacity is expanded in the future. However, the total capacity of 180 million litres exceeds the cap for subsidy. Similarly, most (3 of the 4) of the biodiesel manufacturers exceed the subsidy cap as well.

In order to further incentivise biodiesel production, manufacturers can claim faster asset depreciation by way of tax incentives. Furthermore, they receive a 50% General Fuel Levy exemption for quantities below 300 000 litres. At present, no similar incentives are proposed for bioethanol as it falls outside of the fuel tax net.

2.2.8 Proposed biofuel manufacturers (January 2014)

The Department of Energy (DoE, 2014) provided an update on the licensing of proposed biofuel facilities in South Africa. **Table 2** shows that eight companies have applied to manufacture biofuel, with a total annual capacity exceeding 1 300 million litres. The preferred bioethanol feedstocks include grain sorghum, sugarbeet and sugarcane. Similarly, the preferred biodiesel feedstocks include canola and soybean.

Table 2 Status of licenses granted by the Department of Energy for biofuel manufacturing facilities in South Africa (DoE, 2014)

Company	Biofuel	Feedstock	Capacity (ML an^{-1})	Location	License
Mabele Fuels	Bioethanol	Sorghum	150	Bothaville, FS	Issued
Arengo 316	Bioethanol	Sorghum	90	Cradock, EC	Approved
Arengo 316	Bioethanol	Sugarbeet	90	Cradock, EC	Approved
Ubuhle RE	Bioethanol	Sugarcane	50	Jozini, NL	Issued
E10 Petroleum	Bioethanol	Sugarcane	4	Germiston, GT	Approved
PhytoEnergy	Biodiesel	Canola	455	Port Elizabeth, EC	Applying
Rainbow Nation	Biodiesel	Soybean	288	Port Elizabeth, EC	Issued
Basfour 3528	Biodiesel	Soybean	170	Berlin, EC	Issued
Exol Oils	Biodiesel	Waste oil	12	Krugersdorp, GT	Approved

FS = Free State; EC = Eastern Cape; NL = KwaZulu-Natal; GT = Gauteng

There are sufficient biofuel manufacturers to produce the target volume of 824 million litres of biofuel, which is required to satisfy the minimum blending rates (see **Section 2.2.4**). If the Cradock and Bothaville bioethanol plants are completed by 2016, the total bioethanol capacity is 240 million litres from approximately 600 000 tons of grain sorghum, which is sufficient to satisfy an E2 blend. The biofuels industry could then produce up to 958 million litres of bioethanol, thus increasing the blending ratio to E10 (the maximum mandatory blending ratio).

The construction of the above-mentioned processing plants has been deferred due to the government's delay in finalising the regulated price and financial support mechanism for licensed producers (refer to **Section 2.2.10** for further detail). There are no plans to build a biofuel processing plant in Mpumalanga, which is a concern for the local government.

2.2.9 Finalised mandatory blending rates (October 2015)

The mandatory blending rates came into effect on 1st October 2015. This means that the petroleum industry is forced to uptake all biofuels produced as long as the volumes meet the minimum required blending rates. Hence, the minimum volume of bioethanol required is approximately 240 million litres by 2016. Similarly, the minimum volume of biodiesel is about 584 million litres.

Biofuels can only be purchased by a blender from a licensed manufacturer of biofuels (c.f. **Table 2**). The blender must pay the regulated price for the biofuel and keep records for five years concerning the volumes of biofuel purchased and from which manufacturer. Each month, such records must be submitted to the Department of Energy. A blender cannot refuse to purchase the volume of biofuel being sold unless the blender has insufficient volumes of petroleum to blend (DoE, 2012a).

2.2.10 Finalised framework and pricing policy (2016?)

Kotze (2012b) added that 1) legislation on a pricing structure that will determine the delivered cost of biofuels, and 2) a government-agreed incentive for biofuels producers must also still be announced, before the biofuels industry can be fully established. The National Treasury still needs to finalise the necessary "support mechanisms" (the word "incentives" is discouraged) to fund, amongst others, the capital investment required by the petroleum industry to implement the blending of biofuel into the fuel supply chain. In addition, the DoE needs to finalise the biofuel pricing policy and DAFF must be also ready to provide support to emerging farmers, before the government can implement the blending rates. An update or revision of fuel tax levies is also expected for bioethanol and biodiesel production. It is hoped that government will announce the regulated price and the financial support mechanism for licensed biofuels producers in the near future.

2.2.11 Twenty-year liquid fuels road map

With regard to the country's 20-Year Liquid Fuels Infrastructure Road Map (DME, 2007b), the report acknowledges the impact of climate change on crop production, especially for biofuel production. Hence, climate change modelling is required to assess this impact and to develop adaptation strategies for affected areas.

The *AQUACROP* model is well suited to estimating the impacts of climate change of feedstock production. The model is sensitive to rising ambient CO_2 levels and how this effects transpiration rates, particularly in C_4 plants. This ability offers an advantage over empirically-based crop models (e.g. Barry Smith suite of crop models) which cannot account for the so-called "CO_2 fertilisation effect".

However, it appears that the new multi-product pipeline from Durban to Johannesburg cannot be used to transport biofuel products due to the potential contamination of jet A1 fuel (DoE, 2014). Thus, biofuel blends need to be transported by road and rail.

2.2.12 Sustainability Issues

The National Biofuels Task Team is required to update the December 2007 national biofuels strategy. The task team must decide to either include or exclude the use of 2nd generation feedstocks. Furthermore, they must provide evidence to either include or exclude maize and Jatropha as permitted feedstocks. Both the Department of Science and Technology (DST) and the Department of Agriculture, Forestry and Fisheries (DAFF) are involved in making these decisions. The DoE is not involved with feedstock cultivation as this is DAFF's responsibility.

2.2.12.1 Exclusion of maize

In order to assess the potential impact on food security, it is crucial that staple food crops as well as their primary growing regions are well understood. From **Table 88** (in **APPENDIX B**), statistics compiled by the FAO are given for South Africa. They show the per capita consumption of calories derived from non-animal products in 2009 (FAOSTAT, 2009). Food groups were ranked on their calorie contribution to the average daily diet and identified maize and wheat as the most important food crops. Together, these crops account for 54.6% of the daily dietary intake. Thus, if staple food crops such as maize and/or wheat are diverted away from food production and towards the biofuels market, the likely shortage could increase food prices. This would affect both food availability and access to food by the rural poor. The production of biofuel using maize and/or wheat can potentially jeopardise food security and therefore requires careful consideration and appraisal. Based on this, it is understandable why maize is excluded as biofuel feedstock in South Africa (DME, 2007a).

Furthermore, local biodiesel production could affect food security if vegetable oils are diverted away from food needs. In total, vegetable oils contribute to 13.3% of the average daily dietary requirements, which is more than that of sugar products. The most popular cooking oil is made from sunflower seed, followed by soybean. From the list of feedstocks proposed in the country's national biofuel strategy (DME, 2007a), only canola (or rapeseed) oil and sugarbeet are non-important food crops.

2.2.12.2 Exclusion of Jatropha

Alien invasive plants are widely considered as a major threat to biodiversity, human livelihoods and economic development. On 3rd April 2009, The Department of Environmental Affairs and Tourism (DEAT) published Government Gazette No. 32090 (DEAT, 2009). It represents the 2nd draft of the Alien and Invasive Species Regulations of the National Environmental Management: Biodiversity Act, 2004 (Act No.10 of 2004). Section 70 is a draft of invasive species which lists Napier grass and *Jatropha curcas* as Category 1b and 2 plants respectively. Should the draft regulations become law, then any species designated under Section 70 will be controlled using permits. Category 1b are species deemed to have such a high invasive potential that infestations can qualify to be placed under a government sponsored invasive species control programme. No permits will be issued and such species should be removed and destroyed. Category 2 are invasive species to be regulated by area. Hence, a demarcation permit is required for the species which will not be issued if plants exist in riparian zones.

2.2.12.3 Economic considerations

At present, the production of bioethanol from soluble sugars stored in sugary juice is more economical than from starch-filled grain, the latter needing an additional pre-treatment to convert starch into fermentable substrate. In addition, the lower the tannin content of starch, the cheaper the bioethanol production. Similarly, the production of bioethanol from lignocellulose (i.e. 2nd generation) material is not yet economically viable.

Swart (2012) undertook an economic feasibility study of commercial biodiesel production in South Africa. His comprehensive PhD study indicated that the cost of using soybean and sunflower as feedstocks was not economically viable since South Africa is a net importer of oil seeds and vegetable oils. Used cooking oil and inedible tallow fat are the only viable feedstocks in the Gauteng area. It is slightly cheaper to use tallow fat rather than used oil for biodiesel production.

Based on Swart's (2012) analysis, the waste oil plant to be built by Exol Oils in Krugersdrop should be more profitable than the facility planned in the Eastern Cape by Basfour (c.f. **Section 2.2.8**). Erasmus (2012) also noted that biodiesel production from fresh cooking oil is not economically viable. Used cooking oil is typically bought from restaurants and caterers because it is currently too expensive to use fresh oil. Approximately one litre of biodiesel is made from a litre of fresh, unused oil (used oil results in a biodiesel yield loss of about 10%).

Sparks (2010) conducted a study to evaluate the economic feasibility of producing on-farm biodiesel from soybeans produced in KwaZulu-Natal. The economics of biodiesel production is highly dependent on the soybean price (i.e. the feedstock input cost) and the soybean oilcake price (i.e. the highest valued by-product). Results indicated that on-farm biodiesel production is currently not economically viable at both the commercial and small-scale level. This is based on a minimum total arable land area of 440 hectares needed to warrant a small scale processing plant. It was estimated that an incentive, in the form of a minimum subsidy of R4.37 per litre of biodiesel, was required for soybean-based biodiesel production on commercial farms. However, the minimum subsidy for collective smallholder biodiesel production was conservatively estimated to be nearly three times higher (R12.14 per litre).

Sparks (2010) concluded that since South Africa historically imports soybean oilcake and soybean oil, government should rather consider promoting small-scale soybean oil crushing ventures as a means for value-adding for smallholders. Importantly, this initiative could have positive spinoffs for domestic livestock industries in terms of increased animal feed production.

At present, only small-scale biodiesel production (i.e. less than 300,000 litres per annum) is exempt from the fuel tax levy (DME, 2007a). The government also offered a fuel tax exemption for bioethanol, a 50% rebate on the fuel levy for biodiesel (> 300 m^3 production) and a three-year "accelerated depreciation allowance" for renewable energy projects. However, this was insufficient to lure investments in the biofuels sector, hence the need to establish a more enabling and supportive regulatory framework (Van der Westhuizen, 2013). Since there are no other incentives or subsidies provided by government for biofuel production, profit margins may be small. Hence, the cost of biofuel production will need to be subsidised by government, especially when the crude oil price is low.

2.2.12.4 Land and water requirements

Of concern to environmentalists is the land and water required to produce sufficient feedstock to meet the biofuel target volumes determined by the mandatory blending rates. Few studies have been conducted which estimate the spatial extent of areas considered suitable for the sustainable production of biofuel feedstocks. Such studies are required to understand the upper bounds of biofuel supply potential as well as the extent of negative environmental consequences that may be associated with large-scale feedstock production. Biofuel supply potential is often constrained by the availability of land on which to grow feedstocks in a responsible manner. However, water scarcity rather than land availability may prove to be the key limiting factor in South Africa. Furthermore, biofuel feedstock production may impact on water use and consequently, aggravate catchment water stress.

Sustainable feedstock production therefore hinges on careful land use planning, which is considered a major challenge in securing a renewable energy future.

2.3 Shortlisting of Bioethanol Feedstocks

In this section (**Section 0**), key issues were reviewed which affect the selection of appropriate feedstocks for the biofuel industry. From the above review, the biofuels project focused its attention on sugarcane, sugarbeet, grain sorghum, sweet sorghum, maize, soybean, canola, sunflower, Jatropha and Moringa. In the sections that follow, a short motivation is given which justifies the shortlisting of each potential feedstock.

2.3.1 Sugarcane

Sugarcane is listed as one of the preferred bioethanol feedstocks in the national biofuels strategy (DME, 2007a). In addition, this feedstock was also highlighted by the DoE as one of the most appropriate commercial feedstocks for bioethanol production. Although sugarcane was not selected as the reference feedstock to represent sugar crops in the South African biofuels regulatory framework (DoE, 2014), it is believed that this crop will be included in future amendments of this policy document.

At present, only one relatively small processing plant (50 ML capacity) plans to use sugarcane as its preferred feedstock. The process of converting sugar-based feedstocks into bioethanol is cheaper and simpler than using starch-based feedstocks. However, sugarcane may be more suitable for bioenergy production using bagasse (i.e. co-generation) as opposed to biofuel production. Since starch-based feedstocks are likely to satisfy the minimum E2 blend (of 240 million litres of bioethanol), bioethanol derived from sugarcane will be used to increase the blending up to E10. At the biofuels technical meeting in July 2012, the recommendation was made to model the water use and yield of sugarcane.

2.3.2 Sugarbeet

The decision to include sugarbeet in the national biofuels strategy (DME, 2007a) and initially as the preferred feedstock for the Cradock bioethanol project appears to be politically driven (and not based on sound agronomic and economic principles). A visit by the Project Team to Cradock in April 2012 revealed that Prof Stephan Kaffka (University of California, Davis, US) originally recommended sugarbeet as the preferred bioethanol feedstock for the Cradock region. Sugarbeet is suited to Cradock's cold and dry winter (Maclachlan, 2012) and thus, this feedstock justifies the location of the bioethanol facility at Cradock. However, supplemental irrigation will be required to establish and maintain a winter crop of sugarbeet in the Cradock region.

Kings (2012) stated that the Cradock bioethanol project has two phases, the first requiring 225 000 tons of grain sorghum. The second phase will use sugarbeet produced by emerging farmers. An IDC tender document (IDC, 2013) also states that sugarbeet is "…outside the current scope of the Project and may be considered as part of the plant's potential future expansion plans only". The Agrarian Research and Development Agency (ARDA; formerly known as Sugarbeet SA) plan is to begin sugarbeet production with designated emerging farmers on government-owned land within three years after the completion of the proposed bioethanol plant (Maclachlan, 2012). It is believed that the Cradock farms would ultimately incorporate sugarbeet as a rotational feedstock for the bioethanol plant.

ARDA stated that sugarbeet would replace the feed crops grown in the Fish River Valley (Maclachlan, 2012). According to Dugmore (2010), maize and lucerne are mostly produced in the Cradock region. Since fresh sugarbeet contains about 75% of water by volume, the Cradock bioethanol facility plans to extract water from the sugarbeet, thus reducing the volume of water to be abstracted from the irrigation canal required for processing the feedstock into bioethanol. The processing plant will abstract water from the Marlow Irrigation Board's canal which runs diagonally across the site where the Cradock processing plant will be built.

At the biofuels inception workshop held in February 2010, it was recommended that because insufficient knowledge exists for South African growing conditions, the Project Team would measure the water use and yield of sugarbeet at Ukulinga. Excluding Ukulinga, sugarbeet has only been grown at Cradock (Dugmore, 2010; Dugmore, 2011) in the Eastern Cape and on a commercial farm near Lichtenburg in the North West Province (Dugmore, 2011).

2.3.3 Grain sorghum

Although grain sorghum was not considered in the national biofuels strategy as a viable bioethanol feedstock, it was also highlighted by the DoE as one of the most appropriate commercial feedstocks for bioethanol production (DoE, 2013). With maize still banned as a biofuel feedstock, grain sorghum is the preferred feedstock of choice for the proposed Bothaville and Cradock bioethanol pants. The 150-million litre facility at Bothaville requires approximately 400 000 tons of grain sorghum annually (Coleman, 2012).

An IDC tender document (IDC, 2013) clearly stated that bioethanol will initially be produced exclusively from grain sorghum at Cradock. Cradock's 90-million litre plant requires approximately 200 000 to 230 000 tons of grain sorghum annually (IDC, 2011). The decision to switch from sugarbeet to grain sorghum as the preferred feedstock is probably due to the IDC's concerns over feedstock supply. Although the former Sugarbeet SA consortium (now called ARDA) has conducted research on sugarbeet over the past 10 years, agronomic factors related to weed and disease control are not yet finalised. According to Maclachlan (2012), ARDA's main research focus is to reduce sugarbeet's high input costs, particularly if the feedstock is produced by emerging farmers.

The selection of grain sorghum as a preferred feedstock by two bioethanol producers provides sufficient motivation to consider this feedstock in the biofuel project. In addition, sorghum was selected as the reference feedstock to represent starch crops in the South African biofuels regulatory framework (DoE, 2014). It is also believed that grain sorghum will be listed as one of the preferred bioethanol feedstocks in a future update of the national biofuels strategy. At the biofuels technical meeting in July 2012, the Project Team therefore recommended that grain sorghum be included in field trial research in the third season.

2.3.4 Sweet sorghum

The biofuels scoping study report (Jewitt *et al*., 2009a) recommended that field-based research is conducted on emerging feedstocks such as sweet sorghum (and sugarbeet). At the biofuels inception workshop held in February 2010, it was also recommended that because insufficient knowledge exists for South African growing conditions, the project should measure the water use and yield of sweet sorghum at the Ukulinga and Hatfield research farms. Sweet sorghum is also being researched at the ARC's Crop Grains Institute at Potchefstroom, Mpumalanga.

At the biofuels technical meeting in July 2012, the decision was made to measure the water use and yield of ratooned sweet sorghum. Hence, the 2011/12 trial at Ukulinga was cut in July 2012 and allowed to re-establish. Fertiliser was applied and the trial was irrigated to initiate growth. However, in December 2012, the trial was abandoned due to poor growth. It is hypothesised that the ratooning trial failed due to the cold winter experienced at the Ukulinga research farm in 2012. A ratoon crop may be possible in the hotter and wetter regions of the country (e.g. along the Zululand coast).

2.3.5 Maize

Lemmer and Schoeman (2011) provided a summary of the events which led to maize being currently banned as a potential biofuel feedstock. The draft national biofuels industrial strategy issued on 15th December 2006 (DME, 2006b) supported the use of maize as a biofuel feedstock, as it could potentially improve food security and could contribute to more stable food prices in the economy. The maize market is limited by demand for the product (both food and feed).

Back in 2007, the Minister of Agriculture was mostly concerned about the demand for export maize by neighbouring countries, as well as the additional demand required for bioethanol production. The Director General of Agriculture added that yellow maize may be considered for bioethanol production, but white maize was not a viable feedstock due to food security concerns. In the past, maize prices have peaked at R2 000.00 per ton, resulting in sharp increases in the price of staple foods products such as maize meal. Based on this, Cabinet decided in December 2007 to exclude maize from the national biofuels industrial policy (DME, 2007a). This decision was made despite Grain SA's appeal to government that maize should not be rejected because its inclusion could ease volatilities in the domestic maize price, boost rural agricultural development and actually improve food security (Lemmer and Schoeman, 2011).

Although yellow maize is not a viable feedstock, a decision was made at the biofuels technical meeting in July 2012, to assess the water use and yield of soybean at Baynesfield in conjunction with WRC Project No. K5/2066 (Mengistu *et al*., 2014). However, the no water use or yield modelling was undertaken for this feedstock.

2.3.6 Cassava

Little information exists on cassava production in South Africa, particularly at a commercial scale. At the biofuels technical meeting in July 2012, it was mentioned that cassava is more valuable as a source of industrial starch and not starch-to-bioethanol production. Based on this evidence, cassava was not considered as a viable feedstock in South Africa.

2.4 Shortlisting of Biodiesel Feedstocks

2.4.1 Soybean

Soybean is listed as one of the biodiesel feedstocks in the national biofuels strategy (DME, 2007a). This feedstock was also highlighted by the DoE as one of the most appropriate commercial feedstocks for biodiesel production (DoE, 2013). In addition, soybean was selected as the reference feedstock to represent oilseed crops in the South African biofuels regulatory framework (DoE, 2014). More importantly, Rainbow Nation Renewable Fuels are planning to utilise this feedstock for their 288 million litre capacity biodiesel plant in Coega, Eastern Cape. A report prepared by the Global Agricultural Information Network (GAIN) estimated the total feedstock required at 1.35 million tons annually, based on a biodiesel yield of 211.8 L t^{-1} of crop (GAIN, 2009). This represents a substantial increase in soybean production from 505 000 tons in 2010. However, some studies (e.g. Sparks, 2010) have challenged the economic viability of biodiesel produced from soybean. At the biofuels technical meeting in July 2012, a decision was made to assess the water use and yield of soybean at Baynesfield in conjunction with WRC Project No. K5/2066 (Mengistu *et al*., 2014).

2.4.2 Canola

Canola is also listed as one of the biodiesel feedstocks in the national biofuels strategy (DME, 2007a). However, PhytoEnergy are planning to utilise this feedstock for their 455 million litre capacity biodiesel plant in Coega, Eastern Cape. Approximately 500 000 ha of planted canola is required to meet the feedstock demands of the processing plant (GAIN, 2009). In the 2010/11 season, only 37 000 tons of canola was produced from 35 000 ha predominantly in the Western Cape. At the biofuels technical meeting in July 2012, a decision was made to model the water use and yield of canola.

2.4.3 Sunflower

Sunflower is listed as one of the biodiesel feedstocks in the national biofuels strategy (DME, 2007a). In addition, this feedstock was also highlighted by the DoE as one of the most appropriate commercial feedstocks for biodiesel production (DoE, 2013). The feedstock is well suited to marginal sites or when low rainfall is expected in a particular season. At the biofuels technical meeting in July 2012, a decision was made to model its water use. However, due to time constraints, the modelling of sunflower yield was not completed.

2.4.4 Jatropha

Jatropha curcas may be declared a Category 2 alien invasive if draft regulations are promulgated, i.e. invasive species controlled by area and thus requires a permit and is not permitted to grow in riparian zones (DEAT, 2009). Jatropha is also considered an invasive species in Hawaii and Australia (GTZ, 2009; Everson *et al*., 2009). Furthermore, DAFF have yet to announce their decision on the future use of Jatropha for biodiesel production.

The scientific literature and other reports indicate a growing disappointment regarding Jatropha's performance, especially in marginal areas where it has been promoted to "thrive". For example, The German Technical Cooperation (GTZ) commissioned an extensive study of Jatropha in Kenya. The report concluded that "Jatropha currently does not appear to be economically viable for smallholder farming when grown either within a monoculture or intercrop plantation model" (GTZ, 2009). The only economically viable option for smallholders is to grow Jatropha as a natural or living fence (mainly used for animal enclosures) with very few inputs (GTZ, 2009).

Based on the above evidence, a decision was made at the biofuels technical meeting in July 2012, to stop the water use and yield monitoring of Jatropha at the Ukulinga site. The consensus was further monitoring would not change the present understanding of this feedstock's water use and yield.

2.4.5 Moringa

Although Moringa is considered a multi-use tree that may provide *inter alia*, food and medicinal products, its role as a potential biodiesel feedstock is questionable. Research to date at the University of Pretoria had been conducted on a lower oil-yielding variety that was sensitive to cold winters. However, a new variety from India was achieving better yields. Further research is required to identify a cultivar that is better suited to the country's cooler areas. The tree is more suited to tropical areas, particularly if grown for its oil yield. Unlike Jatropha seeds, oil derived from the Moringa tree is edible. Based on the perceived value of the oil for human consumption *vs*. biodiesel production, it is unlikely that Moringa will become a significant biofuel feedstock in South Africa.

2.5 Prioritisation of Feedstocks

Lemmer and Schoeman (2011) highlighted the importance of a multi-feedstock approach to sustainable biofuel production in South Africa. Such an approach will enable producers to select feedstocks best suited to the agro-climate of the regions where the processing plants are situated and thus, to minimise logistic costs by sourcing crops grown closest to the plants. The economic viability of producing biofuel from feedstocks which are not currently produced in sufficient quantities remains a major concern.

2.5.1 Bioethanol production

As highlighted in **Section 2.2.6**, the two feedstocks with the highest potential for bioethanol production in South Africa are sugarcane and grain sorghum. Of these two feedstocks, research effort was focused on grain sorghum as there are two proposed sorghum-to-bioethanol factories that require over 600 000 tons of grain. At this stage, yellow maize is not considered a viable feedstock for bioethanol production, but this could change depending on whether the ban on maize is lifted in the near future. Although sweet sorghum shows potential for use in bioethanol production, further research is required to 1) improve the soluble sugar content through breeding trials, and 2) determine the best management practises to optimise biomass and sugar production. Priority for sugarbeet is considered low and depends on ARDA's future plans to incorporate this feedstock into the supply mix for the Cradock bioethanol facility. In addition, research is required to breed cultivars better suited to

South Africa's dryland growing conditions. Finally, little information exists on cassava production in South Africa, particularly at a commercial scale. Hence, this feedstock exhibits the lowest priority for bioethanol production.

2.5.2 Biodiesel production

The two feedstocks with the highest potential for biodiesel production in South Africa are soybean and sunflower. However, the largest biodiesel plant in South Africa plans to utilise canola and for this reason, canola is deemed to have the highest potential. Due to the value of animal feed by-products derived from soybean, this feedstock is deemed to have high potential. Sunflower is well adapted to growing on marginal sites in South Africa and is thus a suitable feedstock for emerging farmers where canola and/or soybean cannot be grown. Tree feedstocks such as Jatropha and Moringa exhibit the lowest potential for biodiesel production due to their low oil yields.

2.5.3 Second generation feedstocks

If the draft regulations pertaining to alien invasive plants are promulgated, then Napier grass will be prohibited for use in biofuel production. Hence, research efforts focused on first generation feedstocks and a "wait-and-see" approach was adopted for second generation feedstocks.

Research effort in Australia is currently focused on cellulosic (i.e. second generation) technology, after the biofuels industry was plagued by rising feedstock prices, which led to a number of processing plants being "mothballed". Research emphasis is on the use of short-rotation coppiced eucalypt (woodchip), as well as high biomass grass hybrids. For example, energy cane hybrids currently produce 30% more biomass, but lower sugar yield. Research into drought tolerance is other focus area, particularly around wheat, sugarcane and sorghum. At present, biofuels are produced mainly from waste streams in Australia, thus avoiding food security issues. Bioethanol is made from 1) a starch-rich effluent from the processing of wheat into food, 2) sugarcane molasses and 3) grain sorghum. Biodiesel is also produced from animal fat (i.e. tallow) and used cooking oil.

2.6 Review of Bioethanol Feedstocks

AIM 2 of this study is to review and characterise the prioritised feedstocks in terms of crop parameters, water use and yield (biomass, biofuel and by-products).

2.6.1 Sugarcane

Sugarcane belongs to genus *Saccharum officinarum* L. of the *Poaceae* (grass) family (Jewitt *et al.,* 2009a). Sugarcane is a tall perennial monocotyledon crop, with stalks 3 to 5 m tall which are 2 to 3 cm thick. The crop has not adapted to survive freezing conditions and is dependent on abundant sunshine for healthy growth. It can be cultivated in the tropical and sub-tropical regions of the world for its ability to store high concentrations of sugar in the stem. It re-emerges when cut, thus enabling multiple harvests to be obtained from a single planting. For commercial sugar production, it is considered a long-term monoculture and can be grown on a large, medium and small scale (Watson *et al.,* 2008). It is harvested in 9 to

24 month intervals, depending on the growing conditions and the variety planted (Tammisola, 2010). There are on-going investigations in South Africa into sugarcane varieties that are suitable for energy production (Jewitt *et al.,* 2009a).

2.6.1.1 Present distribution

Sugarcane originated in the South Pacific Islands and New Guinea (Duke, 1983). It is largely geographically distributed in the lower latitudinal areas found on either side of the Equator, with the majority being cultivated between 0° and 33° latitude (Watson *et al*., 2008). Sugarcane is grown in 14 cane-producing areas is South Africa which extend from the Eastern Cape (Northern Pondoland) through the coastal belt of KwaZulu-Natal and the Midlands, up into the Mpumalanga Province (DAFF, 2012c). The current sugarcane mills in relation to the sugarcane production areas are shown in **Figure 6**. The map shows that sugarcane growing areas north of the Felixton mill are current irrigated.

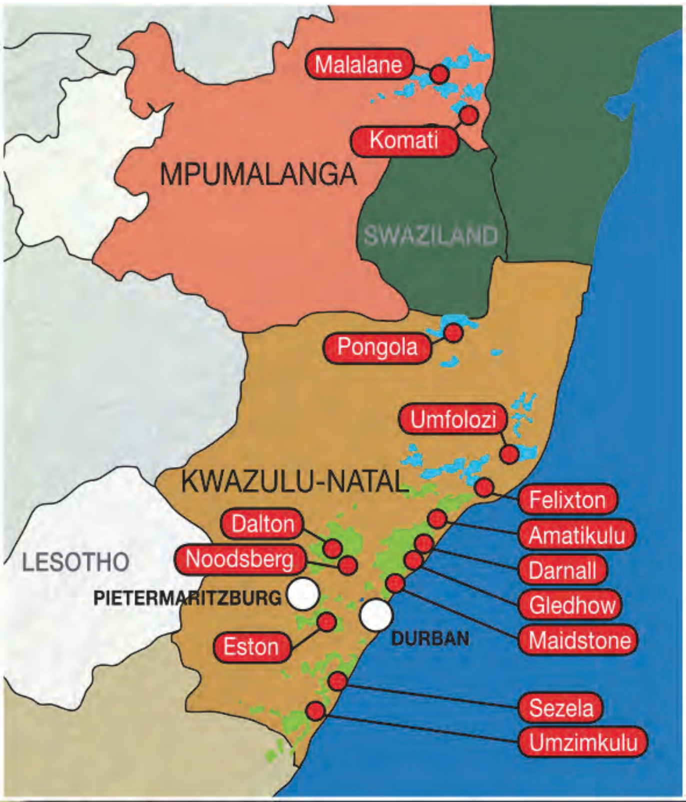


Figure 6 Locations for sugarcane mills (in red), together with rainfed and irrigated cane production areas shown in green and blue respectively (SASA, 2012)

Sugarcane is mainly produced as a mono crop in South Africa. About 20% of the plant is composed of tops and green leaves. Freshly cut cane tops can be fed to mature (and pregnant) beef cows (Smith, 2006). Approximately 68% of sugarcane is grown within 30 km of the eastern coastline and 17% in the high rainfall areas of Kwazulu-Natal. The remainder is grown in the northern irrigated areas that comprise the Pongola and Mpumalanga lowveld. There are 1 550 commercial growers (including more than 378 black commercial growers) who produce 84.7% of the total sugarcane production. There are 27 580 are small-scale growers mainly on tribal land, of whom 13 871 delivered cane for crushing in 2010/11, accounting for 8.6% of the total crop. Milling companies with their own sugar estates produce 6.7% of the crop. Hence, there are 29 130 registered cane growers in South Africa (DAFF, 2011b).

The total area planted to sugarcane expanded in the mid 1990's, primarily as a result of the establishment of the Komati Mill in Mpumalanga and the relocation of the Illovo Mill to its current site in Eston. Since then, no further significant expansion has taken place, due mainly to land competition from urban expansion along the KwaZulu-Natal coastline. Since cane is a perennial crop, the area planted is less subject to fluctuations in supply compared to other crops such as maize (DAFF, 2011b).

2.6.1.2 Season length

According to Smith (2006), sugarcane can be planted in the northern regions (i.e. Lowveld of Mpumalanga) under irrigation in any month except for June and July (soil temperature too low for germination). In the KwaZulu-Natal Mistbelt (i.e. Midlands), planting usually takes place from mid-September to mid-October. Planting from early August to the end of October is typical along the coastal areas of KwaZulu-Natal. The season length varies from 12 to 14 month in hot areas (i.e. coastal areas), up to 18 to 24 months in cool areas (inland areas).

Owing to the larger number of ratoon crops that can be harvested from a single planting (average of 5 to 6, but up to 10), the decision was made to consider ratoon sugarcane and not a newly planted (or re-planted) crop. Hence, all months were considered for mapping suitable production areas. In this study, it is assumed that sugarcane is harvested in August and re-generates (i.e. ratoons) in September (Smith, 2006).

2.6.1.3 Growth criteria

A summary of growth criteria gleaned from the literature for sugarcane in given in **APPENDIX D**. From this, minimum and maximum limits for optimum, sub-optimum and absolute growth conditions were derived. In **Table 3**, a distinction was made between temperature thresholds for ripening (i.e. in latter part of the season) and those used for the remainder of the 12-month growing season.

Table 3 Growth criteria for sugarcane derived from values published in the literature

Variable	**Abs**	**Sub**	**Opt**	**Opt**	**Sub**	**Abs**
	Minimum			**Maximum**		
Seasonal rainfall (mm)	850	1 100	1 300	1 500	1 800	2 000
Monthly mean temperature (ºC): Sep-Apr	15	20	22	30	32	35
Monthly mean temperature (ºC): May-Aug	8	10	12	14	20	24
Monthly mean relative humidity (%): Sep-Apr	30	70	80	85	90	95
Monthly mean relative humidity (%): May-Aug	20	35	45	65	75	85
Soil depth (mm)	400	700	1000			

The productivity of this crop is dependent on the two most important ecological requirements for efficient growth, namely adequate moisture and temperature (Tarimo and Takamura, 1998). To ensure that growing conditions are sufficiently moist, the minimum annual precipitation should be 850 mm. Sufficient water distribution over the growing season is a major requirement to satisfy sugarcane production. For optimum production, 1 300 mm of rainfall should fall per year (Jewitt *et al*., 2009a). Sugarcane yield is directly proportional to the amount of water used under prevailing climatic conditions. Singels (2015) noted that sugarcane is not suited to areas where the annual rainfall is below 650 mm.

Sugarcane grows comparatively slowly during both the early and late stages of its growth cycle. The optimum mean daily temperature for rooting and sprouting of the planted stem is > 20°C. Stalk growth is optimum at 22 to 30°C and 10 to 20°C is necessary for ripening (to reduce vegetative growth and to increase sucrose levels) (Tammisola, 2010; Jewitt *et al*., 2009a). Maximum temperatures below 20°C and above 34°C result in minimum growth for sugarcane (Smith, 1998). The monthly minimum temperature for June and July should be above 5°C to avoid frost-prone areas. However, Singels (2015) suggested the average minimum temperature in July should be greater than 7°C.

According to DAFF (2012c), high humidity (80-85%) favours rapid cane elongation during the main growth period. Hence, humidity is beneficial for sugarcane growth and not a condition that triggers disease occurrence. In addition, a moderate humidity range of 45 to 65%, coupled with limited water supply, is favourable during the ripening phase. This information also appears on the website[6] for Netafim's Agricultural Department, which has successfully cultivated sugarcane in diverse climates and growing conditions worldwide. The website also indicated that sugarcane ripens from 270 to 360 DAP for a 12-month crop cycle (i.e. from June to August). However, in this study, the month of May was also including in the ripening phase as shown in **Table 3**.

Sugarcane prefers growing in 1 m deep soils, with available content water greater than 150 mm. However, roots may extend to a depth of 5 m. Singels (2015) noted that sugarcane is not suited shallow soils with a depth of less than 30 cm. The crop prefers a water table below 1.5 to 2.0 m, since waterlogging can increase the susceptibility to diseases and bacterial infections (Watson *et al*., 2008). Accumulated annual sunshine duration greater than 1 200 hours is required to achieve optimum growth (Jewitt *et al*., 2009a).

Sugarcane has no special soil requirements and therefore does well under a range of soil conditions (Tammisola, 2010). Sugarcane grows best in well-structured and aerated loams and sandy soils with the optimum pH around 6.5, but the plant can survive in soils with a pH of 4.5 to 8.5 (Jewitt *et al*., 2009a; Tammisola, 2010).

2.6.1.4 Crop water use

Sugarcane yield is directly proportional to the amount of water used under prevailing climatic conditions. The approach adopted by Jewitt *et al*. (2009b) involved the sub-division of the sugarcane production areas in KwaZulu-Natal into three regions, *viz*. inland, northern coastal and southern coastal. The city of Durban provides the boundary between northern and southern coastal production regions. Areas with an average altitude of 400 m or above are classified as inland. K_c values for the inland region were derived from experiments conducted at Eston in the KwaZulu-Natal midlands (**Table 4**). Similarly, experiments conducted at Kearsney Manor and Umzinto represent the northern and southern coastal areas respectively (Jewitt *et al*., 2009b).

[6] http://www.sugarcanecrops.com/climate/

Table 4 Representative values for crop coefficients (K_c) for unstressed ratoon sugarcane for the three main production areas in KwaZulu-Natal (Jewitt *et al*., 2009b)

Reg[1]	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
IL	1.08	1.15	1.17	1.01	0.99	0.83	0.85	0.77	0.84	0.81	0.97	0.99
NC	1.14	1.16	1.16	1.01	1.05	0.90	0.93	0.88	0.99	1.00	1.10	1.05
SC	1.12	1.16	1.16	0.99	1.03	0.85	0.88	0.82	0.98	0.89	1.06	1.01
AV	1.11	1.16	1.16	1.00	1.02	0.86	0.89	0.82	0.94	0.90	1.04	1.02

[1]IL - Inland region; NC - north coast region; SC - south coast region; AV - average of all three regions

In this study, the crop coefficients for each sugarcane growing region (e.g. Inland, south coast & north coast) were averaged and used to estimate sugarcane water use, which reduced the total number of national runs required. This was based on an analysis of the preliminary model runs, which showed that when the individual region *vs*. averaged crop coefficients were used, there is no significant difference in the stream flow results. Hence, the averaged K_c values shown in **Table 4** were used in this study for land suitability mapping and water use modelling of sugarcane.

In addition, crop coefficients for planted sugarcane from FAO (FAO, 2002) were also considered to test the mapping approach adopted in this study (**Table 5**). The minimum and maximum length (i.e. ripening takes 30 to 60 days) of each growth stage for sugarcane corresponds to a 12- and 24-month growth cycle respectively. For the purposes of mapping areas suitable for cane production and for modelling sugarcane water use, a 12-month growth cycle was assumed in this study.

Table 5 FAO-based crop coefficients (K_c) for unstressed planted sugarcane (FAO, 2002)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1.18	1.18	1.18	0.93	0.93	0.80	0.80	0.68	0.80	0.95	1.10	1.10

2.6.1.5 Crop yield

The average cane yield for the country is 66.11 tons per harvested hectare which means about 20.25 million tons of cane is crushed each year (**Table 6**). The projected cane production figures for the previous two seasons (2012/13 & 2013/14) are also shown in **Table 6**.

Table 6 Total commercial sugarcane production over a 10-year period (DAFF, 2011b)

Year	Area Harvested	Cane Production	Cane Yield	Cane Sucrose	Sugar Production	Cane/ Sugar
	ha	x 1000 t	t ha^{-1}	%	x 1000 t	
1998/99	316 357	22 930	72.48	13.36	2 646	8.67
1999/00	313 294	21 223	67.74	13.77	2 532	8.38
2000/01	322 858	23 876	73.95	13.08	2 730	8.77
2001/02	325 704	21 157	64.96	13.11	2 396	8.83
2002/03	321 234	23 013	71.64	13.71	2 763	8.33
2003/04	325 956	20 419	62.64	13.70	2 419	8.44
2004/05	316 010	19 095	60.43	13.52	2 235	8.54

Year	Area Harvested	Cane Production	Cane Yield	Cane Sucrose	Sugar Production	Cane/ Sugar
	ha	x 1000 t	t ha^{-1}	%	x 1000 t	
2005/06	318 856	21 052	66.02	13.74	2 507	8.40
2006/07	305 600	20 279	66.36	12.92	2 236	9.07
2007/08	307 380	19 724	64.17	13.47	2 282	8.64
2008/09	287 380	19 255	67.00	13.69	2 269	8.49
2009/10	278 133	18 655	67.07	13.68	2 188	8.53
2010/11	271 080	16 016	59.08	14.14	1 909	8.35
2011/12	270 705	16 800	62.06	12.94	1 822	9.17
Average	**305 753**	**20 250**	**66.11**	**13.49**	**2 354**	**8.63**
2012/13*		18 162			2 142	
2013/14*		20 727			2 370	

*Estimate obtained from SASA website[7]

The table above shows that there was a decline in cane production between 2010/11 and 2011/12. According to DAFF (2011b), the major factors responsible for this decline are:

- the diminishing profitability of growing cane in terms of input costs versus financial returns,
- adverse weather conditions (particularly droughts),
- poor cane contractor performance and service,
- high contracting rates,
- limited capital availability, and
- withdrawal of cane supply support (in some regions), traditionally provided by sugar milling companies.

Harvested sugarcane is transported to 14 sugar mills situated in Kwazulu-Natal and Mpumalanga (**Figure 6**), where it is washed and chopped. The chopped fibre is mixed with water and pressed to produce cane juice. The fibrous mass left after pressing is known as bagasse, and is used for animal feed, paper manufacturing or as a bioenergy feedstock to generate heat (co-generation). The 14 sugar mills are designed for energy balance, which means the bagasse is used by the mill to generate steam and electricity.

After further heating and filtration, the cane juice goes into an evaporator and vacuum pan where much of the remaining water is removed. The resultant syrup is then centrifuged to separate sugar crystals from the molasses (thick, dark fluid rich in vitamins and minerals). Molasses is used in cattle feed and to make brewer's yeast and alcoholic drinks (e.g. cane spirits). The raw sugar crystals are further refined to remove impurities (mostly molasses), with the final product being pure white sugar (DAFF, 2011b).

The industry produces an estimated average of 2.35 million tons of sugar per season (i.e. ≈8.62 tons of cane produces 1 ton of sugar). The sugar content varies from 12.92 to 14.14% with an average of 13.49% (**Table 6**). The projected sugar production figures for the previous two seasons (2012/13 & 2013/14) are also shown in **Table 6**. Between 50 to 60% of this sugar is marketed in the Southern African Customs Union (SACU) comprising of

[7] http://www.sasa.org.za/sugar_industry/FactsandFigures.aspx

South Africa, Swaziland, Lesotho, Botswana and Namibia. The remainder is exported to markets in Africa, Asia and the Middle East (DAFF, 2011b).

2.6.1.6 Disease incidence

In Schulze *et al*. (2010a; 2010b), maps showing the mating, maintenance and mortality indices for Chilo and Eldana moths are given. Both moths lay eggs which produce borers which attack cane stalks, causing severe loss in cane quality. The maps were derived using temperature (and not humidity) as the surrogate driver variable. A review of available literature did not reveal a relationship between humidity and sugarcane disease incidence. According to DAFF (2012c), high humidity levels favour rapid stalk elongation during the main growth period. Hence, humidity is an optimum growth criteria and not a surrogate variable for disease occurrence. The reader is referred to **Section 2.6.1.3** for further discussion.

2.6.1.7 Biofuels suitability

In 2011, the US became the largest supplier of bioethanol made from maize, with Brazil importing a record high 1,497 million litres of bioethanol from the US. By the end of 2012, Brazil once again dominated world bioethanol production from sugarcane, which should remain the case in 2013. However, Brazil experienced severe frosts in the early morning of the 24 and 25 July 2013 which damaged about 18% of cane standing uncut in fields[8]. The frost changes the composition of sugars in the cane stalk (i.e. less sucrose) which causes crystallisation problems and mills will this favour bioethanol over sugar production.

Brazil has demonstrated that sugarcane is well suited to bioethanol production. The amount of land needed to produce bioethanol from sugarcane is relatively low due mainly in advances in technologies (**Figure 7**). Goldemberg (2008) estimated that within a five-year period (2000 to 2004), the bioethanol yield in Brazil increased from 2 000 to 5 917 litres per hectare of sugarcane grown. This yield improvement was mainly attributable to new advanced hybrids and genetically modified sugarcane, new cultivation techniques and new biorefinery technologies used to extract the sugar from the cane stalk and ferment it.

[8] http://www.agweek.com/event/article/id/21358/

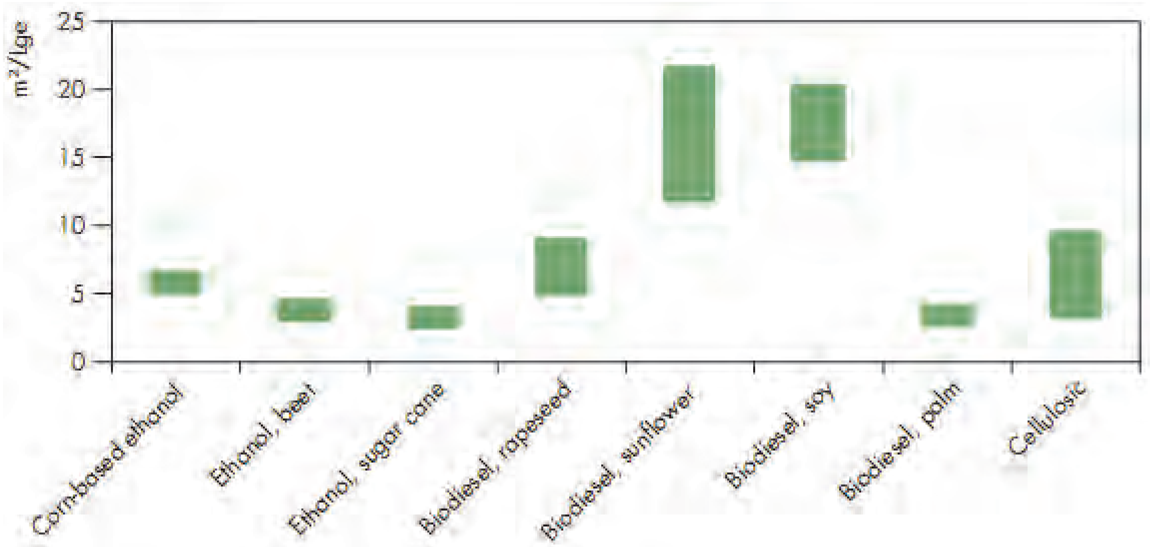


Figure 7 Land-use intensity for different types of biofuels, where m^2/Lge denotes land area in square metres per litre of gasoline equivalent (IEA, 2010)

Bioethanol production from grain sorghum will likely satisfy the minimum 2% blend (equivalent to 240 million litres) mandated by government. The use of sugarcane would increase the bioethanol blending ratio above 2%, but capped at 10% by the mandatory blending legislation. The sugar industry could then produce up to 958 million litres of bioethanol, thus increasing the blending ratio to E10. Tongaat Hulett CEO Peter Straude estimated that a 2% blend could be achieved with 400 000 tons of sugar. He also mentioned that South Africa can produce an annual surplus of sugar between 600 000 (E3 blend) and 1 000 000 tons, which is sufficient for an E3 to E5 blend (Naidoo, 2011). Sugarcane is similar to sweet sorghum in that the sugar quality of the stalk juice degrades rapidly post-harvest and therefore should be processed into bioethanol as soon as possible. This is well documented in the literature, together with numerous solutions to minimise the cut-to-crush time.

In summary, the biofuels industry can create an alternative market for surplus cane production which will encourage expansion of the industry. According to REEEP (2007), cane sugar is exported on a regular basis from South Africa to neighbouring African countries as well as to overseas countries. It is recommended that exported cane could be the initial source for bioethanol production. There is less risk of food/fuel competition because South Africa has consistently produced a surplus of sugarcane. In addition, the sugarcane industry is committed to first meeting the needs of the food market, before any surplus is diverted to the biofuels market.

2.6.2 Sugarbeet

Sugarbeet belongs to the *Chenopodiacae* family and is a deciduous single stem herb (FAO, 2007). It provides about 16% of the world's sugar production from the large tuber (FAO, 2012b). Sugarbeet has been proposed as one of the potential bioethanol feedstocks in South Africa. However, the problem facing South Africa is that there is no reliable information available for the potential production of sugarbeet in South Africa (DoE, 2012a) and it is not as widely used as sugarcane for bioethanol production (Brandling, 2010).

2.6.2.1 Present distribution

Although this crop originated from Asia, it is now grown in many countries (FAO, 2007). Most of the world's sugarbeet is grown in Europe's temperate regions between 30º and 60ºN. France, Germany, Poland and the UK are the dominant sugarbeet producing countries in Europe. Approximately 75% of world sugar production per annum is derived from beet grown in Europe, followed by North America (11%), Asia (8%) and South America (3%). Wherever sugar beet is grown in the world, climate and soil are the two major determinants of success (Draycott, 2006).

The world's supply of sugar is obtained from only two crops, namely sugarcane and sugarbeet. Sugarbeet is mainly in temperate zones (Cattanach *et al*., 1991), but can be grown in different climates. By comparison, sugarcane is grown in warmer, more tropical climates. For example, sugarbeet is also grown in the sub-tropics and is known for its high tolerance to saline and alkaline soils (FAO, 2012b). It is also grown as a summer crop in maritime, prairie and semi-continental climates. In addition, sugarbeet can be grown as a winter or summer crop in Mediterranean regions and some arid environments (Campbell, 2002).

2.6.2.2 Season length

It should be noted that the growing period for sugarbeet is dependent on the region's biophysical characteristics. From the available literature, Brandling (2010) suggested the growing period is normally from 140 days up to 200 days. FAO (2012b) indicated the season is typically 160 to 200 days long. For this study, a seven-month season (i.e. 210 days) was assumed with two different planting dates, namely 1st September (i.e. summer) and 1st June (i.e. winter). The latter planting date was also suggested by Morillo-Verlade and Ober (2006). In Cradock, the planting date will typically be May 1st (after the first frost which usually occurs in late April), with a season length of nine months (Maclachlan, 2012).

2.6.2.3 Growth criteria

A summary of growth criteria gleaned from the literature for sugarbeet in given in **APPENDIX D**. From this, minimum and maximum limits for optimum, sub-optimum and absolute growth conditions were derived (**Table 7**).

Table 7 Growth criteria for sugarbeet derived from values published in the literature

Variable	**Abs**	**Sub**	**Opt**	**Opt**	**Sub**	**Abs**
	Minimum			**Maximum**		
Summer Seasonal Rainfall (mm)	400	500	600	800	900	1 000
Winter Seasonal Rainfall (mm)	350	450	550	750	850	950
Monthly mean temperature (^{o}C)	5	10	15	20	25	30
Monthly maximum relative humidity (%)				60	70	80
Soil depth (mm)	500	700	900			

According to the above table, sugarbeet is optimally suited to areas that receive between 600 to 800 mm of rainfall per summer growing season (550 to 750 mm for a winter planting). This range is similar to that given by FAO (2007) of 550 to 750 mm for total water requirement over the growing season. In high rainfall and humid areas, the plant is more susceptible to both above-ground (i.e. leaf spot) and below-ground (i.e. root rot) diseases.

The optimum daily minimum temperature for seed germination is 7 to 10°C, but seeds can also germinate at 5°C. During vegetative growth, higher day temperatures are preferred. To obtain higher sugar yields, the hourly night temperature should range between 15 and 20°C and the hourly day temperature should vary between 20 and 25°C in the latter part of the growing period (FAO, 2012b). Daily maximum temperatures greater than 30°C can greatly decrease sugar yields during this period (FAO, 2012b). In order to achieve maximum productivity, the optimum mean monthly temperature range is approximately 15°C to 25°C (Petkeviciene, 2009; Wahab *et al*., 2012).

From the available literature, the soil depth required for the viable cultivation of sugarbeet ranges from a minimum of 500 to 600 mm, to a maximum range of 1 200 to 1 500 mm. Sugarbeet is known for its high tolerance to saline and alkaline soils (FAO, 2012b). The absolute lower and upper pH thresholds are 4 to 9 respectively, with an optimal range of 6.5 to 8 (Christenson and Draycott, 2006). Heavy textured or clay soils should be avoided as the crop is highly sensitive to root rot which is aggravated by water logged conditions (Johl, 1980).

2.6.2.4 Crop water use

Single crop coefficients for sugarbeet were obtained from the crop trials at Ukulinga. Summer and winter K_c values were obtained from the 2010/11 and 2013 seasons respectively, as shown in **Table 8**. The initial crop coefficient values ($K_{c\ ini}$) at Ukulinga were higher than those reported by Morillo-Velarde and Ober (2006), which is probably due to the transplanting of seedlings. The winter K_c values did not follow a typical crop coefficient curve because irrigation was withheld to induce water stress and thus, prevent root rot disease as recommended by Maclachlan (2012).

Table 8 Single crop coefficients (K_c) for each sugarbeet growth stage

Growth stage	Length of growth stage (days)	K_c (Summer)	K_c (Winter)	K_c Morillo-Velarde and Ober (2006)
Initial	24-45	0.77-0.78	0.81-0.85	0.40-0.50
Development	35-75	0.78-1.05	0.75-0.85	0.75-0.85
Mid-season	50-90	1.06-1.07	0.73-0.76	1.05-1.20
Late-season	15-50	0.84-0.85	0.76-0.86	0.90-1.00

2.6.2.5 Crop yield

According to FAO (2012b), commercial yields range from 40 to 60 t ha^{-1} of fresh beet with 15% sugar content. Sugar yield is determined by both tuber size and sugar concentration. In mild climate regions, sugarbeet is harvested and delivered to the factory for processing within a few days. In regions with cold winters, the harvest is delayed until freezing temperatures are anticipated (Campbell, 2002). In 2011, production of sugarbeet was about 234 million tons from about 5.9 million ha (FAO, 2012b).

2.6.2.6 Disease incidence

Diseases can significantly reduce potential crop yield if precautionary measures are not taken. If disease occurs in the early stages of sugarbeet establishment and growth, it may destroy the entire crop. Both relative humidity and temperature can affect disease incidence.

For example, downy mildew outbreaks can occur at temperatures between 5 and 20°C and relative humidity of 80 to 90%. Similarly, powdery mildew may occur at lower humidity levels of 30 to 40% (Asher and Hanson, 2006).

In this study, a threshold of 60% for maximum (not mean) monthly relative humidity was considered low risk for disease outbreak, which concurs with the figures of 60% and 65% provided by Wood *et al*. (1980) and Maclachlan (2012) respectively. Higher humidity levels increase the possibility of disease occurrence, especially leaf spot (i.e. *Cercospora*). To avoid disease outbreaks, sugarbeet will be grown in winter at Cradock, when conditions are typically cold and dry. Sugarbeet seed should be planted into moist soil to ensure germination. Supplemental irrigation is necessary to establish the crop, thereafter irrigation is withheld to induce crop stress and minimise root rot (Maclachlan, 2012).

It is recommended that sugarbeet is only planted once every 3 to 4 years to minimise the build-up of nematodes. A cyst-forming nematode caused the closure of some sugarbeet processing factories in Germany where neighbouring farms practiced monoculture (Draycott, 2006). In addition, experience indicates that monoculture is also likely to exacerbate weed control problems by increasing the populations of some weeds that are difficult to control. Hence, sugarbeet is almost always grown in rotation with other crops. In South Africa, an autumn planting of sugarbeet followed by a summer planting of sweet sorghum would be ideal. Crops like sweet sorghum can suppress nematode infestation. However, breeding research is required to produce short-season sweet sorghum varieties to allow for this ideal rotation. The problem typically occurs in May when the beet should be planted, but the sweet sorghum is still busy maturing. Draycott (2006) reported that catch crops can also be used to control nematodes. Nematode-resistant cultivars of cruciferous green manure crops (e.g. white mustard & oil radish) are planted after sugarbeet, then ploughed in 2 to 3 months later. This technique has been widely used in some countries (e.g. Germany, Italy & Spain) to maintain soil organic matter content and conserve nitrogen in the topsoil.

2.6.2.7 Biofuel suitability

The interest in sugarbeet as a biofuel feedstock is due to its ability to accumulate a large quantity of sugar in its storage root. This occurs mainly in the ripening phase, resulting in the lower part of the root containing the highest concentration of sugar (16-20% of fresh weight). This concentration decreases progressively toward the upper parts of the crown, i.e. 7-9% sugar (Draycott, 2006).

The sugar content of sugarbeet tubers rapidly deteriorates post-harvest. This is similar to most crops that produce sugar (e.g. sugarcane). Hence, sugarbeet will need to be grown with a 70 to 100 km radius of the bioethanol plant (Maclachlan, 2012). This will reduce the time between harvest and juice extraction as well as minimise transportation costs. The Department of Agriculture, Forestry and Fisheries recommends that feedstocks are produced within an 80 km radius of the processing facility.

2.6.3 Types of sorghum

The type of sorghum grown for biofuel production depends on the type of conversion process that will be used. Biomass yield, sugar yield and grain yield of sorghum is strongly influenced by both genetic and environmental factors. Sorghums produce different amounts of carbohydrates (structural *vs*. non-structural) which can be used to distinguish each type (**Table 9**). Structural carbohydrates include hemicellulose, cellulose, and lignin (important as a second generation feedstock), while the non-structural carbohydrates include sucrose, glucose, fructose and starch (important as a first generation feedstock). Although all types of sorghums produce lignocellulose that could serve as feedstock for second generation biofuels, energy (and fibre) sorghums contain more structural carbohydrates and are therefore more efficient for energy (and fibre) production (Zegada-Lizarazu and Monti, 2012).

Table 9 Carbohydrate composition of different sorghums (Zegada-Lizarazu and Monti, 2012)

Sorghum type	Structural (%)	Non-structural (%)
Forage	59-63	22-28
Sweet	53	37
Energy/Fibre	77	20

Forage and sweet sorghums are tall and grown primarily for their biomass. Sweet sorghum is bred to produce sugar levels similar to sugarcane. Both forage and sweet sorghums are thick stemmed, with typically 60 to 70% moisture (wet basis) content at harvest. Energy sorghum is forage/sweet sorghum bred for high biomass production. For the tall biomass hybrids, lodging resistance is also an important consideration. In comparison, grain sorghum is relatively short in stature (0.6-1.2 m tall) and grown for grain production (Turhollow *et al*., 2010). Sorghums are therefore divided into four distinct types based on the amount of different carbohydrates they produce, *viz*.:

- Grain sorghum: produces large quantities of grain (approximately 50% of total biomass) and is commonly grown in regions that are more arid. The grain is composed of approximately 75% starch and may be used as a food grain, feed grain or bioethanol production.

- Forage sorghum: produces lower quantities of grain (approximately 25% of total biomass). They are used for grazing or hay production or chopped and ensiled for animal feed. Hybrids are bred to enhance forage quality and palatability. They may have application as a 2nd generation feedstock where lower lignin content is desirable.

- Sweet sorghum: produces high concentrations of soluble sugar, which is predominantly sucrose with variable levels of glucose and fructose. Hybrids are being bred as feedstocks for mainly bioethanol production. Growth can be prolific when environmental conditions allow the plants to reach their full genetic potential.

- Energy or fibre sorghum: produces high quantities of lignocellulosic biomass. These sorghums are highly photoperiod sensitive, meaning that the crop can effectively photosynthesise throughout the entire growing season. The absence of reproductive growth, particularly in temperate climates, reduces sensitivity to short periods of drought (USDoE, 2011). Energy sorghum can be used to biofuel and bioenergy production. Fibre sorghums can also be used for fibre production, in particular the manufacture of paper from cellulose (Zegada-Lizarazu and Monti, 2012).

Energy sorghums have a photoperiod shorter than the day length at the end of the growing season (i.e. first frost in temperate climates), which allows the crop to maximise biomass production. These photoperiod sensitive hybrids begin reproductive growth (i.e. flowering) when day length reaches a certain threshold (typically 11.5-13.5 hours). The absence of reproductive growth, particularly in temperate climates, means biomass production is maximised. In contrast, photoperiod insensitive sorghums initiate flowering after a set amount of time, regardless of day length. For example, grain sorghum has been bred in temperate climates to do this (Turhollow *et al*., 2010).

2.6.4 Sweet sorghum

As noted in the previous section (**Section 2.6.3**), sweet sorghum (*Sorghum bicolor* L.) is similar to grain sorghum, except the crop has sugar-rich stalks. Sweet sorghums are distinct due to their higher sugar content in stalks (Brix 10 to 18%) from flowering to maturity. By comparison, grain sorghum has a Brix value of 9 to 11% during the same period (Srinivasa Rao *et al*., 2009).

2.6.4.1 Present distribution

Sweet sorghum is the fourth major cereal crop of the world in production and fifth in planted area (after wheat, rice, maize and barley). It is mostly grown in the semi-arid tropics (SAT) of the world where production is constrained by poor soils, low and erratic rainfall as well as low inputs (Srinivasa Rao *et al*., 2009). Sorghum and particularly sweet sorghum, is a fast growing C_4 plant native to tropical zones, but with a wide adaptability to different environmental conditions. It can be grown in tropical, sub-tropical as well as temperate zones (Zegada-Lizarazu and Monti, 2012).

2.6.4.2 Season length

Sweet sorghum has a relatively short crop rotation of 4 to 5 months (Srinivasa Rao *et al*., 2009). In sub-tropical areas, farmers should benefit from two harvests per annum. Dryland farmers in the tropics can get up to three sweet sorghum crops per year. However, sorghum farmers rarely get more than one crop a year in temperate climates (ABW, 2008).

The duration from emergence of seedling to tillering is about 30 days. About 47-55 days after seedling emergence, the plants enter the jointing/elongation stage as the leaf surface area expands quickly and the plant rapidly elongates. During elongation, the soil should be fertile and weeds should be controlled. Stem height increases with daylength and therefore stems are shorter when grown at the Equator. After booting, it produces the final leaf or the flag leaf. About a week later, it then begins earing and after 2-5 days, it blooms. Maximum water use occurs at blooming and this is when irrigation water should be applied. After completing pollination, the milk stage begins and pressed seeds contain a thick milky liquid. During the wax stage, a waxy paste is expressed from pressed seeds. After 30 days from blooming, the mature stage is identified by dry and hard seed (Guiying *et al.,* 2003).

2.6.4.3 Growth criteria

According to scientists at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), an estimated 50 percent of grain sorghum growing areas could be sown with sweet sorghum (ABW, 2008). Sweet sorghum can be grown on less fertile lands and is also drought tolerant.

Although sorghum is considered a dryland crop, sufficient moisture availability for plant growth is critically important for high yields. According to Reddy *et al.* (2008), sweet sorghum grows well in areas receiving more than 700 mm annual rainfall. Srinivasa Rao *et al.* (2009) noted that optimum rainfall is 550 to 800 mm over the growing season. While sorghum will survive with a supply of less than 300 mm rainfall over the season of 100 days, it responds favourably to additional rainfall or irrigation water. Typically, sweet sorghum needs between 500 to 1000 mm of water (rain and/or irrigation) to achieve good yields of 50 to 100 t ha^{-1} total above ground biomass (fresh weight).

Sweet sorghum can be grown in the temperature range of 15 to 37°C with the optimum daily temperatures between is 32 to 34°C (Srinivasa Rao *et al*., 2009). The plant thrives when daytime temperatures are above 30°C (ABW, 2008). Sorghum can be found at elevations between sea level and 1 500 m. In East Africa, it grows at altitudes of 900 to 1 500 m. Cold-tolerant varieties are grown between 1 600 and 2 500 m in Mexico.

The preferred day length is 10 to 14 hours, with relative humidity 15 to 50%. Both grain yield and stalk sugar content will decline if the crop experiences a short daylength, low night temperatures and low radiation levels. A large temperature difference between day and night, after flowering will favour the accumulation of sugar in the stalk and nutrients in the seed (Srinivasa Rao *et al*., 2009).

Sorghum grows readily in saline or alkaline soils and can withstand stress (ABW, 2008). Sweet sorghum possesses twice as many secondary roots as maize at any one stage of growth. The secondary roots grow out from the base of the stalk node near the soil surface after the plant has produced 3 to 5 leaves (Guiying *et al.,* 2003).

2.6.4.4 Crop water use

Sweet sorghum is claimed to be a water use efficient crop. For example, sugarcane requires about eight times more water to grow, compared to sweet sorghum. According to Reddy *et al*. (2008), two rotations of sweet sorghum in tropical areas will consume about 8 000 m^3 of water. However, as highlighted by Jewitt *et al*. (2009a), these figures are subject to much debate. In addition, there are several inconsistencies in the available literature (e.g. Mastrorilli *et al*., 1999; Sakellariou-Makrantonaki *et al*., 2007) regarding the water use and yield of sweet sorghum. Thus, further highlighting the need for field trials to establish the water use and yield under South African conditions.

An advantage of sorghum is that it can become dormant under adverse conditions and can resume growth after a relatively severe drought. An early drought experienced before panicle initiation will stop growth, but the plant remains vegetative. It will resume leaf production and flower when conditions again become favourable for growth. A mid-season drought can halt leaf development. The crop tolerates erratic rainfall and will recover if wilted for up to 14 days. Sorghum is, however, susceptible to sustained flooding, but will survive temporary waterlogged conditions better than maize (Srinivasa Rao *et al*., 2009).

In subtropical and tropical environments, sweet sorghum is technically a perennial crop and is planted from seed, but typically grown and managed as an annual crop. Single cut yields are generally lower, which is likely due to increased night temperatures, but cumulative yields are higher due to the ratoon potential of the crop. Hence, two harvests are possible in a year, compared to a single annual harvest in temperate regions (USDoE, 2011). This means the water use efficiency of sweet sorghum grown in tropical climates will differ to that grown in temperate climates.

2.6.4.5 Crop yield

Current sweet sorghum hybrids and varieties yield on average about 3 to 5 t ha^{-1} of grain and 50 to 80 t ha^{-1} of biomass. This compares favourably with other C_4 grasses such as banana grass and miscanthus (Srinivasa Rao *et al*., 2009).

Sweet sorghum can produce up to 2 5 t ha^{-1} of grain for either human (food), animal (feed) or bioethanol (fuel) consumption. In 2006, breeding of sweet sorghum hybrids (at the International Crops Research Institute for the Semi-Arid Tropics or ICRISAT) was already underway. The best hybrid produced 9.15 and 3.28 t ha^{-1} of sugar (18% Brix) and grain yield respectively. Another top performer produced 7.57 and 7.19 t ha^{-1} of sugar (16% Brix) and grain yield respectively (Reddy *et al.,* 2007). Experiments in Inner Mongolia showed that the net return of sweet sorghum is twice of that of sugarbeet (Guiying *et al.,* 2003).

Once the main stem has been harvested, the dormant bud of the stubble can also grow into a tillering stalk. The growth period of new stalks is shorter as the carbohydrates accumulate quickly since the root system is already well established (Guiying *et al.,* 2003). Re-generated (i.e. ratooned) plants can be used for silage.

2.6.4.6 Disease incidence

Sweet sorghum is susceptible to biotic and abiotic stresses such as striga, shoot fly, stem borer, shoot bug, aphids, anthracnose, grain mould and leaf blight (Srinivasa Rao *et al*., 2009). A fungal disease called *Ergot* can affect the grain production in humid areas. This was experiences at Ukulinga, which is hotter and more humid than growing conditions at Hatfield. The whiter the grain colour, the more susceptible it is to fungal diseases such as Ergot.

2.6.4.7 Biofuel suitability

Sorghum is considered a highly productive C_4 photosynthetic grass that is well adapted to warm and dry growing conditions. Sorghum can be rotated with maize, soybean, cowpea and rye (Zegada-Lizarazu and Monti, 2012). Sorghums should be carefully selected for a region, taking into consideration photoperiod sensitivity and the goal of production (e.g. grain, sugar, biomass, sugar + grain, biomass + grain, or biomass + sugar + grain).

To produce bioethanol from sweet sorghum, the stalks (containing 10 to 15% sugars) are stripped of their leaves and crushed to extract the sugar juice, which is then distilled and transformed into bioethanol. Hence, the grain is not involved in the bioethanol process and only used for food production (ABW, 2008). Bioethanol is produced from sweet sorghum stem juice using fermentation technology similar to the molasses-based process used in the sugarcane industry (Reddy *et al*., 2008). Srinivasa Rao *et al.* (2009) also stated that sweet sorghum-based bioethanol is sulphur-free and cleaner than molasses-based bioethanol, when mixed with gasoline.

The world's first commercial bioethanol plant using sweet sorghum as the primary feedstock is situated in India and began operation in June 2007. The plant produces about 40 kilolitres of bioethanol daily sweet sorghum feedstock produced by some 1 000 farmers in the Andhra Pradesh region of India. India intends to use a 10 percent bioethanol blend to save an estimated 80 million litres (21 million gallons) of gasoline each year to ease the country's growing dependency for gasoline and to reduce carbon emissions (ABW, 2008).

2.6.4.8 By-products

Sweet sorghum is considered a multi-purpose crop that can be used for food, fuel, fodder, fibre and fertiliser production. Hence, sweet sorghum is a multi-purpose crop which can be cultivated for the simultaneous production of (ABW, 2008):

- grain from its ear head (for food, mainly flat breads and porridges),
- sugary juice from its stalk (for making syrup or bioethanol), and
- bagasse and green leaves (as an excellent fodder for animals, or as organic fertiliser, or for paper manufacturing).

Typically, sweet sorghum produces grain for human consumption and the stover (leaves and stalks) are used for livestock fodder. Freshly cut stover can be used as forage for cattle. The stover can also be preserved as silage for feeding farm animals when there is scarce supply of green grasses and other green fodder crops.

The use of stover to produce bioethanol therefore diverts biomass away from feeding livestock, potentially causing shortages of animal fodder. However, the crushed stalks (bagasse) and stripped leaves (by-products of the bioethanol production process) are also a source of animal fodder. A recent study conducted by Blümmel *et al.* (2009) concluded that sweet sorghum can provide food (grain), animal fodder (bagasse combined with leaf residues) and bioethanol at the same time. The study examined the sweet sorghum grain-bioethanol-fodder value chain involving 18 hybrids and 16 varieties (i.e. 34 cultivars) of sweet sorghum. Average yields of bagasse plus stripped leaves provided 5.8 t and 6.7 t of fodder per hectare for hybrids and varieties respectively, which is a substantial amount of feedstock. For comparison, average yields of stover provided 11.7 t ha^{-1} and 13.9 t ha^{-1} for hybrids and varieties respectively.

To produce organic fertiliser from sweet sorghum residues, the bagasse (pulp or dry refuse left after the juice is extracted from sweet sorghum stalks) and leaves (collected after stalk stripping) are mixed with a Compost Fungus Activator (CFA) such as *Trichoderma harzianum*. This single-celled fungus hastens the decomposition of organic materials high in lignin and cellulose (like bagasse). Hence, the composting time is shortened from three months to just three to four weeks. One hectare of sweet sorghum will yield about 50 to 75 tons of stalks and produce from 22 000 to 35 000 tons of bagasse. The bagasse can provide approximately 88 to 151 bags of organic fertiliser. Since organic fertilisers recycle nutrients from plant residue, it is a cheap alternative or supplement to inorganic fertilisers (ABW, 2010).

2.6.5 Grain sorghum

Sorghum belongs to the *Poaceae* family and is a perennial crop grown in temperate regions (Jewitt *et al.,* 2009a). The genus sorghum consists of wild and cultivated species (Menz *et al.,* 2002). The stem is succulent and solid, with a diameter of between 5 to 30 mm. Selfpollination usually occurs in sorghum (Menz *et al.,* 2002), since only about 6% is natural cross-pollination (DAFF, 2010b).

Sorghum is native in Africa and its country of origin is Ethiopia and now it can be found in most dry areas of the world (Dicko *et al*., 2006). Worldwide, the production of grain sorghum is approximately 70 million tons from 50 million ha of land. In South Africa, sorghum is cultivated by both smallholder and commercial farmers. The Limpopo Province produces approximately 20,000 tons of sorghum from about 25 342 ha. The Provinces of Mpumalanga, North-West, Northern Cape, Eastern Cape, KwaZulu-Natal and Free State also produce sorghum (DAFF, 2010b).

2.6.5.1 Present distribution

Sorghum is native to Africa, its country of origin is Ethiopia, but now it can be found in most dry areas of the world (Dicko *et al*., 2006). Worldwide, the production of grain sorghum is approximately 70 million tons from 50 million ha of land. In South Africa, sorghum is cultivated by both smallholder and commercial farmers.

According to DAFF (2010e), sorghum was produced mainly in the Free State (57%), Mpumalanga (24%), and Limpopo (14%) Provinces during the 2007/08 season. It is important to note that no grain sorghum is produced in the Eastern Cape Province. Similar figures for the 2009/10 season (obtained from Mabele Fuels' website[9]) with the Free State being the largest producer (52%) of grain sorghum. Mpumalanga was second (24%), followed by Limpopo (15%), North West Province (7%) and Gauteng (2%). The Limpopo Province produces approximately 20 000 tons of sorghum from about 25 342 ha (DAFF, 2010b).

2.6.5.2 Season length

According to Smith (2006), sorghum is planted from late October to mid-December. Du Plessis (2008) indicated that sorghum is normally planted from mid-October to mid-December. Since the crop is sensitive to frost, planting is usually delayed until after the last frost. If planting is delayed until mid-December, an early maturing cultivar should be planted (Smith, 2006). According to van Heerden (2013), the growing season varies from 120 days (for early maturing cultivars) to 135 days. DAFF (2010e) noted that sorghum is normally harvested from January to April. In this study, November was considered the optimum planting month for all areas, with the crop harvested during the month of March. Hence, the months from November to March were used for mapping purposes.

2.6.5.3 Growth criteria

A summary of growth criteria gleaned from the literature for grain sorghum in given in **APPENDIX D**. From this, minimum and maximum limits for optimum, sub-optimum and absolute growth conditions were derived (**Table 10**).

[9] http://www.mabelefuels.com/products-services/grain-sorghum/

Table 10 Growth criteria for grain sorghum derived from values published in the literature

Variable	Abs	Sub	Opt	Opt	Sub	Abs
	Minimum			Maximum		
Seasonal rainfall (mm)	400	450	650	800	1 000	1 200
Monthly mean temperature (ºC)	15	20	25	30	32	35
Monthly minimum relative humidity (%)				40	60	80
Soil depth (mm)	300	500	800			

Sorghum is grown in drier regions because the crop is drought-resistant, requiring < 300 units of water to produce one unit of dry matter (Smith, 1998). The crop is drought-tolerant because the leaf is covered by a thick waxy layer, which reduces transpiration (DAFF, 2010b). The adequate annual rainfall range for grain sorghum is between 300 to 750 mm (DAFF, 2010b). Floral initialisation can be stopped by early drought, whilst late drought stops leaf development (DAFF, 2010b). In the drier western parts of South Africa, about 400 mm of annual rainfall is required and in the wetter eastern parts about 800 mm is required (Du Plessis, 2008). Pannar (2011) stated that sorghum is well adapted in areas with a summer rainfall of 400 to 800 mm. However, wet and humid areas affect seed set.

The ideal growing temperature is 25 to 30°C with a minimum of 15°C. For optimum grain production, grain sorghum requires a maximum daily temperature of 25 to 30°C (Pannar, 2011). A temperature of 27 to 30°C is required for optimum growth and development. The temperature can, however, be as low as 21°C, without a dramatic effect on growth and yield (du Plessis, 2008; DAFF, 2010b). Sorghum requires warm weather for germination and growth, whilst freezing temperatures are detrimental to sorghum (du Plessis, 2008). The optimum daily maximum temperature for germination ranges between 20 and 35°C and the germination minimum temperature ranges between 7 and 10°C (du Plessis, 2008; DAFF, 2010b). The crop prefers a soil temperature of 15°C or above, with sufficient water at a preferable depth of 10 cm (du Plessis, 2008). Exceptionally high temperatures cause a decrease in yield (du Plessis, 2008). Periods with temperatures less than 15°C or greater than 35°C at flowering can cause poor seed set (Smith, 2006).

The requirements for soil depth vary in the literature from shallow (du Plessis, 2008; DAFF, 2010b) to deep (Smith, 2006; Pannar, 2011). In general, maize is usually planted on sites with deeper soils as sorghum is better adapted to shallower soils. Sorghum possesses both primary and secondary roots. Initially, the primary roots provide nutrients to the seedlings and this function is then taken over by the secondary roots. The roots can reach a depth of up to 2 m and they grow laterally and downward.

Sorghum can be grown in a wide range of soils, including loams, deep sandy loams, cracking clays and low-potential shallow soils with high clay content. Sorghum can survive in soils that are not suitable for maize production but they grow poorly on sandy soils. Sorghum can tolerate alkaline salts, unlike other crops, and the optimum pH (KCL) ranges between 5 and 8.5. The optimum clay content in soils ranges between 10 and 30%. Short periods of waterlogging can be tolerated by sorghum, compared to maize (du Plessis, 2008; DAFF, 2010b).

2.6.5.4 Crop water use

Single crop coefficient values obtained from FAO (FAO, 2002) and from the Ukulinga 2012/13 trial are shown in **Table 11** for grain sorghum. The values indicate that sorghum's water use is similar to that of soybean (see **Section 2.7.1.4**). However, sorghum is considered a more drought tolerant crop which can tolerate erratic rainfall and will recover even if wilted for up to 14 days (Smith, 1998). However, sorghum is sensitive to water stress during flowering, which takes place 50 to 70 days after planting. Hence, rainfall during the stress-sensitive third month should exceed 100 mm, because severe water stress during flowering causes pollination failure (Smith, 1998).

Table 11 Single crop coefficients (K_c) for each sorghum growth stage

Growth stage	**Length of growth stage (days)**	**K_c (FAO, 2002)**	**K_c Ukulinga**
Initial	20-25	0.3-0.4	0.52
Development	30-40	0.7-0.8	1.00
Mid-season	40-45	1.0-1.2	1.03-1.05
Late-season	30	0.7-0.8	0.90
At harvest		0.5-0.6	0.79

2.6.5.5 Crop yield

Production and consumption figures for grain sorghum were obtain from two literature sources. The Department of Agriculture, Forestry and Fisheries (DAFF, 2010e) provided generalised long-term (i.e. 13-year) figures whereas Grain SA provided more detailed, short-term (i.e. 5-year) data. Both sets of figures are provided in the sections that follow.

In 2007/08, producers planted 69 000 ha of sorghum and harvested 176 000 tons, thus yielding 2.55 t ha^{-1} on average (**Table 12**). Approximately 76 000 tons of surplus grain sorghum was carried over from the previous season and combined with 32 000 tons of imported grain, the total grain supply for 2007/08 season was 284,000 tons. Of this, 184 000 and 17 000 tons were consumed as food and feed respectively. Hence, grain sorghum is mainly used for malt/brew production and meal. The total demand was 241 000 tons (including 27 000 tons of exported grain), which left a surplus of 43 000 tons that was carried forward to the following season (i.e. 2008/09). The 2009/10 season produced the largest sorghum crop since 2004/05, with an average yield of 3.23 t ha^{-1}. The average yield for the 2010/11 season was low due to unfavourable weather conditions. In 2011/12, competitive maize prices resulted in less sorghum being planted. The projected surplus grain was estimated at 26 000 tons for the 2011/12 season (Lemmer and Schoeman, 2011).

Table 12 Supply and demand for grain sorghum from 2007 to 2012 (Lemmer and Schoeman, 2011)

Year	**2007/08**	**2008/09**	**2009/10**	**2010/11**	***2011/12****
Area planted (x 1000 ha)	69	87	86	87	*69*
CEC crop estimate (x 1000 ton)	176	255	277	197	*160*
Yield (ton/ha)	2.55	2.94	3.23	2.27	*2.31*
Deliveries (x 1000 ton)	176	251	279	190	*160*
Stocks on 1 April (x 1000 ton)	76	43	63	93	*58*
Imports (x 1000 ton)	32	0	4	0	*44*
Total supply	**284**	**293**	**347**	**283**	***262***
Food consumption (x 1000 ton)	184	179	182	182	*183*
Feed consumption (x 1000 ton)	17	15	19	22	*21*
Other gain/loss (x 1000 ton)	12	-1	1	-4	*7*
Exports (x 1000 ton)	27	37	52	24	*25*
Total demand	**241**	**230**	**254**	**225**	***236***
Surplus on 31 March (x 1000 ton)	43	63	93	58	*26*

*Estimated and not actual figures

2.6.5.6 Disease incidence

Ergot is a fungal disease which affects grain yield (and quality) of sorghum. According to Montes *et al*. (2003), minimum relative humidity is highly correlated to ergot disease incidence, especially for late-maturing (i.e. long-season) hybrids. Disease incidence rose from 0 to 70% with increasing as minimum relative humidity from 30 to 100%. The risk of infection is highest at the flowering stage. Montes *et al*. (2009) reported that ergot severity increased to 40% as minimum relative humidity rose from 40 to 80%, especially 1 to 3 days after flowering initiation (i.e. anthesis). Both studies also showed that disease incidence is also correlated to maximum and minimum temperature. This is not surprising considering the inverse relationship that exists between hourly temperature and relative humidity (high RH occurs when temperatures are lowest). Hence, disease incidence is highest when conditions are cool and humid at flowering.

2.6.5.7 Biofuel suitability

The South African grain sorghum production trend for the 1997/98 to 2009/10 growing season is illustrated in **Figure 8**. The seasonal fluctuation in production and consumption of grain sorghum is evident, as well as the linear trend line which shows the decline in production over the 13-year period (Lemmer, 2009). During the 2000/01 growing season, production sharply increased as a result of larger plantations, especially the bitter cultivars (Mashabela, 2012). This season illustrates that the country can provide higher quantities of grain sorghum if the demand exists. Production also increased in the 1997/98 and 2004/05 growing seasons (Lemmer, 2009), due to higher price anticipations (Mashabela, 2012). However, due to current market conditions, grain sorghum farmers are expected to decrease plantings and shift to maize because of its higher profitability (Mashabela, 2012).

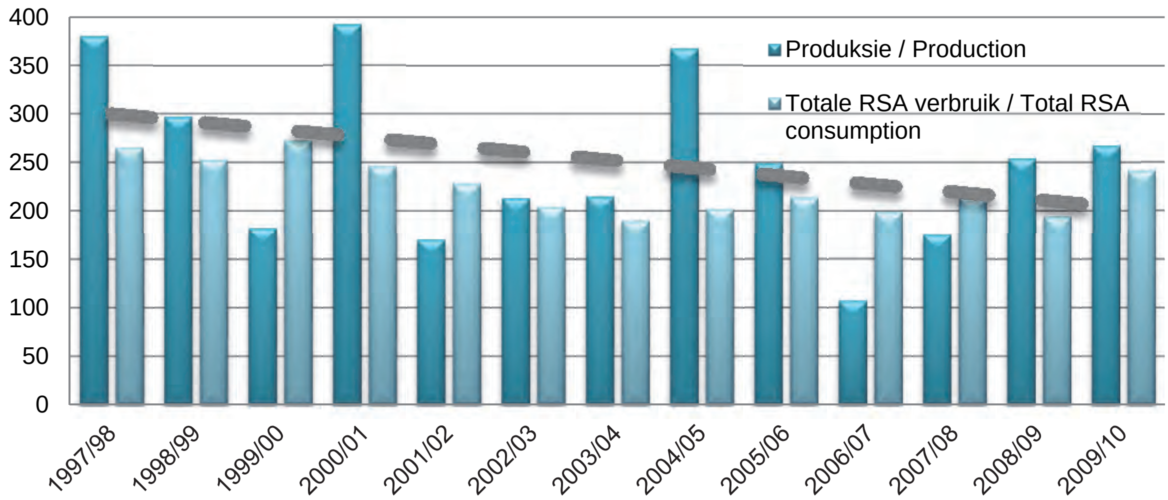


Figure 8 Seasonal grain sorghum production and consumption (x 1000 tons) in South Africa from 1997/98 to 2009/10

From **Figure 8**, it is evident that the grain sorghum industry requires an alternative market for their product, which Grain SA expects will be the emerging biofuels market. Large parts of South Africa are better suited to sorghum rather than maize because the crop is drought-resistant, which makes it more suitable for emerging farmers to produce (DoE, 2012a). To date, two processing plants have selected grain sorghum as their preferred feedstock (DoE, 2014). This is despite the comment made by SASOL that "it is currently not economically viable to produce bioethanol from sorghum" (DAFF, 2010e). Bioethanol production requires the use on non-bitter (i.e. tannin free) sorghum grain. Based on evidence from the research trials conducted at Ukulinga, feeding birds may become a serious problem for small-scale farmers attempting to growing tannin-free varieties. A successful crop will require birds to be frightened off daily, especially around emergence and from the grain filling stage up to maturity.

Some agronomists are concerned that the increased demand for grain sorghum will attract maize farmers to plant grain sorghum, thus decreasing the area planted to maize. The Mabele Fuels website[10] states that "local maize farmers will be encouraged to plant grain sorghum rather than sit with large surplus maize harvests". Mabele Fuels commissioned Grain SA to deliver an objective assessment of the impact of grain sorghum production on food security in South Africa (Lemmer and Schoeman, 2011). The reported stated that assuming and E2 blend, "the total decline in the area under maize amounts to 73 000 ha by 2020 and the price impact on both white and yellow maize seems negligible". Furthermore, the anticipated reduction in planted area would be absorbed by reduced exports to neighbouring counties and the lower demand for yellow maize used for animal feed production (offset by DDGS produced from the grain-to-bioethanol conversion process). However, Lemmer and Schoeman (2011) stated that for E5 blending, the price of white and yellow maize is expected to increase by 2020 and thus, food security may be compromised in terms of the affordability of maize consumer products.

[10] http://www.mabelefuels.com/policies-responsibilities/food-vs-fuel/

Of the 230 000 tons of grain required by the Cradock bioethanol project, a minimum of 30% must be produced by emerging (i.e. BEE) farmers predominately located in the Eastern Cape (IDC, 2011). DAFF (2010e) estimated that between 40 000 and 90 000 tons of sorghum is produced annually by developing farmers. However, no grain sorghum was produced in the Eastern Cape in 2007/08.

An advantage of using grain sorghum for bioethanol production is that the feedstock can be stored in silos prior to processing. This will assist in feedstock supply logistics, considering the bioethanol plant requires grain all year round, especially during the non-growing season. Sorghum grain is similar to maize grain and is usually dried to a moisture content of 10 to 12% (bulk density of 520 to 720 kg m^{-3}), which allows for efficient storage and transport (Turhollow *et al*., 2010). In addition, the feedstock can be railed to the Cradock site from the major sorghum growing areas situated in the Free State. This may be necessary if the Eastern Cape Province is unable to supply sufficient feedstock to the Cradock factory. However, this additional transport cost will increase the price of bioethanol produced at Cradock, compared to the Bothaville facility. For the Bothaville facility, road and rail will be utilised to transport the feedstock from farms to the refinery at a maximum distance of 150 km away.

2.6.5.8 By-products

Kotze (2012a) reported that an estimated 600 000 tons of grain sorghum required for bioethanol production will produce about 175 000 to 200 000 tons of DDGS, offsetting the sorghum (≈40 000 tons per annum) and maize currently used to produce animal feed. Mabele Fuels[11] has entered into proposed off-take agreements (Sale of DDGS Agreement). These agreements will come into effect once the Bothaville plant is in operation and endure for a fixed period of three years. The agreements are necessary to ensure that the animal feed market in South Africa will be able to absorb the entire annual production capacity of 107 000 tons of DDGS from the Bothaville facility.

Kings (2012) reported that the Cradock plant will produce 75 000 tons of animal feed as a by-product of the grain sorghum-to-bioethanol conversion process. Thus, local livestock farmers would not have to import fodder from Gauteng. No information was found in the available literature pertaining to whether or not the Cradock plant had similar agreements in place. The starch content in the grain can also be used for industrial applications (Almodares and Hadi, 2009).

2.7 Review of Biodiesel Feedstocks

2.7.1 Soybean

Soybean belongs to the *Fabaceae* family. It is a bushy, erect, leguminous annual plant that prefers short days and requires warm temperatures (Jewitt *et al.,* 2009a; DAFF, 2010a). Plant height is usually 40 to 100 cm with a well-developed root system and each plant produces between 3 and 350 pods (DAFF, 2010a). The stem is round and hairy with many branches. The leaves are alternate and the inflorescence has one or two self-fertile flowers. Soybean has two growth stages: the first is from emergence to flowering (vegetative) and the second from flowering (reproductive) to maturation (Kandel, 2012). Soybean is

[11] http://www.mabelefuels.com/products-services/ddgs/

determinate in nature with a bush habitat, but some can be indeterminate, depending on the cultivator (FAO, 2012a). If the crop is planted with other crops such as maize and sorghum, it ensures nitrogen fixation for maintaining and replenishing soil fertility (Ngalamu *et al*., 2012). Soybean can be used for livestock feed, human nutrition, industrial use and also as a source of bioenergy and is thus considered a multi-purpose crop (Chianu *et al*., 2009).

2.7.1.1 Present distribution

Countries growing soybean (top producers) are mainly the USA, Brazil and Argentina, where the annual production is about 77.3, 44.5 and 30.3 million tons per year respectively. Production from these countries is more than twice Africa's average because the legume was only recently introduced to the continent (Ngalamu *et al.,* 2012). The production of soybean in South Africa ranges from 450 000 to 500 000 tons per year, with an average yield of 2.5 to 3 t ha^{-1} under dryland conditions. **Table 13** shows the main soybean production areas in South Africa (DAFF, 2010a).

Table 13 Production of soybean per Province in South Africa from 2006 to 2010 (DAFF, 2011a)

Province	**Production per Province (%) by year**				
	2006	**2007**	**2008**	**2009**	**2010**
Mpumalanga	49.5	37.3	43.4	50.9	42.3
Free State	18.2	16.5	21.8	19.2	26.8
KwaZulu-Natal	14.7	22.0	14.9	14.7	13.0
Limpopo	8.1	12.2	7.6	8.5	8.9
North West	6.4	8.8	9.6	3.6	4.8
Gauteng	2.5	2.0	1.9	2.4	3.6
Northern Cape	0.4	0.7	0.6	0.4	0.3
Eastern Cape	0.2	0.5	0.3	0.3	0.2

In terms of crop rotations, irrigated soybean is planted in summer and is typically followed by winter wheat. Soybean is inter-cropped with maize, with a typical 1/3 soybean and 2/3 maize ratio used by KZN farmers. However, some farmers plant equal portions of soybean and maize in a rotation (Sparks, 2010).

2.7.1.2 Season length

According to Smith (2006), the optimum planting window for soybean grown in cooler areas is 20th October to 15th November. Similarly, the optimum planting window in warm and hot areas is 1st November to 20th November. In this project, the 1st November was considered the optimum planting date for all regions. The growth cycle of soybean is typically 150 days (Smith, 2006). According to DAFF (2010a), in South Africa the crop is planted from November to December and harvested from February to March. Hence, the months from November to March were used for mapping purposes.

2.7.1.3 Growth criteria

In the biofuels scoping study (Jewitt *et al*., 2009a), only rainfall and temperature were used for mapping potential areas for the different biofuel feedstocks. In this report, relative humidity and soil depth were also used as additional mapping criteria for soybean. A summary of growth criteria gleaned from the literature for soybean in given in **APPENDIX D**.

From this, minimum and maximum limits for optimum, sub-optimum and absolute growth conditions were derived (**Table 14**).

Table 14 Growth criteria for soybean derived from values published in the literature

Variable	Abs	Sub	Opt	Opt	Sub	Abs
	Minimum			Maximum		
Seasonal rainfall (mm)	450	550	700	900	1 000	1 100
Monthly mean temperature (ºC): Nov	10	13	15	18	25	33
Monthly mean temperature (ºC): Dec-Mar	10	18	23	27	30	33
Monthly mean relative humidity (%)				60	75	80
Soil depth (mm)	200	300	500			

Preference was given to growth criteria obtained from local sources, such as the Department of Agriculture, forestry and Fisheries (DAFF), the Agricultural Research Council (ARC) as well as local scientists such as Barry Smith (e.g. Smith, 2006). In addition, the field experiments provided additional information on site factors that may limit optimum growth. This is important as some of the growth criteria were obtained from the international literature. In **Table 14**, a distinction was made between temperature thresholds for germination (i.e. in November) and those used for the remainder of the five-month growing season (i.e. December to March).

Soybean is best adapted to summer rainfall regions where more than 450 mm falls in the growing season (Smith, 1998). The crop can also do well under irrigation in dry and warm regions. Soybean plants can tolerate drought because of their deep rooting system, but moisture is essential during the flowering stage (DAFF, 2010a). The plant has some degree of frost tolerance if frost occurs prior to flowering (FAO, 2012a).

The minimum required heat units for soybean should exceed 1 500 (base 10^{o}C). The optimum heat units for soybean are around 1700, whilst heat units above 2 600 cause a severe yield reduction (Smith, 2006). The required total monthly rainfall over the growing season ranges between 550 mm and 700 mm. The required daily temperature is 20^{o}C for the minimum and 30^{o}C for the maximum.

Soybean's tap root may extend to over 1.5 m and all available soil water can be drawn up to 1.8 m but under normal conditions, all water is drawn from the first 0.6 to 1.3 m of the soil (FAO, 2002). Smith (2006) reported a maximum rooting depth of 1.2 meters for soybean, with an effective rooting depth of 600 mm. Therefore, soils with a depth from 600 to 1 200 mm are preferable. Nieuwenhuis and Nieuwelink (2002) observed rooting depths of 1 to 1.5 m in well-drained silt loam and clay loam soils. However, the crop can also grow on shallow soils which have a depth of 200 mm, provided moisture is not limiting to growth (Palmer and Ainslie, 2006).

2.7.1.4 Crop water use

K_{cb} values for soybean were obtained from the *SAPWAT3* database for cultivars of medium-season length, i.e. 121 days (Van Heerden, 2013). *SAPWAT*[12] (Version 3) is a crop water use model (not a crop growth model) designed to estimate the crop water use requirements under different irrigation systems as well as management regimes. The model and its

[12] http://www.sapwat.org.za/

required input data (climate & basal crop coefficients) are maintained by PicWat (Van Heerden *et al*., 2009). According to the *SAPWAT*3 database, soybean transpires at a rate 15% higher than that of the reference crop during the development- and mid-season growth stages. Transpiration rates are low when the crop emerges, indicative of small leaf area during establishment (**Table 15**). During the development and mid-season, transpiration rates remain high, then slightly decrease as the crop matures. Hence, soil water deficits during growth periods when transpiration rates are high, usually results in reduced growth and thus yield loss. It is assumed that the late-season value of 0.90 remains constant during the harvesting period (i.e. 121 to 150 DAP).

Table 15 Basal crop coefficients (K_{cb}) derived from the *SAPWAT*3 database for soybean growth stage (Van Heerden, 2013)

Growth stage	Length of growth stage (days)	K_{cb} (*SAPWAT3*)
Initial	30	0.10
Development	30	1.15
Mid-season	60	1.15
Late-season	1	0.90

According to Allen *et al.* (1998), K_{cb} may be only 0.05 to 0.10 lower than K_c values during the mid-season stage. This indicates that soil water evaporation is small at full canopy cover. However, the largest difference between K_c and K_{cb} is found in the initial growth stage where evapotranspiration is predominantly in the form of soil water evaporation (i.e. crop transpiration is low).

The use of K_{cb} and K_c values to weight monthly rainfall totals was evaluated by Khomo (2014), who showed that the Free State is not suitable for soybean production when K_{cb} is used for rainfall weighting. From **Table 13**, 22% of soybean production occurred in the Free State in 2010. Based on this, Khomo (2014) concluded that the use of K_{cb} values is not recommended. Hence, monthly K_c and not K_{cb} values were used in this study to determine the optimum distribution of monthly rainfall over the growing season.

K_c values for soybean were obtained from the FAO (FAO, 2002) and from the Baynesfield Estate as shown in **Table 16**. The water use and yield of soybean under dryland conditions was studied at Baynesfield in Season #3 (2012/13) as part of another WRC-funded project (K5/2066; Mengistu *et al*., 2014).

The initial- and late-season crop coefficients for soybean grown at Baynesfield were higher than those reported in the international literature. According to the FAO, initial K_c values (i.e. $K_{c\ ini}$) are typically small and often less than 0.4. The initial crop coefficient value ($K_{c\ ini}$) will be high when the soil is frequently wet from rainfall or irrigation events. The higher the evaporating power of the atmosphere (i.e. ET_o), the quicker the soil will dry between water applications, resulting in lower $K_{c\ ini}$ values (Allen *et al.,* 1998). Soybean is rarely grown under full irrigation, but supplemental irrigation during critical growth periods will substantially increase yields (FAO, 2002).

Table 16 Single crop coefficients (K_c) for each soybean growth stage

Month	Growth stage	Length of growth stage (days)	K_c (FAO, 2002)	K_c Baynesfield
November	Initial	20-25	0.3-0.4	0.72
December	Development	25-35	0.7-0.8	0.72
January/February	Mid-season	45-65	1.0-1.2	1.00-1.03
March	Late-season	20-30	0.7-0.8	0.84
April	At harvest		0.4-0.5	0.72

K_c increases rapidly during the crop development stage, reaching a maximum during the mid-season. Based on FAO's peak K_c value, soybean's water use is up to 20% higher than that of the reference crop. This is higher than the peak K_c values measured at Baynesfield in 2012/13. K_c during the mid-season remains relatively constant for most growing conditions, then its declines as the crop senesces (Allen *et al*., 1998).

The use of international *vs*. locally derived K_c values to weight monthly rainfall totals was evaluated by Khomo (2014), who showed that the central region of Mpumalanga is not suitable for soybean production when FAO K_c is used for rainfall weighting. From **Table 13**, the majority of soybean is grown in Mpumalanga. Based on this, Khomo (2014) concluded that the use of locally derived K_c values is recommended, compared to values derived from the international literature. In addition, Allen *et al*. (1998) strongly encouraged the use of crop coefficients deemed appropriate for local conditions. Hence, monthly K_c for Baynesfield (and not FAO values) were used in this study to determine the optimum distribution of monthly rainfall over the growing season.

2.7.1.5 Crop yield

According to DAFF (2010a), the production of soybean in South Africa ranges from 450 000 to 500 000 tons per year, with an average yield of 2.5 to 3 t ha^{-1} under dryland conditions. However, these production and yield figures differ to those reported by Lemmer and Schoeman (2011) in **Table 17**.

In 2007, producers planted 183 000 ha of soybean and harvested 205 000 tons of oil seed, thus yielding 1.12 t ha^{-1} on average (**Table 17**). Approximately 132 000 tons of surplus seed was carried over from the previous season and combined with 121 000 tons of imported seed, the total oil seed supply for 2007 season was 457 000 tons. Of this, 21 000 and 192 000 tons were consumed for food and feed respectively. In addition, 134 000 tons was crushed for oil and oilcake products. Hence, the total demand was 361 000 tons (including 13 000 tons on-farm consumption & 1 000 tons exported), which left a surplus of 97 000 tons that was carried forward to the following season (i.e. 2008).

Table 17 Supply and demand for soybean from 2007 to 2012 (Lemmer and Schoeman, 2011)

Year	2007	2008	2009	2010	*2011**
Area planted (x 1000 ha)	183	165	238	311	*418*
CEC crop estimate (x 1000 ton)	205	282	516	566	*709*
Yield (ton/ha)	1.12	1.70	2.17	1.82	*1.70*
Deliveries (x 1000 ton)	205	264	504	535	*709*
Stocks on 1 April (x 1000 ton)	132	97	90	113	*105*
Imports (x 1000 ton)	120	16	1	2	*3*
Total supply	**457**	**377**	**595**	**650**	***816***
Food consumption (x 1000 ton)	21	28	31	34	*31*
Feed consumption (x 1000 ton)	192	114	172	203	*180*
Oil-cake production (x 1000 ton)	134	137	115	185	*260*
Other uses (x 1000 ton)	13	2	8	2	*7*
Exports (x 1000 ton)	1	5	156	121	*180*
Total demand	**361**	**287**	**482**	**545**	***658***
Surplus on 31 March (x 1000 ton)	97	90	113	105	*158*

*Estimated and not actual figures

Similar to sunflower, the planted area is determined by the profit margin of soybean compared to other summer crops. This is affected by the surplus stock from the previous season, the local crushing capacity (to extract the oil) as well as the farmer's decision to plant other crops (e.g. sunflower or maize) instead of soybean. The area planted is also affected by the demand for certain products, with a shift from feed to oil-cake protein experienced in 2008 and projected in 2011. This explains why the area planted varied substantially over the 5 years. The higher yield in 2008 offset the lower area planted, which reduced the need to import soybean to satisfy local demand. Producers planted a record 418 000 ha in 2011, with production projected at 709 000 tons. An average yield of 1.70 t ha^{-1} is expected, with relatively high exports and ending stocks estimated at 180 000 and 158 000 tons respectively (Lemmer and Schoeman, 2011).

2.7.1.6 Disease incidence

In general, most broadleaf crops that produce oilseed (e.g. sunflower, canola and soybean) should be grown once every four years to avoid disease issues, especially root rot (e.g. *Sclerotinia*). Soybean rust is caused by two fungal species, namely *Phakopsora pachyrhizi* and *Phapkopsora meibomiae*. However, *P. pachyrhizi* (also known as Asian or Australian soybean rust) is the most aggressive and widespread (Kawuki *et al*., 2003). Soybean rust was first reported in February 2001 near Vryheid in northern KwaZulu-Natal. It then spread to other parts of KwaZulu-Natal as well as the eastern Highveld region (Pretorius *et al*., 2001). The disease has since occurred in every season in South Africa (Jarvie, 2009).

Soybean rust reduces yield by causing premature defoliation of leaves, which decreases the number of filled pods and reduces the weight of seeds per plant (Van Niekerk, 2009). Yield losses can reach up to 60% in severe cases and depends on the time of onset (i.e. infection) and if weather conditions are favourable for the fungus to spread (Kloppers, 2002).

Soybean rust is considered a worldwide threat to soybean production due to its impact on yield reduction (Kawuki *et al*., 2003). Moisture on the surface of the leaves is essential for spore germination and therefore, leaf wetness caused by, *inter alia*, high humidity and dew provides suitable conditions for spore germination (Van Niekerk, 2009). Caldwell *et al*. (2002) stated that rust outbreaks are most severe with relative humidity levels of 75 to 80%. According to Nunkumar (2006), disease incidence (measured as number of pustules per lesion) was significantly higher at 85% and 95% relative humidity, than compared to 75%. Hence, a relative humidity of 75% or more provides adequate moisture for the germination of soybean rust.

Caldwell *et al*. (2002) indicated that rust infection begins during or after the flowering stage and is generally not noticed until the pods are set (i.e. R3/R4 growth stage). However, Nunkumar (2006) showed that plants are most susceptible to infection at the late vegetative (V6) and early reproductive (R1) growth stages. This coincides with the onset of flowering which usually occurs 40 to 50 DAP, with the flowering period being 25 to 35 days (Smith, 2006). Van Niekerk (2009) indicated that risk increases in January, peaks in February and declines in March.

2.7.1.7 Biofuel suitability

The Biofuels Industrial Strategy of the Republic of South Africa identified three primary field crops to be considered as feedstocks for domestic biodiesel production, namely sunflower, canola and soybeans (DME, 2007a). Whitehead (2010; cited by Sparks, 2010) indicated that sunflower and canola are grown in relatively small quantities in KwaZulu-Natal (largely due to relatively unfavourable growing conditions). Hence, soybean is the only viable option for biodiesel production in KwaZulu-Natal.

According to Sparks (2010), the use of by-products from biofuel processing can contribute significantly to the economy of South Africa. The relatively high market value of oilcake provides soybean the greatest potential as a first generation feedstock. Hence, it is believed that the relatively high market value of soybean oilcake in particular may result in soybeans having the greatest potential as a first generation biodiesel feedstock than canola and sunflower (Meyer *et al*., 2008).

2.7.2 Canola

Canola originates from rapeseed in that it is a genetically modified version of this plant, which is not found naturally. Canola forms part of the *Brassicaceae* (mustard) family and was adopted for use in Canada during 1978 by the rapeseed industry in order to facilitate the expansion of this industry (Toxopeus and Mvere, 2004; Ehrensing, 2008). It is an annual, cruciferous herb with a taproot system. The plant produces tuber-like rutabagas below ground and exhibits rapid growth after establishment (DAFF, 2010d). Canola stem height varies from 75 to 175 cm, with primary and secondary branches. Canola is a dryland winter crop (unlike soybean, sunflower and groundnut, which are summer crops). It is therefore suitable as a rotational and a complementary crop to the existing crops in South Africa (Marvey, 2008).

2.7.2.1 Present distribution

Brassica napus originated in the Mediterranean region and Eastern Asia, abut over time has spread into Europe. Seed production started during the Middle Ages in Europe. Canola is now ranked as the second largest source (after soybean) of vegetable oil in the world. Worldwide, it has passed sunflower, peanut and cottonseed oil production during the past 20 years (Raymer, 2002). Canada, China and many western European countries are the main producers of canola. Due to fungus vulnerability, insect pests, bacteria and nematodes, canola distribution is limited to temperate and sub-temperate regions worldwide (Duke, 1983).

Canola (*Brassica napus* L.) is a relatively new crop in South Africa, which was introduced about two decades ago. Since its introduction in 1992, the canola industry has grown rapidly, especially in the southern Cape (DAFF, 2012b). Canola production in South Africa is relatively new, with only 500 tons produced in 1994, which increased to 44 200 tons in 2005 and approximately 112 000 tons in 2013 (DAFF, 2014).

Canola is mainly grown in the Western Cape as a winter crop for cooking oil and animal feed (DAFF, 2010d). This vegetable forms a significant proportion of animal feedstock, especially during months when grazing and other sources of food are not available (Raymer, 2002; Toxopeus and Mvere, 2004). Currently, canola is also produced in other areas of South Africa, such as the Northern Cape, Free State, Eastern Cape, KwaZulu-Natal, Limpopo and North West Provinces (DAFF, 2012b).

Canola is known as an excellent rotation crop for the control of crop pests and soil diseases (Booth and Gunstone, 2004). The crop is therefore often grown in rotation with broadleaf crops such as alfalfa, mainly to minimise plant diseases and weed problems in order to increase crop yields. In South Africa, canola is commonly grown in rotation with wheat to reduce the economic risk of root diseases (Tesfamariam *et al*., 2010). Canola is a winter crop and when cultivated in rotation with maize or wheat, it enhances the yield of these crops by up to 25% (Fouché, 2015).

2.7.2.2 Season length

The number of growing days required for the growth of this crop varies depending on the region in which cultivation is occurring. From the available literature, the following dates and periods were indicated for the summer planting and growth of canola:

- September 1 with a 90 day growing period,
- December 15 with a 100 day growing period, and
- March 15 with a 110 day growing period (Myburgh, 1985).

These growing periods mainly apply to the Eastern Cape, Karoo, KwaZulu-Natal and winter rainfall region (Myburgh, 1985). According to Cumming *et al.* (2010), early planting promote high yields and canola can be planted in the Western and Southern Cape as early as in the middle of April, as long as there is sufficient soil moisture. According to DAFF (2010d), canola should be planted from April to May and harvested from August to September. Fouché (2012) suggested that canola in the Western Cape should be planted with the first rains of autumn/winter, i.e. February onwards. In the Free State, Eastern Cape and KwaZulu-Natal Provinces, planting should occur with the last summer rainfall from January to early April (Fouché, 2012).

2.7.2.3 Growth criteria

Fouché (2015) describes canola as a very hardy crop with exceptional compensation abilities, which is able to withstand extreme drought and cold conditions (including frost occurrence). A summary of growth criteria gleaned from the literature for canola in given in **APPENDIX D**. From this, minimum and maximum limits for optimum, sub-optimum and absolute growth conditions were derived (**Table 18**). Canola is considered a drought tolerant crop which requires some water at emergence (i.e. > 25 mm) and the remainder (as little as 275 mm) over the growing season. Before germination can take place, the seed first needs to absorb sufficient water (Cumming *et al*., 2010).

Table 18 Growth criteria for canola derived from values published in the literature

Variable	**Abs**	**Sub**	**Opt**	**Opt**	**Sub**	**Abs**
	Minimum			**Maximum**		
Seasonal rainfall (mm)	100	300	600	900	1 200	1 500
Monthly mean temperature (ºC)	5	10	15	25	30	35
Monthly minimum relative humidity (%)				80	85	90
Soil depth (mm)	500	700	1 000			

There are conflicting reports in the available literature regarding canola's seasonal rainfall requirements. For example, Cumming *et al*. (2010) stated that canola requires an optimum rainfall of 400 to 500 mm in the growing season, of which 200 to 210 mm should occur during the flowering stage. A seasonal rainfall of 200 to 300 mm is ideal for April to October to produce 1 to 2 t ha^{-1} (Cumming *et al*., 2010). Fouché (2012) noted that under dryland conditions, 200 to 450 mm of rainfall will yield 1.2 to 3 t ha^{-1}. However, optimum rainfall of 600 to 700 mm per season will yield 4 to 6 t ha^{-1}. If either the minimum or maximum optimum thresholds are exceeded, it may have a detrimental impact on crop yields, which could significantly affect the economic viability of production.

According to literature, canola is capable of surviving instances where these thresholds are exceeded, provided that the levels of exceedance are within a reasonable margin, as is indicated in **APPENDIX D**, where both optimum and absolute threshold values are indicated (Tesfamariam, 2004; FAO, 2006; Jewitt *et al*., 2009a; DAFF, 2009; DAFF, 2010d; Tesfamariam *et al*., 2010; Cumming *et al*., 2010).

According to the literature reviewed, temperature is a significant factor with regard to the yields per hectare that can be achieved, as it can influence the rate at which photosynthesis occurs and therefore, the growth of the plant. For example, Seetseng (2008) stated there is a direct and proportional relationship between increased temperature and earlier maturity of the crop. If the absolute temperature thresholds for canola are exceeded then it is possible that the mortality rate of the crop will increase significantly, thereby decreasing yields proportionally. The absolute minimum temperature that these crops can survive is between 0 and 5°C, while the absolute maximum temperature is between 35 and 41°C. The optimum temperature range, in order to achieve the maximum productivity for these crops, is approximately 10 to 30°C (Tesfamariam, 2004; FAO, 2006; Bahizire, 2007; DAFF, 2009; Jewitt *et al*., 2009a; Cumming *et al*., 2010; Canola Encyclopaedia, 2013a; Nel, 2015). According to Cumming *et al*. (2010), temperatures are optimal at 20 to 25°C for photosynthesis to take place, whereas the monthly optimal temperature for germination are 15 to 20°C. The optimum mean annual temperature for canola production is between 5 and 27°C (Duke, 1983).

The soil depth required for the viable cultivation of canola ranges from 500 to 600 mm as a minimum depth. The maximum depth range is 1200 to 1500 mm. Additionally, soil pH is an important soil characteristic which can result in decreased crop yields. For canola, the absolute upper pH threshold is 8.5 and the absolute lower pH threshold is 5.5, while the optimal range of 6.5 to 7.6 (or 8). Canola is capable of growing in a wide range of soil textures ranging from light to heavy, although the optimum soil texture for best crop yield would be medium (FAO, 2006; Jewitt *et al*., 2009a; DAFF, 2010d; Cumming *et al*., 2010; Canola Encyclopaedia, 2013a; Canola Encyclopaedia, 2013b; Nel, 2015).

2.7.2.4 Crop water use

Single crop coefficient values obtained from Majnooni-Heris *et al*. (2012) are shown in **Table 19** for canola. These values were measured over two seasons (2010 & 2011) using a lysimeter at the University of Tabriz, Iran. The peak value was decreased from 1.20 to 1.15 to compensate for advection which occurs in arid and semi-arid regions such as Iran.

However, canola is sensitive to water and temperature (> 30°C) stress during anthesis, which can also impair pollination (Cumming *et al*., 2010). Hence, rainfall during the stress-sensitive third month should exceed 100 mm, because severe water stress during flowering causes pollination failure (Smith, 1998).

Table 19 Single crop coefficients (K_c) for each canola growth stage (Majnooni-Heris *et al*., 2012)

Growth stage	**Length of growth stage (days)**	K_c
Initial	20-25	0.60-0.80
Development	25-35	0.80-1.00
Mid-season	45-65	1.00-1.15
Late-season	20-30	0.60

According to Cumming *et al*. (2010), the description canola's different growth stages is more complicated than that of winter cereals. The reason is the different stages cannot be easily separated from each other. The growth stages do not chronologically follow on from one another, but rather overlap partially because of the indeterminate growth pattern of the canola plant. Fouché (2015) stated that canola has a long flowering period of 4 to 10 weeks, compared to 10 to 14 days for wheat.

2.7.2.5 Crop yield

In 2007/08, producers planted 33 000 ha of canola and harvested 40 000 tons of oil seed, thus yielding 1.20 t ha^{-1} on average (**Table 20**). Approximately 11 000 tons of surplus seed was carried over from the previous season and thus, the total oil seed supply for the 2007/08 season was 49 000 tons. Of this, 39 000 tons was crushed for oil and oilcake products. Hence, the total demand was 38 000 tons (including 1 000 tons on-farm consumption), which left a surplus of 11 000 tons that was carried forward to the following season (i.e. 2008/09).

The area planted to canola remained relatively constant from 2007 to 2010, with sufficient production meeting local demand. The majority of canola produced is used for oil and oilcake products. In 2008/09, the lower yield was due to unfavourable growing conditions in the Cape production regions. Producers planted 44 000 ha in 2011/12 and with an expected average yield of 1.32 t ha^{-1}, this could result in record canola crop of 57,000 tons. Despite some growth in domestic consumption, ending stocks are estimated at an all-time high of 20 000 tons (Lemmer and Schoeman, 2011).

Table 20 Supply and demand for canola from 2007 to 2012 (Lemmer and Schoeman, 2011)

Year	2007/08	2008/09	2009/10	2010/11	*2011/12**
Area planted (x 1000 ha)	33	34	35	35	*44*
CEC crop estimate (x 1000 ton)	40	31	40	37	*57*
Yield (ton/ha)	1.20	0.91	1.15	1.06	*1.32*
Deliveries (x 1000 ton)	38	31	40	37	*57*
Stocks on 1 April (x 1000 ton)	11	11	11	10	*9*
Imports (x 1000 ton)	0	0	0	0	*0*
Total supply	**49**	**42**	**51**	**46**	***67***
Feed consumption (x 1000 ton)	0	1	1	2	*2*
Oil-cake production (x 1000 ton)	39	31	42	35	*45*
Other losses (x 1000 ton)	-1	-1	-2	0	*0*
Exports (x 1000 ton)	0	0	0	0	*0*
Total demand	**38**	**31**	**41**	**37**	***47***
Surplus on 31 March (x 1000 ton)	11	11	10	9	*20*

*Estimated and not actual figures

Dryland yields of 1.5 to 2.3 t ha^{-1} can be realistically achieved if the crop is managed correctly, which increases to 4 t ha^{-1} under irrigation. Hence, water use efficiency ranges from 0.64 to 1.12 kg m^{-3}. This equates to a yield range of 1.92 to 3.36 t ha^{-1} from 300 mm of soil moisture. A high WUE of 0.92 kg m^{-3} was obtained in 2012 by a farmer (Izak Smit) in the very dry Eendekuil area in northern Swartland (Fouché, 2015).

2.7.2.6 Disease incidence

However, Anderson *et al*. (2003) warned that broadleaf oilseed crops (e.g. sunflower, canola and soybean) should not be grown more than once in four years on the same land to avoid possible disease problems, especially root rot (e.g. *Sclerotinia*).

Relative humidity affects both the rate of transpiration and the soil water content. The information available on relative humidity thresholds is scarce, but indications are that there is a relatively broad range within which these plants can survive of between 20 to 80% humidity (Zeleke and Wade, 2012).

2.7.2.7 Biofuels suitability

Globally, canola is out-competing all other biodiesel crops and about 65% of canola feedstock is already used for biodiesel. However, in the European Union countries, the figure is even higher and 80% of canola feedstock is mainly used for biodiesel. China is also a major producer of canola, and has already started to produce biodiesel from this source (Balat and Balat, 2010). Extensive production of canola also takes place in India, where about 58% of its total yield is used for biodiesel (Ardebili *et al*., 2011).

In South Africa, PhytoEnergy Pty (Ltd) has expressed interest in establishing canola as a viable biofuel feedstock crop. At full capacity, the processing plant requires 1.115 million tons of canola from approximately 500 000 ha for biodiesel production. However, this will require the rapid expansion (over a 5-year period) of canola production in the Free State, KwaZulu-Natal and the Eastern Cape. The location of areas that will support economically viable production of canola is dependent on various biophysical factors, which are further described in this report (DAFF, 2010d).

According to Fouché (2015), canola is a suitable biodiesel feedstock since it has a 40% or higher oil yield, compared to the 20% for soybeans. Canola oil is deemed a better biodiesel feedstock than soybean oil “due to its gel point" (Radebe, 2013). Biodiesel made from canola produces esters with properties comparable with that of conventional diesel fuel when it is burnt (Lopes and Steidle Neto, 2011).

2.7.2.8 By-products

In South Africa, canola oilcake is also used as a source of protein in animal feeds and it can also be used as a high quality organic fertiliser. In the industrial market, canola oil is suitable for biodiesel production because of its good emulsifying characteristics. The oil is also an excellent insect repellent (DAFF, 2012b).

3 FEEDSTOCK WATER USE EFFICIENCY

As mentioned, one of the major outcomes of the biofuels project is to estimate or quantify the water use efficiency of selected biofuel feedstocks (i.e. **AIM 6**). This chapter focuses on the methodology adopted to derive the measurements of water use and yield that are required to estimate water use efficiency (WUE).

Cowan and Farquhar (1977) defined WUE as the ratio of gross primary production to transpiration, i.e. the amount of assimilated carbon per unit of water loss by transpiration. However, Rajabi *et al*. (2009) defined WUE as total dry matter (TDM) produced per unit water used. Since many different definitions of WUE exist in the literature, it is important to clarify the specific definition of WUE adopted in this report, as well as the methodology (and units) used to quantify the term.

3.1 Introduction

Water use and its associated impact on the environment are measured using various metrics dependent on the source of water, the process which removes the water and the degree of quality degradation. These metrics are described next in greater detail.

3.1.1 Concepts of water use

3.1.1.1 Green *vs*. blue water

The concepts of blue water and green water are commonly used to define the water source. Green water is precipitation held in the unsaturated soil zone and is therefore available for plant growth. Blue water refers to surface water stored in channels (rivers and canals) and reservoirs (dams, lakes, wetlands) as well as groundwater contained in aquifers (Hoff *et al*., 2010). By definition, irrigated agriculture receives blue water (from irrigation) as well as green water (from precipitation), whilst rainfed agriculture receives green water only. Hoeksta *et al.* (2011) defined grey water as a metric that quantifies the volume of freshwater that is required to assimilate the load of pollutants based on acceptable water quality standards.

Biofuel feedstock water use can therefore include green water, blue water (surface and groundwater) as well as grey water consumption. Conveyance and application losses can also be accounted for in water use studies (Yeh *et al*., 2011). This project focused mainly on measuring and estimating green water consumption (i.e. total evaporation of selected feedstocks). Blue water (irrigation) is applied to the field trials because green water is deemed insufficient to meet the maximum evaporative requirements of the crop. The prerequisite for determining crop coefficients is a well-watered, non-stressed crop (Allen *et al*., 1998). Additional research is also being conducted to separate consumptive water use (i.e. maximum evaporation) into its productive (i.e. transpiration) and non-productive (soil water evaporation and interception loss) components.

In terms of water use modelling, a land use change from natural vegetation to cultivated feedstock may result in a reduction in blue water generation. This reduction, if declared significant, may lead to the feedstock being classified as a stream flow reduction activity (or SFRA) in accordance with South African water law. Commercial forest plantations in South

Africa are declared a SFRA because exotic tree species can increase the interception of green water which then contributes to enhanced wet canopy evaporation rates. Similarly, the typically deep rooting distribution of exotic trees can lower the water table, thus affecting blue water generation.

3.1.1.2 Consumptive water use

According to Yeh *et al*. (2011), consumptive water use is defined as the removal of water from the hydrological cycle and is therefore no longer available for the immediate use by humans and/or the ecosystem. Such water is “consumed” through processes such as transpiration and evaporation of free water, soil water as well as intercepted water. Water “incorporated” or “embedded” in products is another form of water removal (i.e. water harvested with crops such as sugarcane, sugarbeet and sweet sorghum). Non-consumptive water use is water that is released back to the environment (i.e. runoff, irrigation return flow, seepage and percolation), with or without a change in its quality (Yeh *et al*., 2011).

Most studies which estimate the water requirements of biofuel feedstocks focus on consumptive use of water (i.e. actual evapotranspiration) and neglect non-consumptive use (Yeh *et al*., 2011). Irrigation return flows from agricultural land can be used productively by a downstream farm. Deep percolation can recharge groundwater or contribute to subsurface runoff as base flow. Hence, “losses” at the field scale are not necessarily losses in the hydrological sense at larger scales (Perry *et al*., 2009). For example, Savenije (2004) stated that evaporation of intercepted water is not considered a “loss” to the water resources system, but merely a “recycling” of rainfall. Water evaporated or transpired, although not immediately available to meet other demands, may eventually return as precipitation but not necessarily in the same watershed.

3.1.1.3 Productive water use

Furthermore, water use can be classified as productive versus non-productive. Productive water use includes water that increases biomass production either directly (such as transpired water and water harvested with the crop) or indirectly (water used for frost control or leaching of salts). Non-productive water use does not contribute directly to plant growth and includes soil water evaporation as well as sprinkler and reservoir evaporation (Yeh *et al*., 2011). Interception is also considered an unproductive flux since the water loss does not contribute to plant growth (Savenije, 2004). The use of mulch layers can reduce non-productive water use (i.e. soil water evaporation) in favour of productive water use (i.e. increased transpiration and biomass production).

Certain land use changes (i.e. conversion of fallow or waste land) may result in a shift from non-productive soil water evaporation to productive transpiration. Although a reduction in runoff may result from the increased transpiration, storm flow and sedimentation load will be lower. Hence, this reduced risk of flooding and improved water quality is beneficial for downstream water users. Soil water content and base flow may also improve from the land use change. However, the net impact of a land use change is dependent on many factors such as the spatial scale of implementation and the demand for water by downstream users as well as the characteristics of that change (e.g. evergreen vs. deciduous, deep vs. shallow rooted etc.).

3.1.1.4 Evaporation terminology

In order to understand crop water use, it is important to distinguish between reference crop evapotranspiration (ET_o), potential evapotranspiration (ET_p) and actual evapotranspiration (ET_a). Evapotranspiration (ET) is the sum of soil water:

- taken up by roots and transpired from plant leaves, and
- evaporated directly from the soil surface.

ET_o is the evapotranspiration rate from a reference "crop", typically a hypothetical grass or alfalfa surface with defined characteristics, not short of water and well maintained. ET_p represents the upper limit of evapotranspiration under optimum conditions (i.e. well-watered and well managed) so that crop production can be maximised under the given climatic conditions. ET_a is the evapotranspiration limited by sub-optimal management practices which impacts on crop growth. Generally, ET_a is less than ET_p except under advective conditions. ET_a can be used to describe the water consumed by a crop. In the introduction, the importance of accurate estimates of crop water use was highlighted. Taylor and Gush (2014) highlighted a number of maximum evaporation (ET_p) models applicable to annual crops and perennial fruit trees. These included the *FAO56*, *SAPWAT* and *SWBPro* models as well as the Penman-Monteith and Priestley-Taylor formulations.

The reference crop (typically short grass or dense alfalfa) provides a standard measure of evapotranspiration that can be determined easily at various locations using climate data. In the literature, ET_o and ET_r represent grass- and alfalfa-based reference evaporation respectively. Since there are two common reference surfaces, the term E_r is also used to describe reference evaporation. In addition, some textbooks (e.g. Schulze, 1995) now refer to potential evapotranspiration (ET_p) as maximum evaporation (E_m). Similarly, actual evapotranspiration (ET_a) is sometimes referred to as total evaporation (E). The latter terminology (i.e. E_r, E_m and E) is preferred, but both are used throughout this document. This decision is related to the debate that the term "evapotranspiration" is outdated because it:

- describes two different processes (i.e. evaporation *vs*. transpiration),
- highlights our inability to conceptualise these processes separately, and
- excludes the role of interception which is often considered only a small proportion of total evaporation (Savenije, 2004).

On a similar note, the term soil evaporation is avoided as the soil itself cannot evaporate, only the water stored within the soil. Hence, the term soil water evaporation is preferred. Various factors affect crop water use (i.e. total evaporation) including crop characteristics, management practices and environmental conditions related to the site's climate, soils and terrain.

3.1.2 The crop coefficient

3.1.2.1 Definition

A commonly used procedure for estimating consumptive water use of irrigated crops is based on the crop coefficient approach. The single crop coefficient (K_c) approach combines soil water evaporation and crop transpiration, whereas the basal crop coefficient (K_{cb}) describes plant transpiration only.

The ratio of crop transpiration (T_c) to reference crop evaporation (ET_o) is called the basal crop coefficient (K_{cb}). However, in this project, crop water use is defined as total evaporation (transpiration + soil water evaporation + interception loss) from the biomass, accumulated over the full productive cycle. The ratio of crop water use (ET_a) to reference crop evaporation (ET_o) is called the single crop coefficient (K_c). Hence, soil water evaporation from the topsoil horizon is excluded in K_{cb} but included in K_c calculations. The evaporation of soil water is considered a non-consumptive use of available soil water, since the loss does not directly contribute to plant growth. Allen *et al*. (1998) describe the methodology for estimating K_c for crops that are not well-watered, but due to the uncertainty it introduces into the estimate, the approach was not adopted in this study.

Crop coefficients (K_c) are normally calculated at research sites by relating the measured crop evapotranspiration under well-watered conditions (i.e. potential evapotranspiration, E_m or ET_p) with the calculated reference crop evaporation E_r (i.e. $K_c = E_m/E_r$). Thus, differences in the crop canopy and aerodynamic resistance relative to the hypothetical reference crop are accounted for by the crop coefficient. Hence, there is no need to determine these parameters for the cropped surface as K_c serves as an aggregation of the physical and physiological differences between various crops and the reference for a well-watered crop. The crop coefficient concept describes the variation in water use over the growing season and facilitates the comparison of water use between crops.

Under well-watered conditions, much of the uncertainty introduced by site-specific conditions is reduced, allowing for the estimation of a generic crop coefficient which is intended to be applied not only where it was derived. Crop coefficients provide a means to estimate the crop's potential evapotranspiration relative to the reference crop evapotranspiration. The value of the crop coefficient depends on crop type, stage of growth and type of reference crop used (FAO56, alfalfa, grass or A-pan).

3.1.2.2 Reference crop evaporation

Reference crop evaporation (E_r) is calculated for a grass (i.e. $E_r = ET_o$) or alfalfa (i.e. $E_r = ET_r$) reference crop and is then multiplied by an empirical crop coefficient (K_c) to produce an estimate of crop evaporation (E or ET_c). Allen *et al*. (1998) attempted to standardise reference crop evaporation, thus providing a common basis for computing crop coefficients. This allows for the transfer of crop coefficient values in both space and time. Hence, the *de facto* standard for estimating reference crop evaporation is a method originally developed by Penman in 1948 and subsequently modified by Penman in 1963, with further improvements suggested by Monteith from 1965 onwards. Monteith's improvements to the Penman equation have been extensively researched by the Food and Agricultural Organisation, FAO (Allen *et al*., 1998). Their modifications are commonly referred to as the FAO Penman-Monteith equation or the FAO56 procedure which is presented in **Section 3.4.1.1**.

3.1.2.3 Generalised K_c curve

The rate of water use varies over the crop's growth cycle (**Figure 9**). The rate at which the crop develops and the time to reach full canopy cover are affected by weather conditions, in particular mean daily air temperature. Therefore, the length of time between planting and full canopy cover varies with climate, latitude, elevation, planting date as well as cultivar (crop variety). Thereafter, the rate of further phenological development (flowering, seed development & ripening) is more dependent on plant genotype and less dependent on weather. Stress caused by high temperatures or lack of soil water can shorten the mid- and late-season growing periods (Allen *et al.,* 1998).

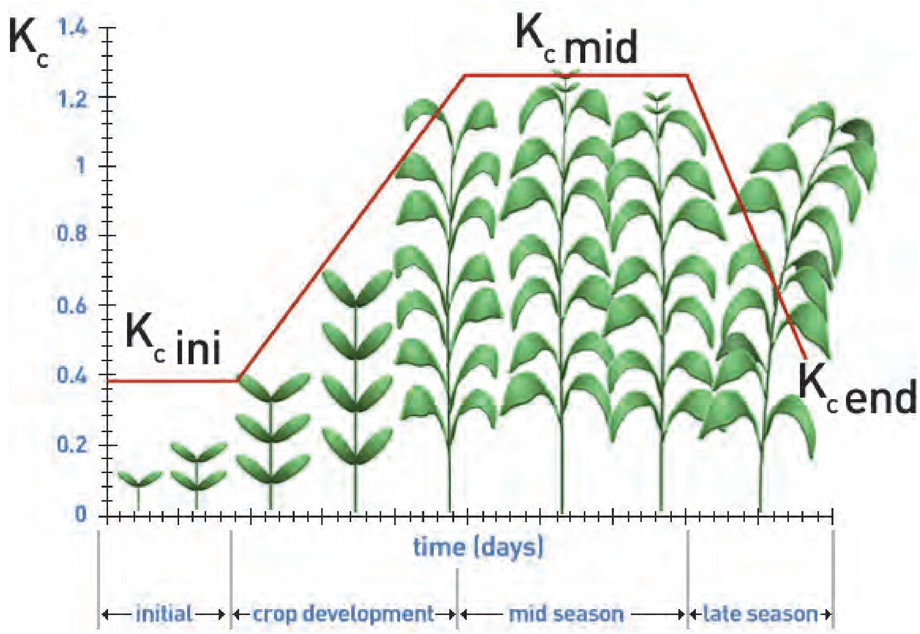


Figure 9 Generalised crop coefficient curve based on the single crop coefficient approach (Allen *et al*., 1998)

While the crop coefficient approach provides a simple and convenient way to estimate crop water requirements for a variety of crops, some uncertainties do exist. Firstly, the crop coefficient approach is not well suited to crops with sparse canopies exhibiting a high spatial variability of soil and vegetation coverage (e.g. row crops, orchards and vineyards). Secondly (and more importantly), many K_c values reported in the international literature are often not adapted to local conditions (Ortega-Farias *et al*., 2009). Crop coefficients are influenced by numerous non-linear interactions of the soil, crop and atmospheric conditions, as well as irrigation management practices. Therefore, locally "calibrated" crop coefficients are required. As highlighted above, K_c is defined for pristine conditions with no water or other stresses (e.g. disease) that will reduce crop water use. Hence, experiments designed to estimate crop coefficients need to be irrigated and well managed.

3.1.3 Water use efficiency

3.1.3.1 Background

Many different definitions of WUE exist in the literature, consequently it is important to clarify the specific definition of WUE being referred to at any particular time, as well as the methods used to determine it and the units employed. The bio-physical WUE of a plant relates some measure of growth (e.g. carbon assimilation or gross primary production), to some measure of water use (e.g. transpiration or total evaporation), over a particular time period. The links and trade-offs between carbon uptake and water loss that take place through photosynthesis and stomatal control have been well researched (Jarvis, 1981; Whitehead, 1998; Law *et al.*, 2002). However, the estimation of WUE may be conducted at vastly different spatial and temporal scales, which requires different measurement approaches (Lindroth and Cienciala, 1996; Tu *et al*., 2008).

At the molecular level, ratios of stable carbon isotopes (e.g. $^{13}C/^{12}C$) combined with an estimate of the leaf-to-air vapour pressure difference, provide a measure of the efficiency of water use in photosynthesis (Farquhar *et al*., 1982; Farquhar and Richards, 1984; Marshall and Zhang, 1994; Dawson *et al*., 2002).

In leaf-level studies, instantaneous WUE may be determined through a combination of gas-exchange measurement techniques consisting of CO_2 and H_2O measurements using instruments such as porometers and infra-red gas analysers (or IRGAs). These describe a plant's demand for water relative to its photosynthetic production (Cernusak *et al.*, 2007).

At the single-tree or stand scale, water use and growth measurements are usually conducted on a number of individual trees over a certain period, typically using heat dissipation or sap flow measurement techniques (Gyenge *et al.*, 2008) and are scaled up according to the planting density (Hatton and Wu, 1995; Wullschleger *et al*., 1998).

At a canopy scale, estimates of WUE are possible using micrometeorological measurements of carbon and water fluxes (Lamaud *et al*., 1997; Law *et al.*, 2002). For example, Krishnan *et al*. (2006) described WUE at this scale as a measure of the amount of Carbon taken up during photosynthesis (*P*) relative to the water lost by the ecosystem (*E*) (WUE = *P*/*E*). Similarly, Lamaud *et al*. (1997) defined WUE as the ratio of photosynthesis over canopy transpiration, representing the loss in water associated with the gain of carbon. In the absence of specific measurements of photosynthesis and transpiration rates, they suggest the use of carbon uptake (net CO_2 flux) and water loss (ET) by the vegetation as surrogates.

At wider regional scales, estimates of WUE are possible using remotely sensed data from which values of total evaporation and biomass production (e.g. gross primary production) may be derived (Lu and Zhuang, 2010). At all scales, the period of measurement is ideally a year or longer, to incorporate seasonal variation, however this may not always be practically feasible, and instantaneous or short term estimates of WUE may result. The slope between changes in biomass accumulation (growth) and water-use represents a measure of WUE. It is thus a ratio that can be altered through changes in growth rate and/or changes in water use.

3.1.3.2 Definition

Since it is mostly the above-ground biomass that provides the economic benefit in biofuel production, it is common for WUE to be defined as above-ground biomass increment per unit of water consumed (Dye, 2000). However, in the case of sugarbeet, below-ground biomass accumulation (i.e. the tuber) is of economic importance.

For the purpose of this study, WUE is defined as the economic yield per unit of water use. Economic yield refers to the utilisable portion of the biomass that contains sugar (stem or tuber), starch (grain) or vegetable oil (seed). Water use is defined as total evaporation (transpiration + soil water evaporation + interception loss) from the biomass, accumulated over the full productive cycle (i.e. growing season).

3.1.3.3 Choice of units

In describing bio-physical WUE, units applicable to the variables of interest, namely feedstock yield and water use, need to be employed. As noted above, the choice of units depends on the application and purpose of WUE studies. Gush and Dye (2009) suggested that grams or kilograms may be used to describe mass of yield produced, whilst kilograms or mm may be used to describe the water transpired or evaporated by the crop, at whatever scale (ha; m^2, km^2) is appropriate. Strictly speaking, an efficiency should have the same unit of measure for both the numerator and denominator (Jones, 2004). Hence, crop yield and water use should both be expressed in kg, with WUE in kg kg^{-1}. However, WUE can equate to a very small number because of the small numerator and large denominator values. Thus, crop yield is expressed in g and not kg (i.e. WUE in g kg^{-1}).

The project's terms of reference stated that water use should be expressed as a volume in m^3. With the denominator in m^3, the numerator (i.e. crop yield) is expressed in kg. The use of tons should be avoided since WUE in t m^{-3} is typically a small number (due to the magnitude of the numerator relative to the denominator). Strictly speaking, this choice of units (i.e. kg m^{-3}) indicates a water productivity (WP) and not a water use efficiency (WUE; in kg kg^{-1}). This argument is the main justification for the change in nomenclature from WUE to WP as noted in the literature (Molden, 1997; Singh, 2005).

3.1.3.4 Calculation of WUE

WUE is defined as the portion of biomass utilised for biofuel production, per unit amount of water consumed by the biomass. In terms of first generation feedstocks, water use efficiency (WUE in kg m^{-3}) is therefore calculated as stem, tuber, grain or oilseed yield (Y in kg ha^{-1}) divided by feedstock water use (i.e. total evaporation or actual evapotranspiration, ET in m^3):

$$WUE = Y/ET \quad \textbf{Equation 1}$$

This definition is similar to that provided by Zhang *et al.* (2010). The main technique used in this study to measure feedstock water use (e.g. surface renewal) estimates total evaporation in mm. A simple adjustment is made to accommodate ET measurements in mm:

$$WUE = Y/(ET * 10) \quad \textbf{Equation 2}$$

This conversion is based on 1 mm of water being equivalent to 1 litre or 1 kg of water per square meter of ground. Transpiration data from sampled trees is scaled up to stand level using planting density and then expressed as mm equivalent depth. **Equation 2** was used to convert WUEs obtained from the literature in kg mm^{-1} to kg m^{-3} to facilitate comparison with figures derived in this study.

Finally, it is also important to be specific about the nature of the yield (e.g. fresh or dry mass, in-shell, de-husked etc.). Where possible, WUE will be calculated for both fresh (i.e. green or wet) mass as well as the mass of dry matter (usually obtained after drying the fresh utilisable mass in an 80°C oven for 48 hours). This aspect sometimes complicates the comparison of WUEs gleaned from the available literature.

3.2 Site Description

In this study, field-based experiments designed to estimate feedstock water use efficiency were conducted at the Ukulinga research farm (Pietermaritzburg) as well as the Hatfield research farm (Pretoria University). In addition, data were obtained for soybean and yellow maize from experiments undertaken at Baynesfield Estate in the KwaZulu-Natal Midlands (Mengistu *et al*., 2014). A brief description of each site is given next.

3.2.1 Ukulinga

The Ukulinga research farm (29^{o}40'S; 30^{o}24'E; altitude 809 m) at receives an average annual rainfall of 750 mm over 113 rain days, with 23% of the MAP falling during the winter months (**Table 102** in **APPENDIX E**). The two wettest months are January and February which receive average monthly totals of 108 and 103 mm respectively. Ukulinga experiences warm to hot summers and mild winters with occasional frost (Camp, 1997). The estimated mean annual temperature is 18.3°C and the hottest and coldest months on average are February (26.5°C) and July (8.0°C) respectively. A summary of the monthly weather data from September 2010 to May 2014 is presented in **Table 105** (**APPENDIX F**).

The agronomic requirements of the sugarbeet, sweet sorghum and grain sorghum trials at Ukulinga were managed by the African Centre for Crop Improvement (ACCI). Two 80 by 80 m plots located on land 5B were used for the experiments. **Figure 10** shows the location of the two plots in relation to the Jatropha trial.

Figure 10 Location of the Jatropha trial site at the Ukulinga research farm as well as the two 80 by 80 m research plots managed by the ACCI

3.2.1.1 Soils data

Experiments were conducted in two plots situated in Land 5B at Ukulinga. The Ukulinga Soils Map of 1982 showed that both plots are dominated by the Westleigh soil form (We: orthic-A over soft plinthic-B). A soil survey was conducted at Ukulinga in august 2010 with the results given next.

Soil type and depth

The topsoil depth is approximately 10 to 15 cm and varies because the site has been previously ploughed and disked. The soil depth decreased diagonally across the plots and down the slope, from 100 cm to 60 cm.

Bulk density

Bulk density is directly related to soil porosity and indicates the degree of soil compaction. It is considered a good measure of soil quality as it affects the ease at which roots can penetrate the soil. Three undisturbed bulk density samples were taken (at the first survey pit) using a 5 cm diameter cylindrical core (10 cm in length) for the topsoil (AP horizon, where P represents a ploughed A-horizon). These samples represent the top 10 cm of the soil profile. Similarly, three samples were taken at a depth of 20 to 30 cm to represent the upper B-horizon, and another three samples from 40 to 50 cm for the lower B-horizon. This exercise was repeated for the second soil survey pit.

All 18 bulk density samples were weighed and placed in a drying oven (at 104°C) over a weekend. UKU1.x represents samples taken from the first pit (indicated by ●1 in **Figure 11**) and UKU2.x for samples from the second pit (pit ●2 in **Figure 11**). Bulk densities varied from 1.31 to 1.50 g cm^{-3} for the first pit and from 1.09 to 1.45 g cm^{-3} for the second soil pit. These bulk density values are high, considering values higher than 1.7 are deemed critical, rendering the soil unsuitable for agriculture. If the density of rock is 2.7, porosity values ranged from 59 to 44% for bulk densities of 1.1 to 1.5 g cm^{-3}. The moisture content of the soil varied from 4.1 to 10.2% in pit #1 and 5.6 to 13.0% in pit #2.

Figure 11 Soil survey pits (red dot) in relation to both 80 by 80 m plots, with the end of each contour marked with a yellow dot

Soil texture

Particle size distribution (dispersed) was determined by the pipette method (Gee and Bauder, 1986). The soil texture analysis was conducted by the Department of Soil Science at UKZN. The proportion of clay, silt and sand for each of the six soil samples is given in **Table 21**. The clay percentage increases with depth at both survey pits. This clay distribution type (increasing with depth) results from a vertical movement of clay particles due to leaching effects.

Table 21 Proportion of clay, silt and sand for three depths in each soil survey pit

Pit no.	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Total (%)	Texture
1	0-10	29.15	42.98	27.87	100.00	Clay loam
1	20-30	30.67	42.11	27.22	100.00	Clay loam
1	40-50	32.75	44.96	22.28	100.00	Clay loam
2	0-10	29.30	46.89	23.82	100.00	Clay loam
2	20-30	34.83	48.09	17.08	100.00	Silty clay loam
2	40-50	35.20	29.22	35.58	100.00	Clay loam

Soil water retention

Six soil samples were taken using a stainless steel 5 cm diameter cylindrical core (5 cm in length). A hammer was used to insert the core into the soil at the correct depth. The hardness of the soil (high bulk densities) limited the number of samples taken. The soil samples were saturated with water and then exposed to various tensions to determine the water retained in the soil at -0, -33 and -1 500 kPa. These values represent the total porosity, drained upper limit and lower limit of soil water available for plant growth (**Table 22**). For more information on the procedure used, refer to Lorentz *et al*. (2001) and Moodley *et al*. (2004).

Table 22 Soil water retention values representing total porosity (TPO), drained upper limit (DUL) and permanent wilting point (PWP) for the two soil survey pits at Ukulinga

Pit no.	Depth (cm)	TPO ($m\ m^{-1}$)	DUL ($m\ m^{-1}$)	PWP ($m\ m^{-1}$)
1	0-10	0.412	0.226	0.187
1	20-30	0.417	0.233	0.194
1	40-50	0.435	0.228	0.172
2	0-10	0.398	0.265	0.212
2	20-30	0.410	0.272	0.226
2	40-50	0.446	0.243	0.207

3.2.2 Hatfield

The Hatfield experiment farm (25^{o}45'S; 28^{o}16'E; altitude 1 327 m) is in the country's summer rainfall region characterised by high intensity and short duration rainfall events with sunny periods between rains. The farm receives an average annual rainfall of 702 mm over 85 rain days, with 14% of the MAP falling during the winter months (**Table 103** in **APPENDIX E**). The two wettest months are December and January which receive average monthly totals of

123 and 137 mm respectively. The estimated mean annual temperature is 17.6°C and the hottest and coldest months on average are January (28.0°C) and June (3.4°C) respectively. Frost spells may occur during winter. A summary of Hatfield's monthly weather data for three seasons is given in **Table 106** (**APPENDIX F**). The soil is a sandy clay loam with a permanent wilting point and field capacity of 128 and 240 mm m^{-1} respectively.

3.2.3 Baynesfield

For WRC Project K5/2066 (Mengistu *et al*., 2014), field measurements were carried out at Baynesfield Estate (29º46'S; 30º20'E; altitude 850 m), approximately 20 km south of Pietermaritzburg in KwaZulu-Natal, South Africa. Baynesfield climate is classified as sub-humid with dry and cool winters and warm and rainy summers. The crops grown mainly at the study site are maize, soybean, sugarcane and avocados. The Baynesfield Estate receives an average annual rainfall of 839 mm over 129 rain days, with 22% of the MAP falling during the winter months (**Table 104** in **APPENDIX E**). The two wettest months are December and January which receive average monthly totals of 130 and 124 mm respectively. The estimated mean annual temperature is 17.5°C and the hottest and coldest months on average are February (26.4°C) and July (5.5°C) respectively. The mean monthly air temperature ranges from a maximum of 21.1°C in January to a minimum of 13.3°C in June. The predominant wind direction is easterly. The farm is situated at an altitude of approximately 850 m and the predominant wind direction being easterly. A summary of the monthly weather data for the 2012/13 growing season (October 2012 to April 2013) is presented in **Table 107** (**APPENDIX F**).

3.3 Trial Description

Trials were conducted over four seasons at the Ukulinga and Hatfield research farms. The African Centre for Crop Improvement (ACCI; based at UKZN) managed all agronomy-related aspects of the field-based research undertaken at Ukulinga. For example, the ACCI advised which cultivars were grown, the preferred planting densities and planting dates as well as the harvesting method. The ACCI also conducted Brix (i.e. total soluble sugar content) determinations for all sugar-based feedstocks harvested at both Ukulinga and Hatfield. In addition, research undertaken at Baynesfield in 2012/13 (i.e. season #3) was deemed relevant for this project and thus, is included in the trial descriptions which are detailed next.

3.3.1 2010/11 season

3.3.1.1 Sugarbeet

The sugarbeet trial (variety EB 0809) was planted at Ukulinga over a two-week period in mid-September 2010 and finally harvested in early April 2011. The agronomic practices adopted to establish and maintain the trial, as well as the weather conditions experienced over the growing season are described next. In addition, the harvesting process and procedure used to analyse sugar content is also discussed.

The 80 by 80 m trial site was disked in July 2010 in preparation for the transplanting of the sugarbeet seedlings. Fertiliser was mechanically spread on 3rd September 2010. A total of 300 kg of 2:3:4 (or 20% N: 30% P: 40% K) fertiliser was applied, as the soils had not been tilled or fertilised for some time. A final disking was done to incorporate the fertiliser into the topsoil and then the trial site was irrigated. The trial site was then sprayed with a pre-emergent herbicide (Acetochlor) on 10th September 2010 and made ready for planting the following week. The land was not rotavated to minimise the risk of heavy soil erosion (and loss) if heavy spring rains should occur.

Sugarbeet seed was sown at the beginning of July 2010 in seedling trays (undertaken by Sunshine Seedlings). The initial germination rate was about 85% and after thinning, improved to 90%. A cold spell experienced during the week of the 9-13 August 2010 delayed seedling growth and the planting date. Planting of the seedlings commenced on the 14th September 2010 and was staggered over a two-week period to decrease the risk of crop failure. Seedlings were transplanted with an inter-row spacing of 50 cm and a between plant spacing of 30 cm (i.e. 66 666 plants per hectare).

In 2010, there are no registered herbicides for sugarbeet in South Africa, so weed control was a labour-intensive manual exercise. Morning Glory and Blackjack were the dominant obnoxious weeds in the sugarbeet trial. During the growing season, LAN fertiliser was applied at a rate of 140 kg N per hectare. The crop was sprayed regularly with fungicides to reduce the level of *Cercospora* (leaf spot) infection. Insecticides were used to control army worm. Drip irrigation was used to maintain optimum soil water conditions in order to maximise crop yield.

In early April, nine sugarbeet samples plots were identified and harvested. The sizes of the plots were as follows: two (20 × 6 m); two (10 × 5 m); and five (10 × 3 m). The beets were harvested in each plot with forks using manual labour and placed in labelled bags (**Figure 12**).

Figure 12 Manual harvesting of the beet using forks. The leaves were stripped in the field and left to decompose

Each harvested line per sample plot was individually washed and weighed (**Figure 13**). The number of tubers per line was recorded, together with the general condition of each tuber. Tuber damage was caused mainly by root rot, with the weed, pest and disease problems affecting the overall yield. Finally, laboratory samples were taken, thus enabling total Brix (i.e. total sugar) yield to be determined.

(a) **(b)**

Figure 13 Sugarbeet tubers washed using pressure hoses (a) to remove excess soil prior to being weighed (b)

3.3.1.2 Sweet sorghum

The sweet sorghum trial (variety Sugargraze) was planted at Ukulinga over a two-week period in early December 2010 and finally harvested in early May 2011. The agronomic practices adopted to establish and maintain the trial are described next. In addition, the harvesting process and procedure used to analyse sugar content are also discussed.

The 80 by 80 m trial site was disked in November 2010 in preparation for seed planting. Fertiliser was mechanically spread at the same rate used for the sugarbeet trial. A final disking was done to incorporate the fertiliser into the topsoil and then the trial site was irrigated. Planting commenced on 7th December 2010. Plant rows were spaced 0.9 m apart, with an in-row spacing of about 0.14 m, resulting in a plant population of about 80 000 plants per hectare (on average). Drip irrigation was used to supplement rainfall in order to ensure optimal growing conditions.

A pre-emergence herbicide (Acetochlor 700) was applied to the soil soon after planting and weeds that emerged later were controlled manually. Some difficulties with bird damage were experienced at the time of emergence, resulting in the replanting of certain portions of the trial. Additional nitrogen in the form of LAN was applied at the knee-high stage and pyrethroid insecticide was used. Weed control using Basagran took place and applied with tractor and hand sprayers.

At flowering, a fungicide was sprayed to reduce infection levels of northern leaf blight and anthracnose as well as an insecticide for the control of stalk borer. This was done during the week of 21st to 25th February 2011 and a helicopter was used to spray the trial due to the height of the sweet sorghum stems (**Figure 14**). A systemic insecticide was also applied during February 2011 to control aphids on the sorghum leaves. No other pest and disease control measures were needed.

Figure 14 Spraying of a sweet sorghum trial at Ukulinga to minimise stalk borer infestation

The harvesting process began on 19th May 2011. A thunderstorm three days prior to harvest resulted in lodging, which meant the sample plots were carefully selected to minimise storm damage effects. A total of 10 sweet sorghum sample plots were selected in the 80 × 80 m trial for harvesting. The sizes of the plots were as follows: six (20 × 10 m); and four (10 × 10 m). The sweet sorghum stems were harvested with secateurs using manual labour. A total of 12 lines in each plot were sampled (i.e. plot width of approximately 11 m).

The leaves and heads were stripped from the stalks and placed in labelled bags for weighing. This was done to determine the portion of leaves and heads as a percentage of the total biomass on a fresh mass basis. Each line of harvested stems was then bundled and weighed in the field to determine the yield of fresh stalk per plot (**Figure 15**).

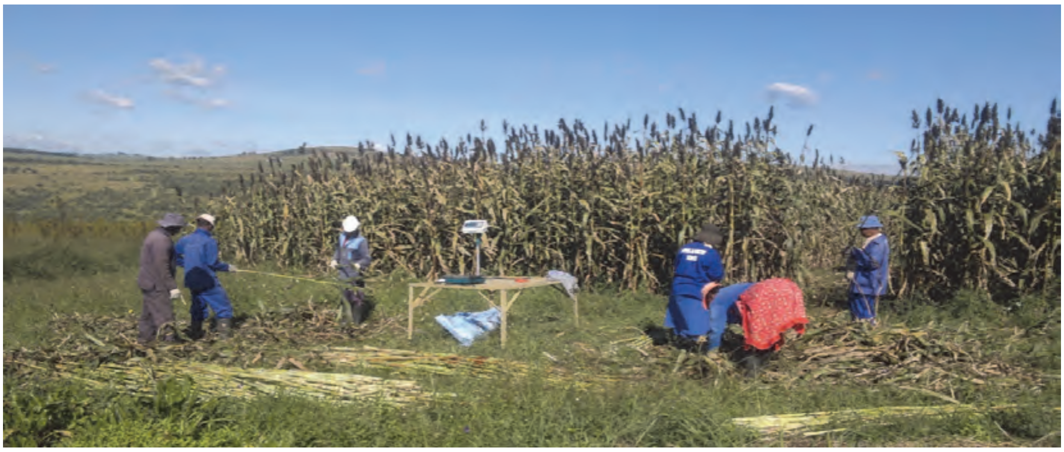


Figure 15 In-field weighing of fresh stalks, leaves and heads to determine each sample plot's fresh stalk yield and the portion of leaves and heads on a fresh mass basis

One line per each sample plot was then placed in ovens for 24 hours at 80°C to dry to constant mass. Once dried, the samples were re-weighed to determine the total dry matter yield per plot as well as the dry matter yield of each component (stalks, leaves & heads). The sixth line of each sample plot was then transported to ACCI's laboratory and placed in an oven for 24 hours at 80°C. Once dried, the biomass was re-weighed to determine the total dry matter yield per plot as well as the dry matter yield of each component (stalks, leaves and heads). A total of 20 sugar yield analyses were undertaken using stalks not damaged by pests (e.g. stalk borer) for the Ukulinga trial.

3.3.1.3 Sweet sorghum (Hatfield)

The sweet sorghum variety Sugargraze was planted in a uniform block of 80 by 80 m (**Figure 16**). This trial was identical to that conducted at the Ukulinga experiment farm, with the aim of creating favourable growing conditions to achieve optimum growth and stalk yield. Drip irrigation was installed to supplement rainfall when needed in order to ensure optimal growing conditions. The trial was planted on 7th December 2010. Plant rows were spaced 0.9 m apart, with an in-row spacing of about 0.2 m, giving a plant population of about 55 000 plants per hectare. The trial was conducted during a wet season (total rainfall of 757 mm over the growing period). During the first six weeks, conditions were very wet and no irrigation was necessary. The plants were harvested when the sweet sorghum crop reached the hard dough stage in May 2011.

Figure 16 MSc student Hanson Hlope standing next to the sweet sorghum irrigation trial located at the Hatfield experimental farm

The harvesting process adopted by Pretoria University at their Hatfield experimental farm was almost identical to that followed at Ukulinga. A randomised sampling technique was used to identify 10 blocks, each 20 m along the row and about 10 m wide. Since the row spacing was approximately 0.8 to 0.9 m, 12 lines were selected in each block. Each block was harvested by line (or row) and stalks were cut just above ground level. Hence, each 20 m line was bundled together and labelled, with the number of stalks recorded. The bundled line was then weighed to obtain the fresh mass and used to estimate the total fresh biomass yield. In order to obtain the dry matter yield, approximately 10% of the stalks from each block were sampled. This was done by selecting two representative lines in each block. For each of the two selected lines, the leaves and heads were stripped from the known number of stalks and weighed to determine the fresh mass of each component. The heads were not threshed to remove the grain. A sub-sample of 2 kg fresh stalks was taken, placed in paper bags and dried at 70°C until constant mass, thereafter it was re-weighed. The same was done for the leaves and heads, from which the dry matter content (%) of each component was calculated. This was then used to calculate the dry matter yields per sample and plot from the total fresh yields.

For sugar content (Brix) determination, 20 cleared stalks of about 1 m in length (about 5 to 6 kg) were taken per sample, tied into bundles and placed in labelled polypropylene bags. These were kept cool until they were sent to ACCI's laboratory (at Ukulinga) by overnight courier for chaff cutting and stalk Brix determination.

3.3.1.4 Sweet sorghum (drought)

This trial was planted on 7th December 2010 with sweet sorghum (variety Sugargraze) and consisted of four different irrigation treatments. Drip irrigation was used to irrigate the experiment. Water meters recorded the exact amounts of irrigation that was applied to each treatment as follows:

- Treatment 1: Control - irrigated once per week. The soil profile was refilled to field capacity, based on neutron probe measurements.

- Treatment 2: Dryland - irrigated only if needed during establishment, thereafter the crop depended on rainfall.

- Treatment 3: Supplementary irrigation only during the early vegetative stage (EVS). Regime during this period was the same as for the control.

- Treatment 4: Supplementary irrigation at late vegetative stage (LVS). Regime during this period was the same as for the control.

The experiment was laid out in a randomised complete block design (RCBD) with four replications. Each plot was 6 m long and 7.2 m wide and consisted of eight plant rows that were spaced 0.9 m apart, and with an in-row spacing of 0.12 m between plants (**Figure 17**).

During the first six weeks, conditions were very wet and no irrigation was necessary. Destructive growth analyses were conducted at Hatfield once every two weeks to monitor growth in response to each of the four irrigation treatments. One plant was sampled from the end of the six middle rows of each plot (leaving one border row on either side), giving a sample size of six plants per plot per sampling. After sampling, the plants were immediately taken to the field laboratory, where they were separated into leaves, stems and heads for further analysis.

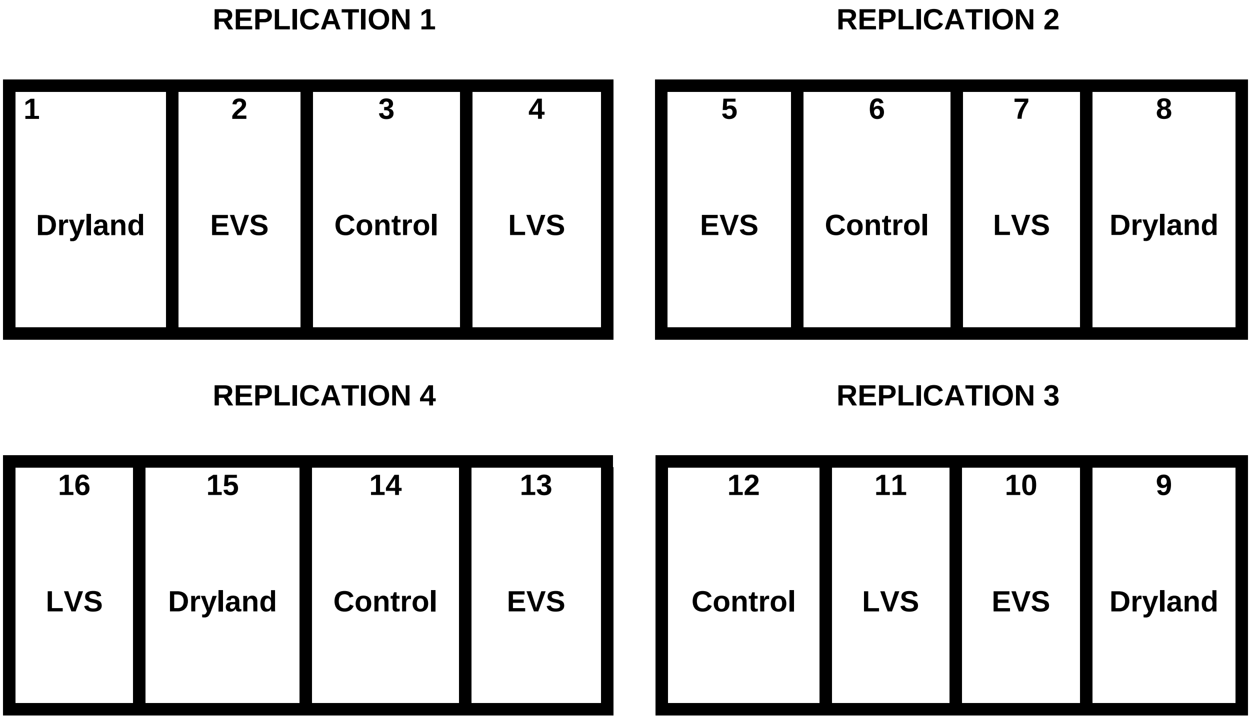


Figure 17 Layout and design of the sweet sorghum irrigation trial located at Hatfield research farm for the 2011/12 growing season

The plants were finally harvested when the sweet sorghum crop was in the hard dough stage. The average height of ten randomly selected stalks in each row was determined using a measuring tape. Plants were then hand harvested with sickles by cutting the stalks just above ground level. All remaining plants (after growth analysis) from the six middle rows per plot were harvested for final yield determination. Each 4.5 m row length was harvested and the number of stalks recorded, thereafter bundled together and labelled. The total bundle was weighed immediately after harvesting to obtain the total fresh biomass yield. Two representative bundles were then selected from each plot and transported to the field laboratory to determine the stalk, leaf and head mass per sample (bundle). The procedures followed for yield and quality determinations were the same as described in **Section 3.3.1.3**.

3.3.1.5 Jatropha

The Jatropha trial was planted in February 2005 as a randomised block design (three blocks) with six treatments per block, i.e. three replicates per treatment, with a total of 18 plots. Each plot had a large area (50 m × 25 m or 0.1 ha) to enable the use of certain micrometeorological techniques and for grazing by livestock. The whole trial was 265 m long × 110 m wide (an area of 29 150 m^2 or 2.915 ha). Trees were planted at a density of 1 100 plants ha^{-1}, in single rows and in aggregate rows called “sets” with wide alleys for forage production.

Seed should be collected when the capsules begin to blacken and split open. Collection is best done by picking seeds directly from the tree or shaking the branches to drop seeds to the ground. For the 2010/11 season, seed was harvested from the Jatropha only (i.e. weed free) plots. An additional harvest was undertaken in May 2011 due to the unusual wet weather experienced during April and May 2011 at Ukulinga as the trees had not yet entered their dormant stage and were still producing seed. The stored seed was then left to dry sufficiently before the de-husking process started.

3.3.1.6 Moringa

Moringa oleifera seedlings developed directly from seeds were planted at two densities (1 m by 3.5 m and 3 m by 3.5 m). The trial was designed as a complete randomised block design consisting of 12 plots divided into three blocks. In each block, there were four plots (two for each density treatment). The plants were watered regularly and fertiliser was applied. Once the plants were established, watering was terminated for three plots from each planting density treatment. The other three plots per treatment continued to receive irrigation according to neutron probe measurements (deficit refilled to field capacity once per week, except during winters) until June 2011. Data were collected on two/four-week basis depending on the season and performance of the plants.

Leaf fresh mass was measured once in summer by stripping all the leaves in sample branches and converted to per plant. The number of newly formed inflorescences and pods were counted once every two weeks. Seed yield was measured after harvesting all the seeds from the pods produced by the plant. Seed yield was measured after harvesting all the pods per plant. The seed oil content was determined using two soxhlet solvent extractors. Hexane was used as solvent to extract the oil. Seed samples were weighed, ground and placed in Whatman single-thickness cellulose extraction thimbles of the soxhlet. The soxhlet system was run for 24 hours. The solvent was then removed through evaporation and the residual oil weighed. The oil content was then calculated as a percentage of the initial seed weight prior to extraction.

3.3.2 2011/12 season

3.3.2.1 Sugarbeet

For the second growing season, transplanting of sugarbeet seedlings commenced on 22nd June 2011, which was completed in early July 2011. The drip irrigation was terminated on 23rd December 2011 in preparation for the harvesting which commenced on 30th January 2012 (and finished on the February 3rd), after 7 months of growth. The agronomy of the trial was very similar to that undertaken in the first season and thus, the description is not repeated here.

3.3.2.2 Sweet sorghum

The second growing season ran from December 2011 to the May 2012. Plant rows were spaced 0.9 m apart, with an in-row spacing reduced to about 8-9 cm to increase the plant population from 80 000 in the first season to 125 000 sph. Again, the agronomy of the trial was very similar to that undertaken in the first season and thus, the description is not repeated here.

3.3.2.3 Sweet sorghum (Hatfield)

The second growing season also ran from December 2011 to May 2012. Plant rows were spaced 0.9 m apart, with an in-row spacing reduced to about 10 cm to increase the plant population around 100 000 sph. Again, the agronomy of the trial was very similar to that undertaken in the first season and thus, the description is not repeated here.

3.3.2.4 Sweet sorghum (drought)
The drought trial coincided with the main 80 by 80 m trial. Since the treatments were identical to those of the first season trial, the description is not repeated here.

3.3.3 2012/13 season

3.3.3.1 Sugarbeet
An autumn planting of sugarbeet began in May 2013 at Ukulinga. Seed for the same sub-tropical variety (EB0809) was sourced from Syngenta on 28th February 2013 and a germination test was conducted by ACCI in the first week of March 2013. These tests showed germination was problematic due to the age of the seed (same seed used in the first trial in 2010). The seed was then sent to Sunshine Seedlings in mid-March 2013, which was treated (i.e. inoculated) with *Trichoderma* to help improve soil disease tolerance. The seed was then germinated in their controlled temperature environment to prepare approximately 60 000 seedlings for transplanting at Ukulinga. Three seeds were planted in each tray compartment to ensure germination due to the age of the seed used. The ratooned sweet sorghum plot (Plot #1) was then mowed and sprayed in mid-March with Roundup to kill the emerging weeds. The field was then disked in preparation for the seedlings. A new irrigation manifold line was installed and dripperlines laid 50 cm apart in preparation for the transplanting. The seedlings arrived from Sunshine two weeks later than expected, due to the germination problems experienced. Transplanting commenced in mid-May 2013 and seedlings were placed in between the drippers (30 cm apart) to reduce the risk of root rot.

Goltix 700 SC (a registered sugarbeet herbicide) was used to combat weeds which. This herbicide was also used in the Cradock trials conducted by the former Sugarbeet SA and the Department of Agriculture. The first application took place in late July 2013 at a rate of 4 L ha^{-1} for post-emergent weed control. A small portion of the trial was sprayed at 8 L ha^{-1} to assess signs of toxicity to Goltix use (which was positive at the higher rate). Unfortunately, Goltix had little impact on Blackjack so manual weeding was then initiated. A post-fertiliser application was done in early August 2013 using LAN 28 at a rate of 140 kg ha^{-1}. A second fertiliser application of LAN 28 was done about a month later, followed by another herbicide application (4.0 L of Goltix) on 11th September. In addition, the trial was sprayed twice with a micro-nutrient foliar feed (using 1.6 L ha^{-1} of Supreme Foliar Feed) to improve growth. A third foliar spray was completed on 2nd October 2013.

The trial was manually watered to avoid problems with root rot that could result from over-irrigation. The TDR system was used to check carefully the profile water content for signs of waterlogging. Irrigation was applied less frequently and for longer periods to avoid the topsoil from being saturated. The trial also received regular applications of fungicide to prevent leaf spot incidence which became a problem in the summer months, due to the associated increase in temperature and humidity. The trial was finally harvest in December 2013.

3.3.3.2 Grain sorghum
On 23rd November 2012, the project took delivery of 25 kg of PAN8816 seed, the same zero-tannin variety tested at Cradock. In the previous week, Plot #2 at Ukulinga was fertilised using 270 kg ha^{-1} of LAN 2:3:2 (22) and sprayed with pre-emergent herbicide (Dual Gold).

On 27th November 2012, seeds were planted 20 cm apart and 50 cm between rows to give a final density of 100 000 sph. The typical planting density for grain sorghum ranges from 65 000 sph (dryland) to 125 000 sph (irrigated). Emergence was noted on 5th December 2012 which unfortunately attracted feeding birds. During December, casual staff monitored the trial site from 4:45 am to 5:00 pm each day to chase the birds. However, portions of the trial were replanted up to 18th December.

The trial was sprayed with herbicide on 9th January 2013, followed by a fertiliser application 5 days later. On 25th January, the trial was treated with fungicide to help prevent leaf blight which was first noticed on 15th February when the crop entered the booting stage. Flowering occurred on 22nd February (day 87), about a week later than expected. The official data for the PAN8816 variety indicates that flowering occurs 79 to 81 days after planting. At the end of February 2013, the trial was approaching the grain filling stage (**Figure 18**) and grain heads required bagging to prevent yield loss by feeding birds.

Figure 18 Grain sorghum trial planted in 2012/13 at the Ukulinga research farm (picture taken on 27th February 2013)

Due to the increased cost of fine mesh bags (from R0.65 to R1.20 per bag), only 25% of the grain heads were protected. **Figure 19** clearly illustrates why grain head protection is a necessary expense for grain sorghum trials. The low tannin grain sorghum variety planted at Ukulinga and Hatfield is particularly palatable to birds due to its non-bitter taste. A total of six sample blocks were demarcated and each grain head was protected with two (old & new) mesh bags. In April 2013, the grain sorghum trial at Ukulinga was unfortunately damaged by bushpig when the electric fence failed.

Figure 19 Two mesh bags used to protect each grain head at Ukulinga, to prevent the unprotected heads from being completely stripped of seed by feeding birds (photograph taken on 17th April 2013)

The official data for the PAN8816 variety indicates the crop is harvested at 135 to 142 days after planting (but not before 15th April for Ukulinga). A decision was made to prematurely harvest the trial on Friday 10th May 2013, before additional sample blocks were damaged by bushpig. The grain heads were harvested from the three remaining sample blocks and stored in bags for subsequent analysis.

3.3.3.3 Grain sorghum (drought)

A grain sorghum drought trial was conducted at Hatfield during the 2012/13 summer season. The trial was planted on 4th December 2012, using the grain sorghum cultivar PAN8816 at a seed rate of about 100 000 plants ha^{-1} at an inter-row spacing of 0.9 m. The experiment was laid out as a completely randomised block design (CRBD) with four water treatments that were replicated four times, giving a total of 16 plots. Each plot measured 5 m in length by 7.2 m wide and comprised of eight rows oriented in an east-west direction. Mineral fertiliser rates were based on soil analysis results and applied before planting at the rate of 130 kg ha^{-1} N, 25 kg ha^{-1} P and 130 kg ha^{-1} K. Another further nitrogen top dressing of 56 kg ha^{-1} N was applied to all plots on 30 December 2012. Agazine at a rate of 2.5 litres per hectare and 0.75 litres per hectare of 2.4D were applied as post emergence herbicides 14 days after emergence.

A drip irrigation system was installed and water meters used to record the exact amounts of water applied to each treatment. Four irrigation treatments were used, similar to that used for the sweet sorghum drought trial. Neutron probe access tubes were installed in the middle of each plot. A neutron probe (Hydroprobe®, Model 503 DR, Martinez, CA, USA) was used to monitor soil water content at 20 cm depth increments to a depth of 1.5 m.

Unfortunately, substantial rainfall occurred directly after application of a herbicide, which resulted in phytotoxic damage and death of some seedlings. Consequently, the plant population was substantially lower than the targeted 100,000 plants ha^{-1}. Gaps were filled in and surviving plants recovered well over time, but growth and development were substantially delayed. The Hatfield trial also experienced problems caused by feeding birds, especially once the sorghum started flowering. Owing to the smaller trial area compared to the Ukulinga trial, the entire trial area was covered with bird net. The trial was treated for stalk borer and aphids when required. Assessments of growth and biomass production were done on 24, 64, 87, 115, 149 and 178 days after planting (DAP). Irrigation was stopped to allow the crop to physiologically mature towards the end of the growing season. The Hatfield trial was harvested on 30th May 2013 (178 days after planting).

3.3.3.4 Yellow maize

The Baynesfield Estate is a commercial dryland farm with adequate fetch for the eddy covariance system used to measure crop water use. The eddy covariance equipment needed for this trial was provided by project K5/2066 (Mengistu *et al*., 2014). The maize crop (yellow maize variety PAN3Q222) was planted on the 22nd October 2012 and started emerging in the first week of November 2012. Seedlings were planted with an inter-row spacing of 76 cm and a between-plant spacing of 22 cm (i.e. 60,000 plants per hectare). The field was sprayed with Dual Gold before emergence and with Acetachlor 900ec, Lambda, and 2.4D after emergence. Nitrogen (40 kg ha^{-1}), 30 kg ha^{-1} (P), and 40 kg ha^{-1} (K) fertiliser was applied. Flux measurements at the maize experimental site were discontinued on the 15th of April 2013, by then most plants were dry and ready to be harvested. The maize crop was left in the field to dry out before it was harvested mechanically in May 2013 using a combine harvester.

3.3.3.5 Soybean

The soybean crop (variety PAN1666) was planted on the 15th of October 2012 and started emerging in the first week of November 2012. Soybean plant density was approximately 365,500 plants per ha (spacing was 76 cm between rows and 3.6 cm between plants). The field was sprayed with Round Up, Classic and Lambda herbicides two weeks after emergence and three weeks later with the same chemicals. Nitrogen (10 kg ha^{-1}), 30 kg ha^{-1} (P), and 40 kg ha^{-1} (K) fertiliser was applied. Flux measurements at the soybean site were discontinued on the 22nd of April 2013. The soybean crop was harvested mechanically using a combine harvester in the second week of May 2013.

3.3.4 2013/14 season

3.3.4.1 Grain sorghum

Planting of the second grain sorghum trial began at Ukulinga on 5th December 2013. A new irrigation manifold line and irrigation dripperline (1 L hr^{-1}) were installed. The establishment of this trial was plagued by feeding birds and thus, seed was re-planted several times which resulted in staggered growth. This was despite efforts to establish a trap crop next to the trial, the use of Bitrex to coat the re-planted seed and the hiring of labour to chase birds from 4:45 am to 5:00 pm each day.

On 24th February 2014, a large thunderstorm occurred in Pietermaritzburg between 5:00 and 6:00 pm. The maximum wind speed recorded at the nearby airport was 45.4 m s^{-1} (i.e. 163 km h^{-1} at 17h25), which resulted in significant damage to buildings and crops at Ukulinga. The high winds and hail experienced during the storm caused leaf stripping and lodging in the grain sorghum trial. Since the trial was more susceptible to pest and disease problems (due to the storm damage), the crop was immediately sprayed with fungicide to minimise Northern Leaf Blight outbreak. However, yield losses due Leaf Blight still occurred, as well as grain losses due to African bollworm. The trial was finally harvested on 4th June 2014.

3.4 Measurement of Water Use

Scientists are still trying to find simple techniques to measure evapotranspiration (ET), which is affected by many factors including, *inter alia*, wind, vapour pressure and radiation. Plants add complexity with issues such as stomatal resistance. Evapotranspiration is measured to determine crop coefficients which are required to establish irrigation scheduling and to quantify the impact of land use change.

There have been significant advances over the past two to three decades in instrumentation, data acquisition systems and remote data access. This has culminated in the availability of "off-the-shelf" evaporation measurement instruments which can be used to enhance the understanding of crop evaporation and its relation to microclimatic conditions (Ortega-Farias *et al.,* 2009).

The various methods used to measure ET are influenced by what is being measured (surface type), the area being measured (spatial scale) and the length of measurements required (temporal scale). The different techniques include the use of lysimeters, porometers at leaf level, heat pulse velocity for individual trees and micrometeorological methods based on the simplified energy balance equation (e.g. Bowen ratio, eddy covariance, scintillometry, surface renewal & temperature variance). A description of the evaporation measurement techniques adopted for use in this project are described next.

3.4.1 Reference crop evaporation

The main climatic factors which affect water use efficiency are evaporative demand of the atmosphere, solar radiation, and rainfall. The evaporative demand of the atmosphere is largely driven by the vapour pressure deficit (VPD) and net irradiance available at the surface. Reference crop evaporation (ET_o) and VPD are good indicators of the atmospheric demand of the atmosphere. However, ET_o is considered as a better normalising factor for evaporative demand than *VPD*. Climate data that are used for calculating ET_o include solar radiation, air temperature, relative humidity, and wind speed. The measurement of climatic factors which affect water use efficiency, specifically those which affect crop yield and total evaporation, are discussed in the following sections.

3.4.1.1 The FAO56 approach

The Penman-Monteith equation (**Equation 3**) calculates E_r (in mm day^{-1}) for a hypothetical grass surface of uniform height (0.12 m) that is green (albedo of 23%), actively growing, completely shading the ground and is not short of water (i.e. irrigated to minimise soil water stress). This definition simplifies the estimation of "potential" evaporation from a reference grass surface. For example, the uniform height of 0.12 m minimises the turbulent effects above the grass surface. Hence, the aerodynamic resistance factor is simply a function of wind speed (u_2) measured at 2 m. Similarly, since there is little or no soil water evaporation occurring, the surface resistance (to transpired water) under well-watered conditions for a uniform crop height becomes fixed at 70 s m^{-1} (Allen *et al.,* 1998).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \textbf{Equation 3}$$

The Penman-Monteith equation (Allen *et al.,* 1998) requires daily weather data from a nearby climate recording station that measures net radiation (R_n in MJ m^{-2} day^{-1}), air temperature (T in °C), wind speed (u_2 in m s^{-1}) and relatively humidity measured at 2 m above the ground. For daily estimates of E_r, the soil heat flux density (G in MJ m^{-2} day^{-1}) is presumed to be zero. The saturated vapour pressure (e_s in kPa) is calculated from daily maximum and minimum air temperature, from which the actual vapour pressure (e_a in kPa) is estimated using relative humidity. The term (e_s - e_a) represents the vapour pressure deficit (kPa), Δ is the slope of the vapour pressure curve (kPa $°C^{-1}$) and γ is the psychrometric "constant" (kPa $°C^{-1}$). The atmospheric pressure (P in kPa) at the site is required for determining γ (γ = 0.0016286P/λ, where λ = 2.501-0.002361T; Shuttleworth, 2007). Allen *et al.* (1998) suggested a value of 70 s m^{-1} for the surface resistance (r_s) of a short grass reference in daily calculations of ET_o. However, Allen *et al*. (2006) recommended new r_s values of 50 and 200 s m^{-1} for hourly (or shorter time-step) calculations during the day and night respectively.

The Penman-Monteith equation includes all parameters that govern energy exchange and water vapour flux from uniform expanses of vegetation. Hence, the Penman-Monteith method provides unambiguous reference evaporation estimates which are consistent in all regions and climates. The FAO56 equation is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. Crop coefficients (K_c) can be calculated for research trials by relating the measured crop evapotranspiration under well-watered conditions (i.e. maximum evaporation, E_m) to the calculated reference E_r (i.e. $K_c = E_m/E_r$) using the FAO Penman-Monteith method.

Allen *et al*. (2000) compared simulated evapotranspiration (ET_o * K_c) with lysimeter-based ET measurements for three crops in Idaho (US). They showed that predictive accuracy for any single day was about ±15% (for 70% of the time). Accuracy for a series of days would improve due to cancelling of random errors. For this level of precision, locally derived K_c values must be determined for pristine conditions having no water or other ET reducing stresses.

Differences in the crop canopy and aerodynamic resistance relative to the hypothetical reference crop are accounted for by the crop coefficient. In other words, the crop coefficient distinguishes the crop from the reference (i.e. grass or alfalfa) surface in terms of difference in height, albedo and surface resistance. Hence, there is no need to determine these parameters for the cropped surface as K_c serves as an aggregation of the physical and physiological differences between various crops and the reference for a well-watered crop. Under well-watered conditions, much of the uncertainty introduced by site-specific conditions is reduced, allowing for the estimation of a generic crop coefficient which is intended to be applied not only where it was derived.

Allen *et al*. (2005) have also recommended the adoption of a second (hypothetical) standardised reference surface, equivalent to a 0.5 m tall crop of dense, full-cover alfalfa (i.e. lucerne). The alfalfa reference is described next in more detail.

3.4.1.2 The ASCE-EWRI approach

In 2005, the Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) produced a report (Allen *et al*., 2005) which provided a standardised approach for calculating reference evaporation, allowing for the direct comparison and transferability of crop coefficients. The report promoted the use of standardised reference evaporation equation based on the FAO Penman-Monteith approach given in the ASCE Manual 70, but for two reference surfaces namely a:

- short, smooth crop (ET_o for a cool-season grass clipped to 0.12 m) and
- taller, rougher crop (ET_r for a full cover of alfalfa with a height of 0.50 m).

Standardised methods were also provided for computing E_r for hourly and daily time steps. The standardised reference evaporation equation (**Equation 4**) uses C_n and C_d to differentiate between the two reference surfaces (i.e. short vs. tall crop) as well as the time step (i.e. hourly vs. daily). C_n also considers the aerodynamic roughness of the surface, whilst C_d considers both the bulk surface and aerodynamic resistances.

$$ET_o \text{ or } ET_r = \frac{0.408\Delta(R_n - G) + \gamma \frac{C_n}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad \textbf{Equation 4}$$

Table 23 provides standardised values for both constants at hourly and daily time steps for each reference surface. Air temperature and relative humidity should be measured 1.5 to 2.5 m above ground level, with wind speed measured at 2 m above a short, grass surface. **Equation 4** assumes a zero plane displacement height of 0.08 m. If the wind speed is measured over a surface having vegetation taller than 0.3 m, then the zero plane displacement should be varied or alternatively, the wind speed adjusted according to guidelines provided by Allen *et al*. (2005). The constants given in **Table 23** correspond to a surface resistance of 30 s m^{-1} for hourly or shorter calculation time-steps (during daytime) and 45 s m^{-1} for daily calculations.

Table 23 Values for the numerator (C_n) and denominator (C_d) constants in **Equation 4** for a short (0.12 m) and tall (0.5 m) reference crop (Allen *et al*., 2005)

Time step	C_n		C_d		Units of ET	Units of R_n & G
	Short	Tall	Short	Tall		
Daily	900	1600	0.34	0.38	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly (during daytime)	37	66	0.24	0.25	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly (during the night)	37	66	0.96	1.70	mm h^{-1}	MJ m^{-2} h^{-1}

Crop coefficients in the literature are commonly referenced to either a grass or alfalfa surface. Without appropriate adjustment, grass-referenced K_c values are not directly comparable with alfalfa-referenced coefficients. Furthermore, grass-based K_c values should be used with ET_o calculated for short grass and similarly, alfalfa-based K_c values should be used with ET_r calculated for alfalfa. Allen *et al*. (2005) also raised the concern that differences in a) rainfall patterns, b) irrigation type and application frequency, as well as c) soil drying and storage characteristics between the site where the crop coefficient values were derived and the intended study site could cause error in total evaporation estimates. In addition, Allen *et al*. (2005) do not recommend the application of reference crop evaporation and crop coefficients during non-growing (i.e. dormant) seasons. Since Allen *et al*. (2005) promote two common reference surfaces (i.e. grass and alfalfa), the term E_r is preferred in this document to indicate reference evaporation. Hence, $E_r = ET_o$ for a short grass reference and similarly, $E_r = ET_r$ for a taller alfalfa reference.

3.4.2 Evapotranspiration

Water use estimates for the Jatropha trees were determined using sap flow measurement techniques (e.g. heat pulse velocity) for transpiration (T), and energy balance techniques (e.g. surface layer scintillometry) for total evaporation (ET). Water use estimates for the Moringa trees were determined using sap flow measurements (heat pulse velocity) and the soil water balance equation using *SWB* model simulations.

3.4.2.1 Heat pulse velocity

The heat pulse velocity (HPV) technique is essentially a tracer method which measures the rate of flux with which heat pulses applied to the conductive xylem portion of woody stems are transmitted vertically by the flow of sap through the stem. It is recognised internationally as an accepted method for the measurement of sap flow in woody plants and has been extensively applied in South Africa (Dye and Olbrich, 1993; Dye *et al*., 1996; Dye, 2000; Gush, 2008; Gush and Dye, 2009). The heat ratio method (HRM) of the HPV technique (Burgess *et al*., 2001) was selected for this study because of its ability to measure accurately low rates of sap flow (Gush, 2008). The HRM requires a line-heater, which is typically 60 mm long and made from 1.8 mm outside-diameter stainless steel tubing enclosing a constantan filament, to be inserted into the xylem of the selected tree at the vertical midpoint (commonly 5 mm) between two temperature sensors (thermocouples), which are 2 mm in diameter. All drilling is performed with a battery-operated drill using a drill guide strapped to the tree, to ensure that the holes are as close to parallel as possible (**Figure 20**).

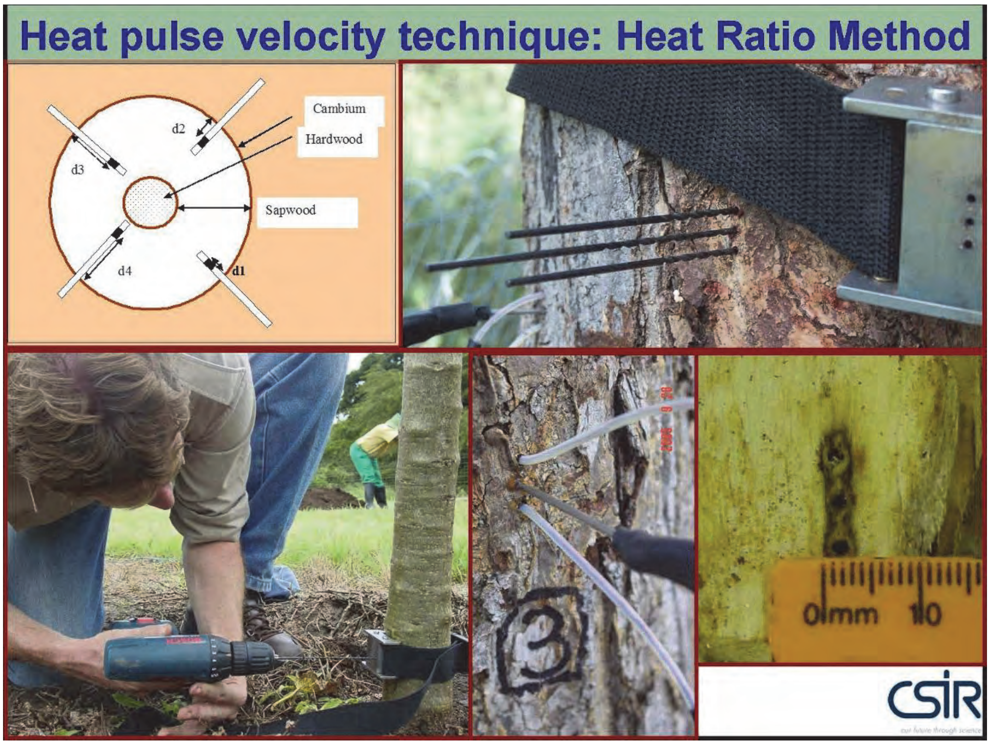


Figure 20 Typical installation of an HPV system to measure sap flow

The velocity of the heat pulse (**Equation 5**) is determined by recording the ratio of the increase in temperature measured by the upstream and downstream thermocouples, following the release of a pulse of heat by the line heater (Marshall, 1958), calculated as:

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) 3600$$ **Equation 5**

where V_h is the heat pulse velocity (cm hr^{-1}), *k* is thermal diffusivity of the wood, *x* is distance (cm) between the heater and either temperature probe, and v_1 and v_2 are increases in temperature (from initial temperatures) at equidistant points downstream and upstream, respectively. Thermal diffusivity (*k*) is assigned a nominal value of 2.5×10^{-3} cm^2 s^{-1} (Marshall 1958). The thermocouple (TC) probes are inserted to different depths below the cambium to sample different regions of the sapwood, as sap flow velocities are known to vary laterally across the xylem. The TC insertion depths are typically determined by sampling the sapwood depth using an increment borer (Haglöf, Sweden), and then arranging the measurement positions accordingly (**Figure 21**).

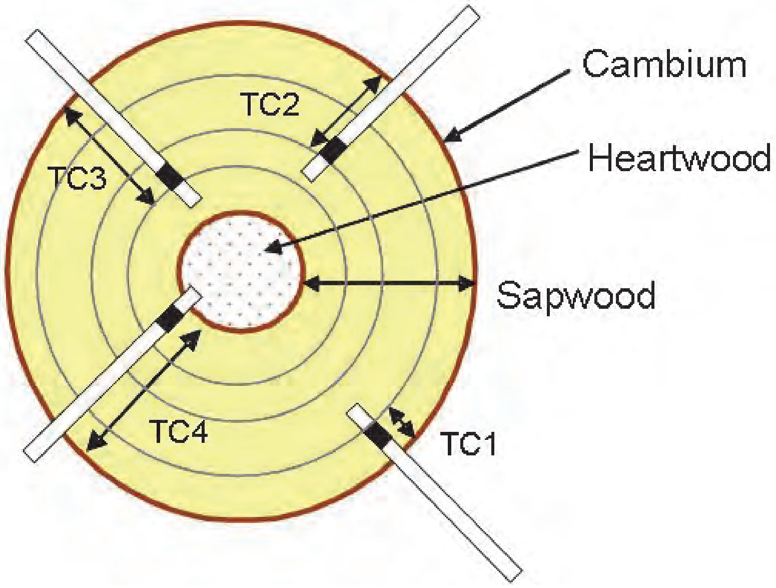


Figure 21 Illustration of a typical sampling pattern of thermocouples within the sapwood, and the associated sapwood areas represented by each thermocouple

Measured heat-pulse velocities were corrected for sapwood wounding caused during the drilling procedure, using wound correction coefficients described by Burgess *et al*. (2001). The corrected heat-pulse velocities were then converted to sap-flux densities according to the method described by Marshall (1958). Finally, the sap-flux densities were converted to whole-tree total sap flow volumes by calculating the sum of the products of sap-flux density and cross-sectional area for individual tree stem annuli (ring-shaped areas determined by below-bark individual probe insertion depths and sap-wood depth). Hourly sap-flow volumes were aggregated into daily, monthly and annual totals. Units of transpired water were mm, which required the scaling up of individual tree sap flow measurements to mm equivalent units, based on the planting density of the trees.

3.4.2.2 Eddy covariance and surface renewal

Total evaporation was estimated using the eddy covariance and the surface renewal methods as the residual of the shortened energy balance equation. Neglecting advection and the stored canopy heat, the shortened energy balance equation was used to estimate the latent energy flux λE (W m^{-2}) which is the energy equivalent of total evaporation as:

$$\lambda E = R_n - G - H \qquad \textbf{Equation 6}$$

where R_n is the net irradiance (W m^{-2}), G the soil heat flux density (W m^{-2}), and H the sensible heat flux (W m^{-2}).

The latent energy flux λE (W m^{-2}) is the result of total evaporation, and condensation at the surface and is the product of the specific latent heat of vapourisation λ (in J kg^{-1}) and the water vapour flux density E (kg s^{-1} m^{-2}). The half-hourly latent energy flux λE (W m^{-2}) was converted into an equivalent total evaporation (ET) in units of mm by multiplying by a factor 0.000733. This factor equals the number of seconds in the half-hour (1800 s) divided by the value of λ (2.45×10^6 J kg^{-1}). The half-hourly ET (mm) was then converted to daily ET by summing the values of the half-hourly ET values for daylight hours when the values of R_n are positive. The seasonal water use of the crop was then estimated by summing the daily ET values for the growing period.

An Applied Technologies, Inc. (ATI) Sonic Anemometer (“Sx” style probe) was used as an eddy covariance system to measure three dimensional wind velocity components, sensible heat flux density, and indirectly the latent energy flux as a residual of the shortened energy balance equation. The sonic anemometer was connected to a CR3000 datalogger (Campbell Scientific Inc., Logan, Utah, USA). All eddy covariance data were sampled at a frequency of 10 Hz and data processed online in the datalogger. The high frequency data, the two-minute, and thirty-minute averages of the covariances between wind speed (*u, v &* *w*), sonic temperature, T_a and wind direction were calculated and stored for further analysis. For a sufficiently long averaging period of time over horizontally uniform surface, the sensible heat flux (*H*) is usually expressed as (Meyers and Baldocchi, 2005):

$$H = \rho_a c_p w' T_a' \qquad \textbf{Equation 7}$$

where ρ_a is the density of air, c_p is the specific heat capacity of air, *w’* denotes the fluctuation from the mean of the vertical wind speed, and T_a' is the fluctuation of air temperature from the mean. The vertical wind speed is responsible for the flux across a plane above a horizontal surface.

For the surface renewal method, one unshielded type-E fine-wire thermocouple (75-µm diameter) was used to measure air temperature placed at a height of 0.5 m above the crop surface. Thermocouple measurement was done differentially and air temperature data was sampled at a frequency of 10 Hz. Time lags of 0.40 s and 0.80 s were used for the surface renewal analysis before forming the second, third and fifth order of air temperature structure function values as required by the Van Atta (1977) approach. The data were then averaged and stored every two minutes in the datalogger. Structure functions using the time lags and the analysis technique from Van Atta (1977) were used to determine the amplitude *a* and the inverse ramp frequency τ characterising temperature fluctuations as presented by Snyder *et al*. (1996). The sensible heat flux density (*H*) at measurement height *z* above the soil surface was determined as:

$$H = \alpha z \rho_a c_p \frac{a}{\tau} \qquad \textbf{Equation 8}$$

where α is a correction or weighting factor, ρ_a is the air density, c_p is the specific heat capacity of dry air at constant pressure. The surface renewal method was calibrated using the eddy covariance system and a correction factor α = 1 was used for the sugarbeet canopy to estimate *H* at 1.0 m above the soil surface.

Additional measurements included the remaining components of the energy balance. Net irradiance was measured using a Q*7 net radiometer (REBS, Seattle, Washington, USA) placed at 1.50 m above the ground surface. Two Hukse flux plates (HFP01-15, Delft, The Netherlands) were used to measure soil heat flux density at a depth of 80 mm and a system of parallel-thermocouples at depths of 20 and 60 mm were used to calculate the heat stored above the plates.

The soil heat flux (G) was estimated as the sum of the flux measured using the soil heat flux plates (G_{plate}) at a depth of 80 mm and the energy flux stored in soil above the plates (G_{store}):

$$G = G_{plate} + G_{store} \quad \textbf{Equation 9}$$

The stored heat flux density was estimated from measurements of the temporal change in soil temperature and the specific heat capacity of the soil above the soil heat flux plate. The stored flux G_{store} was calculated as (Savage *et al*., 2004):

$$G_{store} = \rho_s c_s \Delta T_s \Delta z / \Delta t \quad \textbf{Equation 10}$$

where ρ_s is the bulk density of the soil (kg m^{-3}), c_s is the specific heat capacity of the soil (J kg^{-1} ^{o}C^{-1}), Δz is the difference in soil depth, ΔT_s is the average soil temperature difference (between 20 and 60 mm) during a measurement interval Δt. The volumetric heat capacity of the soil was calculated as:

$$\rho_s c_s = \rho_s c_{ds} + \rho_w c_w \theta_v \quad \textbf{Equation 11}$$

where c_{ds} is the dry soil specific heat capacity (≈800 J kg^{-1} ^{o}C^{-1}), ρ_w is the density of water (1000 kg m^{-3}), θ_v the volumetric soil water content (m^3 m^{-3}), and c_w is the specific heat capacity of water (4 190 J kg^{-1} ^{o}C^{-1}).

3.4.2.3 Surface layer scintillometry

A dual-beam surface layer scintillometer (model SLS40-A, Scintec Atmosphärenmessetechnik, Tübingen, Germany), was used to measure the sensible heat flux density every 2 minute. The surface layer scintillometer (SLS) was positioned at a height of 2.4 m above the soil surface and the path length between the receiver and transmitter units was 65 m. The SLS40-A model employs a diode laser source with an output wavelength of 670 nm and 1 mW (2 mW peak) mean output power. A laptop computer was connected to the signal processing unit of the scintillometer through the serial port. The beam displacement and detector separation distances are 2.5 mm each with a detector diameter of 2.7 mm. Software together with an instrument allows online measurements at a frequency of 1 kHz and subsequent calculation of micrometeorological parameters such as: the structure parameter for refractive index of air; structure parameter for temperature; the inner scale of turbulence as indicated by the inner scale of refractive index fluctuations; kinetic energy dissipation rate; sensible heat flux density H; momentum flux density and the Obukhov length L_o (Thiermann and Grassl, 1992). The two-minute estimates of all SLS-calculated parameters were stored on a computer hard drive for further analysis.

The SLS sensible heat flux is determined as (Hill, 1997):

$$H = \rho_a c_p T_* u_* \quad \textbf{Equation 12}$$

where T_* is temperature scale of turbulence, and u_* is the friction velocity. The same set of energy balance instruments used for the Applied Technologies eddy covariance system were used to measure the remaining energy balance components. The 2-minute sensible heat flux estimates were averaged into half-hourly values for the latent energy flux calculations.

Net irradiance was measured using a pyrradiometer (Philipp Schenk GmbH, Wein, Austria). The soil heat flux was measured using three Hukse flux plates (HFP01-15, Delft, The Netherlands) which were placed at a depth of 50 mm below the soil surface. The soil heat flux plates are designed to minimize heat flow disturbance and are calibrated to take in to account the heat stored above the plates. The pyrradiometer and the soil heat flux plates were connected to a CR10X datalogger. The half-hourly latent energy flux λE (W m^{-2}) was calculated as a residual of the shortened balance equation and converted into total evaporation ET (mm). The annual water use of the Jatropha trees was then estimated by summing the daily ET values for the hydrological year (2006 to 2011).

3.4.2.4 Soil water balance method

Total evaporation (*ET*) was calculated using the soil water balance equation as:

$$ET = \Delta S + P + I - D - R \qquad \textbf{Equation 13}$$

where ΔS = the change in soil water storage, P = rainfall, I = irrigation, D = drainage below the bottom of the root zone and R = runoff, with all variables in mm. P was obtained from the rain gauge measurements, I was obtained from water meter readings, and R was assumed to be zero. ΔS was calculated from neutron probe measurements. If the trial was conducted during a very wet season, it was difficult to determine drainage from neutron probe measurements alone and thus, *SWB* model simulations were used to help estimate drainage.

3.4.2.5 *SWB* simulation of water use

Therefore, the FAO model in *SWB* was used to estimate the water use of Moringa using the approach described next. Crop coefficients (K_c) were calculated as follows:

$$K_c = ET_c / ET_o \qquad \textbf{Equation 14}$$

where ET_o is reference evaporation, estimated using the FAO56 Penman-Monteith method (Allen *et al*., 1998). Crop maximum evaporation (E_m) was calculated as follows:

$$E_m = ET_o * K_{c\ max} \qquad \textbf{Equation 15}$$

where $K_{c\ max}$ represents the maximum value for K_c following rain or irrigation. It is selected as the maximum of the following two expressions (Allen *et al*., 1998):

$$K_{c\ max} = 1.2 + [0.04 \cdot (u_2 - 2) - 0.004 \cdot (RH_{min} - 45)] \cdot (H_c / 3)^{0.3} \qquad \textbf{Equation 16}$$

or

$$K_{c\ max} = K_{cb} + 0.05 \qquad \textbf{Equation 17}$$

where:

u_2 = mean daily wind speed at 2 m height (m s^{-1}),
RH_{min} = daily minimum relative humidity (%),
H_c = mean maximum plant height during the period of calculation (m), and
K_{cb} = basal crop coefficient value.

Maximum evaporation (E_m) for the crop is partitioned into maximum crop transpiration (E_{tm}) and maximum soil water evaporation (E_{sm}).

$$E_{tm} = K_{cb} * ET_o$$
$$E_{sm} = (1 - FI) \cdot E_m \qquad \textbf{Equation 18}$$

The fraction of canopy cover (FI) is estimated following the method of Allen *et al*. (1998):

$$FI = E_{tm} / E_m \qquad \textbf{Equation 19}$$

Daily K_{cb} values are then calculated from FI, E_m and ET_o using the following equation:

$$K_{cb} = (FI * E_m) / ET_o \qquad \textbf{Equation 20}$$

The procedure given in **Table 24** is used to determine K_c and K_{cb} values for the initial, mid-season and late season growth stages as well as the length of growth stages in days, according to Allen *et al*. (1998) unless indicated otherwise.

Table 24 Procedure to determine K_c and K_{cb} values for the initial, mid-season and late season growth stages as well as the length of growth stages in days

Growth stage	Description of procedure
Initial	Runs from planting date to approximately 10% ground cover (FI = 0.1). The K_{cb} for the initial growth stage is equal to the daily calculated K_{cb} at FI = 0.1
Crop development	Runs from end of initial stage until FI is 90% of maximum FI. Allen *et al*. (1998) recommended the beginning of mid-season when the crop has attained 70 to 80% ground cover. If a treatment did not attain 70% ground cover, the beginning of the mid-season was taken as the day at which FI is 90% of the maximum FI following Jovanovic and Annandale (1999).
Mid-season	Runs from effective full cover (end of the development stage) to the start of maturity. The start of maturity is assumed to be when FI drops to the same value it had at the beginning of the mid-season (Jovanovic and Annandale, 1999). K_c and K_{cb} equal to average daily K_c and K_{cb}, respectively during the mid-season stage.
Late season	Runs from end of mid-season stage until end of the growing season. Daily K_c and K_{cb} for late season is equal to the calculated K_c and K_{cb} respectively, at end of growing season.

3.4.2.6 Summary

A summary of which method was used for each crop studied at the three trial sites is given in **Volume 1**.

3.4.3 Soil water content

3.4.3.1 Neutron probe

At Hatfield, a neutron probe (Hydroprobe®, Model 503 DR, Martinez, CA, USA) was used to monitor soil water content at 20 cm depth increments to a depth of 1.5 m. The probe is lowered into a metal tube which is inserted into the soil. The probe contains a sealed radioactive source and a detector. Fast neutrons are emitted by the radioactive source, which are then converted to slow neutrons by hydrogens atoms in the soil water. The amount of soil neutrons is related to the soil's water content. The probe measures soil water content of a volume of soil about 30.5 cm wide and 15 cm deep. It is recommended that neutron probes are calibrated using volumetric soil water content measurements (Prichard *et al*., 2004).

3.4.3.2 Diviner probe

The Sentek Diviner 2000 utilises the dielectric properties of the soil to measure soil volumetric water content by means of FDR (Frequency Domain Reflectometry). The measurements are recorded using a capacitance sensor at different depths within a PVC access tube inserted into the soil profile. It is a light and portable system (a cable connects the rod with the capacitance sensor to the datalogger) and may readily be used to quickly sample a number of soil moisture monitoring sites. The probe at the end of the rod is inserted by hand into the access tube, and the soil water content is measured and recorded at 10 cm increments. Data is stored to the attached datalogger, and may be downloaded for further analysis. Once the diviner probe has been calibrated, the accuracy is ±0.5% (Charlesworth, 2005).

3.4.3.3 Time domain reflectometry

Time Domain Reflectometry (TDR) system transmits a very short rise time electromagnetic pulse along a coaxial system which includes a TDR probe for soil water measurements and samples and digitises the resulting reflection waveform for analysis or storage. The elapsed travel time and pulse reflection amplitude contain information used by the on-board processor to quickly and accurately determine soil volumetric water content, soil bulk electrical conductivity, rock mass deformation or user-specific, time-domain measurement.

TDR is a relatively new method of measuring soil moisture. TDR methodology was previously used in the telecommunications industry to identify discontinuities in cables. An electromagnetic wave is propagated down a cable and reflected indicating discontinuities or breaks in the cable. Using time travel analysis, it is possible to determine the point of discontinuity or damage to the cable. Development of TDR technique in the 1980's for measuring volumetric soil water content is presented in Topp *et al*. (2003).

The time travel of a propagated signal is dependent on the velocity of the signal and the length of the waveguide or cable. The velocity of the electromagnetic wave is in turn dependent on the dielectric constant of the material surrounding the waveguide and can be expressed as:

$$\Delta t = \frac{2L\sqrt{K_a}}{c}$$ **Equation 21**

where K_a is the apparent dielectric constant, c is the velocity of the electromagnetic signal in free space, L is the waveguide length, and Δt is the travel time. The apparent probe length which is the actual unit measured by TDR devices can be defined as:

$$L_a = \frac{c\Delta t}{2}$$ **Equation 22**

In terms of the dielectric constant (K_a), the two equations above can be simplified as the ratio of the apparent probe length (L_a) to the real probe length (L).

$$\sqrt{K_a} = \frac{L_a}{L}$$ **Equation 23**

TDR can be used to estimate soil moisture because the dielectric constant of water relative to other soil constituents is high. Consequently, it is possible to develop a relationship between changes in dielectric constant and volumetric soil water content (θ_v). The relationship between dielectric constant and volumetric water content has been described by Topp *et al.* (1980) and Ledieu *et al.* (1986) empirically using polynomial and linear equations. This empirical relationship was first described by Topp *et al.* (1980) as:

$$\theta_v = -5.3*10^{-2} + 2.92*10^{-2} \cdot K_a - 5.5*10^{-4} \cdot K_a^2 + 4.3*10^{-6} \cdot K_a^3$$ **Equation 24**

and later developed further by Ledieu *et al*. (1986) as:

$$\theta_v = 0.1138 \cdot K_a^{0.5} - 0.1758$$ **Equation 25**

These empirical relationships provide a good estimation of soil moisture in mineral soils where θ_v < 0.5 $m^3\ m^{-3}$ which covers the entire range of interest in most soils with an estimation error of 0.013 (Jones *et al*., 2002). Soils with θ_v > 0.5 $m^3\ m^{-3}$ or with high organic or clay contents may require soil specific calibration. An alternative is the dielectric mixing approach which uses dielectric constants and volume fractions for each soil constituent to derive a relationship describing the composite dielectric constant. This physically based approach was used by Roth *et al.* (1990) and Friedman (1998) but estimates of porosity are required for this technique.

The high frequency pulse (Giga Hertz) that is sent down a cable attached to the TDR100 is reflected and the reflected waveform digitised. A probe consisting of metal rods is attached to the end of a coaxial cable. The probe is identified as a discontinuity in cable impedance which causes a change in wave amplitude. This makes it possible to identify the start points and end points of the probe. The travel time is used together with the velocity to gather distance information across the length of the probe. This apparent length of the probe is dependent on water content of the soil around the probe.

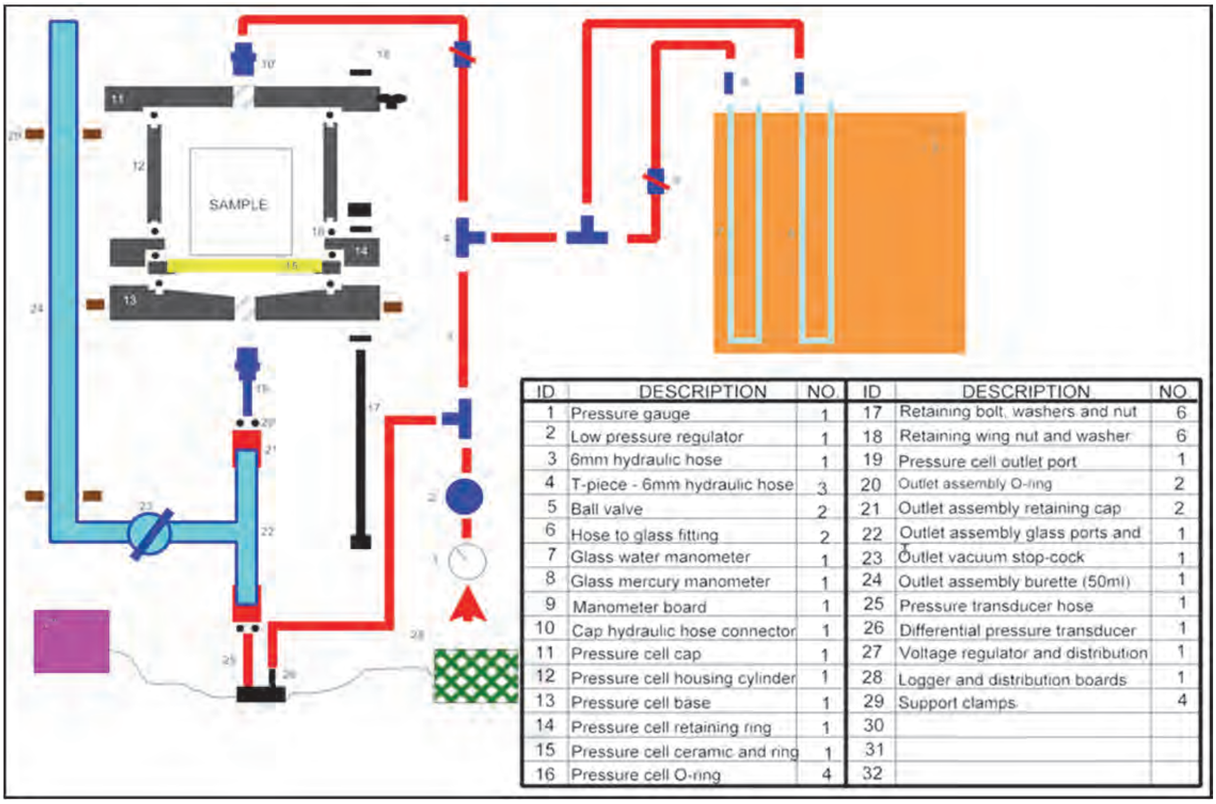
TDR has number of advantages over other techniques used for volumetric soil moisture measurement. The main advantages are: (i) superior accuracy; (ii) calibration under normal conditions is minimal; (iii) TDR has excellent spatial and temporal resolution; (iv) measurements are easily automated using loggers and multiplexers; (v) soil disturbance is minimal and there is no danger to hazardous exposure of radiation offered by other techniques such as neutron probes (Jones *et al*., 2002). The results are usually accurate within an error limit of approximately 1 to 2% (Anisko *et al*., 1994; Jones *et al*., 2002; Chandler *et al*., 2004).

A critical limitation of the TDR system that can affect the accuracy of volumetric soil moisture content is the air gap effect (Dobriyal *et al*., 2012). This occurs when there is a poor electrical contact between the probes and the soil. This problem can be created during installation. Patterson and Smith (1985) recommend the use of narrow pilot holes drilled into the soil to prevent gaps created by the insertion of the probes at an inconsistent angle. This can be particularly useful in hard soils where probe insertion may be difficult. This also reduces compaction of the soil when the probe is inserted, although the Campbell Scientific TDR Probe Instruction Manual states that the soil will experience rejuvenation of soil structure with time from wetting/drying cycles.

The volumetric soil moisture content is assumed to be uniform around the vicinity of the probe, with the measurement being the average soil moisture of the material surrounding the probe. However, this may in reality not be the case and a study by Chan and Knight (1999) shows that signal noise may be created if soil moisture is not evenly distributed across the length of the probes.

3.4.3.4 Soil water retention characteristics

Soil water parameters (i.e. total porosity, field capacity and permanent wilting point) were estimated using the outflow pressure method, shown in **Figure 22**. It is designed to measure soil water parameters between 0 and 1 bar (or 100 kPa). Conventional methods of determining soil water retention parameters are dependent on monitoring the equilibration of the volumetric water content. However, in this method, they are determined by monitoring the time to equilibration of the matric potential (Lorentz *et al*., 2001). The advantage of this is it allows for the water outflow to be controlled rather than just letting it flow until equilibration is reached (i.e. no water outflow), thus saving time for the observer.



ID	DESCRIPTION	NO.	ID	DESCRIPTION	NO.
1	Pressure gauge	1	17	Retaining bolt, washers and nut	6
2	Low pressure regulator	1	18	Retaining wing nut and washer	6
3	6mm hydraulic hose	1	19	Pressure cell outlet port	1
4	T-piece - 6mm hydraulic hose	3	20	Outlet assembly O-ring	2
5	Ball valve	2	21	Outlet assembly retaining cap	2
6	Hose to glass fitting	2	22	Outlet assembly glass ports and	1
7	Glass water manometer	1	23	Outlet vacuum stop-cock	1
8	Glass mercury manometer	1	24	Outlet assembly burette (50ml)	1
9	Manometer board	1	25	Pressure transducer hose	1
10	Cap hydraulic hose connector	1	26	Differential pressure transducer	1
11	Pressure cell cap	1	27	Voltage regulator and distribution	1
12	Pressure cell housing cylinder	1	28	Logger and distribution boards	1
13	Pressure cell base	1	29	Support clamps	4
14	Pressure cell retaining ring	1	30		
15	Pressure cell ceramic and ring	1	31		
16	Pressure cell O-ring	4	32		

Figure 22 A diagram of the outflow pressure apparatus for measuring soil water parameters of undisturbed soil cores (after Lorentz *et al*., 2001)

Before the soil samples were analysed, both the samples and the ceramic discs (no. **15** in **Figure 22**) were saturated. The ceramic discs were considered saturated after being submerged in water for at least 24 hours. This was done to remove air bubbles that could potentially disrupt the flow of water during measurements. The bottom of the soil cores were first sealed with permeable ceramic discs (**15**) to ensure no soil fell out during the saturation procedure. Thereafter, a glass container was half-filled with water so that the soil cores were not fully submerged in water. Following that, an electric pump was used to remove as much air as possible, thus creating a vacuum which ensured the soil cores were saturated.

After the saturation process, the following procedure was used for each soil sample:

- The soil sample was weighed on a sensitive balance with an accuracy of up to 0.001 g.
- The pressure cell base (**13**) was filled with water to remove any air bubbles.
- The stop-cock (**23**) of the burette (**24**) was opened to allow water and air bubbles to flow into the outflow burette.
- The soil sample was placed into the pressure cell housing (**12**).
- The pressure cell ring was then used to retain the sample (**14**).
- Finally, the soil sample was enclosed (**11**).

Air pressure (**2**) was then applied to the sample so water (e.g. 5 mm) could drain into the burette (known as the drainage phase). When no more water drained out, the stopcock was closed until equilibration was reached between the applied air pressure and the liquid in the soil sample. This is known as the equilibration phase (or steady state) and at this point, the matric potential remained constant. The pressure transducer (**26**) measured the difference in pressure between the pores of the sample and the air pressure applied. This was monitored by observing the changes in matric potential values displayed on a computer monitor. Air pressure was applied at different levels throughout this experiment to vary the matric potential. The amount of water that is available for plant use is retained at matric potentials of between -10 to -1 500 kPa. The low matric potential (e.g. 0 kPa) applied in the beginning (i.e. water easily drained out) and a higher matric potential (33 kPa) correspond to porosity and the field capacity respectively. For lower matric potentials, the water manometer (**6**) was used for observations. At higher matric potentials, the mercury manometer (**7**) was used.

At a matric potential of -1 500 kPa, most crops wilt because the soil water is not available for plant uptake (Schulze *et al*., 1995). Each soil core was carefully removed and weighed again, then transferred to a pressure pot that was operated at 15 bars (-1 500 kPa) of pressure to ascertain the wilting point. Before using this technique (similar to **Figure 22**), a ceramic disc that could withstand pressures of 15 bars was saturated with water for over 24 hours. A similar approach for the free drainage phase and equilibrium state was used, but in this instance, the water was allowed to drain out of the samples until an equilibration state was reached. Once equilibrium was reached (i.e. no more water dripped out into the burette), the soil sample was weighed, then oven dried for 48 hours and finally re-weighed. Measurements were then used to calculate the dry bulk density of the soil (**Equation 26**), from which the porosity of the soil was calculated (**Equation 27**):

$$\rho_b = M_s / V_s \qquad \textbf{Equation 26}$$

$$\Phi = 1 - (\rho_b / 2.65)$$ **Equation 27**

where ρ_b is the soil bulk density (g cm^{-3}), M_s is the dry mass of soil core (g), V_s is the volume of each soil core (cm^3), Φ is the porosity of the soil (fraction) and 2.65 is the normal particle density (g cm^{-3}).

Using a Microsoft Excel spreadsheet, calculations were done using porosity, bulk density and readings recorded from the burette to obtain the soil water content at the different applied pressures. These values corresponded to the soil water content at saturation (i.e. porosity), field capacity and permanent wilting point.

3.4.3.5 Saturated hydraulic conductivity

The saturated hydraulic conductivity of the three soil samples was determined using the constant head method (**Figure 23**). This method works by applying Darcy's law, (**Equation 28**) across the permeameter pressure ports. This law describes the basic flow of liquids in permeable materials (Singh *et al*., 2011):

$$Ks_{ij} = \left(\frac{\Delta l_{ij}}{H_i - H_j}\right) \times \left(\frac{Q}{A}\right)$$ **Equation 28**

where:

Ks_{ij} = saturated hydraulic conductivity of the soil between port i and j (cm s^{-1}),
l_{ij} = length of the soil material between ports i and j (cm),
H_i = total hydraulic head at port i (cm),
H_j = total hydraulic head at port j (cm),
Q = volumetric outflow rate (cm^3 s^{-1}) and
A = total cross-sectional area of the column (cm^2).

This technique was selected due to the following advantages: 1) it is simple and easy to set up, and 2) it is a direct application of Darcy's law, thus giving reliable results that mimic field conditions (Lorentz *et al*., 2001). However, the disadvantages include: 1) the soil material may be disturbed which does not reflect actual field conditions, 2) the manometer tubes can periodically block due to air bubbles which affects the results, and 3) the soil must have a uniform structure to get a consistent hydraulic conductivity across the ports. The reader is referred to Lorentz *et al*. (2001) for the steps that were taken to calculate the saturated hydraulic conductivity using this method.

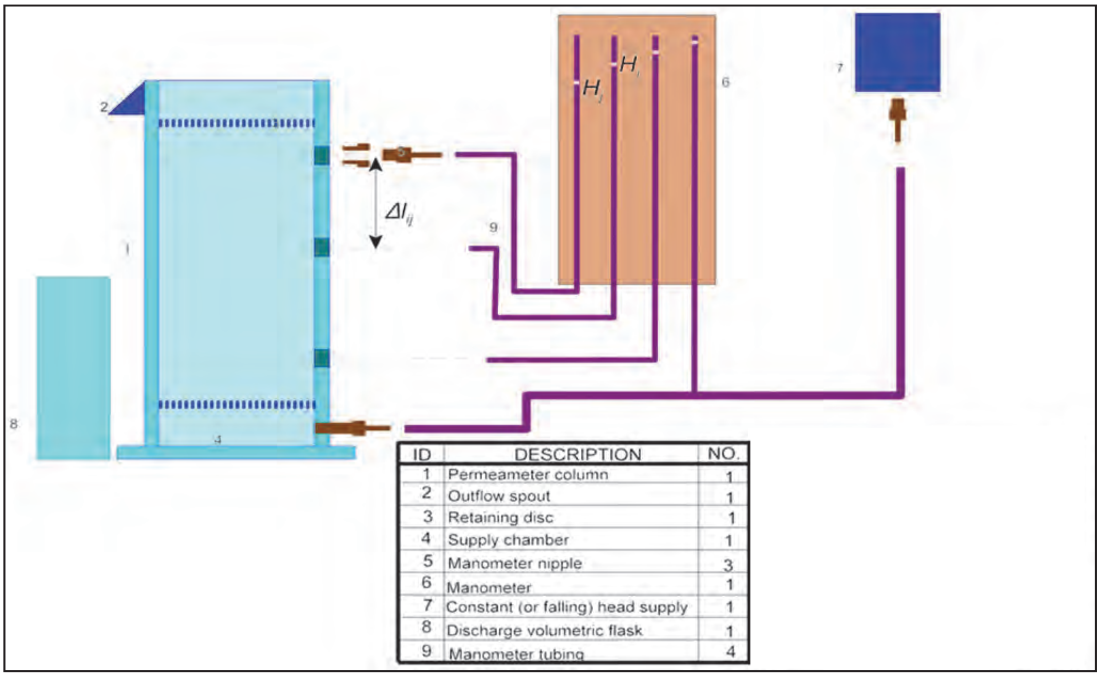


Figure 23 A diagram of the constant head method for measuring the soil hydraulic conductivity of undisturbed soil samples (after Lorentz *et al*., 2001)

3.5 Instrumentation

3.5.1 Weather data

3.5.1.1 Ukulinga

The climatic variables required to calculate reference evaporation (solar or net radiation, air temperature, relative humidity and wind speed) were measured by automatic weather stations (AWS) located over natural grassland (i.e. mixed grass) that is rainfed (i.e. non irrigated). The grass was cut at least once a month (but preferably every 2nd week) during the summer rainfall season. The two AWSs located at the Ukulinga research farm are owned and maintained by the CSIR (**Figure 24a**) and the ARC (**Figure 24b**).

(a) **(b)**

Figure 24 Automatic weather stations located on the Ukulinga Farm and owned by the a) CSIR and b) the ARC

The ARC's weather station is located along the main farm road (30.40615E; -29.66740S; XY in degrees decimal) at an altitude of 805 m (**Figure 25**). Similarly, the CSIR's weather station is located in Plot #3 (30.41332E; -29.66959S; XY in degrees decimal) at an altitude of 782 m. Plots #1 and #2 are roughly located between the 780 and 785 m contours as shown in **Figure 25**.

Figure 25 Location of the two trial sites (Plot #1 & Plot #2), in relation to Plot #3 (Jatropha trial) and the two automatic weather stations (5 m contours shown as white lines)

The ARC's AWS is approximately 615 and 640 m from the centre of plots #1 and #2 respectively. In comparison, the CSIR's AWS is about 605 and 685 m from the respective centres of Plot #1 and #2. The two weather stations are about 735 m apart. Since there are two AWS located on the Ukulinga Farm, data from one station could be used to patch the other if errors (i.e. missing data) occurred due to equipment failure or battery problems. For example, the ARC's faulty tipping bucket rain gauge was replaced in May 2011 and rainfall data for a three-month period was replaced with observations recorded by the CSIR's rain gauge.

The Campbell Scientific AWS (Campbell Scientific, Logan UT, USA) situated at the Jatropha trial (Plot #3) comprised of the following sensors:

- Vaisala HMP35C sensor for measuring relative humidity and air temperature,
- RM Young cup-anemometer for measuring wind speed (R.M. Young, Inc., USA),
- LI-200X pyranometer for measuring solar radiation (LI-COR Corporation, Nebraska, USA),
- Texas Instruments tipping bucket rain gauge (TE525 Texas Instruments, USA), and a

- CR10X datalogger (Campbell Scientific, Inc., Utah, USA).

Stored climate data were downloaded weekly using a laptop computer. The datalogger also calculated saturated vapour pressure, ambient vapour pressure, vapour pressure deficit and reference evaporation (FAO Penman-Monteith method).

The second Campbell Scientific AWS owned by the ARC utilised weather sensors that were practically identical to the CSIR's station. As shown in **Figure 24**, the main difference between the two weather stations was the enclosure housing the air temperature and relative humidity sensor (standard Stevenson screen which is not ideal, compared to the preferred heat shield). Stored climate data are downloaded daily via a telemetry link by the Agricultural Research Council (ARC) based at the Department of Agriculture at Cedara (located approximately 29 km from Ukulinga). The climate data are received from the ARC via e-mail requests every two months.

3.5.1.2 Hatfield

Daily weather data were collected from an AWS located 1 372 m above sea level, at 28.25968E and -25.74920S (XY in degrees decimal). The station is located about 100 m from the trial sites (sorghum and Moringa). The automatic weather station instruments consist of an Apogee silicon pyranometer (Apogee, Logan, Utah, USA) to measure solar radiation, an electronic cup anemometer (R.M. Young, Inc., USA) to measure average wind speed, an electronic tipping bucket rain gauge (TE525 Texas Instruments, USA), a Vaisala HMP50 electronic temperature and relative humidity sensor and a CR200 datalogger (Campbell Scientific, Inc., Utah, USA). Weather data was downloaded once a week using a laptop computer. This AWS is therefore similar to that owned and managed by the CSIR at Ukulinga.

3.5.1.3 Baynesfield

Meteorological data (solar radiation, air temperature, wind speed, relative humidity, and atmospheric pressure) was obtained from an automatic weather station located at Baynesfield (Mengistu *et al*., 2014). The instrumentation used was also very similar to that used at Ukulinga and Hatfield.

3.5.2 Transpiration

3.5.2.1 Jatropha (Ukulinga)

A CR10X or CR1000 data-logger connected to AM16/32 multiplexers (Campbell Scientific, Logan UT, USA) may be programmed to initiate the hourly heat pulses and record data from the respective thermocouple pairs, while the heater probes are connected to a relay control module and 12VDC battery (**Figure 26**). Heat pulse velocity data require correction for sapwood wounding caused by the drilling procedure, using wound correction coefficients described by Swanson and Whitfield (1981). The corrected heat pulse velocities are then converted to sap flux densities by accounting for wood density and sapwood moisture content (Marshall, 1958). Finally, the sap flux densities are converted to whole-tree total sap flow by calculating the sum of the products of sap flux density and cross-sectional area for individual tree stem annuli (determined by below-bark TC insertion depths and sapwood depth). The final analysis involves the conversion of the hourly HPV values to total daily sap flow (in litres and millimetres).

Figure 26 Hardware utilised for the monitoring of transpiration (sap flow)

3.5.2.2 Moringa (Hatfield)

The heat ratio method (HRM) of the HPV technique (Burgess *et al*., 2001) was used for estimating water use from the Moringa trees. Sample plants were selected from irrigated and non-irrigated treatments. Three probe sets were radially inserted to different depths in the sapwood of each plant 5 mm below the cambium (**Figure 27**). Each probe set consisted of a central line heater and two temperature measuring probes at equidistant (5 mm) downstream and upstream from the line heater. A CR1000 datalogger was connected to two AM16/32 multiplexers (Campbell Scientific, Logan UT, USA). The control module/datalogger was programmed to provide a heat pulse and measurements were recorded every hour. All estimates of sap velocity were corrected for probe implantation effects (Swanson and Whitfield, 1981) based on an estimated wound width of 4 mm. HRM configuration, correction for wounding and other operational details are given by Burgess *et al*. (2001).

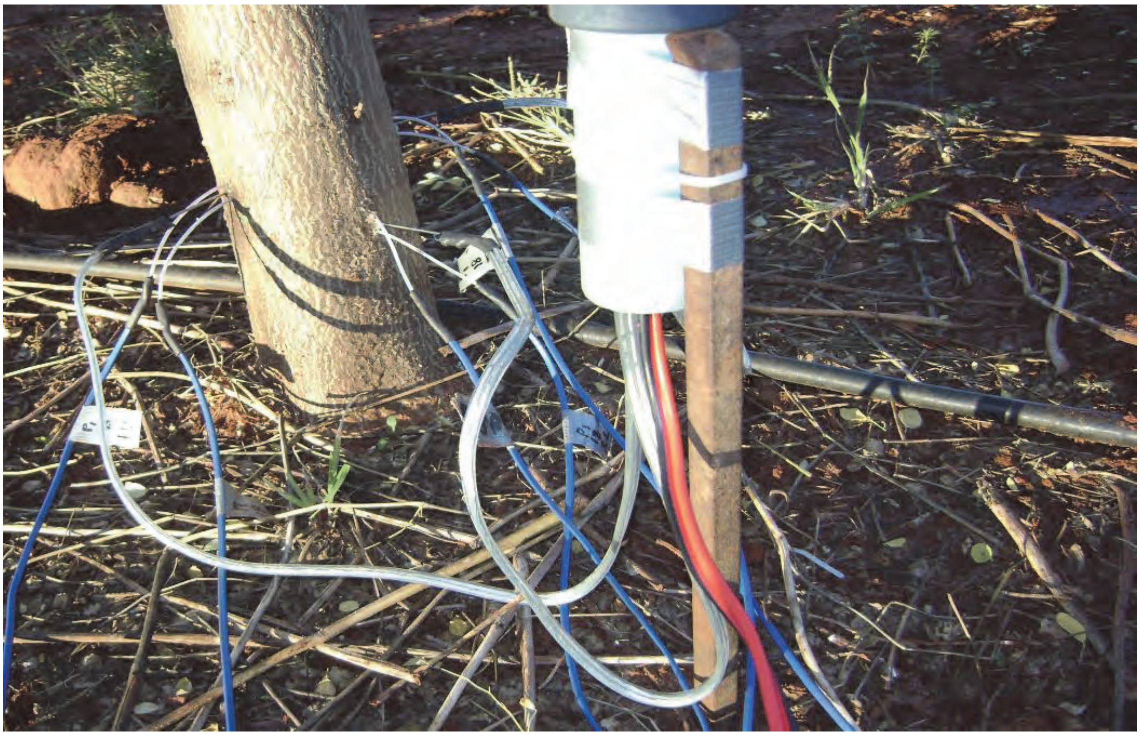


Figure 27 HPV probe sets inserted in a *Moringa oleifera* tree at the Hatfield experimental farm, University of Pretoria

3.5.3 Evapotranspiration

3.5.3.1 Annual crops

Water use was estimated as the actual evapotranspiration from the cropped surface, accumulated from planting date to harvest date. It is expressed as the total evaporation (soil water evaporation + transpiration + interception) in mm or m^3 for the growing period. Total evaporation was estimated using the surface renewal method as the residual of the shortened energy balance equation. The latent energy flux was determined indirectly as the residual of the shortened energy balance equation.

The eddy covariance method was also used to calibrate the surface renewal method and obtain the weighting factor (α). A sonic anemometer was used as an eddy covariance system to measure three dimensional wind velocity components and sensible heat flux density every 30 minutes (**Figure 28**). The sonic anemometer was connected to a CR3000 datalogger (Campbell Scientific Inc., Logan, Utah, USA) and 12V DC (90 Ah) battery housed in the strongbox.

For the surface renewal method, one unshielded type-E fine-wire thermocouple (75-µm diameter) was used to measure air temperature placed at a height of 0.5 m above the canopy surface (**Figure 28**). The fine wire prevents the sensor from absorbing direct solar radiation and heating up, thus introducing error. This thermocouple was used for estimating the sensible heat flux and high frequency measurements. Thermocouple measurement was done differentially and air temperature data was sampled at a frequency of 10 Hz. Time lags of 0.40 s and 0.80 s were used for the surface renewal analysis before forming the second, third and fifth order of air temperature structure function values as required by the Van Atta

(1977) approach. The data were then averaged and stored every two minutes in the CR3000 datalogger.

Additional measurements included the remaining components of the energy balance. Net irradiance was measured using a Q*7 net radiometer (REBS, Seattle, Washington, USA) placed at 1.50 m above the ground surface (**Figure 28**). Two Hukse flux plates (HFP01-15, Delft, The Netherlands) were used to measure soil heat flux density at a depth of 80 mm and a system of parallel-thermocouples at depths of 20 and 60 mm were used to calculate the heat stored above the plates.

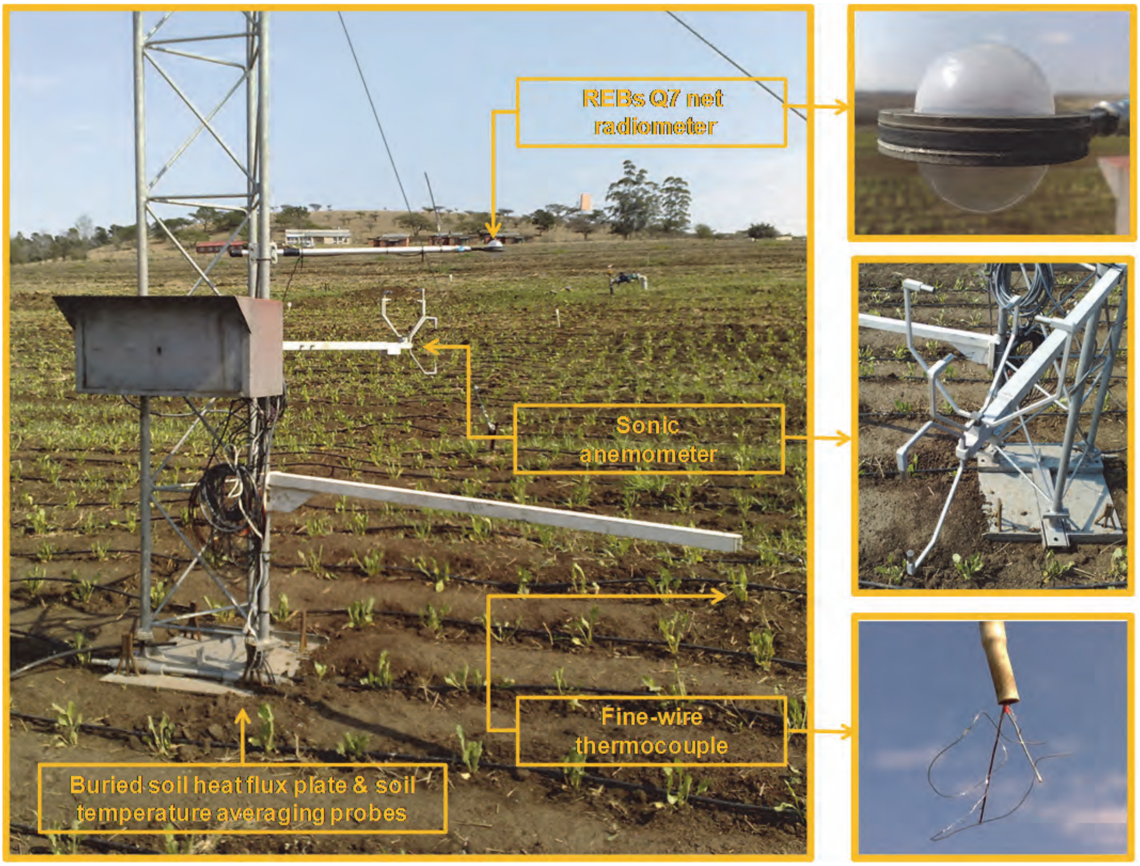


Figure 28 Lattice mast situated near the centre of the 80 by 80 m sugarbeet trial and rigged with a fine-wire thermocouple, sonic anemometer and net radiometer

3.5.3.2 Jatropha (Ukulinga)

Four months of ET data was obtained from February to May 2011 using a Surface Layer Scintillometer (SLS). The SLS transmitter and receiver were mounted and secured to steel poles, in order to measure total evaporation diagonally across two adjacent Jatropha only (i.e. weed-free) plots at Ukulinga (**Figure 29**).

(a) **(b)**

Figure 29 View from the steel pole which supported the SLS receiver used to measure total evaporation diagonally across two adjacent Jatropha only (i.e. weed-free) plots at Ukulinga in January 2011

3.5.3.3 Moringa (Hatfield)

The soil water balance equation (**Equation 13**) and *SWB* model simulations were used to estimate crop water use. If the trial was conducted during a very wet season (e.g. 2010/11), it was difficult to determine drainage from neutron probe measurements alone and thus, *SWB* model simulations were used to help estimate drainage.

3.5.4 Soil water content

3.5.4.1 Ukulinga

A Campbell Scientific TDR100 system (Campbell Scientific, Logan UT, USA) connected to an RR1 battery was used to measure volumetric soil water content. The TDR system consisted of a TDR100 Time Domain Reflectometer, a Campbell Scientific CR1000 datalogger, three SDMX50 coaxial multiplexers and 16 TDR probes. Eight CS605 probes were installed in the first plot (i.e. Plot #1 in **Figure 25**) and the remaining eight in Plot #2.

The probes were installed by excavating a pit 1 m deep (in each plot) to measure volumetric soil water content at different depths. Narrow holes were drilled into the soil prior to installation of the probes because the soil was hard and impenetrable. Four CS605 probes were installed at depths of 0.1 m, 0.2 m, 0.4 m and 0.6 m into the south-facing of the pit and another duplicate set of four probes at the same depths into the north-facing of the pit (**Figure 30**). Finally, the pit was then backfilled with soil without mixing the different horizons. Half-hourly and daily volumetric water content was then calculated from the dielectric constant using the Ledieu *et al*. (1986) equation.

(a) **(b)**

Figure 30 "Before" (a) and "after" photographs (b) of the Perspex mini-rhizotron access tube and CS605 probe installation (0.1, 0.2, 0.4 and 0.6 m depths) at Ukulinga in September 2010

3.6 Measurement of Feedstock Yield

The growth of each annual crop was monitored over the growing season using a variety of instrumentation as explained below.

3.6.1 Feedstock growth

3.6.1.1 Leaf area

Leaf Area Index (LAI) is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. LAI is a dimensionless value, typically ranging from 0 for bare ground to 6 for a dense forest.

Random samples of leaves at emergence (or just after transplanting) were used to determine initial leaf area using an LI-3100C Portable Leaf Area Meter (LI-COR, USA). According to its designers, once the meter has been calibrated, it has a combined accuracy and precision of 99% (LI-COR, 2009). This value is required to determine the initial canopy cover (CC_o) for crop models such as *AQUACROP*.

Once plant leaves reach a sufficient size after successful crop establishment, a LAI-2200 plant canopy analyser (LI-COR, USA) was used to measure leaf area index. Initially, measurements are taken regularly (i.e. weekly) until maximum LAI was reached. Thereafter, measurements were taken fortnightly due to slow canopy growth. The advantage of the LAI-2200 over similar instruments (e.g. AccuPAR LP-80 ceptometer) is that it does not require calibration. However, LAI-2200 readings can be affected by non-uniform cloud cover and direct sunlight. These limitations can be overcome by following procedures given in the manual (LI-COR, 2009).

3.6.1.2 Plant senescence

A chlorophyll meter (Minolta SPAD 502) was used to derive an index of chlorophyll content of the crop. These measurements were related to the time taken for the plant to senescence (i.e. when chlorophyll content begins to decline). Measurements were taken from the upper surface (i.e. ad axial) of the mature leaves. The measurements from the chlorophyll meter are based on comparing leaf transmittance at two wavelengths, namely 650 nm and 940 nm. Therefore, the obtained values are proportional to the chlorophyll content of the leaves (Manetas *et al*., 1998; Pinkard *et al*., 2006). The design of the chlorophyll meter is based on the assumption that changes in the ratio of transmittance between the two wavelengths are purely based on chlorophyll levels. However, this is not always the case, since certain plants change leaf colour at different development stages (Manetas *et al*., 1998). The time to the start of senescence is another parameter required by crop models such as *AQUACROP*.

3.6.1.3 Photosynthetic active radiation

Data on plant growth was collected at weekly (or bi-weekly) intervals for annual crops and at monthly intervals for perennial crops (i.e. trees). The fraction of photosynthetically active radiation (*PAR*) intercepted by the canopy (FI_{PAR}) was measured using a Sunfleck ceptometer (Decagon Devices, Washington, USA). PAR measurements consisted of three series of measurements conducted in rapid succession on cloudless days. A series of measurements consisted of one reference reading above and ten readings beneath the canopy, which were then averaged. FI_{PAR} was calculated as follows:

$$FI_{PAR} = 1 - \frac{PAR\ below\ canopy}{PAR\ above\ canopy}$$ **Equation 29**

3.6.1.4 Root development

The minimum effective rooting depth was obtained from measuring the root length of emerged plants (or transplanted seedlings). The maximum effective rooting depth was obtained using a 3D mini-rhizotron scanner (CI-600 Digital Root Imager; CID Inc., Washington, USA.). This technique allowed for non-destructive measurements of root growth over time. This was achieved by installing transparent (i.e. clear) perpex access tubes into the soil profile. The scanner was inserted into these tubes to record images at various depths. Before using the scanner, it was calibrated by inserting the camera into a non-transparent tube (to mimic the darkness in the soil) to ensure it revolved completely (i.e. 360 degrees). Mini-rhizotrons have been used to study root development, root turnover, root parasitism and proliferation by fungal hyphae (Faget *et al.,* 2010). The minimum (Z_{min}) and maximum (Z_{max}) rooting depth is required by hydrological and crop yield models.

3.6.2 Feedstock yield

A destructive sampling technique was used for taking periodic measurements of both fresh and dry biomass (leaf, stem, head and/or tuber). These measurements are used to convert from fresh to dry yield weight. Fresh weight was determined by weighing samples on a scale (accurate to 3 decimals of a gram). The sample was deemed dry after reaching constant mass after oven drying for over 48 hours at temperatures ranging from 65 to 75°C. Final biomass, yield and the harvest index (HI) were all determined at harvest time.

In order to minimise labour costs, only a portion (e.g. 50%) of the entire trial was typically harvested. The sample plots were chosen in areas where damage (caused by weeds, pets and/or diseases) as minimal and also to avoid “edge effects”. Finally, plants near the irrigation system’s main manifold line (i.e. centre of the trial) were also excluded. This avoided plants exposed to fine water leaks from the saddles which connect the dripperlines to the manifold, which may have influenced the yield of neighbouring plants.

3.7 Estimation of Biofuel Yield

In order to meet one of the aims of the biofuels project (**AIM 6**), water use efficiency was also expressed in terms of biofuel yield per unit of water consumed by the total biomass. In the context of biofuels, *biofuel use efficiency* (m^3 m^{-3}) is defined as the biofuel yield (in m^3), relative to the water used to produce the feedstock (m^3). Where possible, bioethanol yield is determined from the sugar content (**Section 3.7.1**) or starch content (**Section 3.7.2**). Similarly, biodiesel yield is determined from the oilseed yield (**Section 3.7.3**). Alternatively, feedstock yields can be converted to biofuel yields using conversion ratios typically reported in the local and international literature (**Section 3.7.4**).

3.7.1 Bioethanol from sugar

3.7.1.1 Juice extraction

Reddy *et al*. (2007) suggested that stripped sweet sorghum or sugarcane stems should be squeezed in a roller press to extract the sugar juice. The resultant juice extract and bagasse can then be weighed to record the respective yields. Hence, the bagasse and juice extract yields (in t ha^{-1}) must correspond to the stem yield. Sugar yield is calculated as a product of Brix (%) and juice extract yield. The bagasse plus leaves can be used for animal fodder production. For example, Miller and Ottman (2010) reported an extraction percentage of juice (i.e. juice weight divided by stalk weight) of 43% for sweet sorghum stalks. This value is typically lower than may be expected with a commercial press, and thus bioethanol yields may be underestimated.

The use of roller mills to extract sugar juice, which is common in India, has three undesirable side-effects. Firstly, the extracted yield will vary with variety, depending on the stem structure. Secondly, the extracted yield also depends on the moisture content of the stalk (i.e. the "wetter" the stalk, the higher the percentage of sugar that can be removed). Finally, it is difficult to replicate results and depends on the mill settings on the day which influences how much of the sugar can be extracted.

The use of roller mills was not adopted at Ukulinga (or Hatfield) because pressing does not remove all sugar from the stem (approximately 10% remains in the bagasse). The preferred method of sugar extraction is via a diffusion process as described in **Section 3.7.1.3**.

3.7.1.2 Biofuel yield

The following equation (**Equation 30**) was used to calculate theoretical bioethanol yield from fresh mass and Brix content. The equation is similar to that published by Zhao *et al*. (2009), who referenced the Institution of Japan Energy (IJE, 2006). The equation below uses fresh mass and not dry mass (there is no difference in calculating theoretical bioethanol yield based on wet or oven dried samples). For example, sweet sorghum stalks normally have a dry sugar content of between 45 and 65% with a dry matter content of between 20 and 35%.

$$\textit{bioethanol yield (L ha}^{-1}\textit{)} = \textit{Brix (\%)} * 0.85 * \textit{fresh yield (t ha}^{-1}\textit{)} * 10 * 0.511 * \textit{FE} / 0.79 \qquad \textbf{Equation 30}$$

Similar equations have also been published by Sakellariou-Makrantonaki *et al.* (2007) who referenced Lipinski (1978). Vasilakoglou *et al*. (2011) also published an equation recently and referenced Sakellariou-Makrantonaki *et al.* (2007) and Zhao *et al*. (2009). Compared to the above method, the equations provided by Zhao *et al*. (2009) and Sakellariou-Makrantonaki *et al.* (2007) tend to underestimate the bioethanol yield, whereas the Vasilakoglou *et al*. (2011) equation over-estimates bioethanol production.

Brix * 0.85 provides the approximate Total Fermentable Sugars (TFS) and is based on results from the Sugar Milling Research Institute (SMRI). Hence, Brix is a measure of fermentable sugars including sucrose, glucose and fructose. The remaining 15% of the Brix is non-fermentable i.e. pentose sugars, mitochondria, ash etc. This value varies with variety and peaks around 85%. Almodares and Hadi (2009) also stated that sweet sorghum juice is assumed to be converted to bioethanol at 85% of theoretical, or 54.4 L bioethanol per 100 kg fresh stalk yield.

The constant 0.51 represents the theoretical bioethanol yield from sugar on a mass basis (i.e. 2 kg sugar produces 1 kg bioethanol; Shuler and Kargi, 2002). This value is based on the stochiometry of the conversion of a six-carbon sugar (1 glucose; $C_6H_{12}O_6$) to 2 bioethanol ($2CH_3CH_2OH$) and 2 carbon dioxide ($2CO_2$) molecules. Although this gives a conversion factor of 0.51, actual fermentation results vary between 44 and 48 g bioethanol from 100 g glucose. This gives a fermentation efficiency (FE) of 0.86 to 0.94. Fermentation efficiency is typically determined from the difference between observed and theoretical bioethanol production. Values of 0.93 and 0.90 were used for sugarbeet and sweet sorghum respectively. Finally, the factor of 10 accounts for the units (e.g. yield in t ha^{-1}; Brix in %) and the constant 0.79 kg L^{-1} is the density of bioethanol required to convert the bioethanol yield to a volume basis.

For sugarcane, sucrose and not Brix (i.e. total fermentable sugar) was used to derive the theoretical bioethanol yield. Sucrose is important to the sugar industry (and not Brix) since it is the main component of table sugar. Hence, the bioethanol yields are slightly under-estimated because the calculation excludes other fermentable sugars (e.g. fructose and glucose). The equation used did not include the conversion factor from Brix to fermentable sugars of 0.85. Furthermore, a fermentation efficiency of 0.90 was selected (c.f. **Equation 31**).

Table 25 shows that the mean cane yield derived from 14 seasons (1998 to 2012) is 66.11 t ha^{-1}. The average sucrose content is 13.5% which provides a mean sucrose yield of 8.9 t ha^{-1}. The average bioethanol yield is 5 179 L ha^{-1} which is equivalent to an extraction rate of 78.4 litres of bioethanol per ton of cane. This agrees favourable with the value of 80 L t^{-1} given in the draft regulatory position paper (DoE, 2014).

Table 25 Comparison of the utilisable yield (stem, sugar & bioethanol) for sugarcane estimated for the past 14 seasons

Season	Fresh cane yield (t ha^{-1})	Sucrose content (%)	Sucrose yield (t ha^{-1})	Bioethanol yield (L ha^{-1})	Extraction rate (L t^{-1})
1998/99	72.48	13.36	9.68	5 626	77.6
1999/00	67.74	13.77	9.33	5 420	80.0
2000/01	73.95	13.08	9.67	5 620	76.0
2001/02	64.96	13.11	8.52	4 948	76.2
2002/03	71.64	13.71	9.82	5 706	79.7
2003/04	62.64	13.70	8.58	4 986	79.6
2004/05	60.43	13.52	8.17	4 747	78.6
2005/06	66.02	13.74	9.07	5 271	79.8
2006/07	66.36	12.92	8.57	4 981	75.1
2007/08	64.17	13.47	8.64	5 022	78.3
2008/09	67.00	13.69	9.17	5 329	79.5
2009/10	67.07	13.68	9.18	5 331	79.5
2010/11	59.08	14.14	8.35	4 854	82.2
2011/12	62.06	12.94	8.03	4 666	75.2
Average	**66.11**	**13.49**	**8.91**	**5 179**	**78.4**

3.7.1.3 Sugar content

The total Brix yield of crops containing sugar (e.g. sugarbeet and sweet sorghum) was determined in the ACCI laboratory at Ukulinga. One degree Brix (°Bx) is equivalent to 1 gram of sucrose in 100 grams of aqueous solution and gives an indication of the ratio of total soluble sugars to water in the sample. Hence, a 25°Bx sample contains 25 g of soluble sugar and 75 g of water. By definition, Brix values can also be reported as per cent values. The determination of Brix is based on a method used by the Eston Sugar Mill Laboratory (but excludes sucrose determination).

Brix determination should be conducted soon after the crop is harvested. To delay the reduction in sugar properties after harvesting, the samples were kept cool in fridges. The sample's Brix content was determined by chopping the sample into small pieces (approximately 1 cm long) using a chaff cutter, then mixed thoroughly and labelled. Then water (2 litres) was added to the chopped sample (1 kg) and mixed for twenty minutes in a specialised high speed blender called a cold digester. Thereafter, the mixture was sieved and filtered using filter paper and Celite powder to remove the fibre. Finally, the filtered liquid was then tested using a laboratory refractometer, which was calibrated using sucrose, to give a reading in degrees Brix.

Total soluble sugar content (%) can be determined from stalk or tuber Brix (%) using the Liu *et al*. (2008) method (**Equation 31**).

$$\text{sugar content (\%)} = 0.8111 * \text{Brix (\%)} - 0.3728 \qquad \textbf{Equation 31}$$

However, the Liu *et al*. (2008) equation should not be used to convert Brix into total sugar content because the formula only performs well for higher Brix values (and higher sucrose levels), but not for lower sucrose levels, which is the case for the Sugargraze variety of sweet sorghum.

3.7.1.4 Sugar degradation

The advantage of producing bioethanol from grain (sorghum or maize) is related to post-harvest logistics. McCorkle *et al*. (2007) reported that field trials in Texas, US (from 2001 to 2003) showed that silage production from sorghum required 40 to 53% less water than using maize. Sorghum grain is similar to maize grain and is usually dried to a moisture content of 10 to 12% (bulk density of 520 to 720 kg m^{-3}), which allows for efficient storage and transport (Turhollow *et al*., 2010). Sweet sorghum is similar to sugarcane in that the sugar stored in the stalk juice needs to be processed fairly rapidly because it degrades rapidly post-harvest. Reddy *et al*. (2007; 2008) showed that sugar yield (t ha^{-1}) decreased by 5.7 and 16.8% only one and two days after harvest, respectively.

Zegada-Lizarazu and Monti (2012) reported a sugar concentration of approximately 20°Bx containing 15% sucrose at the ripe stage for sweet sorghum. However, a delayed harvest can lead to reduced °Bx and stem sucrose content. Chopping of stalks into smaller stems does not reduce °Bx and sucrose up to 48 hours after harvesting. However, 50% of fermentable sugars are lost after one week of harvest in chopped material. In addition, sweet sorghum exhibits a narrow harvesting window of 20 to 40 days, which adds to the challenge of getting the feedstock to the processing plant with the maximum sugar content.

3.7.2 Bioethanol from starch

3.7.2.1 Biofuel yield

The following equation (**Equation 32**) was used to estimate theoretical bioethanol yield from starch-based feedstocks. It was derived by the Institution of Japan Energy in 2006 (cited by Zhao *et al*., 2009). This equation is based on 1 gram of starch being hydrolysed into 1.11 grams of glucose, with each gram of glucose generating 0.51 grams of bioethanol.

$$\textit{bioethanol yield (L ha}^{-1}\textit{)} = \textit{extractable starch content (\%)} * \textit{dry grain yield (t ha}^{-1}\textit{)} * 10 * 1.11 * 0.511 * FE / 0.79 \qquad \textbf{Equation 32}$$

In the above equation, it is important to take into account the moisture content on the grain product. The moisture content is determined using an oven-dried method (72 hours at 103°C). Hence, the dry grain mass must be adjusted to remove the mass of water before the conversion to bioethanol takes place. This is achieved using this simple equation:

$$\textit{dry grain yield (t ha}^{-1}\textit{)} = \textit{dry grain yield (t ha}^{-1}\textit{)} - [\textit{dry grain yield (t ha}^{-1}\textit{)} * \textit{moisture content (\% w/w)} / 100] \qquad \textbf{Equation 33}$$

Starch can be hydrolysed by enzymes to produce the monomeric sugar glucose, which is readily metabolised by the yeast to produce bioethanol. Using the average starch content of each grain crop, the theoretical bioethanol yield can be determined by considering that 1 g of starch produces 1.11 g of glucose (via hydrolysis) and 0.511 g of bioethanol is produced per g of glucose. Finally, 1 g of bioethanol is equivalent to 1.266 mL of bioethanol. Hence, the theoretical bioethanol yield of grain crops is given in **Table 26**.

Table 26 Theoretical bioethanol yield of certain grain crops (Drapcho *et al*., 2008)

Grain crop	Average starch (%)	Starch range (%)	Theoretical bioethanol yield (mL g^{-1} or L kg^{-1})
Maize	72	65-76	0.52
Wheat	77	66-82	0.55
Barley	57	55-74	0.41
Sorghum	72	68-80	0.52
Oat	58	45-69	0.42
Rice	79	74-85	0.57

The theoretical bioethanol yield given in **Table 26** does not take into account any conversion efficiencies (e.g. fermentation efficiency) associated with the industrial processes used. Excluding the food *vs*. fuel debate (i.e. food security concerns), the table shows that rice and wheat exhibit the highest bioethanol yield. This information also highlights the sensitivity of bioethanol yield to starch content.

3.7.2.2 Fermentation efficiency

In this study, a value of 0.909 was used for the fermentation efficiency (FE). Görgens (2013) indicated that the FE ranges from 90 to 95% (when compared to the theoretical maximum, which can be achieved under industrial conditions). Grain samples from the 2012/13 trials at Ukulinga and Hatfield as well as the 2013/14 trial at Ukulinga, were sent to Stellenbosch University for analysis (**Table 29**). The average bioethanol produced was 90.9% of the theoretical value, which represented an average of nine samples (six in 2012/13 & three in 2013/14). The analysis used the Simultaneous Saccharification and Fermentation (SSF) process to convert starch to bioethanol. The FE value of 0.91 is similar to barley as shown by the following study.

Banerjee and Kundu (2013) determined the fermentation efficiency of two different processes used to convert starch to bioethanol for three feedstocks, *viz.* rice, potato & barley (**Table 27**). Samples were dry milled in a laboratory to duplicate a typical hammer mill in which the grain is ground down so that 60 to 90% has a particle size of 250-350 µm. The ground samples were then mixed with water to form a mash, which is then treated with enzymes to convert the liquefied starch to a pre-saccharified state. The mash was then fermented using yeast without stopping the enzymatic action. Thus, the simultaneous enzymatic saccharification and fermentation (SSF) action yielded slightly more sugar and subsequently more bioethanol. This process was compared to the traditional method of allowing the enzymatic process to first complete, before the slurry is fermented to produce alcohol (i.e. Individual Saccharification and Fermentation or ISF).

Table 27 Efficiency of the Individual (ISF) *vs.* Simultaneous (SSF) Saccharification and Fermentation process used to convert starch to bioethanol (Banerjee and Kundu, 2013)

Feedstock	Fermentation efficiency (%)	
	ISF	SSF
Potato	94.5	96.0
Rice	91.7	93.9
Barely	89.8	91.2

Figures for starch content and expected bioethanol yield were also provided by Banerjee and Kundu (2013) in **Table 28**. These expected bioethanol yields appear to consider the fermentation efficiency associated with the technology used to convert starch into bioethanol. This highlights the range in starch contents and bioethanol yields reported in the available literature. Where possible, locally derived starch contents for a particular crop variety should be used in the equation presented above.

Table 28 Overview of starch content and expected bioethanol yield for various grain feedstocks (Banerjee and Kundu, 2013)

Grain crop	Starch range (%)	Expected bioethanol yield (mL g^{-1} or L kg^{-1})
Maize	60-63	0.38-0.40
Wheat	58-62	0.36-0.39
Barley	54-65	0.34-0.41
Sorghum	55-65	0.36-0.42
Triticale	63-69	0.40-0.44
Rye	55-62	0.35-0.37

3.7.2.3 Starch content

A review of the literature revealed that Adetunji and Taylor (2012) developed a database on the quality attributes of improved sorghum varieties and cultivars, in order to boost sorghum utilisation in South Africa. This database was obtained from the International Sorghum and Millet Collaborative Research Support Program (INTSORMIL) website (http://intsormil.org/). The database provided a grain extract content (measure of grain starch content and availability as % dry basis) of 74.2% for PAN8816 (Chiremba, 2010). Wang *et al*. (2009) reported a sorghum starch content range of 64 to 74% (grain dry mass). Since grains with higher starch content should produce higher bioethanol yields (Wang *et al*., 2009), grain starch content should be measured.

Görgens (2013) warned of the inaccuracy associated with using a theoretical yield equation, compared to a laboratory study. He added that a relatively simple method exists for conducting laboratory-scale fermentations for grain starch. Unfortunately, ACCI does not have the laboratory equipment to measure extractable starch content. However, grain starch content can be measured by a number of laboratories in the country (e.g. Stellenbosch University; SA Grains in Pretoria). Grain samples from the 2012/13 trials at Ukulinga and Hatfield were sent to Stellenbosch University for analysis. The analysis was repeated for the 2013/14 Ukulinga trial. The actual fermentable starch contents are shown in **Table 29** below.

Table 29 Total and extractable starch content (%) of grain sorghum (PAN8816) samples

Site	Sample	Year	Total starch (%)	Extractable starch (%)	Fermentation efficiency
Ukulinga	1	2012/13	66.1	64.8	0.906
	2	2012/13	66.5	66.5	0.898
	3	2012/13	65.9	64.3	0.917
		Average	**66.2**	**65.2**	**0.907**
Hatfield	1	2012/13	71.2	69.5	0.919
	2	2012/13	71.3	70.2	0.913
	3	2012/13	68.8	68.4	0.913
		Average	**70.4**	**69.4**	**0.915**
Ukulinga	1	2013/14	63.5	61.9	0.897
	2	2013/14	62.6	63.8	0.901
	3	2013/14	65.4	61.8	0.915
		Average	**63.8**	**62.5**	**0.904**

According to the South African Grain Laboratory, the 10-year weighted average[13] for white and yellow maize is 72.0 and 72.6% respectively (**Table 30**). In general, yellow maize has a higher starch content than white maize. The starch content of South Africa's maize crop varies seasonally with the average starch content of yellow maize decreasing from 74.2% in 2010/11 to 73.0% 2011/12. The average starch content of 72.6% for yellow maize was converted to extractable starch content using a factor of 0.926. Patzek (2006) determined the mean starch content of 71.46% and mean extractable starch of 66.18% from over 700 samples of maize analysed (i.e. 66.18/71.46 = 0.926).

Table 30 Comparison of the utilisable yield (grain, starch & bioethanol) for yellow maize estimated for the past five seasons, assuming a moisture content of 12.5% and a fermentation efficiency of 90.4%

Season	Grain Yield ($t\ ha^{-1}$)	Grain starch (%)	Extractable starch (%)	Starch Yield ($t\ ha^{-1}$)	Bioethanol Yield ($L\ ha^{-1}$)	Extraction rate ($L\ t^{-1}$)
2002/03		72.0	66.7			
2003/04		71.1	65.8			
2004/05		71.7	66.4			
2005/06		71.5	66.2			
2006/07		73.3	67.9			
2007/08	3.03	72.3	67.0	1.78	1 159	382.4
2008/09	4.92	73.2	67.8	2.92	1 905	387.1
2009/10	5.62	73.4	68.0	3.34	2 182	388.2
2010/11	4.87	74.2	68.7	2.93	1 911	392.4
2011/12*	4.70	73.0	67.6	2.78	1 815	386.1
Average	**4.63**	**72.6**	**67.2**	**2.75**	**1 794**	**387.2**

*Estimated and not actual figures

[13] http://www.sagl.co.za/Portals/0/Maize%20Crop%202011%202012/Page%2049.pdf

According to Patzek (2006), total starch content can be used to estimate bioethanol yield for processing plants using the dry grind process. However, for those using wet milling, extractable starch should be used. Extractable starch is therefore the amount of starch that can be expected to be recovered in a wet milling operation. This value is lower than the starch content and is affected by grain variety, environmental conditions and management practices (e.g. nitrogen application rate).

3.7.3 Biodiesel from bio-oil

3.7.3.1 Biofuel yield

The following equation (**Equation 34**) was used to determine the theoretical biodiesel yield from oilseed crops. The equation assumes that all of the bio-oil can be extracted from the seed (i.e. the equation provides the theoretical biodiesel yield).

$$\textit{biodiesel yield } (L\ ha^{-1}) = \textit{bio-oil content } (\%) * \textit{dry seed yield } (t\ ha^{-1}) * 10 * 0.95 / 0.92 \qquad \textbf{Equation 34}$$

The conversion efficiency was assumed to be 95% (Nolte, 2007), but it depends on the process used to convert the bio-oil into biodiesel (Achten *et al*., 2008):

- homogeneous alkali catalysed alcoholysis.
- enzymatic catalysed alcoholysis (60-70% efficiency) and
- supercritical alcoholysis (90% efficiency).

The density of oil also varies amongst feedstocks. The value of 0.92 kg L^{-1} is typical for soybean, canola, sunflower and Jatropha. However, the density of *Moringa oleifera* oil is 0.90 g cm^{-3} or (0.90 kg L^{-1} 0.90 g ml^{-1}) which is equivalent to 1.111 L kg^{-1} (Atabani *et al*., 2013).

The recoverable oil fraction is clearly affected by the pressing technology used. For hand powered small scale pressing, about 60% of the total oil is extractable. With mechanised pressing equipment, about 75% of the oil can be recovered. Commercially available pressing systems used for large-scale crushing can reach up to 90%. Industrial extraction with organic solvents (mainly hexane) yield near 100% of the oil content (Jongschaap *et al*., 2007). According to Jongschaap *et al*. (2007), an extraction efficiency of 75% is normally used for Jatropha oil. Similarly, Sparks (2010) stated that the 6% of the oil remains in soybean oilcake (i.e. 94% extraction efficiency).

3.7.3.2 Bio-oil content

The bio-oil content was not measured in this study, except for Moringa. Hence, typical values were obtained from the literature. The oil contents adopted in this study are as follows:

- canola: 40% (Fouché, 2015),
- sunflower: 38% (Nolte, 2007),
- soybean: 18% (Nolte, 2007),
- Jatropha: 35% (Jongschaap *et al*., 2009; Atabani *et al*. (2013), and
- Moringa: 31% (measured).

The seed oil content for Moringa was determined using two soxhlet solvent extractors. Hexane was used as solvent to extract the oil. Seed samples were weighed, ground and placed in Whatman single-thickness cellulose extraction thimbles of the soxhlet. The soxhlet system was run for 24 hours. The solvent was then removed through evaporation and the residual oil weighed. The oil content was then calculated as a percentage of the initial seed weight prior to extraction. Oil extraction results showed that that Moringa seeds contained about 31% oil by mass for the irrigated and dryland treatments. This was lower than previous reported results of 35 to 41% (Rashid *et al*., 2008; Da Silva *et al*., 2010; Abdulkareem *et al*., 2011).

The average soybean oil content was extracted from the Protein Research Foundation's website, based on results obtained from the annual Super Soya competition in KwaZulu-Natal (**Table 31**). No oil content (only protein level) was available prior to the 2008/09 season. Based on these values, the average soybean oil content is approximately 20%, slightly higher than the 18% assumed in this study.

Table 31 Oil content of soybean obtained from the annual Super Soya competition in KwaZulu-Natal (Source: http://www.proteinresearch.net/)

Year (Region)	Soybean oil content (%)	
	Range	Average
2008/09 (S-KZN)	20.5-22.3	21.3
2008/09 (N-KZN)	13.2-28.1	20.8
2007/08 (S-KZN)	19.7-23.2	21.3
2008/09 (N-KZN)	18.3-22.7	20.5

3.7.4 Extraction rates

The draft national biofuels strategy (DME, 2006a; 2006b) reported that a ton of sugarcane (fresh mass), maize (dry mass) and soybean (dry mass) can produce 81, 402 and 171 litres of biofuel respectively. Similarly, Meyer *et al.* (2008) reported comparable figures of 78, 402 and 194 litres of biofuel per ton of sugarcane, maize and soybean respectively. A literature review produced a range of biofuel extraction rates for various feedstocks as shown in **Table 32**. It is important to note that the extraction rates for starch-based crops (e.g. grain sorghum & maize) are higher than values given in the literature because the moisture content of the crop was not considered.

It is important to note that biofuel extraction rates are continuously improving with time. Goldemberg (2008) estimated that within a five-year period (2000 to 2004), the bioethanol yield in Brazil increased from 2 000 to 5 917 litres per hectare of sugarcane grown. This improvement was mainly attributable to new advanced hybrids and genetically modified sugarcane, new cultivation techniques as well as new bio-refinery technologies. Hence, the conversion ratios mentioned above are dependent on the technology used to produce the biofuel and therefore "improve" with time.

Table 32 Biofuel production in m^3 (and litres) per ton of crop yield

Feedstock	**Extraction rates for fresh yields**		**Source**
	(m^3 t^{-1})	**(L t^{-1})**	
Sugarcane	0.081	81.4	(DME, 2006a)
	0.078	78.0	Meyer *et al.* (2008)
	0.068	68.0	Garoma *et al*. (2011)
	0.080	80.0	DoE (2014)
	0.078	78.4	Theoretical biofuel equation
Sugarbeet	0.074	75.0	Maclachlan (2012)
	0.084	83.5	Theoretical biofuel equation
Sweet sorghum	0.074	74	Smith and Frederiksen (2000)
	0.069	69	Prasad *et al*. (2007)
	0.054	54.4	Almodares and Hadi (2009)
	0.060	59.7	Theoretical biofuel equation
Cassava	0.170	170	Duke (1983)
	0.070-0.110	70-110	Asiedu (1989)
	0.150-0.200	150-200	Wang (2002)
	0.100-0.150	100-150	Phillips *et al*. (2004)
	0.100	100	Adeoti (2010)
Feedstock	**Extraction rates for dry yields**		**Source**
Grain sorghum	0.380	380	Du Preez *et al*. (1985)
	0.372	372	Smith and Frederiksen (2000)
	0.370	370	BFAP (2008)
	0.400	400	Lemmer and Schoeman (2011)
	0.417	417	Kotze (2012b)
	0.417	416.7	DoE (2014)
	0.384	383.6	Theoretical biofuel equation
Maize	0.402	402.3	DME (2006a)
	0.387	387	Smith and Frederiksen (2000)
	0.402	402	Meyer *et al.* (2008)
	0.373-0.417	372.6-417.3	Drapcho *et al*. (2008)
	0.360	360	Garoma *et al*. (2011)
	0.436	435.8	Theoretical biofuel equation
Soybean	0.171	171.4	DME (2006a)
	0.194	194.0	Meyer *et al.* (2008)
	0.212	211.8	GAIN (2009)
	0.185	185.2	DoE (2014)
	0.154	185.9	Theoretical biofuel equation
Sunflower	0.398	398	Meyer *et al.* (2008)
	0.392	392.4	Theoretical biofuel equation
Canola	0.413	0.413	Theoretical biofuel equation
Jatropha	0.380	380.4	Jongschaap *et al.* (2009)
	0.361	361.4	Theoretical biofuel equation
Moringa	0.327	327.2	Theoretical biofuel equation

4 PARAMETERS USED FOR MODELLING

This chapter provides a description of the parameters required by the hydrological and crop models used in this study. A summarised version of the parameter values is provided in **Volume 1**. This section therefore pertains to **AIM 4** and **AIM 5** of this project's terms of reference.

4.1 Introduction

Taylor *et al.* (2008) reviewed a number of models designed to estimate crop water use. Their findings showed that a number of parameters and variables are common to these different models. For example, the crop coefficient (or crop factor) is required by the *SAPWAT*, *SWB* and *ACRU* models. Variables describing the water holding capacity of the soil (e.g. soil texture and depth) are also common. Pereira *et al*. (2006) stated that if soil water is not limiting, transpiration will largely be governed by the leaf area. Hence, a number of models require information on leaf area index. In the following sections, these parameters and variables are described in more detail.

4.2 Water Use Parameters (*ACRU*)

Hydrological models such as *ACRU* require various input parameters and variables which are used to represent sub-catchment physiographic conditions as well as certain characteristics of the land use under consideration. A *parameter* is considered as any input where only one value represents the sub-catchment, whereas a *variable* has more than one value.

4.2.1 Background

4.2.1.1 Rainfall/runoff response

Schulze and Horan (2011) noted that runoff response is most sensitive to rainfall, reference evaporation and certain soil characteristics. Thus, key parameters and variables that influence runoff generation in *ACRU* are shown in **Table 33**.

Table 33 Key parameters and variables in *ACRU* that influence rainfall/runoff response

Variable	**Definition**
CORPPT	Monthly precipitation adjustment factors (e.g. to account for differences in monthly rainfall between the selected driver station and spatially averaged estimates for the sub-catchment).
CORPAN	Monthly APAN adjustment factors (e.g. to adjust Penman-Monteith evaporation estimates to APAN equivalent evaporation).
EFRDEP	Effective soil depth for colonisation by plant roots.
SMDDEP	Effective soil depth from which storm flow generation takes place (set to topsoil depth).
QFRESP	Storm flow response fraction for the catchment (set to 0.30).
COFRU	Base flow recession constant (set to 0.009).

Mean annual runoff estimates are extremely sensitive to rainfall input, especially in high intensity rainfall areas (Schulze, 1995). Therefore, it cannot be over-emphasised that great care must be taken when deriving the monthly adjustment factors (i.e. *CORPPT* variable). These factors are applied to point rainfall data (observed at a rainfall recording station) to improve its representativeness of “average” catchment conditions (Schulze, 1995).

If *CORPPT* > 1, it indicates that the sub-catchment’s rainfall is higher than the station’s rainfall. Similarly, *CORPPT* < 1 suggests that the sub-catchment’s rainfall is consistently lower than that of the driver rainfall station. Similarly, the *SMDDEP* parameter also exhibited extreme sensitivity in areas with shallow soils and high rainfall intensities.

Monthly *CORPAN* factors are necessary since *ACRU* is an APAN driven agrohydrological model, despite the fact that FAO56 (i.e. the Penman-Monteith) has become the *de facto* reference evaporation since 1998. Furthermore, Schulze (1995) suggested that when in doubt, CAY values should be over-estimated rather than under-estimated.

The effective rooting depth (*EFRDEP*) is used to determine the thickness of soil which is "active" in the soil water budget as well as the maximum depth that roots can "extract" water. It is assumed to be the total soil depth (i.e. sum of depth of A- and B-horizon depths), with no impeding layer which restricts root growth (e.g. stone lines, plough or hard pans).

The effective soil depth which is considered to be contributing to storm flow generation is specified by the parameter *SMDDEP* in *ACRU*. This depth accounts for the different dominant runoff producing mechanisms which may vary in different climates, as well as with land use, tillage practice, litter/mulch cover and soil conditions.

4.2.1.2 Land cover/use

Land cover and land use affect hydrological responses through canopy and litter interception, infiltration of rainfall into the soil and the rates of soil water evaporation and transpiration from the vegetation layer. The key parameters and variables that account for land cover/use are shown in **Table 34**. *CONST, COIAM, CAY (or ELAIM), VEGINT* and *ROOTA* should be the minimum set of parameters specified for each land use type.

For most situations, Schulze (1995) recommends that transpiration and soil water evaporation are calculated as separate components (i.e. *EVTR* = 2). Variables such as *PCSUCO* and *COLON* are only valid when *EVTR* = 2. This means that soil water evaporation is higher for *EVTR = 1* as there is no suppression due to the presence of a soil cover (i.e. crop residue). However, transpiration should be lower when *EVTR = 1*, but overall, *AET* should be similar for both *EVTR* values.

In *ACRU*, the variable *COIAM* takes cognisance of surface roughness (e.g. after ploughing) and initial infiltration before storm flow commences. Higher values of *COIAM* under forests, for example, reflect enhanced infiltration while lower values on grassland in summer months are the result of higher rainfall intensities (and consequent lower initial infiltrations) experienced during the thunderstorm season.

Table 34 Key parameters and variables in *ACRU* that account for land cover/use

Variable	Definition
FOREST	Option to simulate enhanced canopy evaporation above forest canopies.
EVTR	Option for estimation of total evaporation as an entity or by soil water evaporation and plant transpiration computed separately.
CONST	Fraction of plant available water at which plant stress sets in. The plant's physiological characteristics determine the onset of wilting in response to drier soil conditions.
COIAM	The coefficient of the initial abstraction, which accounts for vegetation, soil surface and climate influences on storm flow generation. This monthly coefficient is used to estimate the rainfall abstracted by interception, surface storage and infiltration before storm flow commences.
CAY	A monthly consumptive water use (or "crop") coefficient, which reflects the ratio of water use by vegetation under conditions of freely available soil water to the evaporation from a reference surface (e.g. APAN equivalent).
ELAIM	Monthly leaf area index (LAI) values. Can be used to calculate monthly interception losses and/or determine the crop's consumptive water use.
VEGINT	Monthly interception loss values, which can change during a plant's annual growth cycle. They estimate the magnitude of rainfall that is intercepted by the plant's canopy on a rainy day.
ROOTA	The fraction of plant roots that are active in extracting soil moisture from the A-horizon in a given month. This fraction is linked to root growth patterns during a year and periods of senescence brought on, for example, by a lack of soil moisture or by frost.
COLON	Extent of colonisation of plant roots if the B-horizon. Determines the amount of water that may be extracted by the plant from the B-Horizon. Hence, this variable reflects the extent to which the subsoil is "colonised" by roots. Total evaporation from the B-horizon is suppressed by the fraction *COLON*/100. Default in *ACRU*: 100%.
PCSUCO	The fraction (expressed as a %) of the soil surface covered by a mulch or litter layer. This layer suppresses soil water evaporation. However, 20% of the soil water evaporation still takes place with 100% cover. Default in *ACRU*: 0%.

While the living roots of a crop can withdraw water from the soil profile, the majority of water uptake occurs where the density of roots is greatest. Where root concentrations are high, the water held in the soil can be removed more easily and at a faster rate than it can where root concentrations are low (Schulze, 1995). Information on rooting distribution is provided using two variables in *ACRU*, *viz*. *ROOTA* and *COLON*. The values used to assess the water use of various biofuel feedstocks is presented in the sections that follow.

4.2.2 Rainfall/runoff

In this section, a new method is proposed to estimate A-pan equivalent evaporation. The method is called the *PENPAN* equation, which was originally developed by Linacre (1994). Evaporimeters are mainly used to determine the effect of climate on the evaporation from open water surfaces such as dams and lakes. According to Allen *et al.* (1998), pans integrate the effect of radiation, temperature, humidity and wind on free water evaporation.

The authors recommended that evaporimeters should be installed inside a short green cropped area that is at least 15 by 15 m in size. The pan should not be installed in the centre, rather at a distance of at least 10 m from the green crop edge in the general upwind direction.

4.2.2.1 The need for pan coefficients

Pan coefficients are influenced by the pan's geometry. In *ACRU*, the Class A evaporimeter (or A-pan) is used to drive various evaporation processes in the hydrological cycle. This pan is commonly used in South Africa and is different to the micro-pans used mainly in China. McVicar *et al*. (2007, p. 209) showed that pan coefficients derived for Chinese micro-pans are lower than Class A-pan coefficients, but with a seasonal range being similar to that of an A-pan.

Pans have also been used to estimate the evaporation loss from vegetated surfaces. For example, pan coefficients ($K_p = ET_o/E_p$) allow evaporation from pans (E_p) to be used for estimating reference crop evaporation (ET_o) for periods of 10 days or longer (but preferably every 30 days, i.e. monthly). Although evaporation from a vegetated surface is largely governed by the same climatic factors affecting open water (and pan) evaporation, several factors explain why K_p values are not unity (i.e. 1). For a 10 m fetch of short green crop, Allen *et al*. (1998) provided pan coefficients which ranged from 0.45 to 0.85. K_p increases with rising humidity values and decreasing wind speeds (i.e. K_p was highest at high humidity and low wind speed). K_p also increases with increasing green fetch distance, especially at low humidity levels. If the pan is surrounded by dry fallow conditions, K_p varied from 0.45 to 0.85 for a 10 m dry fetch. K_p was also highest at high humidity and low wind speed. However, K_p decreased with increasing dry fetch distance.

In *ACRU*, the reciprocal of the pan coefficient (i.e. E_p/ET_o) is used to adjust Penman-Monteith reference crop evaporation estimates (ET_o) to A-pan equivalent values (E_p), since the model is driven by the latter (and now outdated) evaporation reference. This adjustment varies monthly (usually higher in winter) and spatially. For a 10 m fetch, typical *CORPAN* values would range from 1.18 to 2.22. In general, K_p < 1 and *CORPAN* > 1, indicating evaporation rates from a vegetated surface are less than that from pans.

Owing to the uncertainty regarding pan coefficient calculations, a possible solution is to adopt an "average" *CORPAN* value (e.g. 1.15 or 1.20) for all months and all locations. However, a review of pan coefficients in the literature (e.g. McVicar *et al*., 2007; McMahon *et al*., 2013) revealed that values vary both spatially and seasonally. Pan coefficients are particularly sensitive to the microclimate and in particular the wind speed and humidity level. As noted earlier, the geometry of the pan also affects the coefficient. Hence, locally calibrated pan coefficients are preferred, but unfortunately, beyond the scope of this study.

4.2.2.2 Previous *CORPAN* values

Various techniques have been published in the literature to determine pan coefficients (K_p). For example, Cuenca (1989) and Snyder (1992) proposed empirical equations which use mean daily wind speed relative humidity as well as upwind fetch to estimate K_p. Allen *et al*. (1998) provided similar regression equations to estimate K_p from wind speed, relative humidity and fetch distance, for both a green and dry fetch. These equations were programmed and tested against Example 22 given on page 86 of Allen *et al*. (1998).

Equation 35 produces a K_p value of 0.83 for a green fetch distance (*FD*) of 1 000 m, a wind speed (u) of 1.9 m s^{-1} and mean RH (RH_{ave}). Thus, the corresponding *CORPAN* value required by the *ACRU* model is 1.20 (i.e. 1/0.83).

$$K_p = 0.108 - 0.0286u + 0.0422\ln(FD) + 0.1434\ln(RH_{ave}) - 0.000631[\ln(FD)]^2 \cdot \ln(RH_{ave}) \qquad \textbf{Equation 35}$$

Assuming a fetch of 200 m for a typical A-pan in South Africa (Schulze, *pers. comm.*), values of E_p/ET_o (i.e. $1/K_p$) were estimated for each quinary sub-catchment using the revised temperature and evaporation database. The results in **Table 35** show higher *CORPAN* values for a dry fetch, due to the greater evaporative demand of the drier, hotter air moving over the pan's water surface. The range in monthly values is also higher for the dry fetch, compared to that of the green fetch. As noted earlier, there is a slight increase in *CORPAN* values in winter (April - September) compared to summer.

Table 35 Monthly *CORPAN* values ($1/K_p$) calculated for each of the 5 838 quinary sub-catchments assuming a green and dry fetch of 200 m and no bird screen

Month	**Green fetch of 200 m**		**Dry fetch of 200 m**	
	Range	**Mean**	**Range**	**Mean**
January	1.18-1.38	1.25	1.42-1.90	1.61
February	1.18-1.38	1.24	1.42-1.91	1.61
March	1.18-1.34	1.24	1.43-1.83	1.60
April	1.19-1.33	1.25	1.44-1.81	1.62
May	1.19-1.32	1.25	1.45-1.79	1.64
June	1.19-1.39	1.26	1.45-1.93	1.66
July	1.19-1.38	1.26	1.45-1.91	1.65
August	1.19-1.36	1.27	1.45-1.88	1.67
September	1.19-1.38	1.27	1.44-1.90	1.68
October	1.19-1.36	1.26	1.43-1.87	1.65
November	1.18-1.39	1.26	1.43-1.92	1.65
December	1.18-1.38	1.25	1.43-1.90	1.63

In previous studies, a decision was made to adopt the more conservative *CORPAN* values derived for a green fetch. Although a green fetch of 1 000 m produces lower *CORPAN* values (e.g. range = 1.17 to 1.34; mean = 1.23 for November), this fetch buffer was considered unrealistic for A-pans in South Africa. The histogram of monthly *CORPAN* values across all quinary sub-catchments calculated for a green fetch of 200 m shows that 79.9% of values range from 1.23 to 1.29 (**Table 110** in **APPENDIX M**). However, 15.4% of all monthly *CORPAN* values exceed 1.29.

An alternative method was sought to estimate *CORPAN* values in order to verify the range observed in the above table. Snyder *et al.* (2005) also developed a set of empirical equations relating unscreened Class A-pan evaporating to reference crop evaporation, using the upwind grass fetch. According to Snyder *et al.* (2005), the method is suitable for semi-arid conditions and would require calibration for humid or windier climates. For this reason, the technique was not considered in this study.

Linacre (1994) developed an equation to provide A-pan equivalent evaporation by modifying an equation he developed in 1993 (Linacre, 1993) for open water evaporation. This equation is termed the *PENPAN* equation and is discussed next.

4.2.2.3 Linacre's *PENPAN* equation

Linacre developed an equation to estimate open water evaporation, which was based on the original Penman (1948) equation. In other words, Linacre made a number of assumptions in order to simplify the Penman equation. For example, Penman's net energy term (R_n) was simplified to ($0.80 \cdot R_s$ - 40) W m^{-2} which is based on a lake albedo (α) of about 0.07. Linacre assumed a constant net longwave radiation loss (R_{nl}) of 40 W m^{-2}. The aerodynamic term accounts for the transfer of heat from the evaporating surface to the overlying atmosphere. Linacre (1993) simplified this term to $2.5 \cdot F \cdot u(T - T_d)$, where F is calculated as ($1.0 - z \cdot 8.7/10^5$), u is the mean wind speed at height 2 m in m s^{-1}. Furthermore, ($T - T_d$) is the difference between mean air temperature (T) and the dew point temperature (T_d). At higher altitudes, the thinner air results in less advective heat transfer. This is taken into consideration using F, which proportionally decreases the air density (ρ) with elevation (z in metres). Finally, Linacre's (1993) equation to estimate open water evaporation is given as:

$$E_{dam} = (0.015 + 0.00042T + z/10^6)[0.8R_s - 40 + 2.5F \cdot u(T - T_d)]$$ **Equation 36**

with temperatures (T, T_d) in °C, F derived from elevation (z) in meters, incoming solar radiation (R_s) in W m^{-2} and wind speed (u) in m s^{-1}, to give evaporation estimates in mm day^{-1}. Linacre also developed an equation to estimate ($T - T_d$) from daily temperature extremes, which he used to simplify the calculation of the vapour pressure deficit (D).

Linacre then modified the above equation to give A-pan equivalent evaporation, which involved taking into consideration the geometry of the circular pan since it affects both solar irradiance and advective heat transfer. For example, the energy term (R_n) was simplified to ($0.71R_s$ - 40) W m^{-2} which is based on a water albedo (α) of about 0.14. This term was derived as the available energy "halfway" between the respective values for water ($0.8R_s$ - 40) and green vegetation ($0.63R_s$ - 40), with the latter derived for an albedo of 0.22 representing short grass.

Assuming an advective heat transfer of $2.5u$ (taken from **Equation 36**), Linacre (1994) combined this with a convective heat transfer coefficient (h) of $4 \cdot u$ W m^{-2} to estimate an effective coefficient for the entire pan as $5.9u$ W m^{-2}. This was calculated from $[(1.15 \cdot 2.5) + (0.97 \cdot 4)u]/1.15$ which takes into account the pan's geometry. The US Class A-pan is 1.21 m in diameter and a wall height of 255 mm, which equates to a water surface area of 1.15 m^2 and an outside area of is 0.97 m^2. Finally, Linacre's (1993) equation to estimate A-pan equivalent evaporation is given as:

$$E_{pan} = [0.71R_s - 40 + 5.9F \cdot u(T - T_d)] / (28.4 + 68.2 \cdot \gamma/\Delta)$$ **Equation 37**

with temperatures (T, T_d) in °C, F derived from elevation (z) in meters, incoming solar radiation (R_s) in W m^{-2} and wind speed (u) in m s^{-1}, to give pan evaporation estimates in mm day^{-1}. In the above equation, ($0.71R_s$ - 40) represents the net energy available at the pan's evaporating surface. However, Linacre (1994) argued that this term must accommodate the additional energy (i.e. heat) which is transferred through the pan's outer wall.

4.2.2.4 Outgoing longwave radiation

Linacre assumed a constant net longwave radiation loss (R_{nl}) of 40 W m^{-2} (or 3.46 MJ m^{-2} day^{-1}) when estimating the evaporative loss from an A-pan. The daily net longwave radiation values (R_{nl}) calculated for each month across all quinaries are given in **Table 36**. The monthly means are higher in winter than compared to summer. This is expected in the summer rainfall regions of South Africa, since there is less cloud cover during the winter months. However, the mean values are above 3.46 MJ m^{-2} day^{-1}, which indicates that Linacre's simplification of the net radiation term results in slighter higher evaporation estimates (and higher *CORPAN* factors, particularly in the winter months).

Table 36 Daily net longwave radiation (R_{nl}) calculated monthly for each of the 5 838 quinary sub-catchments using Equation 39 of Allen *et al*. (1998; p 52)

Month	**Daily net longwave radiation (MJ m^{-2} day^{-1})**	
	Range	**Mean**
January	0.50 - 7.26	3.98
February	0.38 - 7.09	3.93
March	0.60 - 6.31	4.07
April	0.82 - 6.23	4.42
May	1.34 - 6.71	4.86
June	1.67 - 7.71	5.34
July	1.81 - 7.82	5.10
August	1.60 - 7.34	4.88
September	0.94 - 7.23	4.69
October	0.61 - 6.56	4.07
November	0.59 - 7.00	4.05
December	0.55 - 6.99	4.41

The histogram of R_{nl} values across all quinary sub-catchments is given in **Table 37**. The results show that there are no negative net longwave radiation values as this was corrected (c.f. **Section 5.5.2.3**).

Table 37 Histogram of daily net longwave radiation (R_{nl}) across all 5 838 quinaries

R_{nl}	**Count**	**% of total**	**Accum. %**
< 0.00	0	0.00	0.00
0.00 - 1.00	90	0.13	0.13
1.00 - 2.00	815	1.16	1.29
2.00 - 3.00	4525	6.46	7.75
3.00 - 4.00	17254	24.63	32.38
4.00 - 5.00	24431	34.87	67.25
5.00 - 6.00	18548	26.48	93.73
6.00 - 7.00	3913	5.59	99.31
7.00 - 8.00	480	0.69	100.00
> 8.00	0	0.00	100.00
Total	**70 056**	**100.00**	

The distribution is bell-shaped with the majority (86%) of values between 3 and 6 MJ m^{-2} day^{-1}. This highlights Linacre's average value of 3.46 MJ m^{-2} day^{-1} is a good approximation for only 24.6% of all quinary sub-catchments. Based on these results, the decision to ignore the "default" value of 40 W m^{-2} and replace it with calculated R_{nl} values is well justified.

Based on the above analysis, a decision was made to ignore the "default" value of 40 W m^{-2} in **Equation 37** and replace it with calculated values. Rotstayn *et al*. (2006) also ignored Linacre's (1994) assumption of a fixed value for net longwave radiation irradiance, arguing it "seems too inflexible for climate-change studies". Hence, Linacre's equation for an A-pan is re-written as:

$$E_{pan} = [0.71R_s - R_{nl} + 5.9F \cdot u(T - T_d)] / (28.4 + 68.2 \cdot \gamma/\Delta)$$ **Equation 38**

4.2.2.5 Augmentation of incoming solar radiation

There are two main sources of heat absorption through the pan's outer wall, namely via advection from the wind and from incoming solar radiation. This regard to the latter, there are four factors to consider:

- exposure of the wall to direct sunshine,
- diffuse radiation from the sky onto the wall,
- solar radiation reflected onto the wall from the ground below, and
- longwave radiation from the surroundings.

In order to estimate the contribution of direct radiation, Linacre (1994) developed a pan radiation factor (*P*) as a function of latitude (*A* in degrees decimal) such that:

$$P = 1.32 + A \cdot 4 / 10^4 + A^2 \cdot 8/10^5$$ **Equation 39**

The fraction of R_s that is direct depends on the cloudiness *C*. Linacre (1994) assumed that *F* was proportional to the fraction of the sky that is not covered by cloud, e.g. $0.9(1 - C/8)$. From Linacre (1993), *C* is defined as the average number of eighths of the sky occupied by cloud at the time of observation (called oktas), which can be estimated from $C = (0.85 - R_s / R_a)/0.047$. Combining these two equations produces:

$$F = -1.14 + 2.39 \cdot R_s / R_a$$ **Equation 40**

which does not match that given by Linacre (1994) as $(-1.5 + 2 \cdot R_s / R_a)$. The range in R_s / R_a from 0.47 (C=8) to 0.85 (C=0) is wider than that suggested by Allen *et al*. (1998) of 0.25 to 0.75. In this study, the lower limit of R_s / R_a was set to 0.23, which means the above equation produces a negative *F* value, which is meaningless. It was therefore decided to replace Linacre's equation with one used by McMahon *et al*. (2013) and Rotstayn *et al.* (2006) as follows:

$$F = -0.11 + 1.31 \cdot R_s / R_a$$ **Equation 41**

where *F* ranges from 0.22 to 0.87 for $0.23 \leq R_s / R_a \leq 0.75$. Linacre (1994) stated that the pan's outer wall is equally exposed to the sky above and the ground below. Thus, the diffuse radiation from the sky above equates to $0.5(1 - F)$, which is then adjusted by the pan's wall area, relative to its water area (i.e. 0.97/1.15). This equates to $0.42(1 - F)$.

Linacre (1994) estimated the reflection of solar irradiance (R_s) from the pan's surroundings onto the pan's wall as 0.42α (where α is the albedo of ground surface, i.e. ≈0.22 for grass; 0.30 for bare soil). He then combined the direct, diffuse and reflected radiation terms to derive the following relationship:

$$H = F \cdot P + 1.42(1 - F) + 0.42\alpha_s$$ **Equation 42**

The three terms in the above equation account for direct, diffuse and reflected radiation respectively. Thus, the incoming solar radiation is augmented by the above fraction. When the sky is completely overcast, R_s / R_a is about 0.25, F is 0.22 and the above equation solves to a factor of 1.50 for a pan surrounded by short green grass (i.e. α_s = 0.22), irrespective of location. When the sky is clear, R_s / R_a is about 0.75 and F solves to 0.87 and the radiation augmentation factor varies from 1.47 to 1.52 for the latitude range 22°S (P=1.37) to 35°S (P=1.43).

A histogram showing Linacre's monthly averaged augmentation factor (H) across all quinaries (i.e. 5 838 *x* 12 = 70 056 values) is given in **Table 38**. The majority of values (85%) occur in the range 1.49 - 1.51, indicating that the incoming shortwave irradiance reaching the pan ($H \cdot R_s$) is 1.5 times the global solar irradiance (R_s) due to the pan's geometry.

Table 38 Histogram of monthly averaged solar radiation augmentation (H) across all 5 838 quinaries calculated using **Equation 42** with α_s = 0.22

H	**Count**	**% of total**	**Accum. %**
1.47	390	0.56	0.56
1.48	4907	7.00	7.56
1.49	18295	26.11	33.68
1.50	18912	27.00	60.67
1.51	22349	31.90	92.57
1.52	5203	7.43	100.00
Total	**70 056**	**100.00**	

The figures given in the above table for South Africa are comparable to those for Australia (due mainly to the similar latitudes of both countries). Rotstayn *et al.* (2006) reported that the augmentation ranged from 1.46 in the far north of Australia to 1.54 over Tasmania (with the surround albedo also set to 0.22). Rotstayn *et al.* (2006) indicated that the increase in shortwave irradiance relative to that at the ground is substantial. Thus, the adoption of Linacre's augmentation factor will significantly affect the calculation of *ACRU*'s *CORPAN* variable.

4.2.2.6 Net energy available for pan evaporation

The ratio of the net energy available to an A-pan (R_{np}) compared to that for a reference grass (R_{nr}) was discussed by Shuttleworth (2010). He defined this ratio as:

$$\frac{R_{np}}{R_{nr}} = \frac{(1 - \alpha_p)R_s - R_{nl}}{(1 - \alpha_r)R_s - R_{nl}}$$ **Equation 43**

where α_p and α_r are the albedo values of the A-pan (= 0.14) and reference grass (= 0.23) respectively. Ignoring R_{nl} in the above equation (i.e. R_{nl} = 0), the ratio (R_{np} / R_{nr}) equates to 1.12. Shuttleworth (2010) varied R_s between 100 and 500 W m^{-2} and R_{nl} from 0 to 100 W m^{-2} and concluded that, for the majority of likely climatic conditions, (R_{np} / R_{nr}) varies from 1.10 and 1.20, with 1.15 being the "mid-range" value.

Thom *et al*. (1981) developed their wind function for an A-pan using measurements taken at the University of Grenoble (France) during the autumn of 1979. The A-pan was surrounded by clipped, freely transpiring, but non-irrigated grass cover. Thom *et al*. (1981) showed that the measured net energy available for pan evaporation was 1.31 times that observed for the surrounding (but non-irrigated) grass cover. This figure does not agree with Shuttleworth's (2010) argument that the net energy ratio approximates 1.15. The approach taken by Shuttleworth (2010) accounts for differences in albedo, but does not acknowledge the additional energy that is absorbed through the pan wall which Linacre (1994) proposed. For example, Riley (1966; cited by Linacre, 1994) reported a 29% reduction in evaporation if the wall and base on the pan are insulated.

Linacre's (1994) net solar radiation term $0.71H{\cdot}R_s$ for an A-pan solves to $1.07R_s$ using a median value of 1.50 for H (c.f. **Section 4.2.2.5**). For a reference grass, the net solar radiation term (R_{ns}) is $0.77R_s$ and thus, the ratio $1.07R_s$ / $0.77R_s$ equates to 1.39 (assuming R_{nl} is zero). When computed R_{nl} is considered, the actual minimum R_{ns} value is 1.41. This is well outside the range (1.1 - 1.2) proposed by Shuttleworth (2010) and higher than the ratio (of 1.31) measured by Thom *et al.* (1981). This may suggest that the *PENPAN* equation may tend to over-estimate PAN-equivalent evaporation.

4.2.2.7 Augmentation of longwave radiation

Linacre (1994) also proposed an additional longwave irradiance from the ground into the sides of the pan in "dry" (i.e. $P < 2.5T_{ave}$) months. When Rotstayn *et al*. (2006) applied this adjustment, they found that the *PENPAN* equation tended to over-estimate E_p. Based on this, the authors omitted the adjustment, arguing that Linacre (1994) unrealistically assumed that the pan wall radiates as a black body. In this study, the suggested augmentation of longwave radiation was also ignored.

4.2.2.8 The modified *PENPAN* equation

Linacre (1994) referred to his simplified version of the Penman equation for A-pan equivalent evaporation (i.e. **Equation 38**) as the "*PENPAN*" Equation. He showed the equation gave excellent agreement between measured and calculated monthly pan evaporation for a limited number of sites in Australia, but also for sites in the US (Wyoming), South Africa (Cedara) and Hong Kong.

Rotstayn *et al*. (2006) used a modified version of the *PENPAN* model to estimate monthly A-pan equivalent evaporation rates driven by GCM output. Rotstayn *et al*. (2006) combined Linacre's (1994) augmented solar irradiance component (**Equation 42**) with an aerodynamic component described by Thom *et al*. (1981). The wind function given by Thom *et al*. (1981; Equation 34 on p 723) for an A-pan is as follows:

$$f(u) = 0.1201(1 + 1.35u) \qquad \textbf{Equation 44}$$

where $f(u)$ is in mm day^{-1} hPa^{-1} and u is the daily averaged wind speed in m s^{-1}. Rotstayn *et al*. (2006) provided the same equation but in SI units (Eqn 3 on p L17715) as:

$$f(u) = 1.39/10^{8}(1 + 1.35u) \qquad \textbf{Equation 45}$$

where $f(u)$ is in kg m^{-2} s^{-1} Pa^{-1} and u is m s^{-1}. This equation provides the rate of pan evaporation in kg m^{-2} s^{-1} which is equivalent to mm s^{-1}. It is multiplied by (60·60·24·100) to adjust the evaporation rate to mm day^{-1}, with pressure in hPa (or mb) as provided by **Equation 44**. McMahon *et al*. (2013) used:

$$f(u) = 1.201 + 1.621u \qquad \textbf{Equation 46}$$

where $f(u)$ is in mm day^{-1} kPa^{-1} and u is the daily averaged wind speed in m s^{-1}.

Rotstayn *et al*. (2006) also recommended a monthly time step so that heat storage in the pan's water can be neglected. Rotstayn *et al*. (2006) obtained very good agreement between measured monthly and annual pan evaporation for Australian sites when using observed radiation, wind speed, humidity and air temperature data. However, they reported the equation tends to overestimate E_p for smaller values of E_p. The authors also adjusted the modelled output by 0.93 to suppress the evaporation (by 7%) caused by a bird guard or screen.

Rotstayn *et al*. (2006) adopted the same albedo values used by Linacre (1994), i.e. α_s of 0.22 to represent a short, green grass surrounding the A-pan and 0.14 for the pan's water surface. However, the noticeable difference in their approach was in the calculation of net irradiance (R_n). Linacre (1994) used (0.71H·R_s - 40), whereas Rotstayn *et al*. (2006) adopted (0.86H·R_s - R_{nl}). The constant 0.86 represents the absorption of solar irradiation by the pan's water surface (i.e. 1 - 0.14). The difference between 0.71 and 0.86 will have a large impact on calculated evaporation values. Note that the replacement of 40 W m^{-2} with calculated values was discussed earlier. The *PENPAN*-type equation used by Rotstayn *et al*. (2006) is as follows:

$$\lambda E_p = \frac{\Delta R_n + \lambda a \gamma D f(u)}{\Delta + a\gamma} \qquad \textbf{Equation 47}$$

where $f(u)$ is a wind function derived from Thom *et al*. (1981). The "constant" a represents the ratio of the effective surface areas for heat and water vapour transfer. Linacre (1994) derived a value of 2.4 from the resistance values [i.e. (200+280)/200], with other values given in **Table 39**. Thom *et al*. (1981) derived a = 2.1 by considering the total area of heat exchange between the pan and the atmosphere, in relation to the surface area. Hence, a value of 1 is assigned to the water surface, with the outside wall being 0.85 (i.e. 0.97/1.15 m^2) and 0.25 for the base of the pan (i.e. 1.00 + 0.85 + 0.25 = 2.10). It assumes that heat exchange between the pan's base and the underlying air occurs on 50% of the area not resting on wooden planks (i.e. 0.50 *x* 0.5 = 0.25).

Table 39 The ratio of effective surface areas for heat and water vapour transfer (*a*) for the Class A evaporation pan

Parameter *a*	**Source**
2.5	Kohler *et al.* (1955)
2.1	Thom *et al*. (1981)
2.4	Linacre (1994)
2.4	Rotstayn *et al*. (2006)
2.75	Rayner (2007)
2.4	Roderick *et al*. (2007)
2.4	Johnson and Sharma (2010)
2.4	McMahon *et al*. (2013)

4.2.2.9 *CORPAN* derived using the *PENPAN* equation

McMahon *et al.* (2013) provided a concise summary of commonly used techniques for estimating daily and monthly actual, potential, reference crop and pan evaporation. The form of the *PENPAN* equation given by McMahon *et al.* (2013) and Roderick *et al.* (2007) for unscreened A-pan evaporation was used in this study, namely:

$$E_p = \frac{\Delta}{\Delta + a\gamma}\frac{R_n}{\lambda} + \frac{a\gamma}{\Delta + a\gamma}\frac{E_a}{1}$$ **Equation 48**

where E_a is the aerodynamic term $f(u)\cdot D$. **Equation 46** (from Thom *et al*., 1981) was used for the wind function and the vapour pressure deficit (*D*) was calculated as per Allen *et al.* (1998) in kPa. Since *u* is set to 2 m s^{-1} in this study, *f(u)* is constant at 4.44 mm day^{-1} kPa^{-1}. Parameter *a* was set to 2.4 to per **Table 39**. Net radiation was estimated according to the procedure determined by Linacre (1994), i.e. $R_n = 0.71H\cdot R_s - R_{nl}$. Hence, the version of R_n adopted by Rotstayn *et al*. (2006) was not used in this study, i.e. $R_n = 0.86H\cdot R_s - R_{nl}$.

The procedure was then repeated with constant *a* in **Equation 48** set to 2.1. From **Table 40**, the analysis showed that the *PENPAN* equation is sensitive to this parameter, affecting the range of *CORPAN* values, more so than the mean. Based on this, the decision was made to select 2.4 as the value for parameter *a*, which represents the ratio of effective surface areas for heat and water vapour transfer (c.f. **Table 39**).

Table 40 Monthly CORPAN values ($1/K_p$) calculated for each of the 5 838 quinary sub-catchments using a modified version of the PENPAN equation with parameter a set to 2.4 and 2.1

Month	***a* = 2.4**		***a* = 2.1**	
	Range	**Mean**	**Range**	**Mean**
January	1.18 - 1.45	1.34	1.26 - 1.44	1.37
February	1.17 - 1.47	1.35	1.25 - 1.45	1.37
March	1.20 - 1.46	1.36	1.27 - 1.44	1.38
April	1.22 - 1.46	1.39	1.28 - 1.45	1.40
May	1.27 - 1.49	1.42	1.32 - 1.47	1.42
June	1.32 - 1.51	1.43	1.36 - 1.48	1.43
July	1.31 - 1.50	1.42	1.35 - 1.47	1.42
August	1.25 - 1.44	1.38	1.31 - 1.43	1.39
September	1.20 - 1.43	1.37	1.27 - 1.41	1.38
October	1.17 - 1.42	1.34	1.25 - 1.41	1.36
November	1.17 - 1.44	1.34	1.25 - 1.42	1.36
December	1.18 - 1.44	1.33	1.26 - 1.43	1.36

With parameter *a* set to 2.4, 75.5% of the *CORPAN* values used in this study range from 1.32 to 1.42 as shown in **Table 41**. The empirical equation provided by Allen *et al*. (1998) in **APPENDIX M** was used to derive *CORPAN* adjustments for the original quinary catchment climate database (Schulze *et al.*, 2011), where 75.6% of the values ranges from 1.09 to 1.18 (**Table 109**). Thus, the modified *PENPAN* equation produces higher monthly A-pan equivalent evaporation estimates than the Linacre (1994) equation. Given that the *PENPAN* equation is a more physically-based approach to estimating *CORPAN*, the empirical equation may tend to under-estimate A-pan equivalent evaporation.

Table 41 Histogram of monthly *CORPAN* values across all 5 838 quinaries using a modified version of the *PENPAN* equation with $R_n = 0.71H \cdot R_s - R_{nl}$

CORPAN	**Count**	**% of total**	**Accum. %**
1.17	3	0.00	0.00
1.18	10	0.01	0.02
1.19	15	0.02	0.04
1.20	8	0.01	0.05
1.21	13	0.02	0.07
1.22	16	0.02	0.09
1.23	36	0.05	0.14
1.24	54	0.08	0.22
1.25	121	0.17	0.39
1.26	204	0.29	0.69
1.27	347	0.50	1.18
1.28	684	0.98	2.16
1.29	1288	1.84	4.00
1.30	2028	2.89	6.89
1.31	3075	4.39	11.28
1.32	3969	5.67	16.95
1.33	4263	6.09	23.03
1.34	4530	6.47	29.50
1.35	5229	7.46	36.96
1.36	5678	8.10	45.07
1.37	5666	8.09	53.15
1.38	5371	7.67	60.82
1.39	5091	7.27	68.09
1.40	4821	6.88	74.97
1.41	4442	6.34	81.31
1.42	3821	5.45	86.76
1.43	2940	4.20	90.96
1.44	2302	3.29	94.25
1.45	1605	2.29	96.54
1.46	1077	1.54	98.07
1.47	704	1.00	99.08
1.48	384	0.55	99.63
1.49	192	0.27	99.90
1.50	61	0.09	99.99
1.51	8	0.01	100.00
Total	**70 056**	**100.00**	

4.2.2.10 Verification of the *PENPAN* equation

A number of studies (e.g. Rotstayn *et al*., 2006; Roderick *et al*., 2007; Johnson and Sharma, 2010; McMahon *et al*., 2013) have used the *PENPAN* equation to estimate PAN-equivalent evaporation in Australia. These studies used $R_n = 0.86H{\cdot}R_s - R_{nl}$ for the pan's net radiation term, which is different to that adopted in this project (i.e. $R_n = 0.71H{\cdot}R_s - R_{nl}$). Thus, monthly pan evaporation estimates would be higher (as well as *CORPAN* adjustments) if the Australian version of R_n was used here.

Rotstayn *et al*. (2006), Johnson and Sharma (2010) as well as McMahon *et al*. (2013) reported that the *PENPAN* equation tends to over-estimate A-pan evaporation, particularly for lower monthly evaporation totals. These studies suppressed the monthly *PENPAN*-modelled evaporation by 7% to account for the shading effect of bird screens, before comparing with observed A-pan data. However, McMahon *et al*. (2013) calculated monthly ratios of *PENPAN* evaporation (E_{pp}; screened) for 68 sites across Australia. They found the averaged E_{pp} / E_p ratio to be 1.078 as shown in **Figure 31**, which highlights the tendency of the *PENPAN* equation to over-estimate A-pan evaporation. Hence, McMahon *et al*. (2013) also recommended that computed *PENPAN* evaporation is downward adjusted by a further 7% to account of this bias.

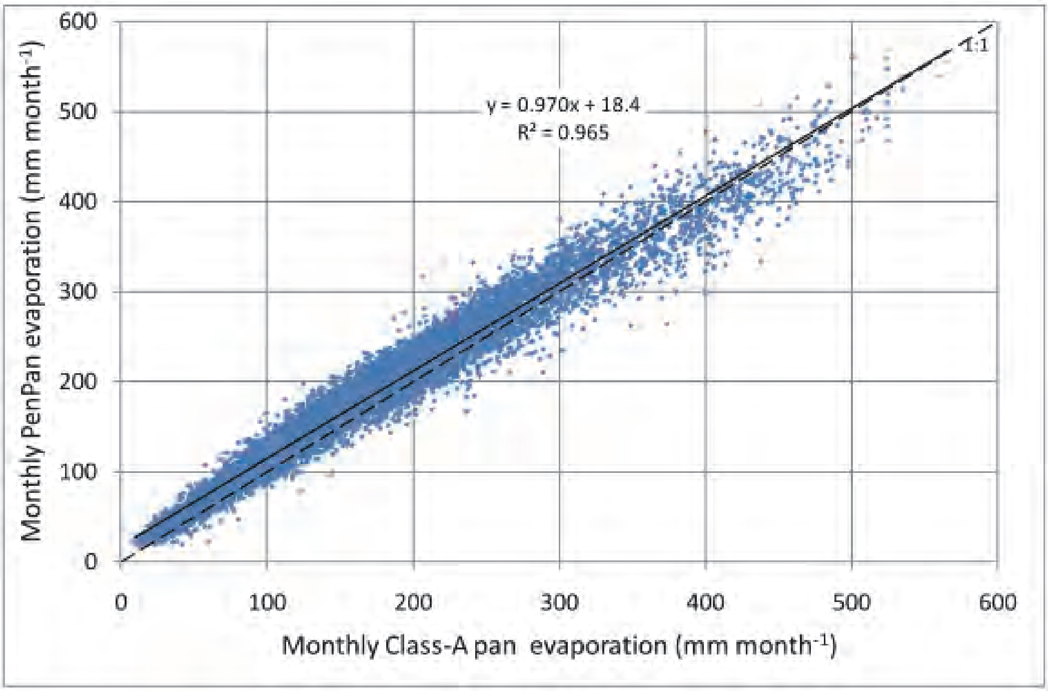


Figure 31 Comparison of monthly *PENPAN* evaporation and Class-A pan evaporation for 68 climate stations in Australia (McMahon *et al*., 2013)

McMahon *et al*. (2013) highlight the importance of appropriately specifying the microclimate around a pan in order to estimate representative pan coefficients and hence, reference crop evaporation estimates. For example, pans surrounded by poor grass cover or dry bare soil are exposed to higher air temperatures and lower relative humidity levels, which increases the evaporation rate (Doorenbos and Pruitt, 1983).

McMahon *et al*. (2013) provided data for six Australian sites, from which K_p (ET_o / E_p) and *CORPAN* (E_p/ET_o) were estimated. From **Table 42**, E_p exceeds ET_o by a factor ranging from 1.28 to 1.60.

Table 42 Comparison of computed FAO56 reference crop evaporation (ET_o) with annual Class A-pan evaporation (E_p; for the period January 1979 to March 2010), for six sites in Australia (McMahon *et al*., 2013)

Location	ET_o (mm)	E_p (mm)	ET_o / E_p	E_p / ET_o
Perth	1 567	2 090	0.75	1.33
Darwin	1 823	2 548	0.72	1.40
Alice Springs	2 012	3 210	0.63	1.60
Brisbane	1 427	1 937	0.74	1.36
Melbourne	1 361	1 757	0.77	1.29
Grove	770	987	0.78	1.28

This evidence highlights the importance of determining pan coefficients for local conditions. Based on these figures, it appears that *CORPAN* values well above 1.2 are justified. This concurs with calculations made using data monthly provided by Sumner and Jacobs (2005).

Sumner and Jacobs (2005) measured actual evapotranspiration (ET_a) from a pasture site within a commercial farm in Florida (USA) over a 17-month period. ET measurements were made in the pasture using eddy correlation (three-dimensional sonic anemometer and krypton hygrometer). A nearby weather station provided Class A-pan evaporation data as well as climate data, from which reference crop evaporation was computed. The data were used to compute pan coefficients and *CORPAN* values as shown in **Table 43**. The results highlight the range in monthly *CORPAN* (E_p / ET_o) adjustments.

Table 43 Class A pan evaporation (E_p) and computed reference crop evaporation (ET_o) over a 15-month period (no evaporation data for two months; Sumner and Jacobs (2005)

YYYY/MM	ET_o (mm)	E_p (mm)	ET_o/E_p	E_p/ET_o
2000/10	3.12	4.33	0.72	1.39
2000/11	2.11	2.77	0.76	1.31
2001/01	1.59	1.91	0.83	1.20
2001/02	2.62	3.37	0.78	1.29
2001/03	3.10	4.64	0.67	1.50
2001/04	4.15	6.33	0.66	1.53
2001/05	4.91	6.81	0.72	1.39
2001/06	4.97	6.22	0.80	1.25
2001/07	4.23	5.16	0.82	1.22
2001/08	2.97	4.02	0.74	1.35
2001/09	2.67	3.89	0.69	1.46
2001/10	2.09	3.05	0.69	1.46
2001/11	1.70	2.19	0.78	1.29
2001/12	1.65	2.06	0.80	1.25
2002/01	2.23	2.93	0.76	1.31

4.2.2.11 APAN adjustment factor

If monthly crop coefficients are derived using FAO56 as the reference (as is the case in this study), they must be adjusted before being used as model input. FAO56 reference evaporation is less than APAN evaporation, due mainly to differences in albedo and wind turbulence above these two reference surfaces. FAO56 assumes a hypothetical grass surface with an albedo of 0.23, whereas a value of 0.14 is suggested by Linacre (1992) for an APAN. Furthermore, the aerodynamic resistance to wind over an evaporimeter (small, flat water body) is different to that of a short (0.12 m tall) grass surface. Finally, there is an additional resistance to water moving through the plant's stomata as well as other resistances to water evaporating from the soil surface. Hence, FAO56 evaporation was adjusted to APAN evaporation using a monthly multiplicative factor. This factor was based on an estimate of APAN equivalent evaporation derived using the so-called *PENPAN* equation.

4.2.3 Land cover/use

4.2.3.1 Crop coefficient

The crop coefficient accounts for differences in the canopy and aerodynamic resistances of the crop being simulated, relative to the reference crop. In other words, K_c serves as an aggregation of the physical and physiological differences between crops and takes into account canopy properties and the aerodynamic resistance of the crop (Taylor *et al*., 2008). The *ACRU* model uses the single crop coefficient which is calculated as the ratio of maximum evaporation (E_m) from the plant at a given stage of plant growth, to the reference crop evaporation (E_r). Hence, the dual crop coefficient approach (Allen *et al*., 1998) is not used, which separates evaporation of soil water from vegetation transpiration.

The monthly crop coefficients (called *CAY* in *ACRU*) determine other secondary functions in the model, such as providing a basis for interception of rainfall and the extent of coverage (or shading) of the soil surface by plant leaves. The monthly crop coefficients used to estimate the water use of each feedstock is summarised **Volume 1**. However, generalised crop coefficient values are provided in the following section. The parameters should be considered a strong simplification of reality since the variability of growing characteristics between different crops and also between varieties of the same crop is large.

<u>Published crop coefficients</u>

Crop coefficient curves should be compared against published values and differences should be described, explained and justified. Allen *et al*. (1998) provided crop coefficients (K_c) for non-stressed, well-managed crops in sub-humid climates (RH_{min} ≈ 45%, u_2 ≈ 2 m s^{-1}) for use with FAO Penman-Monteith method. The relative length of each crop development stage as well as typical crop coefficient values are provided in **Table 44** for potential biofuel feedstock crops.

Table 44 Length of each crop development stage (*L*) as a fraction of the whole growing period as well as crop coefficient (K_c) for the initial period (ini), crop development (dev), mid-season (mid) and end of season (end) periods (Allen *et al*., 1998)

Crop class	Relative length of crop development stage				Crop coefficients		
	L_{ini}	L_{dev}	L_{mid}	L_{end}	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Maize	0.17	0.28	0.33	0.22		1.20	0.35
Millet	0.14	0.21	0.39	0.25		1.00	0.30
Sorghum - grain	0.16	0.28	0.32	0.24		1.10	0.55
Sorghum - sweet						1.20	1.05
Soybean	0.14	0.25	0.43	0.18		1.15	0.50
Sunflower	0.19	0.27	0.35	0.19		1.15	0.35
Cassava	0.10	0.19	0.43	0.29	0.30	0.80	0.30
Sugarbeet	0.28	0.22	0.28	0.22	0.35	1.20	0.70
Canola						1.15	0.35
Sugarcane - virgin	0.09	0.15	0.47	0.30	0.40	1.25	0.75
Sugarcane - ratoon	0.09	0.25	0.48	0.18			

In **Table 45**, Portmann *et al.* (2010) produced three generalised crop coefficients for 26 crop classes using the MIRCA2000 data set, as well as the length of each crop development stage as a fraction of the growing period. The crop coefficient values were defined according to guidelines by Allen *et al.* (1998).

Table 45 Length of each crop development stage (L) as a fraction of the whole growing period as well as crop coefficient (K_c) for the initial period (ini), crop development (dev), mid-season (mid) and end of season (end) periods (Portmann *et al.,* 2010)

Crop class	Relative length of crop development stage				Crop coefficients		
	L_{ini}	L_{dev}	L_{mid}	L_{end}	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$
Maize	0.17	0.28	0.33	0.22	0.30	1.20	0.40
Millet	0.14	0.22	0.40	0.24	0.30	1.00	0.30
Sorghum	0.15	0.28	0.33	0.24	0.30	1.10	0.55
Soybean	0.15	0.20	0.45	0.20	0.40	1.15	0.50
Sunflower	0.19	0.27	0.35	0.19	0.35	1.10	0.25
Cassava	0.10	0.20	0.43	0.27	0.30	0.95	0.40
Sugarbeet	0.20	0.25	0.35	0.20	0.35	1.20	0.80
Canola	0.30	0.25	0.30	0.15	0.35	1.10	0.35

The length of each crop development stage (L) as a fraction of the crop growing period corresponds with that shown in **Figure 32**. As a general rule-of-thumb, the change from the initial to the crop development stage occurs when the canopy cover is approximately 10%. Similarly, the mid-season growth stage occurs between 70 to 80% canopy cover (Schulze, 1995).

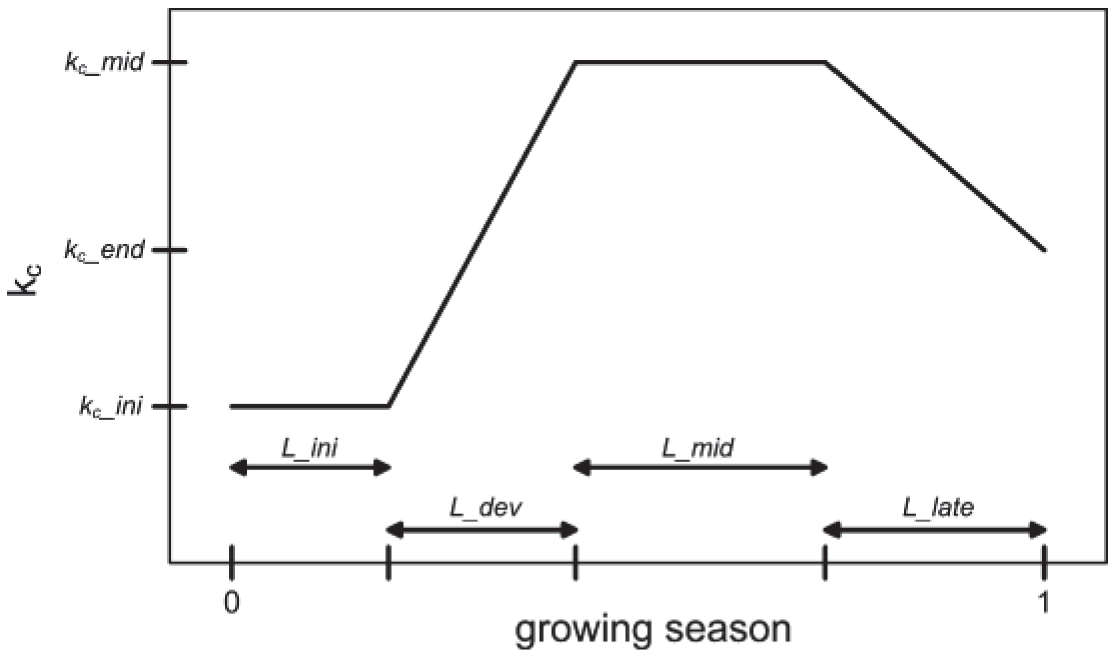


Figure 32 Development of the crop coefficient curve based on parameters listed in **Table 44** and **Table 45** (Siebert and Döll, 2010)

4.2.3.2 Leaf area index

Leaf Area Index is the ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. LAI is a dimensionless value, typically ranging from 0 for bare ground to 6 for a dense forest.

In *ACRU*, it is optional (although hydrologically desirable) to utilise LAI as a growth/consumptive water use parameter, rather than the crop coefficient concept. The user needs to provide typical monthly values (called *ELAIM*) via the menu or daily values (*ELAID*) via the composite file. The 12 monthly values of crop coefficient (*CAY*) or leaf area index (*ELAIM*) are converted internally in *ACRU* to 365 (or 366 for leap years) daily values using Fourier analysis.

4.2.3.3 Interception loss

Shuttleworth (2007) defined interception loss as the difference between the gross rainfall (measured above the canopy or in a nearby clearing) and net rainfall (the sum of through fall and stem flow measured below the canopy at ground level). The problem with troughs placed below the canopy to measure through fall is the systematic error introduced with wetting the surface troughs, resulting in under-estimated interception losses.

According to Savenije (2004), interception is one of the most under-estimated processes in analysis of runoff production from rainfall. The international literature (Calder, 1990; Beven, 2001; Bulcock and Jewitt, 2012) Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands, South Africa has shown that evaporation of water intercepted by the vegetation's canopy can be a significant component of the water balance in certain environments. The evaporation of intercepted water occurs immediately after the rainfall event, usually on the same day in warm climates or within a day if cooler conditions prevail. For example, Shuttleworth (1993) observed that half of the evaporation of intercepted water occurred during the storm itself. If a significant portion of the energy available for evaporation (i.e. latent heat) is consumed by intercepted water, then less energy is available for the evaporation of transpired water as well as soil water.

Shuttleworth (1993) also stated that evaporation of water intercepted by forest stands can often exceed the rate of open water evaporation, owing to the role of turbulence in enhancing the evaporation process. Shuttleworth (2007) highlighted the need for separate modelling of the transpiration and interception components, especially for wet forest canopies. Based on this recommendation, interception loss will be modelled for the biofuel feedstocks studied in field experiments.

The monthly interception losses (called *VEGINT* in *ACRU*) represent the amount of rainfall that is evaporated after a rainfall event. In *ACRU*, it is assumed that rainfall events occur in the late afternoon. Hence, rainfall stored by the land cover's canopy is evaporated the following morning, thus reducing the evaporation demand (which governs the potential evapotranspiration rate). The monthly *VEGINT* values used in this study for each feedstock are summarised in **Volume 1**.

In this project, the initial intention was to use the variable storage Gash model (Bulcock, 2011) to estimate interception loss for each feedstock. This model requires daily climate data as well as monthly leaf area indices for each feedstock. However, this approach was abandoned because *ACRU* does not include the evaporation of intercepted water as part of total evaporation from the crop surface. Hence, total evaporation (i.e. actual evapotranspiration) is the sum of transpired water and water evaporated from the soil surface (and excludes evaporation of intercepted water). Furthermore, stream flow estimated using the *ACRU* model is only slightly sensitive to changes in monthly *VEGINT* values (Schulze, 1995; p AT23-6).

4.2.3.4 Soil depth

ACRU is a two soil horizon hydrological model requiring soils information for both the topsoil (A-horizon) and subsoil (B-horizon). *ACRU* requires the thickness (in metres) of both the topsoil (*DEPAHO*) and subsoil (*DEPBHO*) horizons. *ACRU* also requires the effective total rooting depth (*EFRDEP*), defaulted to *DEPAHO* + *DEPBHO*. The effective rooting depth is used to determine the thickness of soil which is "active" in the soil water budget and the maximum depth that roots can "extract" water.

The proportion of active roots (**Section 4.2.3.5**) and the degree of colonisation of roots (**Section 4.2.3.6**) in each soil horizon are commonly used to describe rooting patterns. These two variables indicate from where within the soil profile, the vegetation is able to extract its soil moisture and are discussed next in more detail.

4.2.3.5 Rooting distribution

Soil water extraction under rainfed conditions takes place simultaneously from both soil horizons and in proportion to the assumed active rooting mass distributions within the respective horizons. The *ACRU* model requires the fraction of active root mass in the topsoil horizon and since it varies seasonally, 12 typical monthly values are needed (*ROOTA*). The corresponding fraction of roots in the subsoil-horizon is then computed by *ACRU* (Schulze, 1995). During periods of plant senescence or when no active root water update occurs (for example, in bare fallow or ploughed situations), the topsoil root fraction is set at 1.00, designating that effectively soil water evaporation from only the topsoil layer, and no transpiration, takes place.

In this study, the rooting distribution was not varied monthly for the perennial crops (especially for ratooned sugarcane) as well as for the shallow-rooted annual feedstocks, e.g. sugarbeet and soybean. For the deeper-rooted annual feedstocks, the fraction of roots in the A-horizon was based on field observations from the trial series. The values were decreased over the growing season to reflect root elongation into the B-horizon, especially for feedstocks with a long tap root system (e.g. sunflower). The monthly *ROOTA* values used in this study for each feedstock are summarised in **Volume 1**.

Published rooting depths

The rooting depth of irrigated and rainfed biofuel feedstocks is provided in **Table 46** (Portmann *et al.*, 2010). They do not represent the effective rooting depth which is often limited by soil characteristics that impede root development such as stone lines. The table also shows the reduction is potential rooting depth that typically results from irrigation.

Table 46 Typical rooting depths of biofuel feedstocks grown under irrigated and rainfed conditions (Portmann *et al*., 2010)

Crop	**Rooting depth (m)**	
	Irrigated	**Rainfed**
Sugarcane	1.2	1.8
Soybean	0.6	1.3
Sunflower	0.8	1.5
Canola	1.0	1.5

4.2.3.6 Root colonisation

While all the living roots of a crop can withdraw water from the soil profile, the majority of water uptake occurs where the density of roots is greatest. Where root concentrations are high, the water held in the soil can be removed more easily and at a faster rate than it can where root concentrations are low.

Root colonisation may be defined as that fraction of the soil matrix under consideration to which roots have ready access to any soil moisture available in that horizon (Schulze, 1995). In *ACRU*, it is assumed that the topsoil is 100% colonised, i.e. roots can utilise/extract all soil water stored in the A-horizon. Hence, the variable *COLON* in *ACRU* represents the root colonisation of the B-horizon. However, colonisation of the subsoil is difficult to characterise given the paucity of root data under farming conditions in South Africa. If no values are input, *ACRU* uses a default value of 100%. Total evaporation (actual evaporation) from the B-horizon is reduced if roots do not colonise the entire subsoil horizon (reduction is by the fraction *COLON*/100). It can be assumed that as *ROOTA* decreases, *COLON* increases. The average depth of the B-horizon for all 5 838 quinaries is 0.338 m.

4.2.3.7 Surface cover fraction

The *ACRU* model is particularly sensitive to this variable (*PCSUCO*), which represents the surface cover beneath the vegetative canopy that can suppress evaporation of soil water stored in the top 10 cm of the soil profile. Surface covers such as mulching layers, litter layers and crop residues (e.g. sugarcane or maize stover) can significantly suppress soil water evaporation if they completely cover the soil surface (e.g. cover fraction = 100%). However, 20% of the soil water evaporation still takes place with 100% cover (the default in *ACRU* is 0%). The values used in the model runs for *PCSUCO* are summarised in **Volume 1**. It is important to note that this variable does not taken into consideration the shading effects of the vegetative canopy.

4.2.3.8 Onset of water stress

The parameter *CONST* in *ACRU* represents the fraction of plant available water (PAW) at which total evaporation is assumed to drop below maximum evaporation, i.e. the onset of plant water stress. The value provides an indication of the plant's susceptibly to water or drought stress. Thus, values approaching zero indicate the plant is drought tolerant. Schulze (2011) noted at *CONST* is typically set to 0.5 for most vegetation types.

4.2.3.9 Coefficient of initial abstraction

The coefficient of initial abstraction (*COIAM*), is a term used in the SCS storm flow equation. It refers to the initial amount of rainfall that does not contribute to the generation of storm flow because of the processes of initial infiltration, interception or temporary surface storage in hollows. The default value is *ACRU* is 0.2, but is increased to over 0.3 in months when the soil is ploughed or under afforested conditions. Thus, this variable indicates the infiltrability into the soil profile. Low values during the wet season will result in more rainfall being converted to runoff, i.e. low *COIAM* equates to low infiltration and therefore greater runoff (Smithers and Schulze, 1995).

4.3 Yield Parameters (*AQUACROP*)

4.3.1 Model evaluation: Terminology

In essence, a model is a simplified representation of a real world system. For example, *AQUACROP* is a simplified interpretation of the effects of water stress on crop productivity. The key challenge is to show the model can realistically predict observations, but more importantly, for the right reasons (Augusiak *et al*., 2014). In order to trust the model's output for decision making purposes, it is important to show the model is not "built on oversimplified and unrealistic assumptions about natural processes" (Pilkey and Pilkey-Jarvis, 2007). The first step involves using a mechanistic-type model, which is considered superior to a statistical- or descriptive-type model. The second step is to calibrate, validate and verify the selected mechanistic model.

Calibration is an iterative process of refining model parameters until the output meets specified performance criteria, i.e. the model is capable of mimicking a predefined dataset (Augusiak *et al*., 2014). Model validation often refers to the comparison of model output against an independent dataset that was not used to calibrate the model (Augusiak *et al*., 2014). Model verification determines whether the model implements the assumptions correctly and that the model is error-free (Sargent, 2011).

According to Farahani *et al*. (2009), a model is initially parameterised for a new crop. Thereafter, the model is calibrated where certain model parameters are adjusted to make the model match the measured values at the given location. Hence, parameterisation is a higher-level adjustment of specific model parameters than calibration. However, Farahani *et al*. (2009), noted that these two terms are used interchangeably in some literature. In this document, the term “parameterisation” refers to the development of a new crop parameter file, which was not undertaken in this study. The term “calibration” refers to the “tweaking” of specific parameter values to improve the outcome of yield simulations.

Sinclair and Seligman (2000) noted that validation is a demonstration that model output more or less fits a set of observed data. However, the process is not necessarily a sufficient indication of validity, particularly when the validation was undertaken after calibration. Thus, validation does not imply universality, where a calibrated model can be readily applied to all scenarios where the crop has, is and will be grown. The development of a universal crop model has proven to be elusive and is inspired by its major benefit, i.e. to relieve the need for laborious field experimentation (Bowen *et al*., 1973).

Scientists have argued that a model can give the right answers, but for the wrong reasons. For example, Oreskes and Belitz (2001) noted that a combination if incorrect input parameters and process representations can still result in good agreement between modelled and observed data. Others (e.g. Shugart, 1984) have argued that models cannot be validated, only falsified. Hence, decision makers should be confident in a model’s appropriateness for application if the model that has yet to be falsified.

According to Augusiak *et al*. (2014), a major obstacle in determining whether a model represents the real world sufficiently well is the confusion caused by terminology used to evaluate model performance. The confusion arises due to the use of ambiguous terms such as validation and verification (Refsgaard and Henriksen, 2004). In practice, verification often overlaps (or blends into) validation (Ormerod and Rosewell, 2006). If a comparison of measured data with modelled data suggests that model predictions are similar to real world observations, then the mechanistic model is assumed to be both a verified implementation of the assumptions made and a valid representation of the real world system. In addition, the terms validation and verification have not been used consistently in the literature, since the understanding of these terms varies amongst scientific authors. Augusiak *et al*. (2014) recently proposed a new set of terminology for evaluating the performance of a model as follows:

- Data evaluation - critical assessment of both quantitative (i.e. numerical) and qualitative (i.e. expert knowledge) data to be used to design, parameterise and calibrate a model.

- Model analysis (i.e. sensitivity analysis) - assessment of 1) how sensitive model output is to changes in model parameters and 2) how well the emergence of model output has been understood.

- Model output verification (i.e. calibration) - critical assessment of 1) how well model output matches observations and 2) to what degree calibration and effects of environmental drivers were involved in obtaining good fits of model output and data.

- Model output corroboration (i.e. validation) - the comparison of model output with independent data that were not used whilst the model was developed, parameterised and verified.

- Implementation verification (i.e. verification) - critical assessment of 1) the model's computer code to check for errors (including bugs and oversights) and 2) whether the model performs as indicated by its description.

Without the availability of appropriate and accurate datasets, a model cannot be conceptualised, built, parameterised, validated and verified. Augusiak *et al*. (2014) pointed out that data quality is determined by measurement errors (e.g. quality of instruments used; frequency of calibration, data logging interval, etc.), experimental design (e.g. choice of sampling site; sample sizes, etc.), as well as and natural heterogeneity and variability inherent in all environmental systems. In addition, experimental data are typically measured for one site over a particular period, which represents only one of the many states of the ecosystem (Augusiak *et al*., 2014).

If model calibration required the "fine-tuning" of a large number of parameters, the higher the risk that successful verification was enforced by unrealistic parameter combinations, i.e. the model produced a representative outcome, but from a combination of factors which does not occur in the real-world system. A sensitivity analysis identifies subsets of parameters that have strong effects on the model outputs. The aim is to understand the model and thus avoid drawing the wrong conclusions from model output. Model evaluations which do not include a sensitivity analysis, are therefore considered too limited (Augusiak *et al*., 2014).

In terms of model output corroboration, the emphasis on new, independent datasets is important because it minimises the risk that the model has been "tweaked" to do the right thing for the wrong reasons. Modellers usually resort to comparing model output with data that already exists, but were not used by the modeller. An ideal form of new data pertains to results of new and specifically designed experiments, which are then used to validate model output. This step strengthens a model's credibility by showing that the model is capable of predicting systems that could not have influenced the model's development (Augusiak *et al*., 2014).

4.3.2 Data evaluation

Sugarcane yield data for eight different planting dates (from 1990 to 1991) was obtained from SASRI. This La Mercy dataset forms part of the Agricultural Model Intercomparison and Improvement Project, or AgMIP (Rosenzweig *et al*., 2013). In brief, AgMIP is a major international effort linking the climate, crop, and economic modelling communities with cutting-edge information technology in order to produce, *inter alia*, improved crop and economic models and the next generation of climate impact projections for the agricultural sector.

Sugarbeet yield data was sourced from the third trial undertaken at Ukulinga in 2013. Soybean yield data measured at Baynesfield Estate was obtained from WRC Project K5/2066 (Mengistu *et al*., 2014). These datasets were used to calibrate the *AQUACROP* model. Two additional datasets derived at Pongola (1968 to 1971) and Komatipoort (2011 to

2012) were then used to validate the calibrated model for sugarcane and sugarbeet respectively.

4.3.3 Model output verification

The crop parameters files used in this study were obtained from different sources as indicated in **Table 47**. It must be noted that for canola and grain sorghum, the parameterisation was not carried out in South Africa, but is assumed to be applicable to local growing conditions.

Table 47 Source of crop parameter files used in study

Crop	Location	Country	Year	Source
Canola	Pincher Creek Alberta	Canada	Unknown	Kienzle (2015)
Canola	Swift Current Saskatchewan	Canada	Unknown	Kienzle (2015)
Sugarbeet	Ukulinga KwaZulu-Natal	South Africa	05/2013-12/2013	Mokonoto (2015)
Sugarcane	La Mercy KwaZulu-Natal	South Africa	06/1989-12/1990	Mokonoto (2015)
Soybean	Baynesfield KwaZulu-Natal	South Africa	10/2012-04/2013	Moyo and Savage (2014)
Maize	Baynesfield KwaZulu-Natal	South Africa	11/2012-04/2013	Moyo and Savage (2014)
Grain sorghum	Bushland Texas	USA	05/1993	*AQUACROP*

Crop models like *AQUACROP* already have default parameter values (derived from model parameterisation) for simulating outputs such as crop yield, water use and water use efficiency. However, calibrating a crop model that can incorporate local conditions and management practices is necessary to assess impacts and adaptability to a changing environment climate across various spatial scales. According to Vanuytrecht *et al*. (2014) and this FAO publication[14], *AQUACROP's* default crop parameters should be "fine-tuned" for local conditions (i.e. calibrated) and ideally, for non-limiting growing conditions (i.e. no soil water or soil fertility stress). Steduto *et al*. (2012; Table 2 on p 44) also recommended that the following crop parameters should be adjusted for each cultivar to reflect local conditions, *viz*.:

- planting date,
- planting density,
- maximum canopy cover (varies with plant density and cultivar),
- maximum rooting depth (Z_{max}),
- the time required to reach Z_{max},
- response to soil fertility,
- reference harvest index and
- length of certain phenological growth stages (cultivar specific).

[14] http://www.fao.org/nr/water/docs/aquacrop_exd_crop.pdf

The following sub-sections list the parameters that were adjusted in order to improve the simulation of crop yield for local growing conditions. For all crops, the planting date, maturity date and planting density were adjusted to reflect local growing conditions. However, calibrations that are more detailed were carried out for sugarbeet and sugarcane as described below.

4.3.3.1 Sugarcane

Although *AQUACROP* is parameterised for sorghum, the overall "goodness" of the parameterisation is not described by Raes *et al*. (2012c; c.f. Annex I). The *AQUACROP* model was originally parameterised for sugarcane with the assistance of SASRI in 2009 using a dataset derived at La Mercy from June 1989 to December 1990. The reader is referred to Steduto *et al*. (2012; *c.f.* Section 3.4; p 174-183) for a description of sugarcane and its parameter values. A decision was made to calibrate *AQUACROP* using the La Mercy trial data. This exercise was also conducted by Mokonoto (2015) and the reader is again referred to his dissertation for more detail.

Differences in parameter values obtained from the original La Mercy parameterisation and the calibration done by Mokonoto (2015) are shown in **Table 48**. The difference in plant type (leafy vegetable *vs*. root/tuber crop) requires further explanation. *AQUACROP* is currently restricted to herbaceous species and simulates yield of fruit/grain crops, leafy vegetables as well as root/tuber crops. According to Vanuytrecht *et al*. (2014), the modelling of forage crops is currently underway at FAO. Alfalfa (*Medicago sativa* L.) was selected as the test crop, since good experimental data are readily available for testing and parameterisation.

Table 48 Differences between *AQUACROP's* default parameterisation for sugarcane and the local calibrated version (La Mercy in 1989)

Parameter	**Mokonoto (2015)**	**Raes *et al*. (2012c)**
Type	Calibration	Parameterisation
Plant group	root/tuber	leafy vegetable
Planting method	Transplanted	Transplanted
Determination of crop cycle length	Thermal	Calendar
Temperature range (°C) for: Crop development Pollination	 13-30 -	 09-32 08-40
Crop cycle length (GDD)	3150	-
Minimum temperature required for full biomass production (°C - day)	10	12
Soil water depletion factor for canopy expansion: Upper threshold Lower threshold	 0.25 0.60	 0.25 0.55
Soil water depletion factor for canopy expansion: Upper threshold	 0.98	 0.90
Crop coefficient when canopy is complete	1.15	1.10
Decline of crop coefficient (% per day)	0.30	0.15
Soil surface area covered by an individual seedling at 90% emergence (cm^2)	10.0	6.50
Number of plants per hectare	133 000	140 000
Canopy growth coefficient Fraction per calendar day Fraction per growing-degree day	 0.029050 0.004205	 0.125480 -
Maximum canopy cover	0.90	0.95
Canopy decline coefficient: Fraction per calendar day Fraction per growing-degree day	 0.010280 0.002222	 0.076150 -
Reference Harvest Index (%)	65	35
Allowable maximum increase of specified HI (%)	20	-
Building up of Harvest Index Starting at root/tuber enlargement (days) During yield formation (GDD)	 279 2255	 73 -
Transplanting to recovered transplant (days/GDD)	015/0040	007/-
Transplanting to maximum rooting depth (days/GDD)	204/1154	060/-
Transplanting to start senescence (days/GDD)	439/2914	330/-
Transplanting to maturity (days/GDD)	490/3150	365/-
Transplanting to start of flowering/yield formation (days/GDD)	130/0541	000/-

4.3.3.2 Sugarbeet

Although *AQUACROP* is parameterised for sugarbeet (Raes *et al*., 2012c; c.f. Annex I), the overall "goodness" of the parameterisation is described as minimal. Crop growth data were obtained from Foggia (41°27'N; 15°35'E, at 90 masl) in southern Italy for March (i.e. Spring) 2000 (Rinaldi and Vonella, 2006). Foggia's climate is described by Rinaldi and Vonella (2006) as hot summers with temperatures exceeding 40°C and A-pan evaporation above 10 mm day^{-1}. Temperatures in winter drop below 0°C and most of the annual rainfall (mean of 550 mm) is concentrated during the winter months. Thus, the sugarbeet experiment was irrigated and fertilised to determine yield under non-limited growing conditions.

It is unknown why the spring 2000 growth data was used to calibrate *AQUACROP*, when the autumn 2001 dataset produced superior tuber and sugar yields (Rinaldi and Vonella, 2006). In addition, Foggia represents a winter rainfall area. Hence, a decision was made to calibrate *AQUACROP* using the data from the sugarbeet trial planted at Ukulinga in May 2013. This exercise was conducted by Mokonoto (2015), who is currently finalising his MSc dissertation. The reader is referred to his dissertation for more detail, with a summarised version given next for convenience.

A transplanting of sugarbeet seedlings was undertaken at Ukulinga in May 2013. An automatic weather station situated near the sugarbeet trial was used to measure daily climatic variables such as rainfall, minimum and maximum temperature, minimum and maximum relative humidity, solar radiation, wind speed and wind direction. These variables were then used to compute reference crop evaporation (ET_o) using the Penman-Monteith equation as described in Allen *et al*. (1998).

Soil samples taken at various depths were used to estimate (using laboratory-based techniques) soil texture and the soil water retention parameters as well as the soil's saturated hydraulic conductivity. A LI-COR portable leaf area meter (Model LI-3100C) was used to measure the area of 10 randomly selected sugarbeet seedlings in order to determine the CC_o parameter (i.e. the canopy cover of the crop at 90% emergence). The Z_{min} (minimum effective rooting depth) parameter was also obtained by measuring the roots of the selected seedlings. A LI-COR plant canopy analyser (model LAI-2200) was used to measure leaf area index weekly until the maximum value was reached (thereafter, bi-weekly measurements were taken). An equation provided by Hsiao *et al*. (2009) for maize was used to convert LAI measurements to canopy cover estimates in order to obtain CC_x (the maximum canopy cover and the time to reach it). Similar canopy cover values were also obtained using an equation provided by García-Vila *et al*. (2009) as shown in **Table 108** (**APPENDIX G**). A Minolta chlorophyll meter (Model SPAD 502) was used to measure leaf chlorophyll content in order to determine the start of crop senescence. The Z_{max} (maximum effective depth) parameter was obtained using a mini-rhizotron camera (i.e. non-destructive sampling method). Destructive sampling was used to measure the difference between fresh and oven-dried plant material (i.e. leaf, stem and tuber). Final biomass, yield and the harvest index (HI) were determined at harvest time in December 2013 (i.e. 189 DAP). Finally, a Campbell Scientific time domain reflectometer system (TDR100 model) was used to measure the volumetric water content of the soil, which was then compared to the simulations done by the model.

The measurements described above were then used to calibrate the *AQUACROP* model for sugarbeet grown in South Africa, which is considered superior than using the parameterisation performed at Foggia in Italy. Differences in parameter values obtained from the Foggia and Ukulinga calibrations of sugarbeet are shown in **Table 49**. The table highlights the number of parameters that were adjusted to improve the performance of the model for local conditions. It must be noted that the Foggia experiment was sown, whereas the Ukulinga trial was transplanted.

Table 49 Differences between *AQUACROP's* default parameterisation for sugarbeet (Foggia, Italy in 2000) and the local calibration (Ukulinga, South Africa in 2013)

Parameter	**Ukulinga (05/2013)**	**Foggia (03/2000)**
Type	Calibration	Parameterisation
Planting method	Transplanted	Sown
Crop cycle length (GDD)	2394	2203
Soil water depletion factor for canopy expansion:		
Upper threshold	0.10	0.20
Lower threshold	0.45	0.60
Minimum effective rooting depth (m)	0.20	0.30
Soil surface area covered by an individual seedling at 90% emergence (cm^2)	5.00	1.00
Number of plants per hectare	66 000	100 000
Canopy growth coefficient		
Fraction per calendar day	0.058010	0.120690
Fraction per growing-degree day	0.005105	0.010541
Maximum canopy cover	0.84	0.98
Time to reach maximum canopy (GDD)	1625	916
Canopy decline coefficient:		
Fraction per calendar day	0.051000	0.054990
Fraction per growing-degree day	0.003540	0.003857
Building up of Harvest Index		
Starting at root/tuber enlargement (days)	121	93
During yield formation (GDD)	1569	1301
Sowing to emergence (GDD)		23
Transplanting to recovered transplant (GDD)	45	
Sowing/transplanting to maximum rooting depth (GDD)	825	408
Sowing/transplanting to start senescence (GDD)	1861	1704
Sowing/transplanting to maturity (crop cycle length in GDD)	2394	2203
Sowing/transplanting to start of tuber formation (GDD)	825	865

4.3.3.3 Sorghum

Although *AQUACROP* is parameterised for sorghum, the overall "goodness" of the parameterisation is not described by Raes *et al*. (2012c; c.f. Annex I). The calibration was undertaken using data obtained from Bushland (Texas, USA) for May 1993. In this study, the

SWB model was only parameterised for grain sorghum (and sweet sorghum). As explained earlier, the *SWB* model is not suitable for multiple runs due to its design and thus could not be used for yield estimation at the national scale. Owing to time constraints, the *AQUACROP* was not calibrated for grain sorghum. Hence, no adjustments were made to the *AQUACROP* parameter file for this crop.

4.3.3.4 Maize

Although *AQUACROP* is parameterised for maize, the overall "goodness" of the parameterisation is described by Raes *et al*. (2012c; c.f. Annex I) as good. However, since maize is currently excluded as a biofuel feedstock due to food security concerns, a national simulation was not carried out.

4.3.3.5 Soybean

Although *AQUACROP* is parameterised for soybean (Raes *et al*., 2012c; c.f. Annex I), the overall "goodness" of the parameterisation is described as medium. The parameterisation was undertaken using data obtained from Patancheru (India) for June 1996. A soybean parameter file was obtained from Mabhaudhi (2015). It is based on observations of crop yield and water use (total evaporation) undertaken at Baynesfield Estate (near Richmond) in KwaZulu-Natal. This 9 300 ha farm produces maize, soybean, sugarcane and avocados. The farm typically rotates maize and soybean, with the land lying fallow in-between each rotation. According to Mengistu *et al.* (2014), the Baynesfield climate is classified as sub-humid with dry and cool winters and warm and rainy summers. Mean monthly air temperatures range from a maximum of 21.1°C in January to a minimum of 13.3°C in June. The mean annual precipitation is 844 mm and the predominant wind direction is easterly.

Table 50 highlights the slight adjustments made to three crop parameters based on yield observations at Baynesfield Estate during the 2012/13 crop season. This emphasises the robustness of the model. This is echoed by Vanuytrecht *et al*. (2014) who added that realistic simulations of maize production were achieved in three different countries using the default model parameters (with minor or no adjustments).

Table 50 Slight differences between *AQUACROP's* default parameterisation for soybean (Patancheru, India) and the local calibration (Baynesfield in 2012/13)

Parameter	**Baynesfield (11/2012)**	**Patancheru (06/1996)**
Type	Calibration	Parameterisation
Number of plants per hectare	328 947	330 000
Canopy growth coefficient (fraction per calendar day)	0.10497	0.10569
Reference harvest index (%)	45	40

The reference harvest index (HI) represents the portion of crop biomass that produces the yield, i.e. the portion containing either sugar, starch or vegetable oil that is converted into biofuel. The model adjusts the reference HI depending on the level of water and/or temperature stress experienced during the crop growth cycle. However, Steduto *et al.* (2012) warned that the reference harvest index should not be altered without good reason, because changing this value requires the re-calibration of the parameters modulating water stress effects on HI.

4.3.3.6 Canola

In this project, the intention was to use the *SWB* model to simulate canola yield since version 4.0 of the *AQUACROP* model does not have a default crop parameter file for canola. However, the *SWB* model cannot be run in "batch mode" which means that model runs must be done manually. A decision was then made to use *AQUACROP* instead of *SWB* for estimates of canola yield. However, the FAO version of *AQUACROP* is not packaged with a parameter file for canola.

Since canola was not studied in the field as part of this research project, a parameter file was sourced from Canada. According to Kienzle (2015), Pincher Creek is cooler and wetter than the Swift Current location (i.e. warmer and drier in comparison). Hence, growing conditions at Pincher Creek were assumed to be representative of winter canola grown in the Western Cape region using a medium-season cultivar. On the other hand, the Swift Creek calibration was assumed to represent a short-season cultivar which would typically be harvested just before the start of spring. Kienzle (2015) noted that the canola parameter file was recently run for a total of 10 584 simulations to provide spatial estimates of yield using nine years of daily climate data.

The planting density in the canola parameter files obtained from Canada was set to 2 500 000 plants per hectare (i.e. 250 plants per m^2). This very high value was queried since the Canola Council of Canada[15] recommends a target population of 70-100 plants per m^2 to maximise yield potential. In addition, 200 or more plants per square metre produces very thin stems and pods mostly at the top of the plants. Thus, plants are more likely to lodge, which can create a suitable micro-environment for diseases such as *Sclerotinia.* A decision was made to reduce the planting density to 350 000 and 250 000 sph for the Pincher Creek and Swift Current canola parameter files respectively (**Table 51**). These values were based on recommendations by Fouché (2012) of 20 to 40 plants per m^2 for dryland conditions (50-70 plants per m^2 under irrigation). Since the parameter file for Swift Current (Saskatchewan, Canada) is based on a short growing season, the plant population was decreased to reduce competition for available resources.

Table 51 Modifications made to the canola parameter file for Pincher Creek and Swift Current to better represent local conditions

Parameter	**Pincher Creek**	**Swift Current**
Number of plants per hectare (original)	2 500 000	2 500 000
Number of plants per hectare (modified)	350 000	250 000

[15] http://www.canolacouncil.org/canola-encyclopedia/crop-establishment/plant-population/
http://www.canolacouncil.org/canola-encyclopedia/crop-establishment/seeding-rate/

4.3.4 Model output corroboration

Two additional datasets derived at Pongola (1968 to 1971) and Komatipoort (2011 to 2012) were then used to validate the parameterised model for sugarcane and sugarbeet respectively.

4.3.5 Model analysis

A sensitivity analysis to model input was conducted using sugarbeet and sugarcane. These two crops were selected due to the extensive calibration that was undertaken using observed growth and yield data measured at Ukulinga and La Mercy. The model was tested for two planting dates (i.e. summer and winter) chosen for each crop. The sugarbeet simulations were conducted for quinary 4 697 in which Ukulinga is located. Similarly, La Mercy is located in quinary 4 719, which was thus used for sugarcane (**Figure 33**).

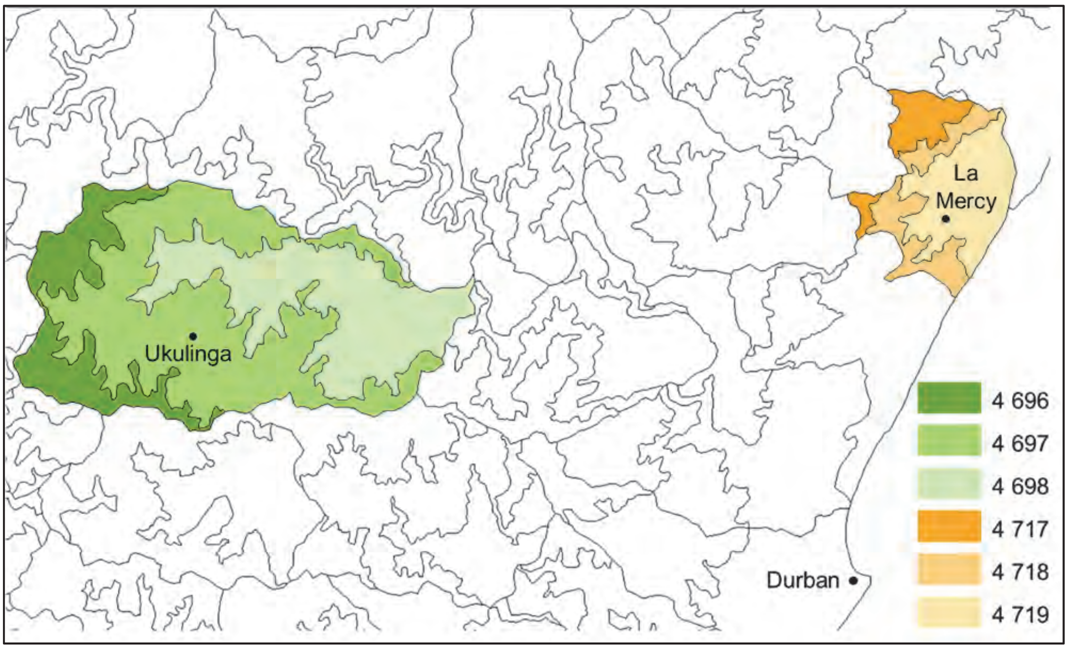


Figure 33 Location of Ukulinga and La Mercy in quinary 4 697 and 4 719 respectively

4.3.5.1 Standalone vs. GUI version

Testing was initially done using actual soil parameters for Ukulinga and La Mercy. Climate data was derived from the original quinary sub-catchment climate database (Schulze *et al.*, 2011) for the respective quinaries. The 50 years of climate data (from 1950 to 1999) was used so that the long term attainable yield could be simulated. As expected, the standalone version of the model produced identical yield and WUE results to the full version (with the Graphic User Interface or GUI).

According to Steduto *et al*. (2012), in order to determine the long-term attainable yield at a location, at least 20 years of daily climate data should be used for simulations. However, 30 years of data is considered the *de facto* standard. The 30-year mean and median statistics of yield and water use efficiency were then compared to that derived from the entire (i.e. 50-year) time series. Since no significant differences in statistics were found, a 30-year simulation would offer considerable savings in computational time compared to the 50-year simulation.

4.3.5.2 Input soils data

The actual soil parameters for Ukulinga and La Mercy (e.g. SAT, FC, WP, K_{sat} and depths for each soil horizon) were then replaced with the quinary-averaged data derived from the quinary sub-catchment soil database. The mean yields for sugarcane for both planting dates were very similar (≤ 0.46 t ha^{-1} difference), despite a deep soil with five horizons for La Mercy compared to a shallower two-layered soil for the sub-catchment. However, the yields decreased for sugarbeet by 1.0 and 1.7 t ha^{-1} for the September and June plantings respectively. This result was not expected considering the soils information for Ukulinga is similar to that for quinary 4 697 as shown in **Table 52**, except for the soil water content at saturation (SAT).

Table 52 Comparison of soils data for Ukulinga compared to that for quinary 4 697

Horizon	Soil parameter	Ukulinga	Quinary 4697
A-horizon	Depth (m)	0.20	0.30
	SAT (vol %)	36.5	42.2
	FC (vol %)	30.0	26.8
	WP (vol %)	17.5	17.8
	K_{sat} (mm day^{-1})	228	207
B-horizon	Depth (m)	0.60	0.49
	SAT (vol %)	36.1	42.6
	FC (vol %)	32.0	29.8
	WP (vol %)	20.8	20.5
	K_{sat} (mm day^{-1})	108	119

4.3.5.3 Climate data

For the next test, the original climate data for both quinaries was replaced with the revised climate data. The revised climate exhibits higher reference evaporation (ET_o) which caused a reduction in sugarcane yield of 11.5 and 10.3% for the February and April plantings respectively. However, the number of crop failures (i.e. seasonal yield = 0.00 t ha^{-1}) increased from 0 to 6 for sugarbeet planted in September (and from 2 to 7 for the June planting).

A yield of 0.00 t ha^{-1} was selected to represent a crop failure and not a higher yield threshold. A simulated yield of 0.50 t ha^{-1} may be deemed a failure for crops with a high harvest index (e.g. sugarcane), but could be economically viable for crops with a low harvest index (e.g. canola). Hence, this threshold is not only crop specific, but also depends on the intended use. For example, a yield of 0.5 t ha^{-1} may be adequate for subsistence farming but not economically viable for a commercial farm.

4.3.5.4 Calendar *vs*. thermal maturity

In *AQUACROP*, the season length can be expressed in calendar days or calculated using thermal time (i.e. based on growing degree days or GDD). The impact on yield output was assessed by changing the season length from calendar days to thermal time. The analysis showed that the model will under-estimate the yield if the calendar-day season is less than the GDD-based season. For example, a yield reduction of 11.3% was simulated for sugarbeet planted in winter due to the calendar season of 198 days being less than the range of 216 to 245 days derived using the GDD concept.

One major drawback of using a variable season (based on thermal time) and not a fixed season length (based on calendar days) is the substantial increase in model run (i.e. execution) time. Although the use of thermal time added to the computational complexity of the model run, more realistic yield estimates should be derived, in particular for cooler areas.

4.3.5.5 Initial soil water conditions

By default, the model assumes the soil water content is at field capacity for the start of the simulation period (Raes *et al*., 2013). This assumption was deemed unrealistic for dryland agriculture. Hence, the model's sensitivity to initial soil water conditions was tested by changing the value from field capacity (the default) to 50% of plant available water (PAW). This resulted in very significant yield reductions of 64.3 and 74.8% for the respective February and April plantings. This was due to the substantial increase in the number of crop failures from 0 to 32 (February) and 36 (April).

Further investigation revealed that the model is particularly sensitive to the availability of moisture in the first growth stage. *AQUACROP* outputs *StExp* which represents the level of water stress that reduces leaf expansion (expressed as a percentage). If this water stress indicator approaches 100% for the start of the 2^{nd} growth stage, the crop dies and no biomass or yield is produced. The decision was therefore made not to change the default option and to leave the initial soil water level at field capacity. However, Steduto *et al.* (2012) suggested setting the simulation start time as the end of the last significant rain. The assumption is made that the field will be kept fallow and weed free and the initial soil water content at planting should be more realistic of field conditions.

4.3.5.6 Start of simulation period

The next test involved setting the start of the simulation period to January (**Figure 51b** in **APPENDIX H**) and not to the set planting date (**Figure 51a** in **APPENDIX H**). *AQUACROP* assumes fallow conditions before the start of the crop cycle, with rainfall and soil water evaporation adding and removing soil water respectively. Hence, the soil water content at planting (i.e. start of the cropping period) should be more realistic of actual field conditions. This option was therefore chosen to account for the "model warmup" period. It had a significant impact on the yield of sugarbeet planted in June (reduction of 28.4%) due to the large increase in the number of crop failures (from 7 to 33). Another option was tested with the simulation period starting one month prior to the crop planting date. This also resulted in a high number of crop failures.

If the simulation period is started before the crop is planted, soil water evaporation from the bare soil dries out the A-horizon, resulting in high leaf expansion stress at the start of the second growth stage, which kills the crop (i.e. zero yield). The decision was therefore made to link the simulation period to the cropping period (i.e. start of simulation period = start of cropping period = crop planting date).

A perusal of a forum[16] dedicated to the DSSAT suite of crop models revealed similar issues being experienced by other model users. Users in the forum suggested that the start of the simulation should be the sowing or transplanting date. If the start of the simulation period occurred before the planting date, it resulted in higher maize and wheat yield predictions.

4.3.5.7 Linked simulations runs

AQUACROP accommodates another option where the start of the next simulation period is the day after the previous crop maturity date (**Figure 52** in **APPENDIX H**). This option accounts for the effects of rainfall and soil water evaporation from the previous harvest date to the next planting date. This option resulted in significant yield reductions, in particular for the June and April planting of sugarbeet and sugarcane respectively. Of more concern was the large increase in crop failures and thus, this option was not used.

4.3.5.8 Summary

It is evident (but not surprising) that the model is sensitive to climate and soils input. In this study, the revised quinary sub-catchment climate database was used for all modelling involving *ACRU, AQUACROP* and *SWB*. The sensitivity analysis showed that for the regional simulations of yield, the crop season length should be based on thermal time and not calendar days. Although this decision improved the reliability of yield estimates, it added considerable complexity to model implementation. With regard to all other model options tested, the "KISS principle" was adopted. In other words, a "Keep It Simple and Straightforward" approach to setting up *AQUACROP* was preferred. Hence, the model's default options of 1) assuming the soil is at field capacity at planting, and 2) setting the simulation period equal to the cropping period were selected for the regional simulations.

4.4 Yield Parameters (*SWB*)

4.4.1 Model output verification

4.4.1.1 Sweet sorghum

The *SWB* model growth parameters determined for sweet sorghum (cv. Sugargraze) from the Hatfield 2010/11 trial are presented in **Table 53** below. These parameters were used to produce the *SWB* simulations shown in **Volume 1** (c.f. Section 4.3.6).

[16] https://groups.google.com/forum/#!msg/dssat/yL-3JztB7kw/tktqrDw_fvEJ
https://groups.google.com/forum/#!msg/dssat/XcyZAszyCI0/RyOXPahDthwJ

Table 53 *SWB* model growth parameters determined for sweet sorghum (cv. Sugargraze) from the Hatfield 2010/11 trial

Specific crop growth parameter	**Value**
Canopy radiation extinction coefficient	0.58
Corrected dry matter-water ratio (Pa)	6.8
Radiation conversion efficiency (kg MJ^{-1})	0.0020
Base temperature (°C)	10
Temperature for optimum growth (°C)	25
Cut-off temperature (°C)	36
Emergence degree days (d °C)	90
Degree days to flowering (d °C)	900
Degrees days to maturity (d °C)	1 600
Transition period degree days (d °C)	200
Degree days for leaf senescence (d °C)	1 100
Maximum crop height (m)	3.45
Maximum root depth (m)	1.4
Fraction of total dry matter translocated to heads	0.05
Canopy storage (mm)	2
Leaf water potential at maximum transpiration (kPa)	-1 500
Maximum transpiration (m)	10
Specific leaf area (m^2 kg^{-1})	12
Leaf stem partition parameter (m^2 kg^{-1})	1.4
Total dry matter at emergence (kg m^{-2})	0.02
Fraction of total dry matter partitioned to roots	0.15
Root growth rate (m^2 $kg^{-0.5}$)	4.0
Stress index	0.95

4.4.1.2 Canola

A trial conducted at Hatfield in the winter of 2002 measured the water use efficiency of canola. The trial was conducted under an automated rain shelter to prevent rainfall interference. A second trial was conducted in an open field during the 2003 winter. Both trials had four water treatments, namely unstressed (the control) and stress applied during the vegetative, flowering and seed filling growth stages (Tesfamariam, 2004; Tesfamariam *et al*., 2010). The *SWB* model growth parameters determined for canola from the 2002 trial are presented in **Table 54** below. The 2003 trial was used to validate the *SWB* model. The results of the calibration and validation are shown in Section 4.3.6 of **Volume 1**.

Table 54 *SWB* model growth parameters determined for canola from the Hatfield 2002 trial (Tesfamariam, 2004)

Specific crop growth parameter	**Value**
Canopy radiation extinction coefficient	0.60
Corrected dry matter-water ratio (Pa)	5.8
Radiation conversion efficiency (kg MJ^{-1})	0.00180
Base temperature (^oC)	5.0
Temperature for optimum growth (^oC)	25.0
Cut-off temperature (^oC)	30.0
Emergence degree days (d ^oC)	77
Degree days to flowering (d ^oC)	997
Degrees days to maturity (d ^oC)	1 742
Transition period degree days (d ^oC)	200
Degree days for leaf senescence (d ^oC)	900
Maximum crop height (m)	2.0
Maximum root depth (m)	1.0
Fraction of total dry matter translocated to heads	0.05
Canopy storage (mm)	2
Leaf water potential at maximum transpiration (kPa)	-1 500
Maximum transpiration (m)	7.0
Specific leaf area (m^2 kg^{-1})	22.8
Leaf stem partition parameter (m^2 kg^{-1})	1.8
Total dry matter at emergence (kg m^{-2})	0.0005
Fraction of total dry matter partitioned to roots	0.2
Root growth rate (m^2 $kg^{-0.5}$)	3.8
Stress index	0.95

5 HYDROLOGICAL IMPACTS OF FEEDSTOCK PRODUCTION

This chapter addresses the following two project aims, *viz*.:

- To determine crop parameters and model water use of specific crops/trees for biofuel that have potential but insufficient knowledge exists in South Africa to promote effective production.

- To assess the impact of land use change on the water balance of selected catchments deemed suitable for biofuel feedstock cultivation.

In this chapter, the approach adopted in South Africa to assess feedstock water use as a possible stream flow reduction activity is given. In addition, the latest revision to the quinary sub-catchment climate database is discussed. However, the final parameters used in the *ACRU* hydrological model (Schulze, 1995) to assess stream flow reduction are provided in **Volume 1**.

5.1 Introduction

5.1.1 Definition of water use

Section 36 of the National Water Act (NWA) declares land that is used for commercial afforestation to be a Stream Flow Reduction Activity (SFRA), and also makes provision for other activities (i.e. land uses) to be so declared if this should prove justified. This would be based on such an activity being "likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly". Thus, "water use" is defined as the difference in runoff generated by the feedstock under consideration and that generated under natural conditions. This builds on the definition accepted for commercial forestry, i.e. the water used by afforestation is the reduction in stream flow compared with the stream flow that would have occurred from natural vegetation.

The current approach taken by the former DWA with regard to SFRAs is to "measure" or "weight" the impact of a change in land use in terms of water use relative to the situation that would have existed under "natural conditions". Thus, "water use" in the context of SFRA assessments is always defined as a mean annual value for the feedstock relative to a "baseline". Furthermore, it does not reflect the consumptive water use of the feedstock over its growth cycle (i.e. total evaporation accumulated over its growth cycle). In order to determine the water use resulting from a land use change, it is necessary to first define the baseline vegetation against which the water use of new land cover should be compared.

5.1.1.1 Evapotranspiration

It is important to note that *ACRU* does not include the evaporation of intercepted water as part of total evaporation from the crop surface. Hence, total evaporation (i.e. actual evapotranspiration) is the sum of transpired water and water evaporated from the soil surface. This is an important consideration when comparing:

- measurements of total evaporation obtained using micrometeorological techniques such as surface layer scintillometry, eddy covariance or surface renewal (which includes interception loss), and

- simulated total evaporation from hydrological models such as *ACRU* (which excludes evaporation of intercepted water).

5.1.1.2 Stream flow reduction

"Water use" in the context of SFRA assessments is defined as the difference in mean annual stream flow (MAR) resulting from a change in land use from the baseline (i.e. natural vegetation) to the cultivation of biofuel feedstock (or crop). This difference (MAR_{base} - MAR_{crop}) is then expressed as a percentage of the baseline stream flow (MAR_{base}). The definition of a SFRA in the NWA provides ambiguity in at least two aspects. The first of these concerns the use of the word "significantly" and the various interpretations thereof and the other concerns the consideration of the impact on the Reserve.

If the impact exceeds 10%, the proposed land use change may be declared as an SFRA (Jewitt *et al*., 2009b). The results provide an indication of whether there would be a positive or negative impact on the sub-catchment's water resources if the "virgin" land cover was replaced by a particular biofuel feedstock and grown under dryland (i.e. non-irrigated) conditions. However, Scott and Smith (1997) highlighted the fact that stream flow reductions during low flow periods may be proportionately greater than for total annual flows. In order to determine the hydrological impact of land use change to feedstock production, it is necessary to first define the baseline vegetation against which the water use comparisons are made.

5.1.2 Modelling approach and application

It is virtually impossible to measure crop water use under all the possible combinations of climate, soils and management conditions in South Africa. Hence, it is necessary to use a model which can accurately simulate water use of crops across all conditions. It is important that crop water use models are able to extrapolate water use over a wide range of conditions and management practices. Hence, it is necessary to use a mechanistic approach that is based on a thorough understanding of the mechanisms driving transpiration. This need eliminates models based on empirical relationships, which can seldom be used in conditions outside the environment in which they were originally calibrated. A review of appropriate hydrological models is given in **Section 5.2.**

The definition of water use adopted in this project (c.f. **Section 5.1.1.2**) requires the comparison of stream flow generated from a sub-catchment under the proposed land use, compared to than from natural vegetation. Although there are now other "natural" vegetation classification systems and maps available (e.g. Mucina and Rutherford, 2006), the classification by Acocks (Acocks, 1953) and subsequent modifications (Acocks, 1975; Acocks, 1988) remains the most widely used baseline vegetation classification and has been used as the basis for estimates of water use by commercial forestry species since 1999.

Furthermore, national water resources planning strategies in South Africa also assess water use and availability against a natural baseline condition, i.e. "naturalised flow" as generated by the Pitman Model. Thus, in line with methods developed to estimate the water of commercial afforestation, the baseline against which feedstock water use is assessed (and hence it's potential to be declared a SFRA) is the Acocks Veld Type. This is discussed further in **Section 5.3**.

In **Section 5.2.2.2**, the importance of estimating APAN equivalent evaporation is stated. Hence, considerable effort was spent on revising the temperature and evaporation estimates for each quinary sub-catchment. This work is detailed in **Section 5.4**. The running of the selected hydrological model at the national level is discussed in **Section 5.6**. The results of the hydrological impact study are presented in **Volume 3**.

5.2 Appropriate Models

The Water Research Commission has funded the development of a number of models designed to promote the improved management of water resources in South Africa. These include the *ACRU* (Agricultural Catchments Research Unit) which is now linked to *MIKE BASIN*, *WAS* (Water Administration System), *SAPWAT* (Crop Water Use Model), *SWB* (Soil Water Balance) and *RISKMAN* (Risk Manager) models. These models were reviewed by Taylor *et al*. (2008) and Pott *et al*. (2008). A summary of their findings is given next.

5.2.1 Overview of models

ACRU is a rainfall-runoff model, whereas *MIKE BASIN* is a node-and-channel network model. *ACRU's* stream flow output is used as input the *MIKE BASIN* model to quantify the extent of over-allocation of water resources in South Africa's catchments. Pott *et al*. (2008) recommended the *ACRU-MIKE BASIN* model combination as a useful platform to assess the hydrological impacts of various operating rules and license allocation decisions on catchment water use. This is particularly useful to water resource managers studying catchments where water resources are already over-allocated. Pott *et al*. (2008) also recommended further development of the *SWBPro-RISKMAN* model linkage to assess the economic impacts of operating rules and license allocations. Based on these recommendations, the decision was made to focus research efforts on using the *ACRU* and *SWB* models to meet the water use modelling objectives of this project. However, since SWB cannot be run in "batch mode", the model cannot be used for national scale assessments of crop water use. Thus, the *ACRU* model was selected to assess the hydrological impacts of land use changes to feedstock production on downstream water availability.

5.2.2 The *ACRU* model

5.2.2.1 Model description

Under the leadership of Prof Roland Schulze, the *ACRU* model (Schulze, 1995) was initially developed by the former School of Bioresources Engineering and Environmental Hydrology based at the University of KwaZulu-Natal in Pietermaritzburg. *ACRU* is an integrated agrohydrological modelling system capable of, *inter alia*:

- water resource assessments,
- design flood estimations,
- crop yield assessments and
- irrigation water demand and supply evaluations.

ACRU is primarily a catchment-scale, daily time-step hydrological rainfall-runoff model. *ACRU* has been linked to the *MIKE BASIN* model developed by the Danish Hydraulic Institute. *ACRU* is used to generate stream flow from non-irrigated (i.e. rainfed) lands in a catchment. The simulated stream flow is then used by *MIKE BASIN* to compute the supply and demand interactions in catchments for given operating rules. The irrigated lands are managed by *MIKE BASIN* and not *ACRU*, as the irrigated lands are subject to operating rules (which rainfed land uses are not) which are easily represented in *MIKE BASIN* (Pott *et al*., 2008).

ACRU is a physical-conceptual, multi-level and multi-purpose model (**Figure 34**), with various outputs which have been widely verified against observations in many countries and conditions. *ACRU* was considered appropriate for meeting the objectives of the biofuels project as the model operates as a process-based, multi-soil layer water budget which is sensitive to land management and changes thereof. The model can output, *inter alia*, the following for each catchment or sub-catchment:

- daily storm flows, base flows and total runoff,
- peak discharge, sediment yields and recharge to groundwater,
- daily soil water content and evapotranspiration, and
- accumulated daily stream flows from all upstream sub-catchments.

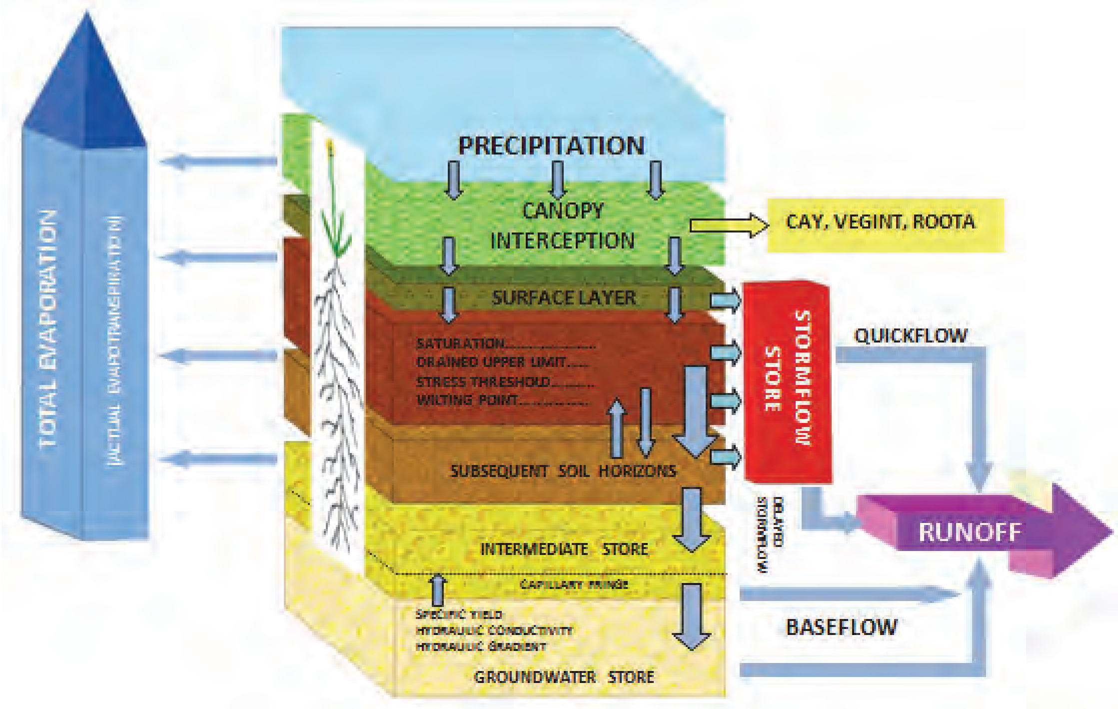


Figure 34 The *ACRU* agrohydrological modelling system: General structure (after Schulze, 1995)

The output from the *ACRU* model can then be used, *inter alia*, for:

- reservoir yield analyses,
- inter-basin transfer and abstraction analyses,
- irrigation demand and supply (including return flows),
- wetland responses, and
- crop yields for selected crops.

5.2.2.2 Parameterisation

The *ACRU* model has been used frequently to assess the impact of land use change on stream flow generation. For example, hydrological response from the riparian zone is particularly sensitive to land use change (Schulze, 1995). The list of parameters and variables in *ACRU* which determine rainfall /runoff response are presented in **Section 4.2**. A *parameter* is considered any input where only one value represents the sub-catchment, whereas a *variable* has more than one value (i.e. values that vary monthly). From this comprehensive list, the sensitive variables are discussed next in more detail.

Since rainfall is the main driving factor in most hydrological models, most attention should be given to this input variable especially in high intensity rainfall areas (Schulze, 1995). In other words, rainfall-runoff models are particularly sensitive to rainfall input and any errors in rainfall are amplified in stream flow simulations (Schulze, 1995). Therefore, it cannot be over-emphasised that great care must be taken when deriving the monthly adjustment factors (i.e. *CORPPT* variable). These factors are applied to point rainfall data (observed at a rainfall recording station) in order to improve its representativeness of "average" catchment conditions (Schulze, 1995).

Schulze and Horan (2011) also noted that runoff response is most sensitive to rainfall, reference evaporation and certain soil characteristics. Similarly, a sensitivity analysis undertaken by Angus (1989) using the Cedara catchment (situated in the KwaZulu-Natal midlands at an altitude of 1 067 m) revealed that total stream flow output from *ACRU* is extremely sensitive to changes in rainfall input. Angus (1989) showed that stream flow output is highly sensitive to changes in:

- A-pan evaporation,
- crop coefficients,
- soil horizon depths (particularly for shallow soils), and
- depth of the soil that contributes to storm flow generation (*SMDDEP*).

Monthly *CORPAN* factors are necessary since *ACRU* is an APAN driven agrohydrological model, despite the fact that FAO56 (i.e. Penman-Monteith) has become the *de facto* reference evaporation since 1998. Schulze (1995) concluded that:

- care must be taken in the determination of realistic APAN equivalent (and crop coefficient) values and
- when in doubt, rather over-estimate than under-estimate these values.

An over-estimation of catchment evaporative demand will result in an under-estimation of runoff generation and thus, planning is based on less water than actually is available (with fewer consequences compared to the corollary being true). Considerable effort was spent on deriving the new (and arguably, more realistic) A-pan evaporation estimates used in this study (c.f. **Section 5.5**).

The effective soil depth which is considered to be contributing to storm flow generation is specified by the parameter *SMDDEP* in *ACRU*. Stream flow generation is extremely sensitive to *SMDDEP*, particularly for sites with shallow soils and high rainfall intensities (Schulze, 1995). *SMDDEP* is often under-estimated in drier locations, which results in over-estimated stream flow (Schulze, 1995). This parameter accounts for the dominant runoff producing mechanisms which may vary in different climates, as well as with land use, tillage practice, litter/mulch cover and soil conditions. For all hydrological simulations in this project, *SMDDEP* was defined as the thickness of the topsoil, which is the suggested default value (Smithers and Schulze, 1995). Schulze (2011) also set *SMDDEP* to the thickness of the topsoil.

Land cover and land use affect hydrological responses through canopy and litter interception, infiltration of rainfall into the soil and the rates of soil water evaporation and transpiration from the vegetation layer. The sensitivity analysis undertaken by Angus (1989) showed that stream flow output is sensitive to changes in crop coefficients. For this reason, this project spent considerable effort in deriving crop coefficient values for selected feedstocks from field-based observations (c.f. **Chapter 3**).

5.3 The Hydrological Baseline

The definition of water use adopted in this project requires the comparison of stream flow generated from a sub-catchment under the proposed land use, compared to than from natural vegetation. Although there are now other "natural" vegetation classification systems and maps available (e.g. Mucina and Rutherford, 2006), the classification by Acocks (Acocks, 1953) and subsequent modifications remains the most widely used baseline vegetation classification and has been used as the basis for estimates of water use by commercial forestry species since 1999.

It may be argued that the impact of conversion of one land use to another, on the available water resources in that area, is best assessed relative to the land use it is replacing, which is rarely natural vegetation. In order to cultivate virgin land (i.e. natural vegetation), the land owner must be granted written permission by the Executive Officer (except if approval was granted under Section 4A of the 1972 Forest Act). Virgin soil is defined as land that has not been cultivated in the previous ten years and thus is referred to as "undeveloped" by the Executive Officer (Niemand, 2011). This is in accordance with the Conservation of Agricultural Resources Act (CARA) 43 of 1983.

However, it must be noted that the approach followed in this project is consistent with that used to regulate commercial forestry as an SFRA. Furthermore, it should be noted that national water resources planning strategies in South Africa also assess water use and availability against a natural baseline condition, i.e. "naturalised Flow" generated by the Pitman Model. Thus, in line with methods developed to estimate the water of commercial afforestation, the baseline against which feedstock water use is assessed (and hence it's potential to be declared a SFRA) is the Acocks Veld Type.

5.3.1 Mucina and Rutherford

A collaborative initiative entitled the National Vegetation Map of South Africa Project (VEGMAP) produced a definitive map of the natural vegetation types of southern Africa in 2006. The project was managed by the South African National Biodiversity Institute (SANBI) with funding from the local government and Norway. This map includes 435 zonal and azonal vegetation types mapped at a working scale of 1:250,000 and sometimes higher resolution (**Figure 35**).

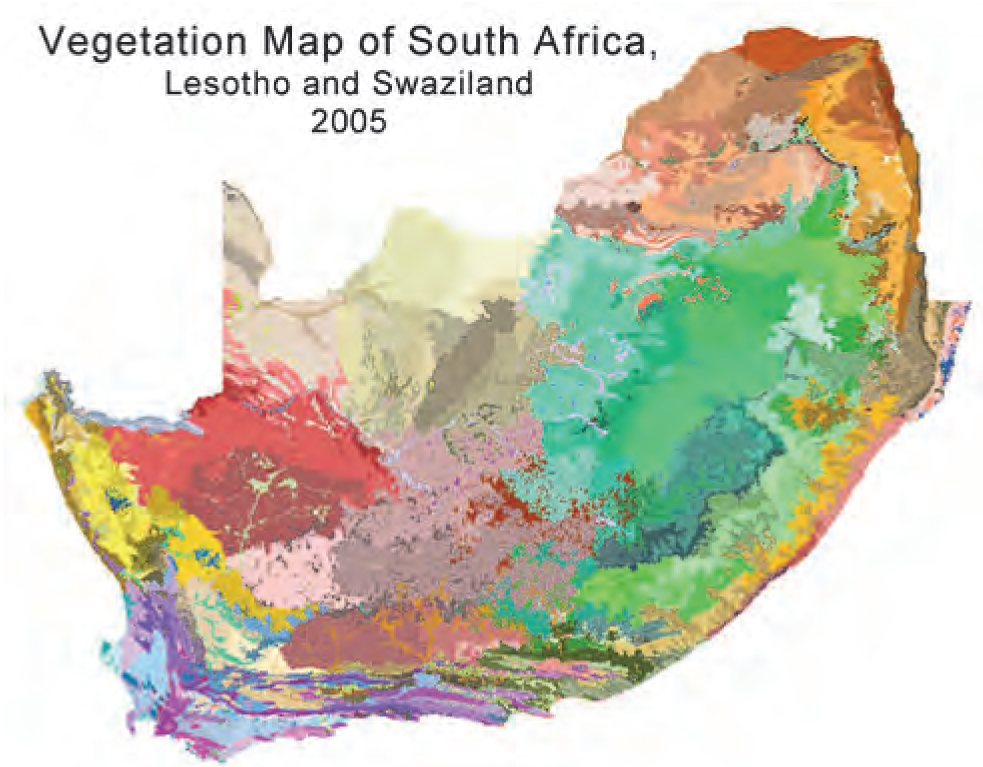


Figure 35 Vegetation map of southern Africa (Mucina and Rutherford, 2006)

It is noteworthy that the WRC has recently funded a new three-year project (WRC Project No. K5/2437), which started in April 2015, to update *ACRU* parameters from those representing the Acocks baseline to those representing the more detailed Mucina and Rutherford (2006) vegetation. This vegetation map includes 435 zonal and azonal vegetation types mapped at a working scale of 1:250 000. It provides more detail on plant characteristics and is considered more spatially explicit than that of Acocks.

5.3.2 Acocks' Veld Types

To date, the Acocks (1988) veld types (70 in total) are the most commonly used indicator of baseline land cover in South African hydrology. Acocks' initiatives in the 1940's and 1950's to document and map the vegetation of South Africa had a significant effect on ecology in the country. Acocks' classification soon became the standard reference for indigenous vegetation of South Africa. Despite the value of Acocks' veld types, it has nevertheless remained unchanged since it was first published about fifty years ago. It is envisaged that the Mucina and Rutherford (2006) vegetation map will replace the Acocks (1988) veld type map, and become the new indicator of baseline land cover for all South African hydrology studies that consider the water use and potential for stream flow reduction of non-irrigated crops.

For each quinary, *ACRU* simulations were performed for the dominant Acocks Veld Type (i.e. that veld type covering the largest area in each quinary). This provided baseline stream flow volumes for each sub-catchment against which estimated stream flow reductions resulting from a land use change to feedstock production could be assessed. Stream flow reductions were therefore assumed to be the difference between stream flow simulated for a quinary where 100% of the dominant Acocks Veld Type is replace by a biofuel feedstock.

Reductions in mean and median annual stream flow totals and low flow indices (driest three months) were calculated in this manner.

5.3.3 Model parameterisation

ACRU input parameters and variables for Acocks Veld Types were obtained from the COMPOVEG database maintained by the CWRR. Model parameters representing Acocks were characterised in accordance with guidelines from the National Botanical Institute. Further explanation on the derivation of these values for the 70 baseline land cover types was provided by Schulze (2004) and Schulze (2008). If the dominant land cover is grassland, the model parameterisation represents the average state of grassland in a particular quinary sub-catchment.

5.4 Original Quinary Sub-catchment Database

In this section, a summary is given of the derivation of the quinary sub-catchments by Schulze and Horan (2011). In addition, a summary of the quinary sub-catchment database developed by Schulze *et al*. (2011) is also given.

For operational decision making, South Africa has been delineated into 22 primary catchments, each of which has been sub-divided into interlinked and hydrologically cascading quaternary catchments. A total of 1 946 quaternaries (originally delimited by the former Water Affairs Department) make up the contiguous area of the RSA, Lesotho and Swaziland (Schulze and Horan, 2011).

Quinary sub-catchments are topographically based sub-divisions of the national quaternary catchments. Each quaternary (4^{th} level) catchment was divided into three quinary (5^{th} level) sub-catchments according to altitude criteria. The upper, middle and lower quinaries of unequal area (but of similar topography) were sub-delineated according to “natural breaks” in altitude by applying the Jenks’ optimisation procedure. This resulted in 5 838 quinary sub-catchments deemed to be more homogeneous than the quaternaries in terms of their altitudinal range (Schulze and Horan, 2011). This implies that the terrain unit classification and dominant soil types are likely to be similar across the quinary.

The rainfall station previously selected to “drive” the hydrological response of each quaternary catchment was also selected to represent the three quinary sub-catchments within the parent quaternary. However, the driver station for 11 quaternaries (i.e. 33 quinaries) was changed in order to improve the representation of rainfall in those catchments (Schulze *et al*., 2011). In total, daily rainfall values from 1 240 stations are used to “drive” the hydrology of the 1 946 quaternaries. By implication, one rainfall station often “drives” the hydrology of numerous quaternaries.

Multiplicative rainfall adjustment factors (called *CORPPT* in *ACRU*) were then determined for each sub-catchment and applied to the driver station’s daily records in order to render the driver station’s daily rainfall to be more representative of that of the quinary. Thus, a unique 50-year daily rainfall record was created for each of the 5 838 quinaries. The adjustment factors were derived by first calculating the 12 spatial averages of all the one arc minute (≈1.6 by 1.8 km) gridded median monthly rainfall values (determined by Lynch, 2004) within each quinary. The ratio of these sub-catchment average median monthly rainfalls to the driver station's median monthly rainfalls was then calculated to arrive at 12 monthly adjustment factors.

The daily temperature database developed by Schulze and Maharaj (2004) for each one arc minute of a degree (latitude/longitude) grid point across southern Africa, was used to derive representative data for each quinary. The grid point with an altitude similar to that of the sub-catchment mean, and located as close as possible to the sub-catchment centroid, was selected to represent each quinary (Schulze *et al*., 2011).

Southern Africa lacks an adequate network of solar radiation stations, each with a long quality controlled record. Hence, solar radiation was estimated from temperature data as described by Chapman (2004) and Schulze and Chapman (2007). From this, daily estimates of reference evaporation (Penman-Monteith or FAO56 equivalent) were derived, as described by Schulze *et al*. (2007d). A default wind speed of 1.6 m s^{-1} was used to derive the FAO56-based evaporation estimates.

Multiplicative evaporation adjustment factors (called *CORPAN* in *ACRU*) were then determined for each sub-catchment and applied to the FAO56 evaporation estimates in order to obtain PAN equivalent values. An equation given by Allen *et al*. (1998; p 82) was used, whereby monthly pan coefficients (K_p) are estimated for a Class A-pan surrounded by a 200 m fetch of short, green vegetation. The method requires the average wind speed (1.6 m s^{-1}), green fetch distance (200 m) and mean relative humidity (%) to calculate monthly K_p, from which the reciprocal (i.e .1/K_p) is used for *CORPAN* in *ACRU*.

Thus, the quinary sub-catchment database consists of 50 years (1950-1999) of daily climate data for each of the 5 838 quinaries. Hence, daily rainfall, maximum and minimum temperature, reference evaporation (Penman-Monteith), incoming solar radiation as well as maximum and minimum relative humidity are available for each sub-catchment.

Values for the hydrological soils variables required by *ACRU* were derived from the SIRI land types identified in each quinary (on an area-proportioned basis). Thus, one set of area-averaged soils attributes has been derived for the entire quinary sub-catchment (Schulze *et al*., 2011). For a more detailed description of the quinary sub-catchment database, the reader is referred to Schulze *et al*. (2011).

5.5 Revised Quinary Sub-catchment Database

In this section, the quinary sub-catchment climate database was revised to improve estimates of temperature and reference evaporation for each quinary. A number of anomalies in the climate database were discovered and corrected.

5.5.1 Updated temperature estimates

The quinary sub-catchment climate database (as described briefly in the previous section) contains daily estimates of maximum and minimum temperature derived by Schulze and Maharaj (2004). These estimates were derived using an algorithm originally developed by Schulze and Maharaj (2004). This algorithm used the 1) altitude difference, and 2) the distance between the temperature station and the point of interest to select two representative stations accordingly. The two stations with the highest weighting are then chosen for the point of interest. Finally, adiabatic lapse rates are used to adjust for altitude differences between the two selected stations and the point of interest.

The algorithm developed by Schulze and Maharaj (2004) was significantly improved by assigning more emphasis to distance rather than altitude difference. In essence, the algorithm uses these two factors to rank initially the five most suitable temperature stations for a particular quinary. The centroid of the quinary is selected as the "point of interest", from which the distance to each surrounding temperature station is computed. The quinary's spatially averaged altitude is then compared to the altitude of the surrounding temperature stations.

This suitability ranking (*RANK*) is more sensitive to the distance factor (*DSTF*, i.e. based on the distance between the station location and the quinary centroid), rather than the altitude factor (*ALTF*, i.e. based on the difference between the station's height and the quinary mean altitude). In other words, the distance factor is assigned far more weighting than the altitude factor as follows:

$$RANK = (10 \cdot DSTF) + (1 \cdot ALTF) \qquad \textbf{Equation 49}$$

For simplicity, distances are calculated in minutes of a degree (not kilometres) and altitude differences in masl. Any station more than 250 minutes of a degree (or 250 * ≈1.7 km = 434 km) away from the quinary centroid is assigned the same factor of 0.1. A station located at the same location as the quinary centroid is assigned a distance factor of 1.0. The distance threshold of 250 minutes was determined through a "trial and error" process where the algorithm was repeatedly run until it produced the same station section as was chosen manually. Similarly, all stations more than 1 500 m above or below the quinary mean is assigned a factor of 0.1 (and 1.0 for zero altitude difference). Again, this threshold was determined by comparing the automated station selection *vs.* manual selections for a range of different quinary sub-catchments.

In another study (Lumsden *et al*., 2011), the station selection algorithm was also used to derive temperature data for each quinary using the output from numerous GCMs for 404 station locations. A distance threshold of 350 minutes was used in this study due to the paucity of stations with future climate record. Ideally, the above-mentioned distance and altitude thresholds should be small as possible. However, there are only 973 climate stations that record temperature across southern Africa. The other problem is the stations are not uniformly spread across the country. There are 123 stations at the same location as another station, with two locations having four stations and 14 locations exhibiting 3 stations.

From the five identified stations, two are then selected as the "best" and used to generate daily temperature data deemed representative of the quinary centroid. The five stations are re-ranked relative to the station furthest away and the station with the greatest altitude difference. This ensures that the "worst" of the five stations exhibits the lowest ranking. However, more weighting is assigned to the altitude factor as follows:

$$RANK = (10 \cdot DSTF) + (3 \cdot ALTF) \quad \textbf{Equation 50}$$

This allows for a station slightly further away from the sub-catchment centroid to be selected if the altitude difference is much smaller than the closest station. Once the two most presentative stations for each centroid location were finalised, lapse-rate adjusted temperature estimates were derived. Finally, quality control checks were performed to ensure that, *inter alia*, maximum temperatures are non-negative and higher than minimum temperatures. The reader is referred to Lumsden *et al*. (2011) for additional information on the methodology.

5.5.2 Updated reference evaporation estimates

To re-cap, the original quinary sub-catchment climate database consists of FAO56 evaporation estimates derived using a default wind speed of 1.6 m s^{-1}. PAN equivalent evaporation values (as required by the *ACRU* model) are obtained using a monthly multiplicative factor based on an equation developed by Allen *et al*. (1998). Once the temperature estimates for each quinary sub-catchment were updated (c.f. **Section 5.5.1**), they were used to derive new FAO56-based reference evaporation values. However, this methodology was modified to account for the research findings of Allen *et al*. (1998), Shuttleworth (2010) and a number of Australian studies (e.g. Rotstayn *et al*., 2006; McMahon *et al.*, 2013).

5.5.2.1 The calculation of net radiation

The calculation of daily net radiation (R_n) is required by the Penman-Monteith (or FAO56) equation to estimate reference crop evaporation (or ET_o). According to Shuttleworth (2010), it defines the net energy available for evaporation to occur. R_n is calculated as the difference between incoming shortwave radiation (R_s) that is absorbed (1- α) by the evaporating surface and the net outgoing longwave radiation (R_{nl}; assumed to be independent of the surface):

$$R_n = (1 - \alpha) \cdot R_s - R_{nl} \quad \textbf{Equation 51}$$

In the above equation, alpha (α) represents the albedo of the evaporating surface and $(1 - \alpha) \cdot R_s$ the net shortwave radiation (R_{ns}). It was noticed that negative outgoing longwave radiation values were being estimated for certain sub-catchments. This meant that instead of R_{nl} being an energy loss (i.e. unavailable for evaporation), it was a gain. Further investigation revealed that negative R_{nl} values occurred when R_s estimates were less than 9.4 MJ m^{-2} day^{-1}, which resulted in relative shortwave radiation (R_s / R_{so}) estimates below 0.259. Hence, the term ($1.35 \cdot R_s / R_{so}$ - 0.35) used in the calculation of R_{nl} becomes negative. This term represents the portion of outgoing longwave radiation that is absorbed by clouds and re-radiated back towards the earth's surface.

5.5.2.2 Incoming shortwave radiation adjustments

Incoming solar radiation (R_s) was estimated from the daily temperature range using the Bristow and Campbell (1984) equation. However, Schulze and Chapman (2007) made two modifications to the original Bristow and Campbell (1984) equation. The modifications were shown to improve estimates of 1) extra-terrestrial radiation (R_a) and 2) estimates of R_s on cloudy and rainy days, across southern Africa.

During clear sky conditions, R_s / R_{so} approaches unity (i.e. 1) which equates to a large net outgoing energy flux (R_{nl}) and thus, less energy available for evaporation. R_{so} is the portion of incoming solar radiation (R_s) that reaches the evaporating surface during cloudless (i.e. clear sky) conditions. According to Allen *et al*. (1998; p 42), the ratio R_s / R_{so} represents the degree of cloud cover, with typical values ranging from about 0.3 (dense cloud cover) to 1.0 for clear skies. Allen *et al*. (1998) recommends that R_s / R_{so} is limited to 1 (i.e. $R_s \leq R_{so}$), but does not mention a check for $R_s < 0.3 \cdot R_{so}$. This check was implemented during the calculation of R_{nl} which revealed a total of 1 414 579 daily instances affecting 3 835 quinaries. These anomalies were then corrected by adjusting R_s to $0.3 \cdot R_{so}$. No events of R_s exceeding R_{so} were found.

Allen *et al.* (1998; p 60) also noted that the fraction of extra-terrestrial radiation (R_a) that reaches the earth's surface (i.e. R_s / R_a) ranges from about 0.25 on a day with dense cloud cover to about 0.75 for clear skies. Roderick (1999) found that the clearness index (R_s / R_a) ranged from 0.26 (totally overcast) to a high of 0.77 to 0.79. Chapman (2004; p109) stated that the upper limit for R_s / R_a is about 0.77 for South Africa. Although this check was implemented, no daily events were noted when generating R_s values for each of the 5 838 quinaries. However, a total of 2 277 605 daily occurrences of $R_s < 0.23 \cdot R_a$ were found, which were corrected. Almost all quinaries (5 834 out of 5 838) were affected by this anomaly.

5.5.2.3 Corrected outgoing longwave radiation

The above-mentioned adjustments to estimated R_s values (i.e. $R_s > 0.3 \cdot R_{so}$ & $R_s > 0.23 \cdot R_a$) ensured that $R_s/R_{so} > 0.30$, thus preventing negative R_{nl} values from being generated. Hence, these checks improved the estimates of net radiation used by the FAO56 method.

5.5.2.4 Dew point temperature check

The dew point temperature was calculated from actual vapour pressure estimates on a monthly basis using equation 3.11 from Allen *et al*. (1998). A check was implemented to test if the average temperature (T_{ave}) was 4°C above the dew point temperature (T_{dew}) on a monthly basis. This difference was suggested by Linacre (1992). A total of 213 795 daily occurrences where $T_{ave} - T_{dew} < 4$°C were noted, but not corrected.

5.5.2.5 Default wind speed

Shuttleworth (2010) suggested that a wind speed of 2.0 m s^{-1} should rather be used in the absence of observed data. This concurs with Allen *et al*. (1998; p 63) who noted that 2 m s^{-1} is the average wind speed for over 2 000 climate stations across the world. Hence, the wind speed was adjusted from the default 1.6 m s^{-1} used in the original quinary sub-catchment climate database (c.f. **Section 5.4**) to 2.0 m s^{-1} for this study.

5.5.3 Revised pan factors

The *PENPAN* equation was applied at the monthly time step so that heat storage in the pan's water could be neglected. Hence, pan coefficients (K_p) were derived for each quinary sub-catchment as the ratio of ET_o and E_p calculated using the FAO56 and *PENPAN* equations respectively. From this, monthly *CORPAN* values were calculated as the reciprocal of K_p.

5.5.4 Adjustment of FAO56-crop coefficients

In the *SFRA* project (Jewitt *et al*., 2009b) and the biofuels scoping study (Jewitt *et al*., 2009a), all crop coefficients derived using the FAO56 reference were divided by 1.20 to adjust them to the PAN-equivalent reference, before being used as input for the *ACRU* model.

In this study, PAN-equivalent crop coefficients [K_c(PAN)] were derived by dividing the monthly FAO56-based crop coefficients [K_c(FAO)] for each feedstock, by the monthly *CORPAN* (i.e. $1/K_p = E_p/ET_o$) values derived for each quinary (**Equation 52**) and thus, represents a unique approach.

$$K_c(FAO) = \frac{E_m}{ET_o} \, x \, \frac{ET_o}{E_p} = \frac{E_m}{E_p} = K_c(PAN) \qquad \textbf{Equation 52}$$

5.6 National Model Runs

In **Chapter 4.2**, the parameters used to run the *ACRU* model were given for each feedstock. In addition, the revision of the quinary sub-catchment climate database were also discussed in **Section 5.5**. This section focuses on the changes that were made to the version of the *ACRU* model used in this study. In addition, the logistics of running the model at the national scale are discussed.

5.6.1 Modifications to *ACRU*

For the final stream flow simulations presented in **Volume 3**, *ACRU* version 3.37 was used. The changes made to the model from version 3.33 (used in previous studies) to 3.37 are briefly highlighted below.

Owing to readily available estimates of daily maximum and minimum temperature, changes were made to version 3.33 of *ACRU* to replace the use of monthly temperatures with daily values. Approximately 19 000 lines of code were scanned for the use of monthly temperature. The most significant change was made in the Ritchie subroutine which is invoked when transpiration and soil water evaporation are estimated as separate components (i.e. when parameter *EVTR* is set to 2). In this subroutine, the daily crop coefficient value is reduced when the plant experiences soil water stress. When this stress is relieved through rainfall (or irrigation), the crop coefficient recovers at a rate determined by the mean monthly air temperature (Kunz, 1994). This recovery was modified to use mean daily air temperature instead. Similarly, the calculation of effective transpiration was also modified to use daily and not monthly temperature. Finally, the calculation of primary productivity was changed to use daily, rather than monthly temperature.

Version 3.34 (and above) of the *ACRU* model was configured to run a maximum of 6 000 sub-catchments, each with 200 years of daily data. This configuration accommodates the current projects undertaken by the Centre (CWRR) which involve running *ACRU* at the quinary level (5 838 sub-catchments), with up to 140 years of daily climate data (1961-2100) derived from GCM output.

In *ACRU* version 3.35, a significant change was also made to a variable called *COFRU*. It represents the coefficient of base flow response, which determines the fraction of daily groundwater store that is released as base flow, which then contributes to stream flow (when *IRUN* is set to 1). On days where drainage doesn't contribute to the base flow store, *COFRU* determines the amount of groundwater store that is released as base flow. In other words, *COFRU* controls the rate of base flow from the groundwater store and was set to 0.009 for the *ACRU* runs.

The user-specified *COFRU* value is adjusted within *ACRU*, depending on whether the base flow store (*RUNCO* in mm) is relatively "full" or relatively "empty". Hence, *COFRU* is now modified using *RUNCO*, based on an exponential function, i.e. *COFRU* increases exponentially from 0.001 to 0.020 as *RUNCO* increases from 0.001 to ≈150 mm. In general, the modification generates more base flow store (*RUNCO*), but releases less base flow. However, when the base flow store is "full", more base flow is released (than compared to before the modification).

A minor correction was also made to set the minimum base flow store (*RUNCO*) to 0.001 mm and not 1.1 mm. This anomaly was noted in dry sub-catchments where little or no base flow is generated (e.g. quinary 2 613). Hence, the base flow store averaged 1.1 mm per day, which over-estimated the runoff generation from the sub-catchment. *RUNCO* was set to 0.001 mm so not to affect stream flow "trickle", but also to avoid division by zero errors (which occurs when other related variables become zero in the model).

ACRU version 3.36 was updated with a new approach to estimate primary productivity for grasslands. However, this modification does not influence the output presented in this report and thus, is not discussed further. Version 3.36 was re-compiled using Intel's FORTRAN compiler software (v14) to produce a new 64-bit version (called 3.37). The Intel compiler was used to create two 64-bit versions of the model, namely one suited to run on a Core 2 Duo PC and the other optimised for a Core I7 PC. However, the new FORTRAN compiler detected a number of variables that were not initialised properly, which were then corrected. Hence, 12 (out of 177) subroutines as well as the main program were modified accordingly.

Both CPU versions of the *ACRU* model were thoroughly tested on drainage basins M and P, to ensure that floating point calculations were the same as those produced by the previous version (i.e. 3.36). However, the new version "crashed" whilst running at the national scale (i.e. for all basins) on drainage basins A, E, G, H, J and Q, affecting 1 512 of the 5 838 quinary sub-catchments. The model was re-compiled to ignore floating point errors to temporarily correct this anomaly.

5.6.2 National runs

Although *ACRU* has been setup to run for all 5 838 quinaries, it cannot complete all quinaries in a single run. In order to simplify the complexity of this task, *ACRU* is run at the primary drainage basin level. Primary basins C and D cannot be run separately as quinary 1 431 (basin C) flows into quinary 1 929 (basin D). Hence, the model runs for each of the 21 basins, since primary's C and D are run together (**Table 55**). This approach improves the time required to complete all 5 838 runs, with the model running fastest for primary M (24 quinaries) and slowest for primary CD (1 443 quinaries).

Table 55 The relationship between each primary drainage basin and the quinary sub-catchments

Primary catchment	Start quinary	End quinary	No. of quinaries
A	1	417	417
B	418	852	435
CD	853	2 295	1 443
E	2 296	2 520	225
F	2 521	2 625	105
G	2 626	2 799	174
H	2 800	3 006	207
J	3 007	3 282	276
K	3 283	3 402	120
L	3 403	3 576	174
M	3 577	3 600	24
N	3 601	3 708	108
P	3 709	3 756	48
Q	3 757	3 969	213
R	3 970	4 059	90
S	4 060	4 233	174
T	4 234	4 635	402
U	4 636	4 821	186
V	4 822	5 079	258
W	5 080	5 526	447
X	5 527	5 838	312
Total			**5 838**

For national scale simulations, the “norm” was to run the model manually for each drainage basin as user intervention was required in-between each step. This resulted in significant time being “wasted” between basin runs. For example, the national runs usually started with primary CD, as this represented the most complex (and longest) task. The run was started in the late afternoon and allowed to complete overnight. The next basin run was started manually the following day and this process was repeated until all subsequent basin runs were completed.

However, considerable effort was devoted to automating the procedure whereby *ACRU* runs non-stop for all 21 basins. This effort has significantly improved efficiency by reducing the overall time required to complete a national run. Furthermore, the automation allows for a feedstock to be re-run if 1) errors are discovered during the analysis, or 2) parameters are refined based on new evidence. Thus, much effort was also spent on ensuring the automation procedure runs smoothly and correctly.

In the past, a national run completed in approximately 26 hours on a Core 2 Duo PC. The automation procedure has since been further optimised, reducing the run time down to 19 hours. No further optimisation is deemed possible and thus, the current automation technique is considered highly efficient (i.e. computational expense is minimised). It is also important to note that the PC's anti-virus software was disabled whilst the model was executing the national runs. This considerably reduces the time to completion.

5.6.3 Modelling approach and application

The approach followed in this project is consistent with that used in the past to estimate the water use of commercial forestry and sugarcane (Jewitt *et al*., 2009b), as well as selected biofuel feedstocks (Jewitt *et al*., 2009a). All these studies used the *ACRU* modelling system to assess the impact of proposed land use changes on stream flow generation, relative the stream flow generated from a land cover of natural vegetation as depicted by the Acocks Veld Type map. Hence, no changes were made to the parameters used to estimate the baseline runoff response. However, numerous other changes were made in this study as summarised below:

- The parameters used for sugarcane differ to those used in the SFRA study undertaken by Jewitt *et al*. (2009b). The values used for the three growing regions (North Coast, South Coast and Inland) were averaged to provide one set of "generic" crop-specific parameters and variables.

- Similarly, the original parameters used for sugarbeet, sorghum, canola, soybean and sunflower in the scoping study (Jewitt *et al*., 2009a) were refined extensively.

- If crop coefficients for a particular feedstock were derived using FAO56 as the reference, they were adjusted to PAN equivalent values using new pan coefficients that vary spatially.

- The rainfall adjustment factors (called *CORPPT* in *ACRU*) used in this study are those described by Schulze *et al*. (2011), which differ to that used in the SFRA and scoping studies.

- Daily estimates of reference evapotranspiration for each quinary were derived using the Penman-Monteith (FAO56) method. Solar radiation was estimated using the technique summarised by Schulze *et al*. (2011). Wind speed was assumed to be 2.0 $m\ s^{-1}$.

- New APAN adjustment factors were determined (called *CORPAN* in *ACRU*) using a unique approach (the modified *PENPAN* equation), which may indicate that APAN evaporation was under-estimated in previous studies.

- The monthly *CORPAN* adjustments were applied to the Penman-Monteith reference evaporation estimates to ensure that the APAN reference crop coefficient values used for natural vegetation were applicable.

- Significant improvements were made to optimise model runs at the national scale in order to reduce computational expense.

- The *ACRU* model was run at the national scale for all 5 838 quinaries, regardless of whether the feedstock can be successfully grown in the quinary.

- For each quinary, *ACRU* simulations were performed for the dominant Acocks Veld Type (i.e. that veld type covering the largest area in each quinary). This provided baseline stream flow depths for each sub-catchment against which estimated stream flow reductions resulting from a land use change to feedstock production could be assessed.

- Feedstock water use was calculated relative to that of natural vegetation, i.e. water use is considered the difference between stream flow generated by the proposed land use and that of Acocks.

- Stream flow reductions were therefore assumed to be the difference between stream flow simulated for a quinary where 100% of the dominant Acocks Veld Type is replace by a biofuel feedstock. Reductions in mean annual stream flow totals and low flow indices (driest three months) were calculated in this manner.

- The model was run in “distributed” mode and not “lumped” mode, which allows for the estimation of stream flow that includes contributions from upstream sub-catchments.

- Output was presented in a form compatible with the utilities and tools used for the management and assessment of existing SFRAs, i.e. for commercial forestry.

The main reason for running the model for all quinaries was to avoid the scenario where, if a land suitability map for a particular feedstock is updated or refined, additional model runs may then be required for quinaries not previously highlighted as being suitable for the production of that feedstock.

In order to run *ACRU* in “distributed” mode, the quinary immediately downstream of the sub-catchment under consideration must be known. For example, the upper quinary “flows” into the “middle” quinary, which then flows into the “lower” quinary. The lower quinary (which now represents the outlet of the original quaternary) flows into the outlet (i.e. lower quinary) of the downstream quaternary, which could then, for example, flow into the sea. This allows the output from the *ACRU* runs to be used for other purposes (other than to meet the objectives of the biofuels project).

6 BIOFUEL YIELD POTENTIAL OF FEEDSTOCKS

This chapter provides a description of the methodology used to derive national estimates of attainable yield for five prioritised feedstocks. This section therefore pertains to **AIM 5** of this project's terms of reference, which requires the determination of biofuel yield potential. In order to determine biofuel yield potential, an estimate of biofuel feedstock yield is first required.

6.1 Introduction

6.1.1 Definition of attainable yield

In thus study, attainable yield is defined as the utilisable portion of the plant biomass that contains sugar, starch or vegetable oil which can be converted into biofuel. This yield was obtained under dryland farming conditions which may be water stressed and thus, is referred to as a water-limited yield potential. Although the crop may be water stressed, it is assumed that soil fertility is not limiting to plant growth and that no competition from weeds exists.

Furthermore, it is also important to be specific about the nature of the yield (e.g. wet or fresh *vs*. dry mass, in-shell *vs*. de-husked etc.). Yield and water use efficiency depend on crop physiology (C_3 *vs*. C_4 crop and variety used), agronomy (planting density and planting date), site conditions (climate, soils and terrain) as well as other management practices (site preparation, irrigation use, fertiliser use & weeding control). By definition, quantification of water use efficiency requires knowledge of the feedstock's yield as well as the water use.

6.1.2 Modelling approach and application

Since it is virtually impossible to measure crop yield (and water use) for all possible combinations of climate, soils and management conditions in South Africa, it is necessary to either develop a new model, or use an existing model. The model should accurately simulate attainable yield of biofuel feedstocks across a wide range of growing conditions and management practices.

According to Teixeira (2008), the most common methods for estimating crop production include calculations range from simple empirical methods, to complex mechanistic crop growth models. By definition, a model is a simplified representation of a real world system. A crop model should be complex enough to comprehensively represent the system, yet simple enough to be applied and used. To date, a single universal crop model does not exist. Instead, numerous crop yield models have been developed that simulate, *inter alia*, different crops, processes and environmental conditions (Steduto, 2006).

6.1.2.1 Empirically-based models

Empirical yield models include equations which predict yield using various agro-meteorological indices such as, *inter alia*, rainfall, temperature, growing degree days and vapour pressure deficits. Typically, such equations are developed using a multiple regression analysis of agro-meteorological indices as independent variables to predict crop yield. Ideally, empirical crop models should not be used in conditions outside the environment in which they were developed.

Smith (1994; 1998; 2006) developed a suite of empirical models to estimate crop yield in South Africa. This was done for a range of crops according to climatic criteria (effective rainfall; accumulated heat units) adjusted for 1) different levels of management, and 2) soils characteristics. These equations should not be applied outside the climatic criteria for optimum growth for a particular crop, nor can they account for the effects of CO_2 on crop yield.

6.1.2.2 Mechanistic-type models

Most crop models are mechanistic, which implies that in a given context, defined by the set of variables, a unique output is calculated (Gary *et al*., 1998). The mechanistic approach is based in a thorough understanding of the mechanisms driving crop growth and yield. However, mechanistic-type models need to be parameterised for each crop cultivar.

Although most mechanistic models have distinctive features, they are based on common principles for estimating crop yield. All crop growth models are based on a “growth engine” that simulates the production of biomass from captured resources, such as solar radiation, carbon dioxide water and nutrients (Steduto, 2006). Most of the growth engines used by different crop models can be grouped into the following three categories:

- Carbon-driven: growth is based on the assimilation of carbon by leaves during the photosynthetic process. These complex models simulate carbon partitioning, root development as well as various other feed-back and feed-forward mechanisms. Parameterisation is quite demanding in terms of time and resources for new crop cultivars.

- Solar-driven: based on a linear relationship between biomass production and intercepted solar radiation, with the slope of this line called the radiation use efficiency or RUE. However, this linear relationship is lost (i.e. becomes non-linear) under water stressed and nutrient deficient conditions.

- Water-driven: based on a linear relationship between biomass production and cumulative transpiration (called the water productivity term). However, the relationship also loses its linearity under water stressed, nutrient deficient or highly saline conditions, similar to the solar-driven growth engine (Steduto, 2006).

6.2 Appropriate Models

The use of Barry Smith’s simple empirical models was not considered appropriate for this study because the models are largely based on experience from KwaZulu-Natal. Thus, extrapolating the results to other Provinces such as the winter rainfall region of the Western Cape may be problematic. Furthermore, Smith has not developed models for canola or sugarbeet as these crops are not grown in KwaZulu-Natal.

Owing to the complexity of carbon-driven models, they were not considered for use in this study. Of the two remaining growth engines, Steduto (2006) stated that water-driven crop models are the most robust and most promising of the three growth engines highlighted. Such models exhibit low sensitivity to stresses and are less prone to errors, provided leaf expansive growth (i.e. leaf area) and conductance are properly simulated. Based on this recommendation, the *AQUACROP* model developed by the FAO was selected for yield simulation. This model is based on a water-driven growth engine. Similarly, the *SWB* model developed by the University of Pretoria was also selected for use, which has a solar-driven growth engine model.

6.2.1 The solar-driven growth engine

Since solar radiation is the primary driving force for all growth engines, some crop models derive the biomass directly from the intercepted solar radiation through a single synthetic coefficient. Such models are therefore based on the solar-driven growth engine. Solar-driven models differ from carbon-driven models as there are no intermediary steps required to estimate biomass accumulation. This does not mean that the underlining processes are absent, but only that they are synthetically incorporated into a coefficient called radiation use efficiency (RUE or ε).

RUE is used to estimate biomass production directly from solar radiation, without the intermediate steps to calculate photosynthesis and respiration. RUE is defined as the ratio of above-ground biomass production (g m^{-2}) to intercepted PAR (MJ m^{-2}) and represents a linear relationship under non-stressed conditions (**Figure 36**). Numerous RUE values are available for different crops and locations in the literature. Sinclair and Muchow (1999) described how to experimentally determine and measure RUE and summarised (with critical analysis) all literature values for a large number of crops (Steduto, 2006).

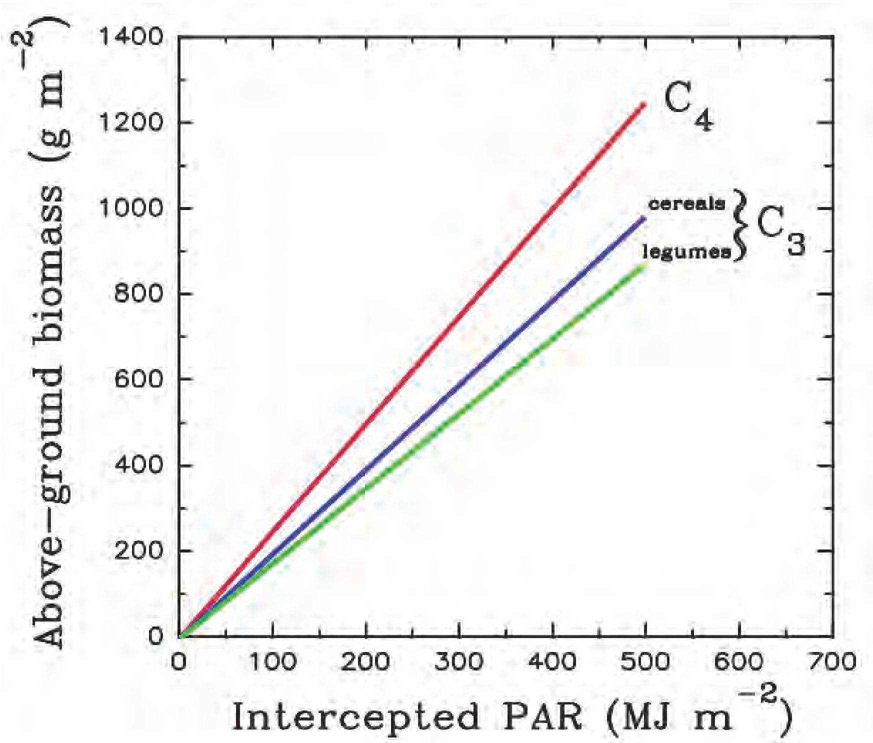


Figure 36 Theoretical relationship between above-ground biomass and intercepted solar radiation for C_4 and C_3 crops. The slope of the linear relationship represents the radiation use efficiency or RUE (after Gosse *et al*., 1986)

The main disadvantage of this type of growth engine is related to the diversity in biomass sampling and intercepted solar radiation measurement techniques, which affect the determination of RUE. Furthermore, the slope of the relationship shown in **Figure 36** loses its linearity under water stressed and nutrient deficient conditions. This non-linearity also occurs when the dry matter produced contains high energy-content compounds such as lipids (Steduto, 2006).

6.2.2 The water-driven growth engine

There is a strong relationship between cumulative biomass production and cumulative canopy transpiration (Tanner and Sinclair, 1983). This relationship is based on the premise that carbon assimilation occurs when the plant is actively transpiring. Hence, stomatal conductance exhibits a similar impact on both the assimilation and transpiration processes. These two processes are controlled by the concentration gradients of CO_2 and H_2O between the ambient air and the intercellular air spaces. The difference between assimilation and transpiration is related to the biochemical carboxylation capacity of the leaves (Steduto, 2006).

The relationship between assimilation and transpiration observed at leaf scale is retained at crop scale, provided that respiration remains a constant proportion of carbon assimilation under different environmental conditions. Hence, dry matter production is estimated from transpiration using the biomass/transpiration (or B/T) ratio, which is also referred to as the water productivity (or water use efficiency) value. Hence, the ratio of biomass production (in g) to transpiration loss (in kg) represents a linear relationship under non-stressed conditions (Tanner and Sinclair, 1983). However, the relationship also loses its linearity under water stressed, nutrient deficient or highly saline conditions, similar to the solar-driven growth engine (Steduto, 2006).

Another disadvantage of this approach is the difficulty in estimating actual transpiration loss from the crop canopy. It is recommended that transpiration is divided by the evaporative demand of the atmosphere (E_r or ET_o), in order to normalise climatic variability across different locations (**Figure 37**). The normalisation appears ineffective when carried out using vapour pressure deficit (Steduto, 2006). It is important to note that carbon assimilation utilises the photosynthetic active component of the captured radiation (i.e. PAR), whilst transpiration utilises all intercepted solar radiation. In general, PAR is a fairly constant proportion (≈50%) of the incident solar radiation (Monteith, 1972).

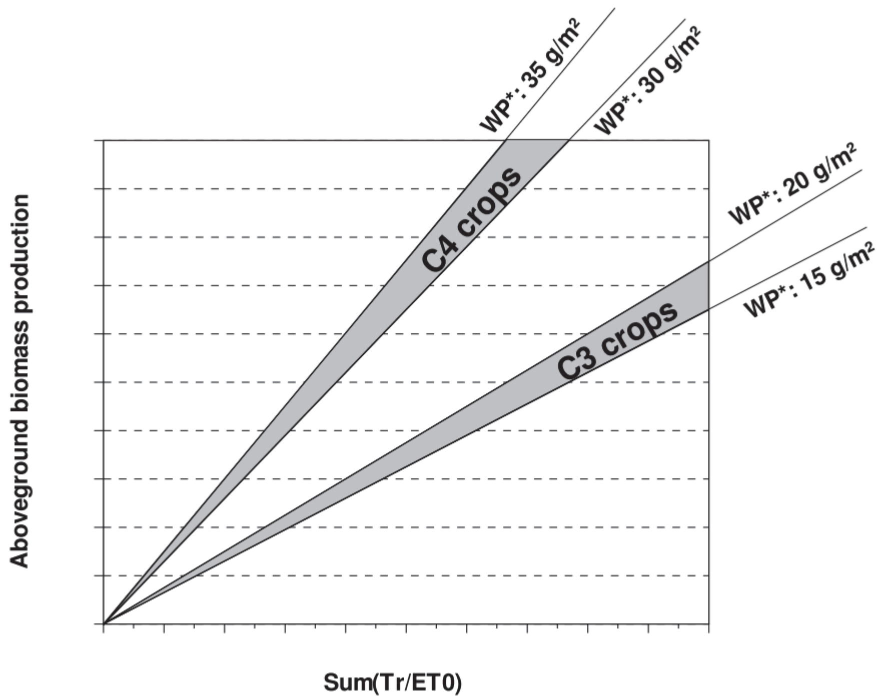


Figure 37 The relationship between above-ground biomass and accumulated transpiration for both C_3 and C_4 crops, after normalisation using ET_o (Raes *et al*., 2011)

6.3 The *SWB* model

The Soil Water Balance (*SWB*) model (Annandale *et al*., 1999) is a mechanistic-type, daily time step, irrigation scheduling model. Although *SWB* was originally developed as a tool for irrigation management, the model is also capable of simulating yield. The user has the option to choose between the crop growth model or a FAO crop factor model. The FAO model cannot simulate crop growth and yield, but an estimation of yield reduction due to water stress is possible. The crop growth model requires the determination of crop-specific model parameters for each crop in order to simulate growth, water use and dry matter production (yield). A description of the parameters required by the crop growth model and the FAO model is given next.

6.3.1 *SWB* parameters (growth model)

The crop-specific parameters required by *SWB*'s growth mode reflect the species' or cultivar's canopy characteristics, degree days to different phenological stages and potential dry matter production (which in turn are affected by a cultivar's genotype and the growing conditions). Model growth parameters for different crops are usually determined from growth analysis data collected from field experiments.

The canopy radiation extinction coefficient for solar radiation (K_s) was determined using a basic equation that describes the transmission of solar radiation through the plant canopy, according to Bouguer's law (Campbell and Van Evert, 1994):

$$FI_s = 1 - exp(-K_s \cdot LAI) \quad \textbf{Equation 53}$$

where FI_S is fractional interception of solar radiation and *LAI* is leaf area index (m^2 m^{-2}). The light extinction coefficient for solar radiation (K_s) is used by *SWB* to predict radiation-limited dry matter production (Monteith, 1977) and for partitioning evapotranspiration into evaporation from the soil surface and crop transpiration (Ritchie, 1972).

Radiation use efficiency (E_c in MJ^{-1}) is determined based on a linear relationship established by Monteith (1977) between accumulated crop dry matter and intercepted solar radiation, which is:

$$DM = E_c \cdot FI_s \cdot R_s \qquad \textbf{Equation 54}$$

where *DM* is dry matter production (g m^{-2}), FI_s is fractional interception for total solar radiation, and R_s is daily total incident solar radiation (MJ m^{-2}). The E_c value was determined by fitting a linear regression equation between cumulative biomass production and cumulative R_s interception. The slope of the regression line forced through the origin represents E_c.

The leaf-stem partitioning parameter was determined as a function of specific leaf area (*SLA* in m^2 kg^{-1}), leaf area index (*LAI* in m^2 m^{-2}) and canopy dry matter yield (*CDM* in kg m^{-2}) (Jovanovic *et al*., 1999). The slope of the regression line represents the leaf-stem partitioning parameter in m^2 kg^{-1}.

$$LDM = CDM / (1 + p \cdot CDM) \qquad \textbf{Equation 55}$$

Canopy dry matter (*CDM*) is calculated as follows:

$$CDM = LDM + SDM \qquad \textbf{Equation 56}$$

LDM is used to calculate *LAI* as follows:

$$LAI = SLA \cdot LDM \qquad \textbf{Equation 57}$$

where *LDM* is leaf dry matter (kg m^{-2}), *CDM* is canopy dry matter (kg m^{-2}) and *SDM* is stem dry matter (kg m^{-2}). The vapour pressure deficit-corrected dry matter/water ratio (*DWR*) is calculated as follows (Tanner and Sinclair, 1983):

$$DWR = (DM \cdot VPD) / PT \qquad \textbf{Equation 58}$$

where *DM* (kg m^{-2}) is above-ground biomass measured at harvest, whilst *VPD* represents the seasonal average vapour pressure deficit. Both *VPD* and *DWR* are in units of Pascal (Pa). *PT* (mm) is potential transpiration and is calculated from potential evapotranspiration (i.e. maximum evaporation) and canopy cover following Allen *et al*. (1998).

Daily *VPD* calculated from measurements of maximum air temperature (T_{max}), minimum air temperature (T_{min}), maximum relative humidity (RH_{max}) and minimum relative humidity (RH_{min}) adopting the following procedure recommended by the FAO56 report (Allen *et al*., 1998):

$$VPD = \left(\frac{e_s(T_{\max}) + e_s(T_{\min})}{2}\right) - e_a$$ **Equation 59**

The term e_a is the actual vapour pressure (kPa) and calculated from measured daily T_{max} and T_{min} (in °C) as well as RH_{max} and RH_{min} (in %) using the following equation (Allen *et al*., 1998):

$$e_a = \left(\frac{e_s(T_{\max})\frac{RHmax}{100} + e_s(T_{\min})\frac{RHmin}{100}}{2}\right)$$ **Equation 60**

In the above equation, $e_s(T_{max})$ and $e_s(T_{min})$ are the saturated vapour pressures (in kPa) at maximum (T_{max}) and minimum air temperatures (T_{min}) respectively. Saturated vapour pressure (e_s) at maximum and minimum air temperature are calculated by replacing T with T_{max} and T_{min} (°C) in the following equation (Allen *et al*., 1998):

$$e_s = 0.6108 \cdot exp\left[\frac{17.27T}{T + 237.3}\right]$$ **Equation 61**

Growing degree days (*GDD* in d °C) is determined from daily average air temperature (T_{ave} in °C) following Monteith (1977):

$$GDD = (T_{ave} - T_{bse}) \cdot \Delta t$$ **Equation 62**

where T_{bse} is the temperature (°C) below which development is assumed to cease and Δt is the time step (i.e. one day). The value of T_{bse} is crop dependent.

6.3.2 *SWB* parameters (FAO model)

For tree crops, the FAO basal crop coefficient approach is used in *SWB* for simulation of crop water use, since tree growth is complex and difficult to simulate when using a generic crop model such as *SWB*. Therefore, the FAO model in *SWB* was used in the current study to estimate the water use of Moringa.

6.4 The *AQUACROP* model

6.4.1 Introduction

AQUACROP calculates crop biomass based on the amount of water transpired. Then, it estimates crop yield as the proportion of biomass that goes into the harvestable parts (e.g. stem, grain, oilseed, tuber etc.). The model separates non-productive consumption of water (soil water evaporation) from the productive consumption of water (transpiration). Furthermore, the timescale used in *AQUACROP* is daily, in order to better represent the dynamics of crop response to water. The model can be used to:

- assess the effect of water shortages on crop production,
- compare the results of several water allocations plans,
- optimise irrigation scheduling (either full, deficit or supplementary), and
- enhance management strategies for increased water productivity and water savings.

The model can also assess crop response to different climate change scenarios in terms of altered soil water, temperature regimes and elevated atmospheric CO_2 concentration. *AQUACROP* simulates daily crop growth, productivity and water use as influenced by changing water availability and environmental conditions. Model results obtained to date provide grounds for confidence in its performance.

Overall, *AQUACROP* can be used to investigate the efficiency and productivity of water use in herbaceous crop production. It is not designed for use with trees and vines. *AQUACROP* is applicable to all major herbaceous crop types: fruit or grain crops; root and tuber or stem-storage crops; leafy or floral vegetable crops, and ratoon forage crops. The model has been paramteterised for the following 14 crops:

- barley (*Hordeum vulgare* L.),
- cotton (*Gossypium hirsutum* L.),
- **maize** (*Zea mays* L.),
- potato (*Solanum tuberosum*),
- quinoa (*Chenopodium quinoa* Willd.),
- rice (*Oryza sativa* L.),
- **soybean** (*Glycine max* (L.) Merr.),
- **sugarbeet** (*Beta vulgaris* L.),
- **sugarcane** (*Saccharum officinarum*),
- **sorghum** (*Sorghum bicolor* (L.) Moench),
- **sunflower** (*Helianthus annuus* L.),
- tef (*Eragrostis tef* (Zucc.) Trotter),
- tomato (*Solanum lycopersicum* L.), and
- **wheat** (*Triticum aestivum* L.; *Triticum turgidum* durum).

Excluding food security concerns, the feedstocks highlighted in bold are considered biofuel feedstocks. Unfortunately, canola is missing from this list. The model developers are currently working on adding other crops (Vanuytrecht *et al*., 2014). Their goal is to provide an overview of each crop's physiology and agronomy, to assist in applying the model at a given location. The crop description includes growth and development, water use and productivity, responses to water deficits as well as expected yields.

6.4.2 Water production function

AQUACROP is based on the water production function (**Equation 63**) where relative yield (*Y*) reduction is related to the corresponding relative reduction in evapotranspiration (*ET*):

$$\left(1-\frac{Y_a}{Y_x}\right)=K_y\left(1-\frac{ET_a}{ET_x}\right) \qquad \textbf{Equation 63}$$

where Y_x and Y_a is the maximum and actual yield, ET_x and ET_a is the maximum and actual evapotranspiration, and K_y is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses. **Equation 63** can be applied to all agricultural crops, i.e. herbaceous, trees and vines. The relationship has shown remarkable validity and allowed a workable procedure to quantify the effects of water deficits on yield.

6.4.2.1 Yield response factor

The yield response factor (K_y) captures the essence of the complex linkages between production and water use by a crop. Hence, it represents many biological, physical and chemical processes. K_y values are therefore crop specific and vary over the growing season according to growth stage. The information provided in **Table 56** helps understand the yield response factor. For example, K_y for sorghum is 0.9 (i.e. drought tolerant), compared to 1.25 for maize.

Table 56 Interpretation of K_y value (Steduto *et al*., 2012)

Value	Meaning
$K_y > 1$	Crop response is very sensitive to water deficit, with proportional larger yield reductions when water use is reduced because of stress
$K_y < 1$	Crop is more tolerant to water deficit, and recovers partially from stress, exhibiting less than proportional reductions in yield with reduced water use
$K_y = 1$	Yield reduction is directly proportional to reduced water use

As mentioned, K_y varies with time to depict the crop's sensitivity to water stress at different phenological stages. **Figure 38** shows that maize is sensitive to water stress at the flowering and yield formation stages. The higher the K_y values (i.e. the steeper the slope), the greater the yield reduction for a given reduction in ET (Steduto *et al*., 2012).

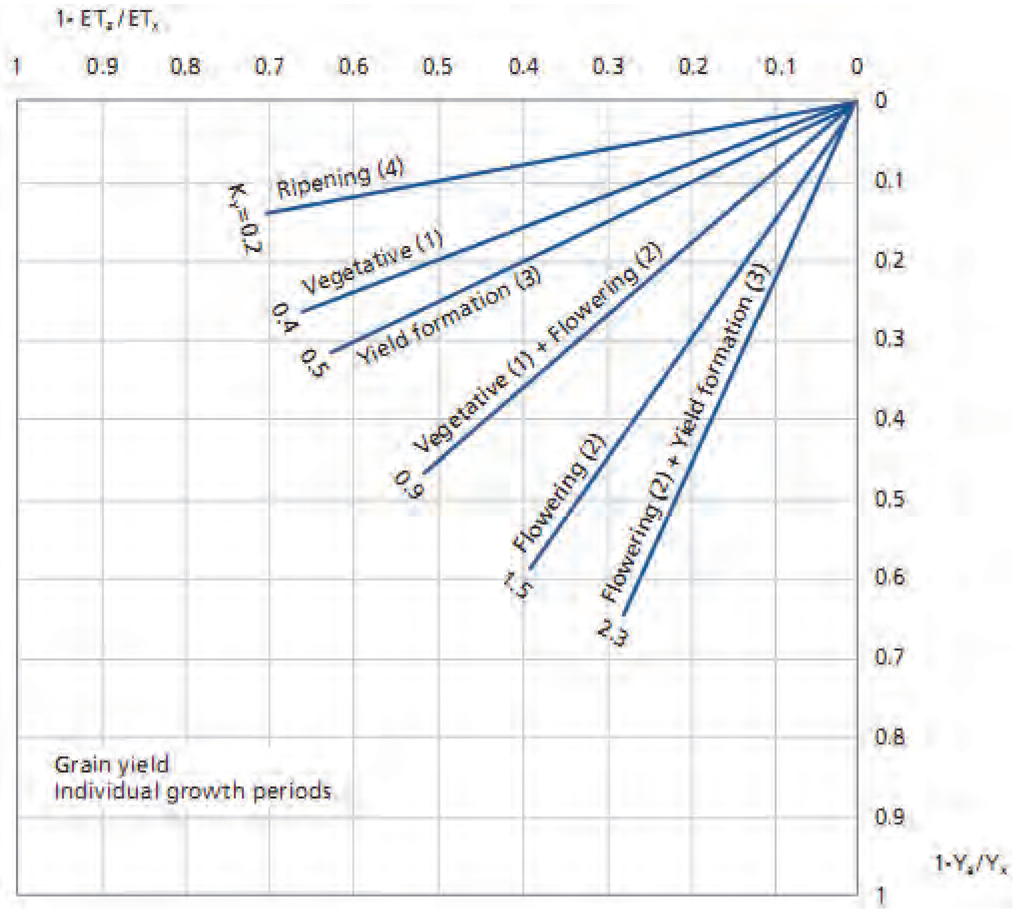


Figure 38 Linear water production functions for maize subjected to water deficits during different growth stages

Stress occurring in the ripening phase has a limited impact, as in the vegetative phase (provided the crop is able to recover from stress in subsequent stages). This approach and the calculation procedures for estimating yield response to water were originally published in the FAO Irrigation and Drainage Paper No. 33 (Doorenbos and Kassam, 1979), considered one of FAO's milestone publications.

6.4.2.2 Estimating maximum yield

Maximum yield (Y_x) is calculated using available local data or from maximum biomass and a corresponding harvest index, assuming agronomic factors (e.g. water, fertilisers, pest and diseases) are not limiting. Refer to Doorenbos and Kassam, 1979) for further information if required.

6.4.2.3 Maximum crop evapotranspiration

Maximum crop evapotranspiration (ET_x) is calculated from the product of crop-reference evaporation (ET_o) and the crop coefficient (or crop factor, K_c), assuming that crop water requirements are fully met. ET_o is a model input, allowing the user to decide which method to calculate this value (e.g. Penman-Monteith or Hargreaves and Samani).

6.4.2.4 Actual crop evapotranspiration

Actual crop evapotranspiration (ET_a) is calculated by considering the available water supply to the crop. Water balance calculations are used to estimate the available soil water content in the root zone on a daily basis. If soil water is readily available to the crop, then $ET_a = ET_x$. When a critical soil moisture level is reached, defined as a fraction of the total plant available water (p), transpiration is reduced because the stomata close and thus $ET_a < ET_x$. When the soil water content reaches the permanent wilting point, ET_a approaches zero. This critical soil-water content (p) is estimated from soil, crop and rooting characteristics and from the ET_o rate. Depletion of soil-water content between p and the permanent wilting point will result in a proportional reduction of ET_a.

6.4.2.5 Actual crop yield

Actual crop yield (Y_a) is calculated using **Equation 63**, using the proper selection of the response factor (K_y) for the full growing season or over the different growing stages. However, for planning and management studies, the yield reduction is expressed in relative terms as a fraction or percentage ($1 – Y_a/Y_x$), rather than an absolute value (Y_a).

6.4.2.6 Limitations

The simplification introduced by using an empirical yield response factor (K_y) to integrate the complex linkages between production and water use by a crop limits its applicability for making accurate estimates of yield responses to water. In addition, other factors also affect crop response to water (e.g. nutrients, different cultivars, etc.) Hence, K_y reflects crop- and site-specific responses to water.

If the aim is to increase efficiency and productivity of water use, **Equation 63** is of limited use and predictions that are more accurate are required for yield response under actual field conditions. *AQUACROP* provides a valid alternative for herbaceous crops, allowing more accurate estimation of actual crop growth and yield under various soil water availability, climate and soil fertility conditions.

6.4.2.7 The improved model

AQUACROP is a dynamic crop-growth model developed to predict yield response of herbaceous crops to water availability. The basic concepts and fundamental calculation procedures are briefly described next.

Intercepted solar radiation is the driving force for both photosynthesis and transpiration, with a direct relationship existing between transpiration and biomass production. Hence, water stress reduces transpiration which then decreases biomass production, which finally reduces crop yield. The key is to separate non-productive soil water evaporation (*E*) from productive crop transpiration (*Tr*).

Biomass production (*B* in kg m^{-2}) is then estimated directly from accumulated crop transpiration (*Tr* in mm; summed over the time period in which biomass is produced) via a water productivity parameter (*WP* in kg m^{-2} mm^{-1}). Hence, $B = WP \cdot \sum Tr$ which is at the core of the *AQUACROP* growth engine. For most crops, only part of the biomass produced is partitioned to the harvested organs to give yield, and the ratio of yield (*Y*) to biomass (*B*) is known as the harvest index (*HI*), hence $Y = HI \cdot B$. Model robustness is enhanced by:

- quantifying the harvest index day-by-day over the yield formation period, and
- normalising *WP* (designated *WP**) using evaporative demand.

*WP** behaves conservatively, remaining virtually constant over a range of environments. The daily time step allowed the important change from a static approach to a dynamic growth model. A schematic representation of *AQUACROP*'s growth engine is given in **Figure 39**.

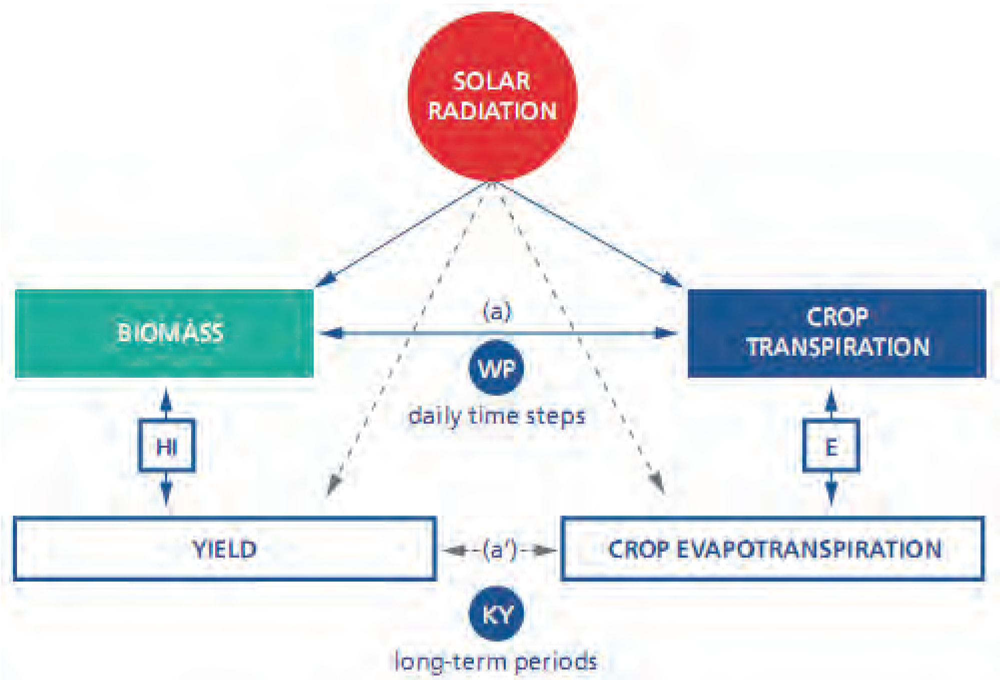


Figure 39 Solar-driven crop growth engine for the dynamic *AQUACROP* model (Steduto *et al*. 2012)

The above diagram illustrates the relationship (a') between crop yield and crop water use (i.e. crop evapotranspiration), via the K_y parameter (**Equation 63**). It also shows how the

AQUACROP model has evolved, based on separation of soil water evaporation (*E*) from crop transpiration and the estimation of yield from biomass via the harvest index (*HI*).

6.4.3 Model structure and components

The above description focused on *AQUACROP*'s crop (i.e. growth and yield processes) and soil (i.e. water balance) components. In addition, the model has two other components, namely:

- climate (rainfall, temperature, evaporation, CO_2 concentration), and
- management practices (including irrigation, fertilisation and mulching).

Hence, *AQUACROP* simulates yield response to water under various management and environmental conditions, including climate change scenarios. However, like most crop models, it cannot account for the effects of pests and diseases. Each component is described next, with emphasis on the model's input data requirements.

AQUACROP uses a relative small number of parameters and fairly intuitive input variables, either widely used or largely requiring simple methods for their determination. Inputs consist of climate data, crop and soil characteristics, and management practices that define the environment in which the crop will develop. These inputs are summarised schematically in **Figure 40** and are stored in climate, crop, soil and management files. The values can be easily retrieved from *AQUACROP*'s database and adjusted within the user interface (Steduto *et al*., 2012).

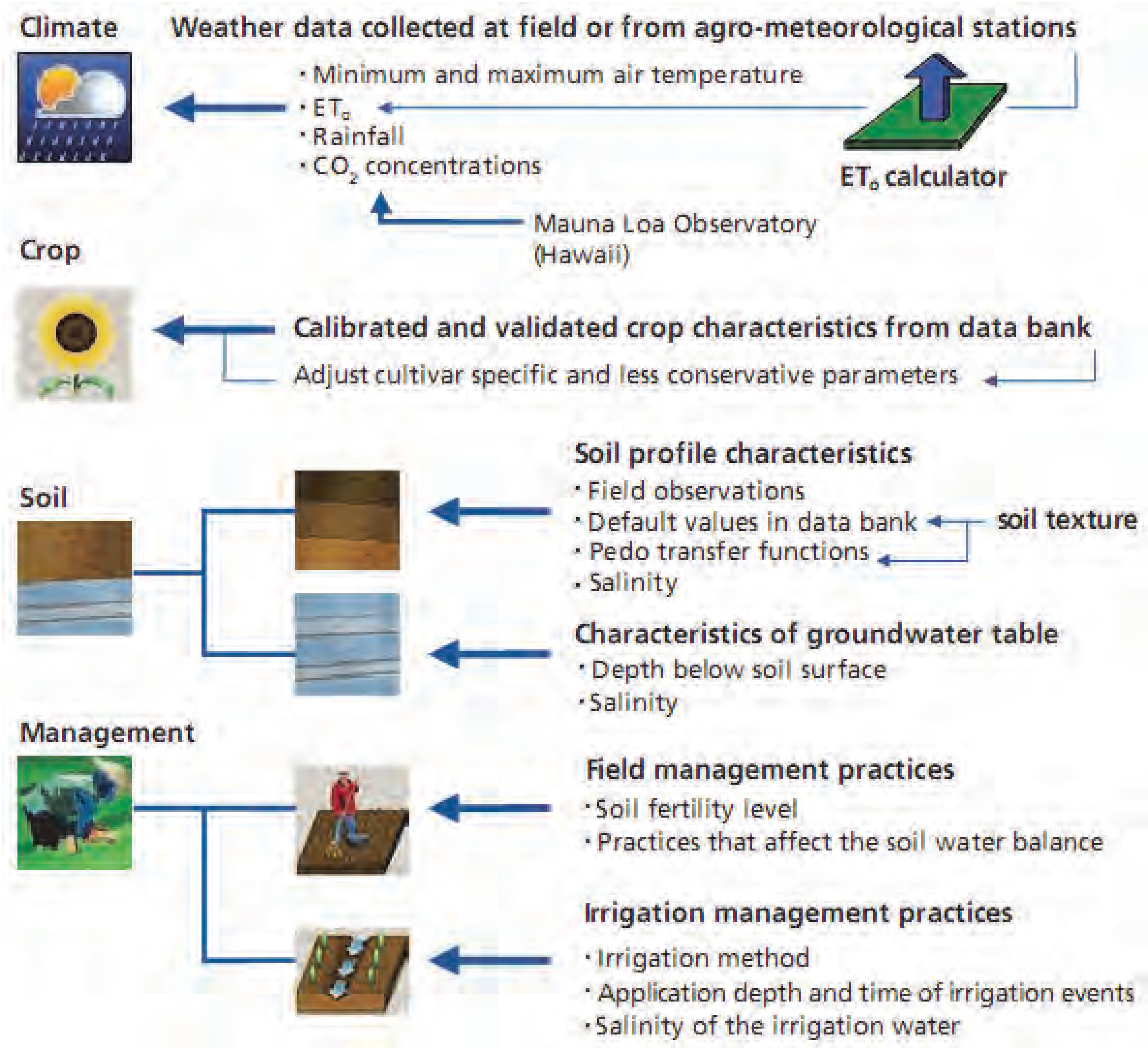


Figure 40 Input data required by *AQUACROP* which defines the environment in which the crop develops

6.4.3.1 Climate

The climate component requires daily rainfall, maximum and minimum air temperature, reference-crop evaporation (ET_o) as well as annual mean carbon dioxide concentration (CO_2) of the atmosphere. Temperature influences crop development (phenology), in particular extreme values (i.e. very cold or very hot). Rainfall and evaporation determine the water balance of the root zone and hence water stress.

6.4.3.2 Soil

A description of the soil profile and characteristics of the groundwater are required. The depth to the groundwater table below the soil surface and the groundwater salinity are two important characteristics. In *AQUACROP*, the soil can be subdivided by the user into five horizons of variable depth, with each horizon (or layer) accommodating different soil physical characteristics as follows:

- the upper limit of water content under gravity, commonly referred as field capacity (FC; or drained upper limit),
- the lower limit of water content when the crop reaches its permanent wilting point (PWP), and

- hydraulic conductivity at saturation (K_{SAT}).

Internally, the model subdivides the entire soil profile into 12 soil compartments as shown in **Figure 41**. The total number of compartments always remains 12, regardless of the number of horizons (Steduto *et al*., 2012). The thickness of each compartment (Δz) increases exponentially with depth, so that infiltration, soil water evaporation and transpiration from the top soil layers can be described with sufficient detail. The soil-water content is updated at the end of the daily time step in each of the 12 compartments. From this approach, *AQUACROP* derives other parameters governing surface runoff, capillary rise, internal drainage and deep percolation. The reader is referred to the *AQUACROP* reference manual for full details (Raes *et al*., 2012a; 2012b).

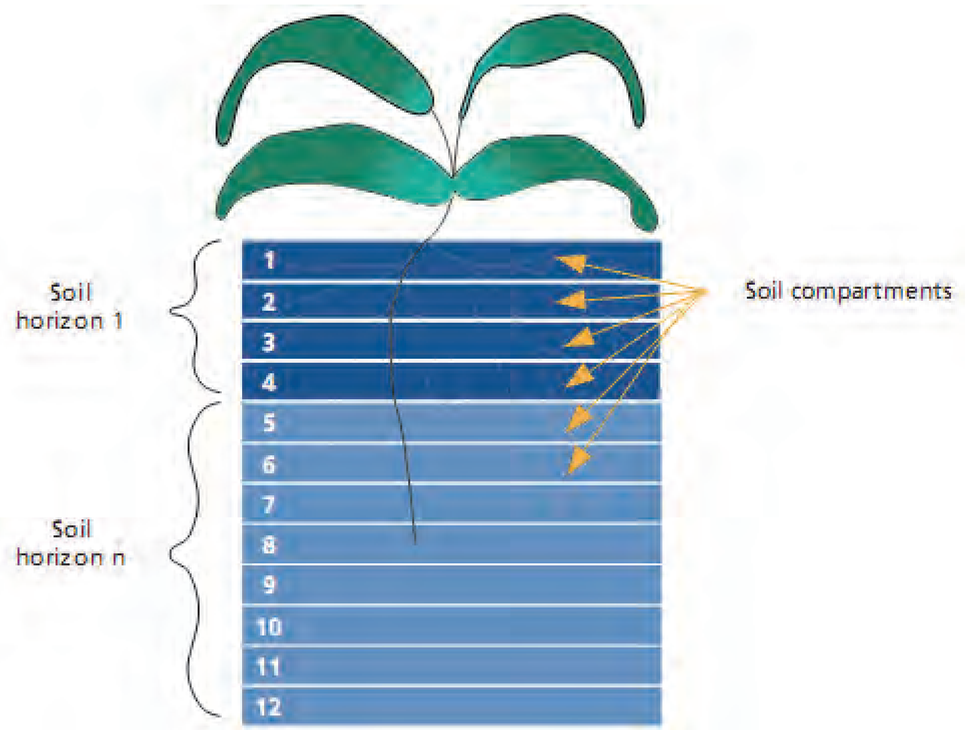


Figure 41 A soil profile with one soil horizon (varying up to five) and 12 soil compartments

A soil water balance is performed by keeping track of the incoming (rainfall, irrigation &capillary rise) and outgoing (runoff, evapotranspiration & deep percolation) water and salt fluxes. When calculating the soil water balance, the amount of water stored in the root zone can be expressed as an equivalent water depth (W_r) or as root zone depletion (D_r). At field capacity, D_r is zero and at permanent wilting point, D_r is equal to total available water (i.e. $TAW = FC - PWP$).

6.4.3.3 Rooting depth

Root water uptake is simulated by defining effective rooting depth (Z_{eff}) and the water extraction pattern. Z_{eff} at planting to near emergence is the soil depth from which the germinating seed or the young seedling can extract water. A minimum effective rooting depth of 0.2 to 0.3 m (Z_{min}) at the beginning is generally considered appropriate.

Under optimal conditions (i.e. with no soil restrictions), the maximum effective rooting depth (Z_{max}) is typically reached when canopy senescence begins (i.e. at maturity). The maximum rooting depth might not be attained due to a soil layer restricting root growth (i.e. stone line), or a shallow groundwater table.

Water extraction by roots follows a typical pattern of 40% from the upper quarter of Z_{eff}, 30% and 20% from the middle two quarters and 10% from the lower quarter of Z_{eff} (when water content is adequate). This pattern can be changed by the user, if warranted by specific physical or chemical characteristics of the soil.

6.4.3.4 Crop

After emergence, the crop grows and develops over its growth cycle by expanding the canopy and deepening the root system, transpiring water and cumulating biomass, while progressing through its phenological stages. The harvest index alters the portion of biomass that will be harvestable. No other partitioning among the various plant organs takes place, thus avoiding the complexity associated with partitioning processes (which remain the most difficult to model). Hence, the crop component of the model includes the following sub-components:

- phenology,
- canopy cover,
- rooting depth (see description given above),
- crop transpiration,
- soil water evaporation,
- biomass production, and
- harvestable yield.

Phenology: *AQUACROP* uses growing degree days (GDD) to account for effects of temperature regimes on phenology and therefore the crop's base temperature is required. The key developmental stages are:

- emergence,
- start of flowering (anthesis),
- root/tuber/stem-storage initiation,
- time when maximum rooting depth is reached,
- start of canopy senescence, and
- physiological maturity.

The calibrated values for each crop serve as a solid starting point. Some parameters may need to be adjusted for different crop cultivars. Calibrations should be done on crops which are not limited by the major nutrients (N, P & K).

Canopy cover: One of the distinctive features of *AQUACROP* is the expression of foliage amount using canopy cover (in fraction or percentage) and not leaf area index (LAI). The initial canopy cover (CC_o) and the canopy growth coefficient (CGC) are required as inputs. These values account for effects of plant density on canopy size. As the crop approaches maturity, green canopy cover begins to decrease due to leaf senescence. This decline is characterised by an empirical canopy decline coefficient (CDC). This parameter is used to either lengthen or shorten the time span from start of senescence to no remaining green canopy (i.e. CC = 0). The starting time for senescence is critical because it determines how long the canopy is most effective in photosynthesis. Calibration of senescence requires accurate field observation (or measurement of LAI) during the late phase near maturity. A typical canopy cover curve is shown in **Figure 42** for maize.

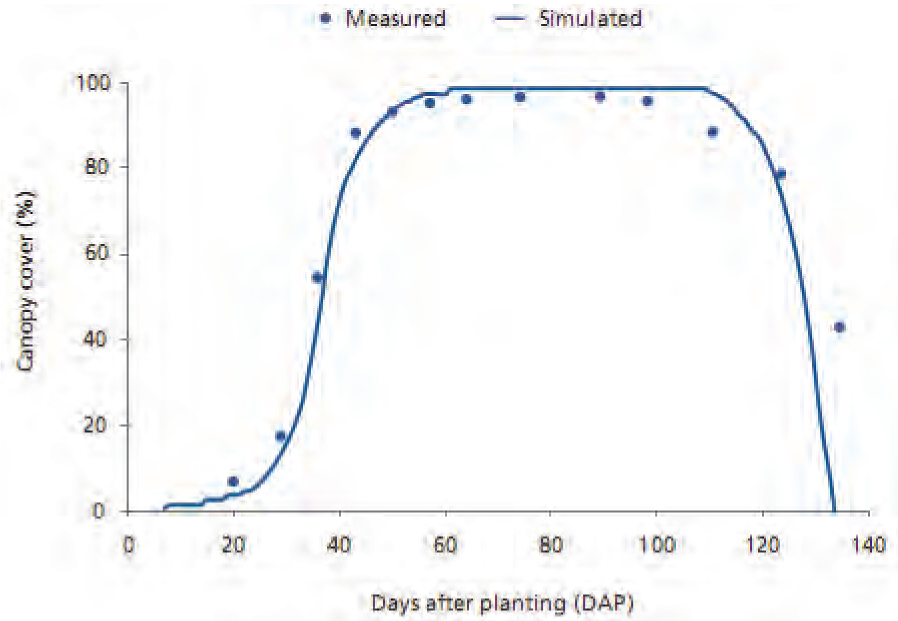


Figure 42 Progress of green canopy cover through the life-cycle of maize under non-stressed conditions (Steduto *et al*., 2012)

Crop transpiration: Transpiration per unit land area is dependent on the fraction of land area covered by the canopy (*CC*) when stomatal opening is not limited by stress. The model requires the crop coefficient (K_c) when the canopy fully covers the ground (i.e. when *CC* approaches 1). This value is used to calculate transpiration (*Tr*) from ET_o.

Soil water evaporation: Soil water evaporation (*E*) takes place from the non-shaded soil surface (i.e. 1 - *CC*). When the soil surface is fully wet, the Stage I potential evaporation rate is 10% more than ET_o and lasts about a day (can be user defined). Thereafter, Stage II evaporation occurs and is calculated by adjusting the potential evaporation rate by an exponentially declining coefficient. At the onset of canopy senescence, a simple factor is applied to reduce the shading effect of the dying canopy.

Biomass production: The biomass water productivity (*WP*) is fundamental to the operation of *AQUACROP* and is remarkably conservative (remaining nearly constant) when normalised for ET_o, provided nutrients (particularly N) are not limiting.

$$WP^* = \frac{B}{\Sigma\left(\frac{Tr}{ET_o}\right)}$$ **Equation 64**

This equation is directly applicable when *Tr* and ET_o data are for daily time intervals. When the time interval is larger than daily, this normalisation requires caution. In the literature, *WP* is commonly normalised for vapour pressure deficit (VPD) instead of ET_o. Using ET_o is superior as it accounts for advective energy transfer, which is ignored when VPD is used.

Harvestable yield: The partitioning of biomass (*B*) into harvestable yield (*Y*) is simulated by means of a harvest index (*HI*). The ratio $HI = Y / B$ is typically at maturity or harvest time. *HI* is increased within the model from zero (at flowering for fruit/grain crops) to an upper reference HI value (HI_o). The rate of increase starts slowly over a short lag phase and then accelerates with time before reaching a steady phase at maturity (**Figure 43**). Calibrated HI_o values can be changed based on good data for a particular cultivar.

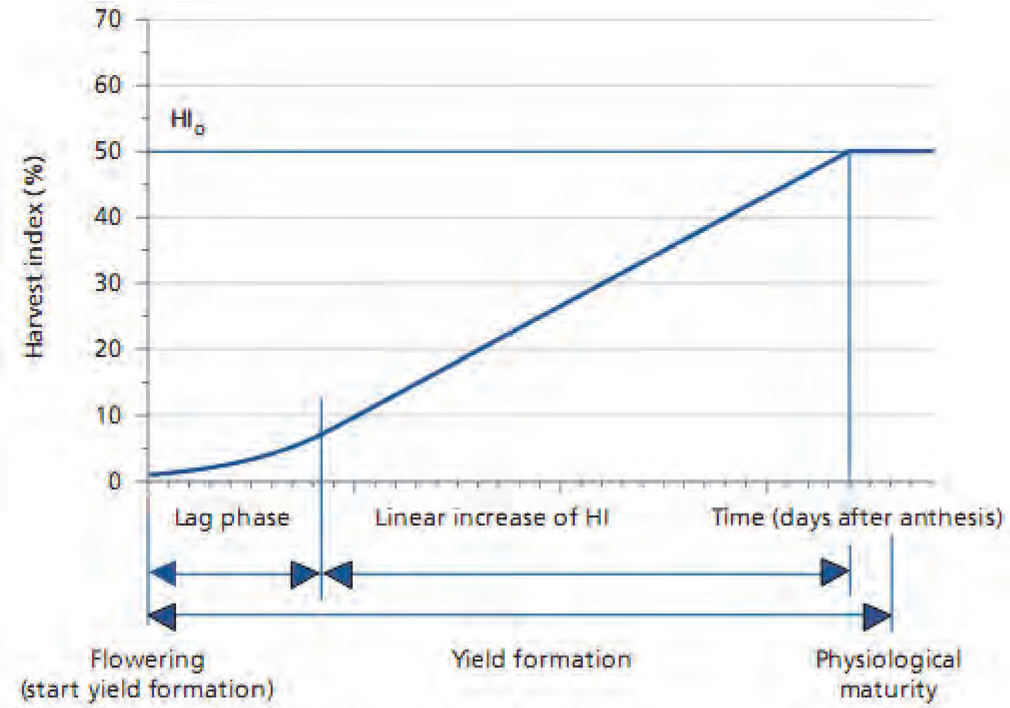


Figure 43 Increase in harvest index (HI) from flowering until physiological maturity for fruit/grain crops (Steduto *et al*., 2012)

Management: *AQUACROP* encompasses two categories of management practices namely the irrigation management (which is quite complete in its various features) and the field management (limited to selected aspects and is relatively simple in approach).

Irrigation management: The model can assess crop yield response under rainfed or irrigated conditions. An additional feature is the estimation of full water requirement of a crop in a given climate. Management options include the selection of water application methods (sprinkler, surface, or drip either surface or underground). The determination of irrigation schedules is done by specifying the time, depth and quality of the irrigation water of each application, or letting the model automatically generate the schedule based on fixed:

- time interval,
- depth per application, or
- fixed percentage of allowable water depletion.

Field management: Three aspects considered by *AQUACROP* include:

- fertility of the soil for growing the crop, whether native or by fertilisation,
- mulching of the soil to reduce soil water evaporation, and
- use of soil bunds (i.e. small dykes) to pond water or control surface runoff and enhance infiltration.

AQUACROP does not simulate the effects of fertility on crop growth. Instead, it provides for adjustment of default values pertaining to pivotal crop parameters (e.g. *CGC*, *CC* and *WP**) based on fertility categories (ranging from near optimal to poor). These adjustments are based on the pattern of canopy evolution, photosynthesis, and WP at different fertility levels reported in several studies. A local calibration is preferred, which involves observing biomass production and canopy development at different fertility levels.

Mulching is considered only for its effect on reducing soil water evaporation (*E*) and is specified by the user in terms of the percentage of soil surface covered and effectiveness of the mulching material. Finally, a bund and its height can be specified to prevent runoff and force all water from rain or irrigation to infiltrate the soil. Bunds also allow the simulation of crops under ponding water such as paddy rice. For soils that are especially permeable, it is also possible to choose “no runoff’ without building bunds.

Dynamics of crop response to stress: Abiotic environmental stresses such as water and temperature can have major negative impacts on canopy development, biomass production and yield. The impact depends on the timing of occurrence, severity and duration. *AQUACROP* is primarily designed to simulate crop responses to water, but with sufficient attention given to temperature. The model also takes an indirect approach to stress induced by mineral nutrient deficiencies or the presence of salts in the root zone.

Stress response functions: Any type of stress is described in *AQUACROP* by means of a stress coefficient (K_s). In essence, K_s modifies its target model parameter, and ranges in value from one (no stress) to zero (full stress). The relative stress level is 0.0 at the upper threshold and 1.0 at the lower threshold. The shape of most K_s curves is typically convex and the degree of curvature is set during model calibration (**Figure 44**).

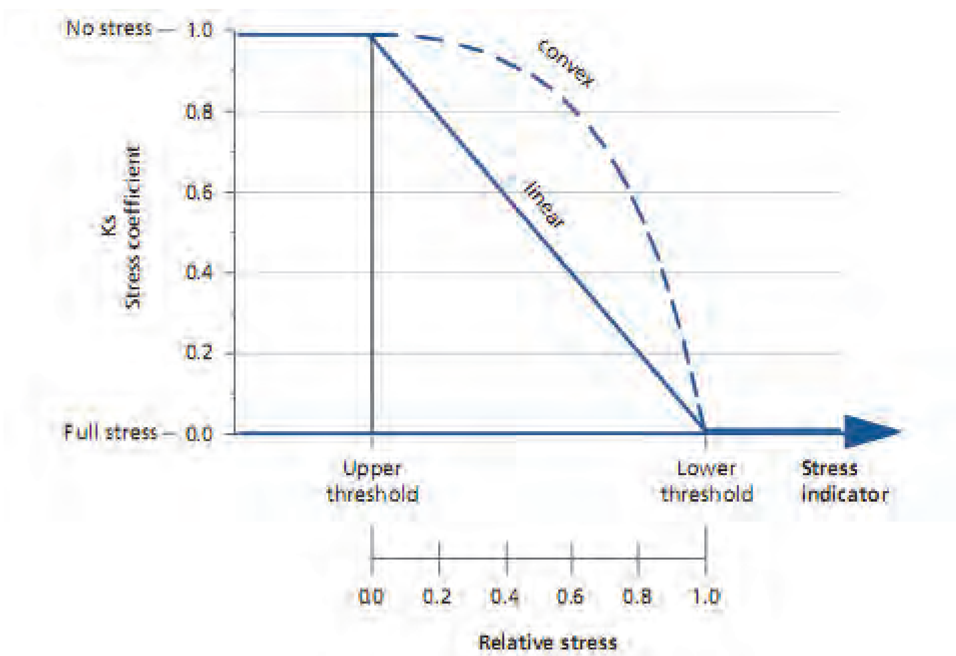


Figure 44 The stress coefficient (K_s) for various degrees of stress and for two sample shapes of the K_s curve (Steduto *et al*., 2012)

For water stress, the shape of the curve can vary between very convex to linear. Conceptually, the more convex the curve, the higher is the crop's capacity to adjust and acclimate to the stress. A linear relationship indicates minimal or no drought tolerance. The stress thresholds, as well as the curve shape, are set by calibration and should be based on knowledge of the crop's drought resistance or tolerance.

The degree of soil fertility is the indicator for soil fertility stress. It varies from 0% (i.e. soil fertility is non-limiting; K_s = 1), to 100% (i.e. crop production is no longer possible; K_s = 0). This avoids the need to simulate nutrient balances, further adding to model complexity. The electrical conductivity of the soil water in the root zone (*ECe*) determines salinity stress. At the lower threshold of soil salinity, K_s becomes smaller than 1 and the stress starts to affect biomass production. K_s becomes zero at the upper threshold for soil salinity and the stress becomes so severe that biomass production ceases. Temperature and water stress are discussed next in more detail.

Temperature stress: By using GDD as the thermal clock, much of the temperature effects on crops, such as on phenology and canopy expansion rate, are presumably accounted for. Indicators for air temperature stress are growing degrees (GDD), minimum air temperatures (cold stress) or maximum air temperatures (heat stress). For example, temperature stress affects pollination, which is inhibited by temperatures either too high or too low.

Aeration stress: Aeration stress is caused by excessive water in the soil profile. A stress coefficient approach is used to modulate *Tr*, hence biomass production and ET. The percentage of soil pore volume occupied by air in the root zone is important, with a settable upper threshold and the lower threshold fixed at zero (i.e. fully saturated soil). When the percentage air volume drops below the upper threshold, K_s starts to decrease below 1.0, causing proportional reduction in *Tr*. Hence, the sensitivity of the crop to waterlogging is specified by setting this upper threshold and by indicating the number of days that waterlogging is present before the stress becomes fully effective.

Water stress: Water stress refers to the stress caused by a lack of water. The threshold for water stress is the soil water depletion (D_r) from the root zone. The upper threshold refers to the soil water that can be depleted before the stress starts to affect the process, while the lower threshold is the root zone depletion at which the stress inhibits the process completely. Water stress affects canopy growth, stomatal conductance, canopy senescence, root growth and the harvest index, but not the normalised water productivity (as shown in the literature). The impact of water stress on each of these components is briefly discussed next.

The plant water status depends not only on soil water status, but also on the rate of transpiration (as determined by atmospheric evaporative demand). Hence, the crop is more sensitive to soil water depletion on days of high ET_o (> 5 mm) and less on days of low ET_o (< 5 mm) *AQUACROP* adjusts the thresholds of the K_s curve according to ET_o. Leaf expansion (hence the canopy) is most sensitive to water stress. On the other hand, stomatal conductance and leaf (hence canopy) senescence are substantially less sensitive.

Root growth is substantially less sensitive to water stress than leaves. In fact, the root to shoot ratio is enhanced by mild to moderate water stress). In *AQUACROP*, there is no link between roots and shoot (canopy and biomass) except indirectly via the effect of root zone water depletion on components of the production process.

Yield also depends on *HI* and the impact of water stresses on HI can be pronounced (wither negative or positive), depending on the timing and extent of stress during the crop cycle. Water stress reduces pollination and fruit (or grain) set, thus decreasing the number of “pods” that can be filled with the available photosynthetic assimilate.

The structural components of *AQUACROP,* including stress responses and the functional linkages between them are shown schematically in **Figure 45**. The numbers represent water stress response functions for (1) leaf expansion, (2) senescence, (3) stomatal conductance and (4) harvest index, as discussed above. The diagram shows the main components of the soil-plant-atmosphere continuum and the parameters driving phenology, canopy cover, transpiration, biomass production and final yield. Solid lines indicate direct links between variables and processes. Dotted lines indicate feedbacks.

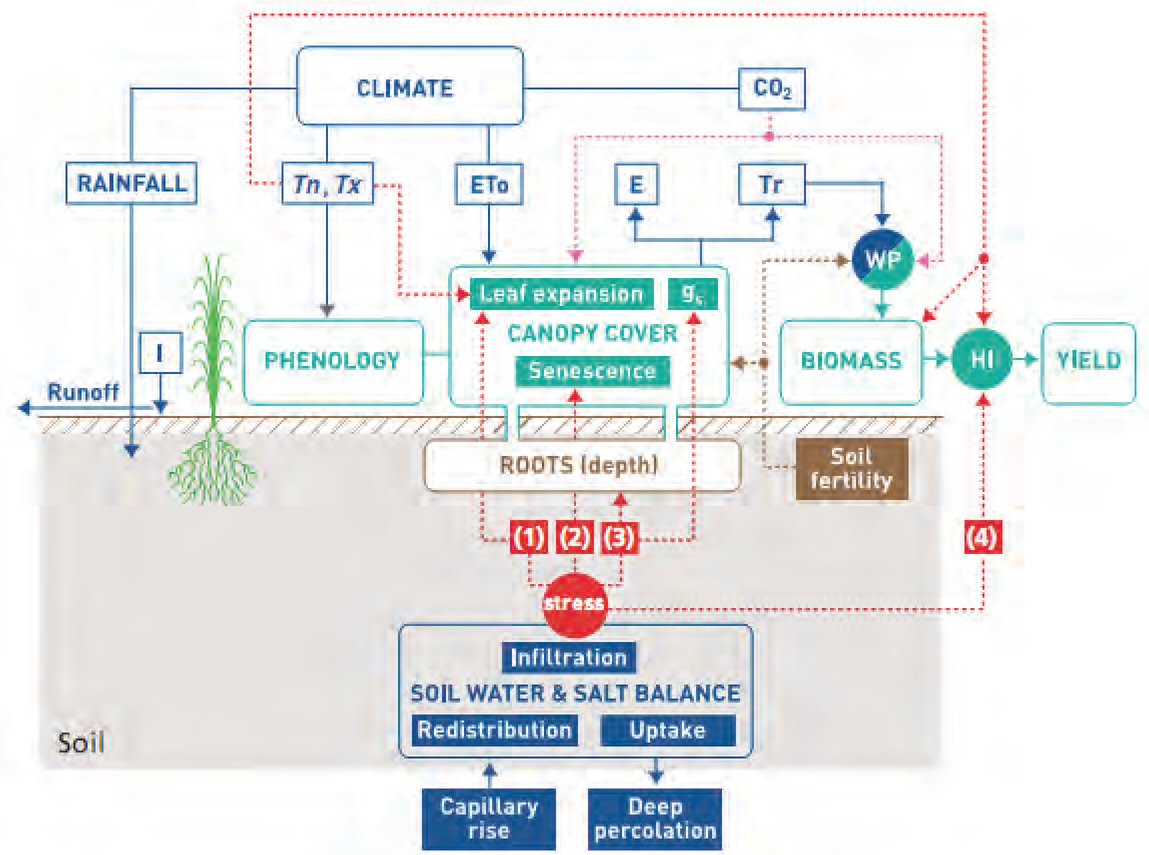


Figure 45 The structural components of *AQUACROP,* including stress responses and the functional linkages among them (Steduto *et al*., 2012)

The symbols used in **Figure 45** are as follows: *I* = irrigation; *Tn* = minimum air temperature; *Tx* = maximum air temperature; ET_o = reference evapotranspiration; *E* = soil water evaporation; *Tr* = canopy transpiration; g_s = stomatal conductance; *WP* = water productivity; *HI* = harvest index; and CO_2 = atmospheric carbon dioxide concentration.

6.4.4 Summary

Similar to other crop-growth models, *AQUACROP* includes various components which simulate the soil-plant-atmosphere continuum. These components deal with climatic (e.g. rainfall, evaporative demand) and atmospheric conditions (CO_2 concentration, exchange fluxes), soil water levels, crop development as well as growth and yield. Crop management, including agronomic practices such as irrigation and fertilisation, is also considered. Simulations are executed at the daily time step, using either calendar days or growing degree days (FAO, 2012c).

Soil water content is simulated by balancing incoming and outgoing water fluxes at the boundaries, considering the soil as a water storage reservoir with multiple layers. *AQUACROP* uses canopy ground cover instead of a leaf area index. Canopy development, stomatal conductance, canopy senescence and the harvest index are the key physiological crop responses to water stress. Evapotranspiration is simulated as crop transpiration and soil water evaporation and the daily transpiration is used to derive daily biomass gain via the normalised biomass water productivity value of the crop. Normalisation is based on reference evapotranspiration and CO_2 concentration to make the model applicable to diverse concentration to make the model applicable to diverse locations and seasons, including future climate scenarios. *AQUACROP* also accommodates different water management systems (e.g. rainfed agriculture, supplemental, deficit and full irrigation) (FAO, 2012c). For additional information, the reader is referred to the *AQUACROP* Reference Manual (Raes *et al*., 2012a; 2012b).

6.5 National Model Runs

The methodology developed and followed in this study to estimate crop yield at the national scale is described next. *AQUACROP* was run nationally to estimate the attainable yield and water use efficiency under dryland conditions.

6.5.1 Revised quinary sub-catchment database

The reader is referred to Schulze and Horan (2011) for further explanation on how the quinary sub-catchments were delineated. Similarly, the reader is referred to Schulze *et al*. (2011) for more detail on how the original climate and soils quinary sub-catchment databases were developed. A summarised version is given in **Section 5.4** for the reader's convenience. However, in this study, a modified version of the quinary sub-catchment climate database was used. The reader is referred to **Section 5.5** for more detail. The soils information required by *AQUACROP* was derived from the quinary sub-catchments soil database as described next.

6.5.2 Soils input

According to Raes *et al.* (2013), the *AQUACROP* model requires the major physical characteristics for each soil horizon. The soils (.SOL) file provides the model with the soil water content (expressed as a volume %) at saturation (i.e. total porosity), field capacity (i.e. drained upper limit) and the permanent wilting point (i.e. lower limit). These soil water retention parameters were obtained from the original quinary sub-catchment soils database as described by Schulze *et al*. (2011). In brief, values for these parameters were derived by Schulze and Horan (2007b) using the *AUTOSOILS* decision support tool (Pike and Schulze, 1995 and updates). This tool was applied to the ISCW soils database (SIRI, 1987 and updates) for each of the soil mapping units (called land types) which cover South Africa. Then, the hydrological properties of all soil series within an individual land type were area-weighted. For each quinary, the values for each parameter were then derived from the land types occurring in that sub-catchment, again on an area-proportioned basis. Values for both the A- and B-horizon for each soil water retention parameter were converted from a soil water content per unit of soil depth (i.e. m m^{-1}) to a volume % (e.g. 241 mm m^{-1} = 0.241 m m^{-1} = 24.1%).

A utility was developed using the FORTRAN programming language to extract the soil water retention parameters from the quinary sub-catchment soils database and re-format them to that required by the *AQUACROP* model. An example for *AQUACROP's* soils (.SOL) file is given in APPENDIX I for sub-catchment 4 696. The model also requires the initial soil water content of the soil profile given in the .SW0 file. A total of 11 676 (5 838 * 2) soil-related files were produced to run the model at a national scale.

An example of a .SW0 file is also provided in **APPENDIX I**, the initial soil water content is taken as the average of the field capacity (FC) and wilting point (WP) values for each of the two soil horizons (expressed as a volume %). As shown in **APPENDIX I**, the *AQUACROP* model requires a number of other soil-related parameters. These are explained in more detail in the sections that follow, together with the methodology used to derive their values.

6.5.2.1 Saturated hydraulic conductivity

The *AQUACROP* model also requires the saturated hydraulic conductivity (K_{SAT}) of each soil horizon. According to Raes *et al*. (2012a), K_{SAT} expresses the property of the soil to conduct water through a soil. When the soil is saturated, all pores are filled with water and the value for the hydraulic conductivity is at its maximum. The saturated hydraulic conductivity or permeability defines the rate for the soil layer to transmit water through the saturated soil under the influence of gravity.

Since this soils parameter is not required by *ACRU*, it was not available in the quinary sub-catchment soils database. Hence, a pedotransfer function was developed to estimate K_{SAT} for the soil water retention parameters. Saxton and Rawls (2006) provided a table of useful equations (Table 1; p 1571) to estimate K_{SAT} (in mm h^{-1}) as follows:

$$K_{SAT} = 1930(\theta_{TPO} - \theta_{DUL})^{[3 - \lambda]}$$ **Equation 65**

where θ_{TPO} and θ_{DUL} are the soil water contents at total porosity (i.e. saturation) and the drained upper limit respectively. The units for each parameter is m m^{-1} and not volume % as indicated by Saxton and Rawls (2006; c.f. Table 1). The term λ represents the inverse of the "slope of the logarithmic tension-moisture curve" and is calculated as follows:

$$\lambda = [ln(\theta_{DUL}) - ln(\theta_{PWP})] / [ln(1500) - ln(33)]$$ **Equation 66**

where θ_{PWP} is the soil water content at the permanent wilting point (in m m^{-1}). The two constants 33 and 1 500 represent the matric potentials (in kPa) at the drained upper limit

(DUL) and permanent wilting point (PWP) respectively. A utility was developed in FORTRAN to estimate K_{SAT} for each soil horizon in mm day^{-1} using the above two equations, with soil water retention parameters extracted from the quinary sub-catchments soils database.

6.5.2.2 Comparison with other K_{SAT} values

In order to validate the above two equations for common South African soils, "typical" particle size distributions (e.g. clay % and sand %) for 11 soil textural classes were used to estimate soil water retention values using various equations provided by Saxton and Rawls (2006; Table 1; p 1571). Owing to their complexity, these equations are not reproduced here and the reader is referred to the reference provided. The estimated soil water retentions and the derived K_{SAT} values (from **Equation 65** and **Equation 66**) are shown in **Table 57**. The percentage of sand and clay for each soil texture is discussed further in **Section 6.5.2.5**.

Table 57 Soil water retentions and saturated hydraulic conductivity estimated for 11 common soil texture classes in South Africa using various equations provided by Saxton and Rawls (2006)

Texture class	θ_{PWP} (m m^{-1})	θ_{DUL} (m m^{-1})	θ_{TPO} (m m^{-1})	λ	K_{SAT} (mm h^{-1})	K_{SAT} (mm d^{-1})
Clay	0.297	0.422	0.479	0.092	0.5	11
Silty clay	0.295	0.428	0.510	0.098	1.4	33
Silty clay loam	0.199	0.350	0.445	0.148	2.3	55
Sandy clay loam	0.163	0.248	0.393	0.110	7.3	175
Sandy clay	0.242	0.347	0.421	0.094	1.0	24
Clay loam	0.193	0.307	0.414	0.122	3.1	74
Sand	0.023	0.063	0.444	0.265	137.2	3292
Loamy sand	0.047	0.097	0.422	0.192	82.6	1983
Sandy loam	0.068	0.139	0.417	0.188	52.5	1259
Loam	0.114	0.217	0.406	0.168	17.4	417
Silty loam	0.117	0.283	0.427	0.230	9.0	216

The calculated values shown in the above table were then compared to that provided in the *ACRU* Theory (Schulze *et al.,* 1995; Table 5.6.1; p AT5-16) and User Manuals (Smithers *et al*., 1995; Table 6.12.1; p AM6.12-42) as shown in **Table 58**. A comparison of **Table 57** with **Table 58** shows good agreement between the soil water retention parameters, with differences ranging from 0.010 to 0.068 m m^{-1} (i.e. 1 to 6.8%). The calculated K_{SAT} values (using **Equation 65**) were generally higher than those provided by Schulze *et al.* (1995), except for the sandy soil, where a significant reduction was noticed (210.0 to 127.2 mm h^{-1}).

Hence, the derivation of K_{SAT} from the soil water content (θ) at the permanent wilting point, drained upper limit and total porosity using the Saxton and Rawls (2006) equations was deemed acceptable for use in this study. However, K_{SAT} values were "capped" at 2 000 mm day^{-1} based on the recommended range of 1 to 2 000 mm day^{-1} suggested by Raes *et al*. (2013). This upper limit was deemed appropriate as it is unlikely that agricultural crops would be grown in "pure" sandy soils and thus, high K_{SAT} values (> 2 000 mm day^{-1}) are unrepresentative.

Table 58 Default soil water retentions and typical saturated hydraulic conductivity for 11 common soil texture classes extracted from the *ACRU* Theory (Schulze *et al.,* 1995; Table 5.6.1) and User Manuals (Smithers *et al*., 1995; Table 6.12.1)

Texture class	θ_{PWP} ($m\ m^{-1}$)	θ_{DUL} ($m\ m^{-1}$)	θ_{TPO} ($m\ m^{-1}$)	K_{SAT} ($mm\ h^{-1}$)	K_{SAT} ($mm\ d^{-1}$)
Clay	0.298	0.416	0.482	0.6	14
Silty clay	0.253	0.390	0.480	0.9	22
Silty clay loam	0.190	0.335	0.473	1.5	36
Sandy clay loam	0.159	0.254	0.402	4.3	103
Sandy clay	0.228	0.323	0.423	1.2	29
Clay loam	0.195	0.312	0.468	2.3	55
Sand	0.050	0.112	0.430	210.0	5040
Loamy sand	0.068	0.143	0.432	61.0	1464
Sandy loam	0.093	0.189	0.448	26.0	624
Loam	0.128	0.251	0.464	13.0	312
Silty loam	0.121	0.272	0.495	6.8	163

6.5.2.3 Curve number (CN)

As shown in **APPENDIX I**, the *AQUACROP* model requires the curve number (CN) for the simulation of surface runoff and its value refers to antecedent moisture class II (i.e. CNII). Although a soil's curve number is a function of its type, slope and relative wetness of the topsoil slope, it also depends on the land use and land cover. Raes *et al*. (2013) provided default CNII values based on K_{SAT} of the A-horizon as shown in **Table 59**.

Table 59 Default CNII values for various saturated hydraulic conductivities (K_{SAT}) of the topsoil (Raes *et al*., 2013)

Typical soil texture	K_{SAT} (mm day^{-1})	CNII
Silty clayey	< 10	85
Sandy clayey	10 - 50	80
Loamy	50 - 250	75
Sandy	> 250	65

The results in the above table show that the soil's runoff producing potential is highest (i.e. 85) for silty clayey textured soils, which conduct water slowly through the soil profile (i.e. more runoff production due to reduced infiltration). Hence, the saturated hydraulic conductivity estimated for the A-horizon (using **Equation 65**) was used to derive the curve number input for *AQUACROP*, which is stored in the soils (.SOL) file for each quinary sub-catchment.

6.5.2.4 Readily evaporable water (REW)

REW expresses the maximum amount of water (mm) that can be extracted during stage I evaporation from a "thin" soil surface layer (0.04 m). Raes *et al*. (2013) provided an equation to derive REW (in mm) from the A-horizon's soil water content at field capacity (θ_{DUL} in volume %) and permanent wilting point (θ_{PWP} in volume %):

$$REW = 0.04(\theta_{DUL} - \theta_{PWP} / 2) \cdot 10 \qquad \textbf{Equation 67}$$

REW values were derived for each quinary sub-catchment and stored in the soils (.SOL file). The range of acceptable values was limited to 15 mm (and no values below 0 mm), based on recommendations by Raes *et al*. (2013).

6.5.2.5 Soil textural classes

Raes *et al*. (2013) provided default values for soil water retention parameters as well as saturated hydraulic conductivity for typical soil textural classes. However, these soil texture classes are based on the USDA[17] soil textural triangle, which is different to that adopted by the South Africa's binomial classification system (MacVicar *et al*., 1977), but identical to that used in the taxonomic classification (SCWG, 1991). Furthermore, the size distribution for silt particles was changed from 0.020 - 0.002 mm (MacVicar *et al*., 1977) to 0.050 - 0.002 mm (SCWG, 1991). The latter matches that used by the USDA soil classification system.

Hence, a soil classified into a particular textural class using the binomial classification may not necessarily match that classified using the taxonomic (or USDA) classification as illustrated in **Table 60**. The typical percentages of clay and sand shown in **Table 60** were obtained from Schulze *et al.* (1995; Table 5.6.1; p AT5-16). However, the sand fraction for a typical clay soil was corrected from 13 to 31% (as the value was identical to the silty clay soil in the same table).

Table 60 Soil textures derived from the proportion of sand and clay particles using the two soil classification systems developed for South Africa

Typical percentages of		**Textural classification system**	
Sand	**Clay**	**Binomial (1977)**	**Taxonomic (1991)**
31	50	Clay	Clay
13	50	*Silty clay*	*Clay*
21	33	*Silty clay loam*	*Clay loam*
65	27	Sandy clay loam	Sandy clay loam
55	40	Sandy clay	Sandy clay
46	32	*Clay loam*	*Sandy clay loam*
93	03	Sand	Sand
86	07	Loamy sand	Loamy sand
75	10	Sandy loam	Sandy loam
57	18	*Loam*	*Sandy Loam*
27	18	Silty loam	Silty loam

In this study, the soil textural classes based on the binomial classification system (MacVicar *et al*., 1977) are used. The reason is that this classification system and not its successor *viz*. the South African taxonomic soils classification (SCWG, 1991), was used for the land type surveys (Fanourakis, 2012). These surveys were conducted in the early 1970s by the former Soil and Irrigation Research Institute (SIRI), which is now the Institute for Soil, Climate and Water (ISCW) of the Agricultural Research Council. The quinary sub-catchment soils database was developed from data obtained from these land types.

[17] http://www.nrcs.usda.gov/wps/portal/nrcs/detail/?cid=nrcs142p2_054167

It is also important to note that methodology given by Saxton and Rawls (2006) to derive the soil water content from the particle size distribution also requires the soil's organic matter percentage. For the values given in **Table 57**, an organic matter content of 2.5% was assumed for all textural classes, as used by Saxton and Rawls (2006; Table 3; p 1577). However, for the soil water retentions given in **Table 58**, the organic matter content for each soil texture was derived from the typical percentage of organic carbon provided by Schulze *et al.* (1995; Table 5.6.1). This organic carbon percentage was by multiplied by 1.724 (known as Van Bemmelen's factor) and is based on the assumption that soil organic matter contains 58% organic carbon (Howard, 1965). The estimated organic carbon content ranged from 0.17 to 1.22%, which is deemed low for agricultural soils. Hence, this variation in organic matter will partly account for differences in the soil water retention parameters between **Table 57** and **Table 58**.

6.5.2.6 Derivation of soil textural class

The soil water retention parameters stored in the quinary sub-catchment soils database represent spatially averaged conditions and were derived from land types that were also averaged. Owing to this procedure, the "average" soil textural class for each quinary soil horizon is not available. Hence, an innovative method was developed for this study to "reverse engineer" the textural class, based on the soil's water retention characteristics. The textural class was then stored in *AQUACROP's* soils (.SOL) file for each of the two soil horizons.

The methodology was adapted from an approach given by Raes *et al*. (2013). The soil's volumetric water content at saturation (i.e. TPO) and at the drained lower limit (i.e. PWP), as well as the plant available water content (i.e. $PAW = \theta_{DUL} - \theta_{PWP}$) were used to classify the soil's texture. The first step involved classifying the soil as a sandy, loamy or clayey texture using its PWP value. For example, clayey soils generally exhibit a PWP value greater than 16.5%. Hence, soils with $\theta_{PWP} \leq 16.5\%$ are either a sandy or a loamy texture. Next, PAW is used to differentiate between sandy ($PAW \leq 10.5\%$) and loamy ($PAW > 10.5\%$) soils. Similarly, θ_{TPO} is used to differentiate between sandy clayey ($\theta_{TPO} \leq 45.5\%$) and silty clayey ($\theta_{TPO} > 45.5\%$) soils. Once the soil has initially been classified into one of four general classes (i.e. sandy, loamy, sandy clayey or silty clayey), it is finally classified as one of 12 textures. For example, specific ranges of θ_{PWP} (as shown in **Table 61**) are used to classify the soil as a silt, silt loam, loam, silty clay loam, silty clay or clay.

The soil water content thresholds given in the above table were derived for 54 "hypothetical" soils, where the sand and clay percentage were varied from 5 to 95% in 5% intervals. The textural class was derived for each soil using the textural triangle according to the binomial classification. The volumetric water contents at TPO, DUL and PWP were calculated using the equations provided by Saxton and Rawls (2006) assuming an organic matter content of 2.5%. The estimated values are shown in **Table 109** in **APPENDIX J** and ranked according to θ_{PWP}. The table highlights the threshold of 16.5% used to distinguish clayey soils from loamy or sandy soils.

Table 61 Thresholds of volumetric water content at saturation (θ_{TPO}) and at permanent wilting point (θ_{PWP}), as well as plant available water (*PAW*), used to determine a soil's textural class

Step	Textural class		θ_{PWP} (vol %)		θ_{TPO} (vol %)		*PAW* (vol %)	
	General	Specific	Lower	Upper	Lower	Upper	Lower	Upper
1	Sandy or loamy		5.0	16.5				
1	Clayey		16.5	52.8				
2	Sandy		5.0	16.5			3.9	10.5
2	Loamy		5.0	16.5			10.5	26.2
3	Sandy clayey		16.5	52.8	41.6	45.5		
3	Silty clayey		16.5	52.8	45.5	61.0		
4	Sandy	Sand	5.0	16.5			3.9	5.0
4	Sandy	Loamy sand	5.0	16.5			5.0	7.0
4	Sandy	Sandy loam	5.0	16.5			7.0	10.5
5	Loamy	Silt	5.0	10.0				
5	Loamy	Silt loam	10.0	16.4				
5	Loamy	Loam	16.4	16.5				
6	Sandy clayey	Sandy clay loam	16.5	52.8	41.0	43.0		
6	Sandy clayey	Sandy clay	16.5	52.8	43.0	44.0		
6	Sandy clayey	Clay loam	16.5	52.8	44.0	45.5		
7	Silty clayey	Silty clay loam	16.5	24.0				
7	Silty clayey	Silty clay	24.0	32.5				
7	Silty clayey	Clay	32.5	52.8				

6.5.3 Climate input

Raes *et al.* (2013) provided a detailed description of the input files required by the latest version (i.e. version 4.0) of FAO's *AQUACROP* model. The model requires a climate (.CLI) file which contains the names of the daily air temperature (.TMP), reference evaporation (.ETo), rainfall (.PLU) and atmospheric CO_2 (.CO2) files. An example of the climate file and its required format is given in **APPENDIX K** for quinary sub-catchment 4696. The format of the .TMP, .ETo and .PLU files is similar, with an example of the temperature (.TMP) file given in **APPENDIX K**.

The revised quinary sub-catchment database consists of 5 838 climate files, each containing 50 years of daily climate data stored in the format required by the *ACRU* model. A utility was developed using the FORTRAN programming language to convert the climate files from *ACRU's* composite file format into the format required by the *AQUACROP* model. During this conversion process, two additional files (.DSC and .DTA files) were created as required by FAO's *ET_o CALCULATOR*[18]. *ET_o CALCULATOR* (version 3.2) is a software utility developed by FAO's Land and Water Division. Its purpose is to calculate reference evaporation (ET_o) according to FAO standards (i.e. as described by Allen *et. al*., 1998). In total, 35 028 (i.e. 5 838 * 6) climate-related files were created in order to run *AQUACROP* at the national scale.

Two quaternary catchments were selected in KwaZulu-Natal, each consisting of three quinary sub-catchments which represent UKZN's Ukulinga research farm (sub-catchment's 4 696-4 698) and SASRI's La Mercy research farm (sub-catchment's 4 717-4 719). The *ET_o CALCULATOR* program was used to generate daily reference (i.e. FAO56 or Penman-Monteith) evaporation data using the description (.DSC) and climate data (.DTA) files as input. The output ET_o data were compared to that calculated for the quinary sub-catchments using the methodology described in **Section 5.5**. Daily ET_o values were accumulated over the 50-year climate record, with slight differences in totals ranging from -104.8 to +3.8 mm as shown in **Table 62**. These differences are considered insignificant and are due to minor variations in daily estimates of only ±0.1 mm, with the majority of daily values being identical. The largest difference in accumulated ET_o data occurred in the upper (i.e. higher altitude) quinaries, namely sub-catchments 4 697 and 4 719 which are associated with cooler temperatures.

Table 62 Comparison of daily reference evaporation estimates derived using FAO's ET_o calculator utility, with those obtained from the revised quinary climate database

Sub-catchment number	Accumulated ET_o estimates (mm)		
	Revised quinary climate database	ET_o Calculator	Difference
4 696	66 145.8	66 250.6	-104.8
4 697	72 554.4	72 611.4	-57.0
4 698	73 232.6	73 256.3	-23.7
4 717	63 350.1	63 370.7	-20.6
4 718	60 445.2	60 452.3	-7.1
4 719	62 346.9	62 343.1	3.8

6.5.4 Multiple project file

In order to run the yield model for successive seasons across multiple quinaries, a multiple project file was first developed. A utility was written in FORTRAN to generate an *AQUACROP* project file for multiple simulations (known as a .PRM file). For each crop season, this file contains, *inter alia*:

- default model parameters for each simulation (e.g. depth of the soil profile from which soil water evaporation can occur; default = 30 cm),

[18] http://www.fao.org/nr/water/eto.html

- first and last day of each simulation period, and
- first and last day of each cropping period (i.e. the crop growing season).

The .PRM also contains the location and name of the:
- climate (.CLI) file,
- temperature (.TMP), reference evaporation (.ETo) and rainfall (.PLU) files,
- soils (.SOL) file,
- crop (.CRO) and atmospheric CO_2 concentration (.CO2) files, and
- initial conditions (.SW0) file.

In addition, the user can also specify other management practices related to irrigation, fertilisation and the use of mulching layers, as well as conditions during the off season (i.e. fallow period). Thus, the above information was generated for each crop and its particular growing season (i.e. 49 to 50 seasons over the historical period 1950-1999), as well as for each of the 5 838 quinaries. For certain crops (e.g. sugarcane, sugarbeet and canola), two different planting dates were set. Owing to the large number of .PRM files required to run *AQUACROP* at a national scale for multiple crops with different planting dates, considerable effort was spent on automating this procedure to generate the .PRM files required by *AQUACROP*.

6.5.5 Crop parameter files

The crop parameter files used in this study were obtained from different sources as detailed in **Table 63**.

Table 63 Feedstock planting dates assumed for the simulation of yield using the *AQUACROP* model

Feedstock	Crop parameter filename	Source
Canola - winter	CanolaPC.CRO	Kienzle (2015)
Canola - summer	CanolaSC.CRO	Kienzle (2015)
Sugarbeet - winter	Sugarbeet_crop_Ukulinga.CRO	Mokonoto (2015)
Sugarbeet - summer	Sugarbeet_crop_Ukulinga.CRO	Mokonoto (2015)
Sugarcane - winter	Sugarcane_crop_LaMercy.CRO	Mokonoto (2015)
Sugarcane - summer	Sugarcane_crop_LaMercy.CRO	Mokonoto (2015)
Soybean	Soybean_Baynesfield_GDD.CRO	Moyo and Savage (2014)
Grain sorghum	Sorghum_GDD.CRO	*AQUACROP*

6.5.6 Growing season length

For all crops, the planting date and maturity date were adjusted to reflect local growing conditions. The dates used in this study are discussed next.

6.5.6.1 Planting date

The planting dates used for the *AQUACROP* model runs are given in **Table 64**. DAFF (2010d) suggested that canola should be planted from early April to mid-June in order to achieve the highest yields. Short season cultivars (70 days) should be used for plantings in

June, whereas longer season (120 days) cultivars are suited to April or May plantings (DAFF, 2010d). Since the Pincher Creek parameter file has a crop season length of 116 days, it is assumed to best represent a slower growing variety in the Western Cape region, with a typical planting date of 1st April (where the majority of canola is currently produced). Similarly, the canola file for Swift Current has a crop cycle length of 75 days and is assumed to best represent a faster growing variety, with a typical planting date of 1st June. However, Fouché (2012) suggested that canola in the Western Cape should be planted when the first autumn/winter rainfall from February onwards. In the Free State, KwaZulu-Natal and Eastern Cape Provinces, winter canola should be planted just before the last summer rains, which is January to early April.

Table 64 Feedstock planting dates assumed for the simulation of yield using the *AQUACROP* model

Feedstock	Planting date	Crop parameter filename
Canola - winter	1st April	CanolaPC.cro
Canola - summer	1st June	CanolaSC.cro
Sugarbeet - winter	1st June	Sugarbeet_crop_Ukulinga.CRO
Sugarbeet - summer	1st September	Sugarbeet_crop_Ukulinga.CRO
Sugarcane - winter	1st April	Sugarcane_crop_LaMercy.CRO
Sugarcane - summer	1st February	Sugarcane_crop_LaMercy.CRO
Soybean	1st November	Soybean_Baynesfield_GDD.CRO
Grain sorghum	1st November	SorghumGDD.CRO

For sugarbeet, two planting dates were also used, with the winter crop representing the expected planting conditions in the Cradock area. According to Maclachlan (2012), planting near Cradock should typically occur from May onwards, after the first frost. Planting too early (i.e. in April) can cause a portion of the plants to bolt (i.e. begin flowering) after a sufficient cold stimulus (i.e. frost). Bolting is unfavourable as it reduces tuber yield and creates infestations of “weed” beet in later years (i.e. the seeds produced are viable). However, simulated yields are expected to be low since an autumn or winter planting would require supplemental irrigation to establish the crop and maintain adequate growth during the dry season. For a summer crop, sugarbeet should be planted in early spring (i.e. soon after the start of the summer rainfall season) so that the crop can be harvested in late summer (i.e. March), thus allowing for a winter crop rotation.

Based on the La Mercy dataset that was used to calibrate sugarcane, the two treatments which produced the highest yields were the 1st February (Treatment #5) and 1st April (Treatment #6) plantings. Hence, these two planting dates were selected to represent a summer (i.e. February) and winter (i.e. April) crop. However, these two planting dates may produce a crop maturity date which does not coincide with the sugar mill season. Mills are typically operational from early April to late December and close for 3 months for maintenance. Sugarcane should be harvested from April to October and thus, additional planting dates may need to be simulated.

A planting data of 1st November was selected for soybean. This was based on the recommendation by DAFF (2010a) that planting from early to mid-November is the most appropriate for optimum seed production in South Africa. In relatively warm areas where high temperatures enhance growth rate, planting as late as the end of December can still produce satisfactory yields. According to the de Beer and de Klerk (2014), the optimum planting date is usually during November. In warmer areas though, soybean can be planted until the first week of January. A planting date during October, especially in areas with a higher altitude, is possible when soil and air temperatures reach acceptable levels early in the growing season.

A planting data of 1st November was also selected for grain sorghum. According to DAFF (2010e), sorghum is typically planted in South Africa from mid-October to mid-December. This concurs with PANNAR (2011) which stated that in most areas planting should take place during late October and November. However, grain sorghum may still be grown successfully as late as January, depending on the climatic conditions, length of growing season available and that required by the cultivar.

6.5.6.2 Maturity date

In *AQUACROP*, the following phenological growth stages need to be expressed in either calendar or thermal time:

- time to emergence (i.e. germination),
- start of flowering,
- length of flowering period,
- start of canopy senescence, and
- time to reach crop maturity (i.e. length of the crop cycle).

The determination of the crop cycle length is set in the crop parameter file (i.e. 0=by growing degree-days; 1=by calendar days). For this study, it was preferential to determine the crop maturity date using thermal time and not calendar days (**Table 65**). The main reason for this is the crop cycle length is dependent on the local climate (and the cultivar choice).

Table 65 Crop cycle length (or length of the crop growing season) in calendar days and growing degree days for each crop

Feedstock	**Season length (days)**	
	GDD	**Days**
Canola - winter	1 086	116
Canola - summer	1 086	75
Sugarbeet - winter	2 394	198
Sugarbeet - summer	2 394	198
Sugarcane - winter	3 150	490
Sugarcane - summer	3 150	490
Soybean	2 700	130
Grain sorghum	1 760	147

AQUACROP uses the growing degree day (*GDD*) concept to account for temperature effects on phenology. *GDD* are calculated using a method described by McMaster and Wilhelm (1997), with the exception that no adjustment is made of the minimum temperature when it drops below the base temperature. This is believed to better represent the damaging or inhibitory effects of cold on plant processes. In *AQUACROP*, this method of calculating *GDD* is known as “METHOD 3” which is detailed next.

GDD are calculated by subtracting the base temperature (T_{bse}) from the average air temperature (T_{ave}), i.e. $GDD = T_{ave} - T_{bse}$. The base temperature is the temperature below which crop development ceases. In *AQUACROP*, an upper threshold temperature (T_{upp}) is also considered and specifies the temperature above which crop development also ceases. The maximum air temperature (T_{max}) is adjusted to fall in the range T_{bse} to T_{upp}. Similarly, the minimum air temperature (T_{min}) cannot exceed T_{upp}. T_{ave} is then calculated from the adjusted T_{max} and T_{min} values and set to T_{bse} if below the base temperature.

The utility that was developed to produce the multiple project file (c.f. **Section 6.5.4**) was modified to read in T_{bse} and T_{upp} from the crop parameter file. The following rules (i.e. pseudo code) were then used to calculate and accumulate *GDD* from the set planting date:

if $T_{max} > T_{upp}$, then $T_{max} = T_{upp}$
if $T_{max} < T_{bse}$, then $T_{max} = T_{bse}$
if $T_{min} > T_{upp}$, then $T_{min} = T_{upp}$
$T_{ave} = (T_{max} + T_{min})/2$
if $T_{ave} < T_{bse}$, then $T_{ave} = T_{bse}$
$GDD = GDD + (T_{ave} - T_{bse})$

The crop cycle length (in *GDD*) is also obtained from the crop parameter file (**Table 65**) and used to determine the crop maturity date. For each season, daily maximum and minimum temperatures are read in from the quinary climate file and used to accumulate *GDD* from the planting date, until they equal or exceed the crop cycle length. This is repeated for each of the 50 possible seasons from 1950 to 1999.

6.5.7 Simulation period

In *AQUACROP*, the simulation period is either linked to the crop growth cycle (i.e. start of simulation period = start of crop period) or can be longer (i.e. the simulation period starts before the set planting date). The model’s sensitivity to changing the start of the simulation period was tested in **Section 4.3.5.7**.

6.5.8 Automation of runs

A decision was made to run *AQUACROP* at the primary basin level in order to keep the methodology consistent with the approach used for the *ACRU* model runs. For the *ACRU* runs, primary basins C and D cannot be run separately as quinary 1 431 (basin C) flows into quinary 1 929 (basin D). Hence, the model runs for each of the 21 basins, considering primary’s C and D are run together. However, Primary’s C and D were run separately for the yield modelling as shown in **Table 66**. Hence, the model runs fastest for primary M (24 quinaries) and slowest for primary D (864 quinaries).

Considerable effort was devoted to automating the procedure whereby *AQUACROP* runs non-stop for each of the 22 basins. This effort has significantly improved efficiency by reducing the overall time required to complete a national run. Furthermore, the automation allows for a feedstock to be re-run if 1) errors are discovered during the analysis, or 2) parameters are refined based on new evidence. Thus, much effort was spent on ensuring the automation procedure ran smoothly and correctly.

Table 66 The relationship between each primary drainage basin and the quinary sub-catchments

Primary catchment	Start quinary	End quinary	No. of quinaries
A	1	417	417
B	418	852	435
C	853	1 431	579
D	1 432	2 295	864
E	2 296	2 520	225
F	2 521	2 625	105
G	2 626	2 799	174
H	2 800	3 006	207
J	3 007	3 282	276
K	3 283	3 402	120
L	3 403	3 576	174
M	3 577	3 600	24
N	3 601	3 708	108
P	3 709	3 756	48
Q	3 757	3 969	213
R	3 970	4 059	90
S	4 060	4 233	174
T	4 234	4 635	402
U	4 636	4 821	186
V	4 822	5 079	258
W	5 080	5 526	447
X	5 527	5 838	312
Total			**5 838**

The decision to run the yield model for all quinaries and not a subset of quinaries where the crop may grow (i.e. based on the land suitability maps), is to facilitate the use of the national yield maps for validation of the land suitability maps, especially since they differentiate low from high potential production areas. Due to time constraints, this approach was not followed in this study but is recommended for future research.

6.5.9 Model run times

6.5.9.1 Canola in the Western Cape

The running of *AQUACROP* for multiple seasons across numerous quinaries was tested using canola for the same 113 sub-catchments identified in the Western Cape (1^{st} April planting date). Two Core i7 PCs with different CPU clock speeds were used for the initial model runs. It was noted that CPU speed affected the execution speed, but disabling the antivirus software did not significantly improve model performance (**Table 67**). When the model runs, it creates a number of temporary files in the *SIMUL* folder and writes the main output files to the *OUTP* folder. The antivirus software settings were modified to prevent scans of new files created in these two folders.

Table 67 Computational performance of the *AQUACROP* model running on two Core i7 PCs with different clock speeds

PC	Lapsed time (HH:MM:SS)	Number of quinaries	Antivirus software
Core i7 (PC #1)	00:39:02	113	Enabled
Core i7 (PC #2)	00:57:16	113	Enabled
Core i7 (PC #2)	00:55:40	113	Disabled

6.5.9.2 Calendar vs. thermal maturity

The advantages of calculating the crop maturity date using thermal time compared to a fixed season length were discussed in **Section 4.3.5.4**. However, the main disadvantage is a considerable increase in the computational time required to perform a national run. This is illustrated using soybean, where the model was run for all 5 838 quinaries for a fixed season length of 130 days, compared to a variable season length based on thermal time. The lapsed times shown in **Table 68** include the additional time required to generate the multiple project file for the thermal time option, considering the temperature file (containing 50 years of daily data) needs to be accessed for each quinary sub-catchment.

Table 68 Computational performance of the *AQUACROP* model with soybean's maturity date set to 130 days after planting, compared to a variable season length based on thermal time

PC	Run time (HH:MM:SS)	Number of quinaries	Maturity date
Core i7 (PC #1)	02:00:39	5 838	Calendar
Core i7 (PC #1)	89:19:09	5 838	Thermal

The results show that the *AQUACROP* model runs significantly slower when estimating yields with crop cycle length based on thermal (i.e. growing degree-days) time than compared to calendar days. For example, the model took 1.24 seconds (calendar) *vs*. 55.08 seconds (thermal) to complete each quinary. However, there is also a difference in the output produced by the model. This is discussed further in **Volume 1**.

6.5.9.3 National runs

Based on the initial testing of *AQUACROP* on 113 quinaries in the Western Cape (**Table 67**), it was projected that a national run would take approximately 1.40 to 2.05 days (or 33.61 - 49.31 hours) to complete. By comparison, *ACRU* took approximately 9 hours for each national water use run. From **Table 69**, *AQUACROP* ran for a total of 1 100 hours (or 46 days) and required almost 1 500 model re-starts to provide yield estimates for five crops (some with two planting dates).

Table 69 Computational time required to complete the national yield estimates using the standalone version of *AQUACROP* model

Feedstock	Planting date	Run time		Number of re-starts
		days	hours	
Canola	1st April	1.46	35.02	44
Canola	1st June	1.71	40.93	37
Grain sorghum	1st November	2.57	61.77	73
Soybean	1st November	3.72	89.32	113
Sugarbeet	1st September	3.80	91.29	112
Sugarbeet	1st June	6.01	144.33	189
Sugarcane	1st April	10.40	249.72	392
Sugarcane	1st February	16.13	387.19	506
	Total	**45.82**	**1 099.57**	**1 466**

The sugarcane simulation for a February planting took 5.73 days (or 137.47 hours) longer than the April planting due to the issue discussed in **Section 6.5.12.4**. To re-cap, the crop season length was limited to a maximum of 730 days for the April simulation. In general, the number of times the model needs to be automatically re-started after a division-by-error occurs, the longer the overall simulation time.

6.5.10 Yield and WUE statistics

A utility was developed to extract specific monthly and seasonal variables from *AQUACROP*'s output files, which included, amongst others, the following:

RAI = monthly rainfall (mm)
ETR = monthly reference evaporation (mm)
= based on Penman-Monteith or FAO56 evaporation (Allen *et al*., 1998)
GDD = growing degree days accumulated for month (°C day)
= calculated with "METHOD 3"
CO2 = monthly ambient CO_2 concentration (ppm)
IRR = amount of water applied as irrigation (mm)
RUN = amount of water lost to surface runoff (mm)
= $(RAI - 0.2 \cdot PMS)^2 / (RAI + PMS - 0.2 \cdot PMS)$
PMS = potential maximum storage (mm)
INF = amount of water infiltrated into the soil profile (mm)
= *RAI* - *RUN*
DRA = amount of water drained out of the soil profile (mm)
UPF = amount of water moved upward by capillary rise (mm)
SOI = amount of water evaporated from the soil surface (mm)
TRA = amount of water transpired from the crop surface (mm)
ETC = total amount of water evapotranspired from the crop (mm)
= *SOI* + *TRA*
CYC = length of crop cycle, from germination to peak yield (days)
BIO = above-ground biomass produced (t ha^{-1})
HID = harvest index (%), and
YLD = dry crop yield (t ha^{-1})

	=	*HID * BIO*
WPY	=	yield produced per unit water evapotranspired (kg m^{-3})
	=	*YLD*/*ETC*

In addition, the number of crop failures (*CFA*, defined as *YLD* = 0.00 t ha^{-1}) was determined for each 50-year simulation and this figure was doubled to express the risk of crop failure as a percentage. For example, a 70% risk of crop failure means that a zero yield was simulated for 35 of the 50 seasons. The total number of seasons (*SEA*) that were simulated was also extracted. If the model run ended prematurely due to a division-by-zero error, then *SEA* is less than the maximum. Typically, the maximum number of seasons is 50, but is reduced to 49 if the crop matures in the year 2000 (or 48 in the case for sugarcane).

In terms of the crop cycle length, the figure calculated by *AQUACROP* (i.e. peak yield attained 203 days after emergence) and the crop maturity length (345 days) were also extracted for each season, from which the mean and median statistics were calculated. For example, *AQUACROP* simulated cycle lengths ranging from 175 to 367 over the 49 seasons, with a mean and median of 228 and 221 days respectively. The crop maturity length (or crop growing cycle) ranged from 337 to 376 days, with a mean and median of 358 and 357 days respectively. It is important to note the differences between these two season lengths.

The calculation of *WPY* by *AQUACROP* was investigated further using sugarcane transplanted on 1st February in quinary 732. The transplanted seedling (i.e. ratoon crop) recovered on 4th February after 40 GDD were accumulated and moved to growth stage 2. On the 15th March (43 DAP), the start of yield formation began (growth stage 4) after 541 GDD were accumulated. Yield formation began on the 28th March (56 DAP) and maximum rooting depth was achieved on 14th May (103 DAP) after the accumulation of 1 154 GDD. On the 24th October (266 DAP), the build-up of the harvest index began. Senescence began on 22nd December (324 DAP) after 2 914 GDD were accumulated and finally, the crop matured on 11th January (345 DAP) after the accumulation of 3150 GDD. The maximum yield of 3.94 t ha^{-1} was realised on 26th August (207 DAP) after 281.3 mm of *ETC* was accumulated. Hence, WPY calculated by the model was 1.40 kg m^{-3} (i.e. 3 943 kg of *YLD* from 2 813 m^3 of *ETC*). The crop cycle length was calculated as 203 days (207 - 4 days for recovery/emergence).

From 208 to 345 DAP (when the crop matured), a further 129.6 mm of soil water evaporation (*SOI*) took place, but no transpiration (*TRA*) and thus no further biomass (*BIO*) or yield (*YLD*) was produced. The total *ETC* accumulated over the growing period of 345 days was 410.90 mm (281.3 + 129.6 mm). This equates to a WUE of 0.96 kg m^{-3} (i.e. 3943 kg of *YLD* from 4 109 m^3 of *ETC*) at maturity. This WUE is labelled as “at maturity” or *WPM* and will always be less than *WPY* which represents the WUE calculated by *AQUACROP* when the maximum (labelled “at peak”) yield is attained (i.e. *WPY* = 1.40 kg m^{-3}). **If these two WUEs differ substantially, the site should not be considered suitable for crop production**. Both WUE values were extracted for each season (maximum of 50 in total), from which the mean, median and coefficient of variation statistics were calculated. *WPY* ranged from 0.99 to 2.18 kg m^{-3}, with a mean and median of 1.59 and 1.62 kg m^{-3} respectively. Similarly, the mean *WPM* is 1.07 kg m^{-3} (median = 1.06 kg m^{-3}) and the range is 0.47 to 2.08 kg m^{-3}.

This quinary was selected to illustrate the large difference between these two WUE estimates using an area which is too hot and dry for viable sugarcane production. For this quinary, the amount of above-ground biomass per unit of evapotranspiration was calculated as 3.26 kg m^{-3} (peak) and 2.23 kg m^{-3} (maturity) for the first season. These figures are below the typical range of 3.5 to 5.5 kg m^{-3} reported by Steduto *et al*. (2012) for sugarcane. The biomass WUE at maturity ranged from 1.17 to 3.20 kg m^{-3} (mean and median of 2.28 and 2.20 kg m^{-3} respectively).

6.5.11 Runoff prediction

In *AQUACROP*, the estimation of runoff is based on the curve number (*CN*) method which is used to calculated the potential maximum storage in mm [*PMS* = 254(100/*CN* - 1)]. Once the water content of the topsoil (to a depth of 0.3 m) is saturated (0.2·*PMS* in mm), any additional rainfall becomes surface runoff. Hence, (0.2·*PMS*) represents the amount of rainfall that must infiltrate before surface runoff begins (i.e. initial abstraction). A soil with a high *CN* will have a *PMS* and thus, most of the rainfall (*RAI*) is converted to runoff (*RUN*). The maximum amount of water (rainfall or irrigation) that can infiltrate the soil (*INF*) is limited by the saturated hydraulic conductivity of the topsoil (Raes *et al.*, 2012b). After the subtraction of surface runoff, the remaining part of rainfall and irrigation water will infiltrate into the soil profile (i.e. *INF* = *RAI* - *RUN*). Infiltrated water is stored in the root zone and if a threshold soil water content is exceeded, excess water percolates out of the root zone reservoir and is lost as deep percolation (i.e. *DRA*). The process of evapotranspiration (*ETC* = *SOI* + *TRA*) removes water from this reservoir. Since, *SOI* and *TRA* are calculated from daily ET_o values, reference evaporation (*ETR*) is therefore a key input for the model.

Since the simulation of final crop yield is sensitive to the timing and magnitude of water stress in the root zone, *AQUACROP* must adequately simulate the soil water balance. Vanuytrecht *et al*. (2014) stated that efforts are currently underway to improve the algorithms that account for root elongation and runoff generation. In addition, future versions of the model will allow the soil to be described more adequately, by extending the required input of soil characteristics and field management practices. In this study, the average runoff predicted by the model was not calculated, nor mapped. The runoff output from the *ACRU* model is considered far superior.

6.5.12 Implementation verification

Before running *AQUACROP* at the national scale for all 5 838 quinaries, a number of tests were carried out to verify the output from the model. The issues that were discovered are described next.

6.5.12.1 *AQUACROP* vs. *SWB*

As explained earlier, the *SWB* model was not designed to be run in “batch” mode. In other words, there is no version that is equivalent to *AQUACROP*’s standalone model. A decision was made to run manually the *SWB* model for a subset of quinary sub-catchments located in the Western Cape where the majority (≈98%) of canola is produced. The sub-catchments were selected using a GIS analysis where the portion of the quinary identified as a canola farm was determined, then expressed as a percentage of the total quinary area and finally, ranked from largest to smallest. Thus, quinaries with at 10% of their area classified as actual canola farms were extracted, which totalled 113 sub-catchments. The canola farm boundaries were supplied by the Department of Agriculture (Western Cape), which were derived from an aerial survey conducted in 2013.

Soils and location data (centroid & altitude) for the 113 identified quinaries were extracted from the quinary soils database, with climate data obtained from the revised version of the quinary climate database. A utility was developed to output the data into the format required by the *SWB* model (**APPENDIX L**). The *SWB* model was then run manually for each sub-catchment, assuming a 1st April planting date. Students at the University of Pretoria took five weeks to complete this task.

The *SWB* model was used to determine the attainable canola yield as well as water use (i.e. actual evapotranspiration accumulated over the growing season). Hence, the model was run for a single point (i.e. the centroid of each quinary sub-catchment), at an altitude that is representative of the average altitude across the entire quinary, using climate data that is also deemed representative of the quinary's centroid location. From the model output, the water use efficiency (WUE=yield/water use) was calculated and expressed in kg m^{-3}).

The *AQUACROP* model was run in batch mode for each quinary sub-catchment comprising of the 22 drainage basins. However, when the model was run for the first time at the national level, a number of problems were encountered. These topics are discussed next.

6.5.12.2 Low first season yield

During the testing phase, it was noticed that *AQUACROP* would simulate low yields in the first season than compared to the next. In order to find a solution to this problem, the two-layer soil profile was converted to a single layer soil for the quinary sub-catchment. This was achieved by weighting the soil water retention parameters using the depth of each horizon relative to the total soil depth. However, this has no effect on the low yield simulated in the first season. Another solution is to increase the minimum effective rooting depth (Z_{min}) to prevent yield loss due to high soil water evaporation which results in low soil water content of the topsoil. Steduto *et al.* (2012) suggested a Z_{min} range of 0.2 to 0.3 m, with a value of 0.30 m set in all default crop parameter files. Hence, Z_{min} refers to the soil depth from which the germinating seed can extract water. However, this option was not attempted in this study.

6.5.12.3 Division by zero errors

When *AQUACROP* was run at the national scale (i.e. for all 5 838 quinaries), the model produced a number of "division-by-zero" errors for selected sub-catchments as listed in **Table 70** for canola. This problem did not occur when the model was tested for the 113 quinaries containing canola farms in the Western Cape. When the error occurred for a particular catchment, the model would stop running, thus requiring user intervention to close the error dialog box and manually stop the model runs. Unfortunately, this type of error prevented the automatic execution of the model at the national scale. Considerable effort was therefore spent on trying to find the cause of this error by testing the model on the affected sub-catchments list in **Table 70**.

Table 70 List of quinary sub-catchments that resulted in division-by-zero errors when simulating canola planted on 1st April and 1st June using the *AQUACROP* model

Crop	Quinary sub-catchment ID
Canola (April)	0202, 0315, 0327, 0329, 0465, 0492, 0510, 0713, 0876, 0889, 0986, 1148, 1297, 1518, 1634, 1709, 1851, 2022, 2048, 2051, 2124, 2142, 2254, 2278, 2468, 2953, 3075, 3238, 3573, 3585, 3829, 4071, 4275, 4395, 4409, 4428, 4619, 4760, 4857, 4908, 4911, 5310, 5467, 5731
Canola (June)	0126, 0248, 0522, 0523, 0670, 0705, 0711, 0990, 1126, 1260, 1386, 1403, 1417, 1529, 1647, 1766, 1854, 1934, 2025, 2154, 2180, 2431, 2781, 2924, 3086, 3223, 3528, 3664, 3888, 4185, 4374, 4503, 4790, 4971, 5252, 5422, 5695

The first step involved running the affected sub-catchments with the GUI version of the model, which also produced the same division-by-zero error. However, this error occurred more frequently (i.e. for other quinaries not listed in **Table 70**) if the simulation period was started before the planting date (i.e. on 1st January). Similarly, the error was made worse when the initial soil water content was set to 50% of PAW (and not at field capacity, being the default option). These findings indicate the division-by-zero error is probably related to the soil water content of the topsoil approaching a zero value. Thus, the initial soil water content (or .SW0) input file was carefully scrutinised for possible errors.

An incorrect setting was found which set the initial soil water content to a specified depth and not for a specific soil layer. This error was fixed and the .SW0 file was re-generated for each quinary sub-catchment. The model was re-tested to ascertain if the division-by-zero error was eliminated. Unfortunately, the error still occurred on some, but not all affected quinaries. It was also found that by increasing or decreasing the K_{SAT} value, the division-by-zero error was eliminated. However, this "workaround" could not be justified and was therefore not considered a "solution". The decision was therefore made to link the simulation period to the crop growth cycle and to assume the soil is at field capacity at planting. The experience gained during the model testing phase confirmed that it is best to keep each simulation as simple as possible.

Considerable effort was spent on developing an automated procedure to monitor the execution of the standalone version of *AQUACROP*. If a division-by-zero error occurred when simulating a particular quinary within a basin run, the model was automatically terminated and re-started on the next quinary. In total, over 2 400 lines of computer code was written to run the model at the national scale. An additional 2 851 lines of code was developed to prepare the input files required to run the model.

6.5.12.4 Maximum season length

During the testing phase, an issue was discovered where the computational time for the *AQUACROP* model to complete multi-season yield simulations was unacceptably high (i.e. too long) for certain quinaries. Further investigation revealed that unrealistic season lengths were calculated for high altitude sub-catchments. This is explained further using two extreme cases found. For quinary 4 840 (average altitude 2 955 m) and 4 489 (average altitude 2 755 m), the length of the first season was calculated as 7 368 and 10 579 days respectively (**Table 71**). The standalone version of the *AQUACROP* model then ran for approximately 20 to 29 years, generating little to no yield (due to the cold temperatures experienced in these mountainous sub-catchments). The main problem was the length of time the model took to complete the yield simulation for such quinaries, given the multiple seasons, each 20 to 29 years in length. Thus, an upper limit of 730 days was set to prevent an unrealistic season length from being calculated in very cold areas. This is based on sugarcane and pineapple which have the longest cycle lengths at 720 and 790 days respectively (Raes *et al*., 2012d; c.f. Annex II; Allen *et al*., 1998).

Table 71 Length of the first three sugarcane seasons for two quinaries, with the planting date set to 1st February

Season	Quinary 4840	Length (days)	Quinary 4489	Length (days)
1st	1950/02/01 1970/04/04	7 368	1950/02/01 1979/01/18	10 579
2nd	1951/02/01 1971/01/11	7 285	1951/02/01 1979/03/11	10 266
3rd	1952/02/01 1972/12/05	7 614	1952/02/01 1980/12/24	10 555

6.5.12.5 Number of seasons

An error was discovered in the algorithm to determine the crop cycle length using thermal time. The problem occurred for crops when the calculated maturity date extended beyond the end of the climate data record (i.e. 1999/12/31). For example, sugarcane planted on 1st February in quinary 4 719 (La Mercy) would typically mature 414 days later. However, the algorithm was designed to limit the maturity date to the last day of climate record (31st December 1999). Hence, when *AQUACROP* ran for the 50th season, it was therefore programmed to start on 1999/02/01 and end on 1999/12/31. However, the yield simulated for this season was lower than the attainable yield since the growing season was incomplete (i.e. too short). In order to prevent yield estimates for incomplete seasons affecting the calculation of the long-term average yield, they were discarded. Hence, the average and median yield for quinary 4 719 was derived from 49 (and not 50) seasons of yield estimates for sugarcane. This error did not occur when the model was tested for canola, since the last crop season ran from 1st June 1999 to 13th August 1999 (i.e. 74 DAP).

It was also discovered that if the maturity date was erroneously set to occur before the planting date, the model went into an infinite loop and would simulate zero yields for each successive year beyond 1999. This severely affected the computational time to complete each quinary. It appears that the model does minimal error-checking of user input data. Hence, it is important that input data are thoroughly checked for errors in order to prevent the "garbage-in, garbage out" syndrome.

7 REGIONS SUITABLE FOR FEEDSTOCK PRODUCTION

The main aim of this chapter is to identify and describe bio-climatic regions suitable for crop/tree systems suitable for biofuel production with reference to, *inter alia*:

- rainfall average and variability,
- surface and underground water resources,
- temperature average and extremes,
- soil properties,
- known pests and diseases, and
- topography.

In order to achieve the objective, a land suitability assessment was completed to identify both high potential (optimum) and low potential (sub-optimum) bio-climatic regions deemed suitable for feedstock cultivation. However, the sub-optimum class was split into two categories, namely moderately suitable and marginally suitable for crop growth.

7.1 Introduction

Land is required for different uses or purposes, namely to provide food, fibre, housing and energy as well as conserving nature and its biodiversity. Escobar *et al*. (2009) stated that because the amount of available land in the world for agriculture is limited, it is necessary to define and identify the fraction of farmland that could be used for the production of biofuels. The selection of land on which to grow the feedstocks is a critical component determining the sustainability of the biofuels industry.

Feedstock demand can be met by 1) an increase in the area under cultivation, and/or 2) through an increase in feedstock yields. Owing to the high volumes of feedstock required for biofuel production in South Africa (e.g. an additional 600 000 tons of grain sorghum), a large increase in the planted area is required to satisfy the demand. Feedstock derived from gains in crop yields and the diversion of feed (not food) crops to biofuel production is insufficient to meet the demand. In other words, the intensification of agricultural production on existing land is deemed insufficient to produce the required volume of feedstock required for biofuel production.

The outcome of this project is to identify land which can be used for feedstock cultivation, taking into consideration present land use. This involves an assessment of land suitability to identify areas suitable for the cultivation of biofuel feedstocks. According to the FAO (2007), land evaluation was developed to comprehensively assess land performances when used for different purposes. Any farmland expansion (whether for food, feed or energy production), should not occur at the expense of valuable ecosystem services and high value natural ecosystems (e.g. forests and areas of high biodiversity). Agro-ecological zoning can be used to distinguish land with the potential for biofuel production from that of high value for food production and biodiversity (Lerner *et al*., 2010). There is considerable interest in the use of less productive land (i.e. marginal land) for cultivation of biofuel feedstock. Marginal lands are those with least (i.e. marginal) economic value. However, the land may have higher social, environmental or ecological value. Once these social, environmental and ecological aspects have been considered, the land may be considered less “marginal”.

The FAO published guidelines for land evaluation (FAO, 1983), which describe the sequence of activities and procedures used in land suitability assessments. These guidelines formed the basis for the methodology used in this project. The first step involved the identification of feedstocks considered appropriate for biofuel production in South Africa (c.f. **Section 2.5**). The next step required the determination of climatic, edaphic and biotic factors which limit feedstock production (**Section 2.6** & **Section 2.7**). These factors were then applied to spatial datasets (**Section 7.4.2**) using the methodology described in **Section 7.4** and **Section 0**.

7.2 Factors Affecting Plant Growth

According to Manske (2001), plant growth factors are controlled by internal regulators (i.e. within the plant) that are modified by environmental conditions. Hence, the long-term climatic conditions across a region largely determine the vegetation types found in that region (Manske, 2001). The important climatic factors influencing plant growth are rainfall and temperature, since these abiotic site factors control the moisture supply and demand at a particular location. Similarly, relative humidity is a surrogate variable that can be used to assess biotic factors affecting planting growth, in particular disease risk.

7.2.1 Rainfall

Water usually accounts for 80% of the weight of the herbaceous plant and is a principal component of the plant cell. Water is biochemically important since it is also the principal component of physiological processes that occur within the plant (Manske, 2001). According to Manske (2001), water is essential for maintenance of the rigidity of plant tissues. When water is limited, biological processes such as temperature control, nutrients and metabolite transport can be negatively affected and this can impact plant grow and development (Manske, 2001).

7.2.1.1 Seasonal rainfall total

Mokonoto (2012) showed that mean annual rainfall (MAP) should not be used to identify areas suitable for crop cultivation. Similarly, mean annual temperature (MAT) is not suitable as an index of moisture demand for plant growth. Such statistics (e.g. MAP & MAT) provide no information about seasonality. The intra-year distribution of rainfall, as described by monthly totals, can explain why two sites with similar seasonal rainfall can exhibit significantly different crop yields. However, plant growth is not only affected by total seasonal rainfall, but also the distribution of rainfall over the growing season.

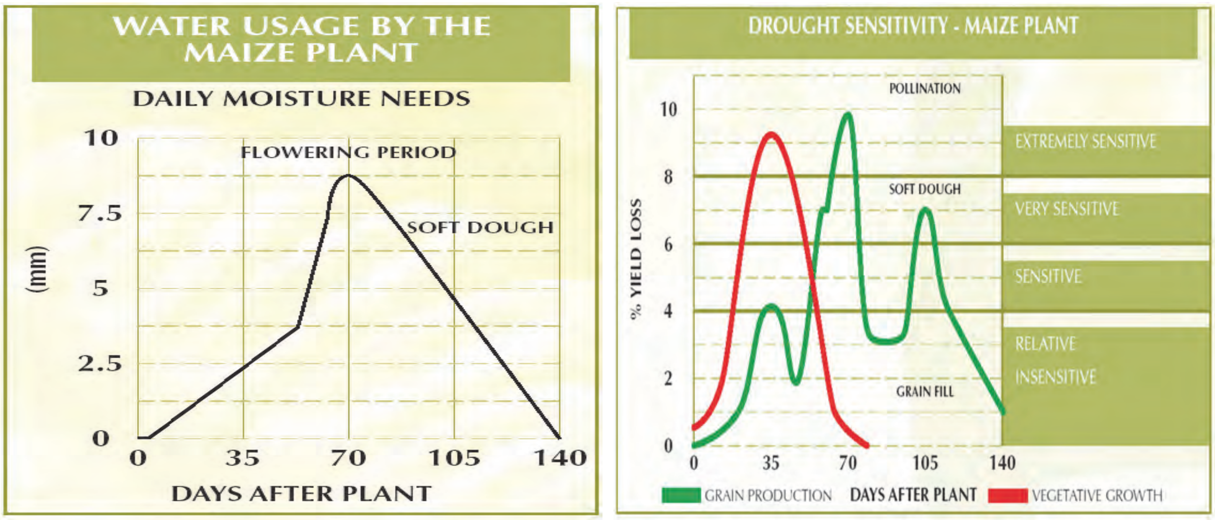
7.2.1.2 Seasonal rainfall distribution

Schulze and Maharaj (2007b) highlighted that plant growth is affected by the duration of the rainy season, i.e. whether the rainfall is concentrated over a short period of the year or spread over a longer period. The rainfall concentration index, determined using Markham's (1970) methodology, calculates a value ranging from 0 to 100%. An index of 100% implies that all rainfall falls in a concentrated time period, e.g. one month. On the other hand, a concentration index of 0% implies a similar rainfall amount in each month. Hence, rainfall concentration describes the duration of the rainy season and varies spatially across southern Africa.

Schulze and Maharaj (2007b) calculated rainfall concentrations for each quaternary catchment, whereas Schulze and Kunz (2010a) repeated the exercise at the quinary catchment scale. Both studies highlighted that the highest and lowest rainfall concentrations are found in the Limpopo and Western Cape Provinces respectively. The rainfall concentration index indicates the distribution of rainfall across the rainy season and is useful in identifying for example, the all-year rainfall season along the southern and eastern coastal areas (Schulze and Maharaj, 2007e). However, the index does not indicate in which month crop water use is highest and thus, in which month the majority of seasonal rainfall should fall. For this, the crop coefficient can be used, which is discussed next using maize as the example crop.

7.2.1.3 The crop coefficient approach

According to Seckler (2003), most crops are sensitive to water stress at both the vegetative growth and fruit/grain development stages. This is illustrated in **Figure 46b** which shows that maize is "extremely sensitive" to water stress during its vegetative growth stage (35 days after planting or DAP) and during pollination/flowering (70 DAP). Thus, maize requires (and uses) more water during its flowering period than any other growth stage. In other words, low rainfall during the second month and especially in the third month could result in the highest loss of attainable yield.



(a) (b)

Figure 46 (a) Water use by maize under well-watered conditions; (b) Sensitivity of maize to soil water stress during each growth stage (Pannar, 2003)

The length or each growth stage in relation to a generalised crop coefficient curve is shown in **Figure 9** (c.f. **Section 3.1.2.3**). According to Allen *et al*. (1998), the initial crop coefficient value ($K_{c\ ini}$) varies with the frequency of wetting events during the initial growth period, i.e. $K_{c\ ini}$ is large when the soil is wet from frequent rainfall or irrigation events and is low when the soil is dry. Maize's water use peaks in the third month (i.e. 70 DAP as shown in **Figure 46a**) which coincides with the peak crop coefficient value (i.e. $K_{c\ mid}$). According to the FAO (FAO, 2002), $K_{c\ mid}$ for maize ranges from 1.05 to 1.20 during the 3rd and 4th month of its growth cycle (**Table 72**). Hence, maize needs most of its seasonal rainfall requirement to fall in the 3rd month.

Table 72 Single crop coefficients (K_c) for each maize growth stage as suggested by FAO (FAO, 2002)

Growth stage	Length of growth stage (days)	K_c (FAO, 2002)
Initial	15-30	0.30-0.50
Development	30-45	0.70-0.85
Mid-season	30-45	1.05-1.20
Late-season	10-30	0.80-0.90
At harvest		0.55-0.50

An innovative approach adopted in this study involved the use of crop coefficients to determine the optimum distribution of rainfall over the growing season on a monthly basis. As noted earlier, the peak K_c value (i.e. $K_{c\ mid}$) indicates the month in which crop water use is highest. If this peak demand for soil water cannot be met, a reduction in attainable yield may occur. However, the approach assumes that rainfall is the only supply of moisture for plant growth. It also neglects the supply of soil moisture from capillary rise, which can be significant for clay soils above perched (or shallow) groundwater tables. Furthermore, the crop coefficient approach does not factor in the soil's ability to retain surplus moisture in one month and make it available for growth in the following month.

7.2.2 Temperature

Temperature plays an important role in the daytime process of plants to synthesise carbohydrates via photosynthesis. According to Smith (2006), photosynthesis increases from 5°C to an optimum leaf temperature of 30 to 35°C. Hence, maximum daytime temperatures of up to 35°C increase the rate of photosynthesis. If the temperatures are too high, plant growth can be negatively affected, e.g. above 35°C for maize flowering (Smith, 2006). However, high maxima can have either a negative effect (e.g. maize) or positive effect (e.g. strawberries) on plant growth (Schulze and Maharaj, 2007a).

The variation of monthly mean temperatures influences the geographic range and the optimum growing areas for certain crop species, in particular for those with a lifecycle extending one year or less (Schulze and Maharaj, 2007a). From the perspective of crop survival, the climatic distribution of a crop is mostly described by minimum temperature. Most sub-tropical crops may die at 5°C and below, even if there is no frost. The term hardiness refers to a crop's tolerance to low temperatures (Schulze and Maharaj, 2007a).

7.2.3 Relative humidity

Relative humidity (RH) plays an important role in plant production. High RH has both positive and negative benefits for plant growth. High humidity levels create favourable conditions for the growth of certain micro-organisms (Schulze, 2007), as well as increase the presence of parasites and weeds (Schulze *et al*., 1997). Extended high humidity (75-80%) coupled with extended periods of cloudy weather during the growing season would favour soybean rust infection and eventual epidemics (Caldwell *et al*., 2002). On the other hand, salt sensitive crops can benefit from being grown in areas of higher relative humidity (An *et al*., 2001).

Basically, increased relative humidity decreases transpiration, which reduces sodium uptake and translocation to plant leaves.

Humidity levels also directly influence the water use of a plant by regulating the transpiration rate. High humidity therefore reduces crop water use, thus enhancing water productivity (Smith, 2006). Relative humidity also indirectly affects leaf growth, leaf water potential, photosynthesis and disease incidence. When relative humidity is high, turgor pressure is also high due to reduced transpiration. Similarly, high humidity levels reduce CO_2 uptake by the leaf, thus indirectly affecting photosynthesis.

7.2.4 Soil depth and texture

The soil provides water, air, nutrients and stability to plants (Hewitt, 2004). Adequate soil conditions, including sufficient water and nutrient supply, are required for plant development and successful crop production (Pessarakli, 1994). Soil texture and effective rooting depth are important factors to consider when determining plant available water (Smith, 2006).

7.2.5 Soil slope

Gentle slopes allow more time for water to percolate into the soil profile, whilst steeper slopes result in greater runoff (i.e. less percolation) and increased soil erosion (Schulze and Horan, 2007a). According to Sys *et al*. (1991), steep slopes pose more difficulties to cultivation than flat land. Steep slopes are also subject to higher rates of water runoff and soil erosion (FAO-IIASA, 2007).

7.2.6 Altitude

In this study, altitude was not considered a mapping criterion because sites with a similar temperature (i.e. MAT isotherm of 16°C) occur at different altitudes in South Africa (i.e. ranging from 900 to 1700 m). Furthermore, altitude is often used as a surrogate for temperature when temperature data are unavailable.

7.2.7 Heat units

Mokonoto (2012) developed a soybean suitability map by identifying areas with a seasonal rainfall of 550 to 700 mm (from October to March) and monthly mean temperatures of 20 to 30ºC. These constraints for optimum growth were obtained from the biofuels scoping study (Jewitt *et al*., 2009a). He then derived a heat unit map by applying the optimum heat unit range (1 500 to 2 600 GDD) to accumulated heat units (base 10°C) for October to March. The heat unit map was superimposed on the optimum growing areas (i.e. rainfall & temperature) map resulting in no loss in potential cultivation area. Mokonoto (2012) then visually compared the temperature and heat unit maps and found very little difference (spatially) between the two datasets. He concluded that either temperature or heat units could be used as mapping criterion, but not both. Based on this evidence, the decision was made to exclude heat units and only consider temperature constraints for growth.

7.2.8 Multiple criteria

The study conducted by Mokonoto (2012) showed that relative humidity (optimum range of 60 to 70%) is the main constraint which limits soybean cultivation. **Table 73** highlights a 50.1% reduction in potential soybean cultivation area after the relative humidity criterion was applied. Soil depth (> 600 mm) was considered next, resulting in a further loss of 18.9% in potential area.

Table 73 Reduction in optimum growing areas deemed climatically suitable for soybean cultivation, caused by applying additional climatic and edaphic constraints to growth (Mokonoto, 2012)

Rainfall & temperature	Heat units	Relative humidity	Soil depth	% area remaining
Y				100.0
Y	Y			100.0
Y	Y	Y		49.1
Y	Y	Y	Y	30.2

This result highlights the sensitivity of the mapping approach to certain criterion, in particular relative humidity, which is used as a surrogate variable for disease incidence (as explained in **Section 7.2.3**). However, the study assumes that each criterion is equally important in terms of plant growth. This is not the case, which is discussed in **Section 7.4.5**.

7.3 GIS-based Case Studies

A Geographic Information System (GIS) is a computer-based tool for solving problems and is defined as a tool for capturing, storing, retrieving, manipulating, analysing and displaying spatial data (Malczewski, 2004). It is typically made up of five components, *viz*. computer hardware, computer software, spatial data, personnel and procedures. GIS has emerged as a powerful tool for overlaying large amounts of spatial information. Land suitability assessment is concerned with the availability of land resources in a given area, in relation to that required by a particular land use. GIS is a useful tool in “matching” land characteristics in a given area with the site requirements of a particular land cover. Four GIS-based studies related to the mapping of bioenergy feedstocks are considered next.

7.3.1 Jatropha’s biophysical potential (2007)

A study funded by the Water Research Commission (WRC) assessed the water use and biophysical potential of *Jatropha curcas* (Holl *et al*., 2007). A literature review was conducted to glean the biophysical requirements that influence the feedstock’s survival and growth. The study used rainfall, temperature, soils, slope and frost information to map areas suitable for Jatropha production. A conservative approach was adopted when defining cut-off limits (or threshold values) for each mapping variable. This was based on the decision that Jatropha should not be planted in marginal areas. Altitude was not used as a mapping criterion as it is strongly correlated with temperature (see **Section 7.2.6** for more information).

Holl *et al*. (2007) adopted a two-phase approach to their mapping exercise. Firstly, the five mapping criteria were used to eliminate areas not suitable for Jatropha production. For example, areas with an MAP < 300 mm and an MAT < 11ºC or > 38ºC were eliminated as potential growth areas. Spatial data was sourced from the South African Atlas of Agrohydrology and Climatology (Schulze *et al*., 1997).

Secondly, the mapping criteria were weighting according to their importance in determining (or influencing) the survival and growth of Jatropha. Rainfall was considered the main driver and therefore weighted 40%. Temperature was also considered important and assigned a weighting of 35%. Soil fertility was given a 10% weighting, with frost, slope and altitude set to 5%. Each mapping variable was then re-classified into specific indices representing marginal, adequate and optimal growing conditions. The exact procedure that was followed was not given in the report by Holl *et al*. (2007).

7.3.2 Bioethanol-from-maize in Kenya (2008)

According to Koikai (2008), land suitability evaluation involves "calculating optimal site locations by identifying possible influential factors, creating new datasets from existing data, reclassifying data to identify areas with high suitability and finally, aggregating these data into one logical result of optimal suitability". In essence, Koikai (2008) identified regions with high maize productivity potential in the Nyanza Province (western Kenya), where potential bioethanol processing plants could be located.

The spatial data layers used to identify sites suitable for the location of a bioethanol processing plant are shown in **Table 74**. Potential sites located in close proximity (< 1.0 mile) were considered highly suitable and assigned a ranking of 3. Each criterion was also assigned a normalised weighting, with proximity to a railway, river and airport considered of lower importance than the other criteria. Hence, a site was deemed highly suitable for a processing plant if it was located in close proximity to a major road, town, power line and existing maize farm.

Table 74 Suitability criteria, rankings and weightings used by Koikai (2008) to identify sites suitable for the location of a bioethanol processing plant

Suitability criterion	**Ranking**			**Weighting**	
	3	2	1		
	High suitability	Medium suitability	Low suitability	Assigned weighting	Decimal weighting
Major road	< 0.5 mi	0.5-1.0 mi	> 1.0 mi	3	0.176
Railway	< 1.0 mi	1.0-3.0 mi	> 3.0 mi	2	0.118
Town	< 1.0 mi	1.0-3.0 mi	> 3.0 mi	3	0.176
Power line	< 0.5 mi	0.5-1.0 mi	> 1.0 mi	3	0.176
Maize field	< 1.0 mi	1.0-3.0 mi	> 3.0 mi	3	0.176
River	< 1.0 mi	1.0-3.0 mi	> 1.0 mi	2	0.118
Airport	< 1.0 mi	1.0-5.0 mi	> 5.0 mi	1	0.059
Total				**17**	**1.000**

7.3.3 Biofuels scoping study (2009)

The biofuels scoping study (Jewitt *et al*., 2009a) identified all crops/trees that can be used for biofuel production and included all feedstocks highlighted in the national biofuels strategy (DME, 2007a). The scoping study undertook an extensive literature review and summarised climatic thresholds for optimum growth of selected biofuel feedstocks. For example, the reported that soybean's optimum seasonal rainfall range is 550 to 700 mm. Similarly, the crop is best suited to areas where the monthly mean temperature ranges from 20 to 30°C. The crop is typically planted around the 1st November and the season length of 150 days.

Optimum growing areas were mapped using a commercial GIS package, with soybean shown as an example in **Figure 47**. The procedure mainly took into consideration 1) monthly rainfall (accumulated over the growing season from November to March), and 2) mean monthly temperature. Various tools and spatial databases, such as the South African Atlas of Climatology and Agrohydrology (Schulze, 2007), were used to develop the maps produced by Jewitt *et al*. (2009a). The approach did not consider other site criteria such as soil depth.

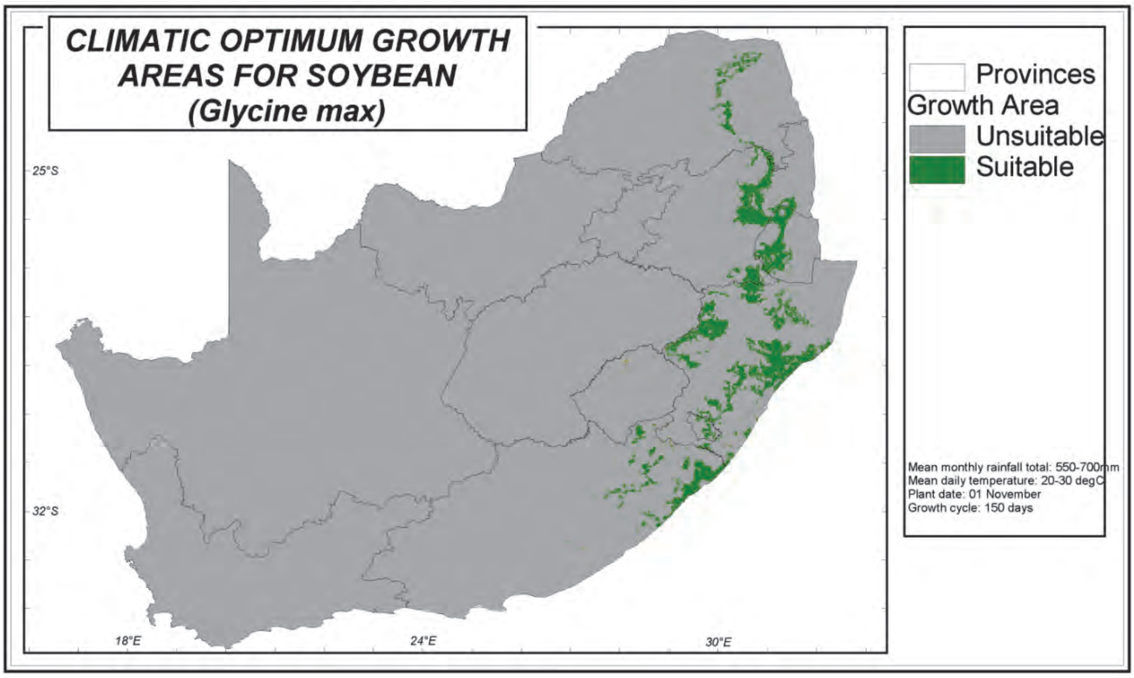


Figure 47 Potential growing areas of soybean in southern Africa (Jewitt *et al*., 2009a)

The scoping study recommended that further investigation was required to differentiate between optimal and marginal land for crop production. The scoping study also highlighted the need for a more detailed mapping/input of biophysical conditions, if the benefit and impact of biofuels is to be adequately assessed at local scales (Jewitt *et al*., 2009a). In addition, the scoping study did not consider current land use, or future land use needs.

7.3.4 Bioenergy production in Africa (2011)

Wicke (2011) used a GIS approach to assess the current bioenergy production potential of semi-arid and arid regions in sub-Saharan Africa. The aim of the project was to identify land that is suitable for biomass production for energy, by filtering out land that is not available or not suitable for inclusion in future bioenergy land use scenarios.

Figure 48 highlights the areas deemed unsuitable for bioenergy production (which were "filtered" out using GIS), based on current land use in Tanzania (one of eight countries considered in the study). Unsuitable areas included high biodiversity areas (e.g. protected areas, biodiversity hotspots, forests & wetlands), agricultural land for food production (including pastureland) as well as other unsuitable land uses (e.g. such as cities, deserts & steep slopes). This study found that land available for bioenergy production in Tanzania was limited mostly by agricultural land use, but also by biodiversity protection and steep slopes (Wicke*,* 2011).

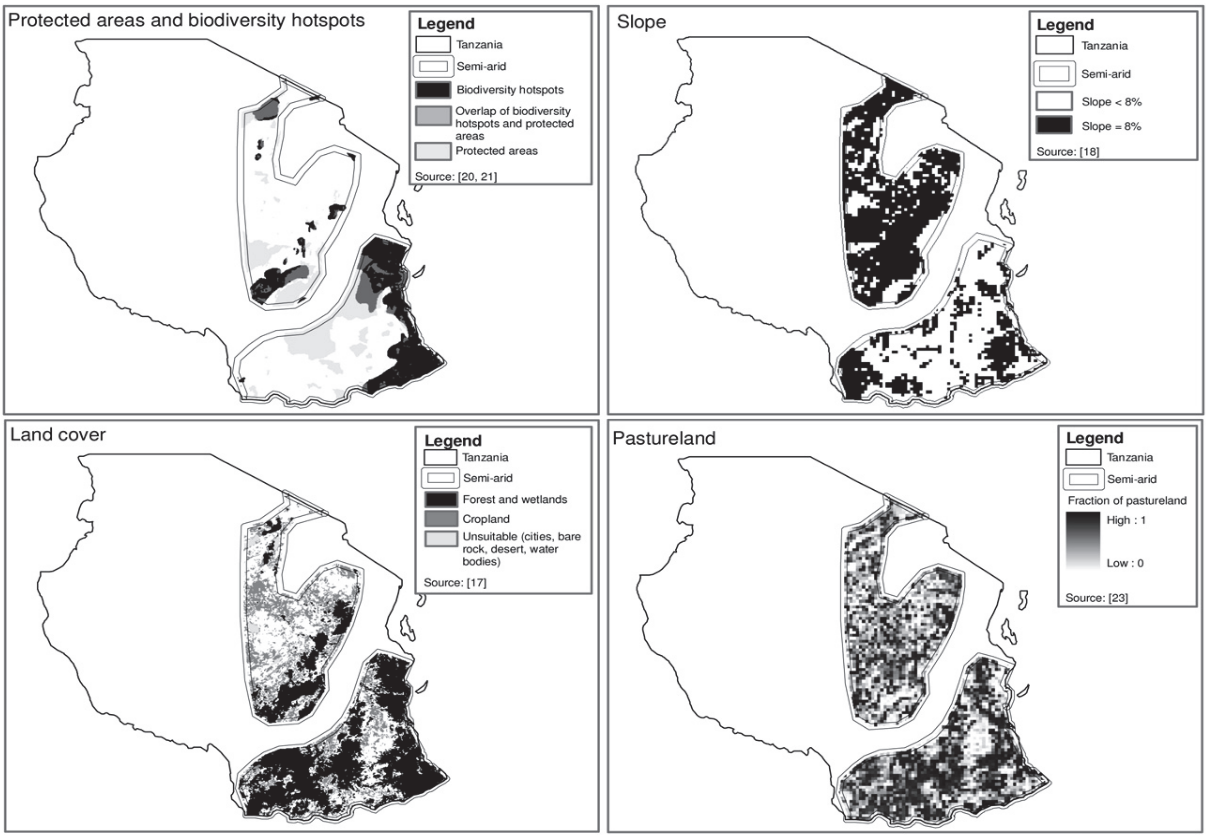


Figure 48 Maps of protected areas and biodiversity hotspots, slope, land cover and pastureland in Tanzania in 2000 (Wicke, 2011)

Although current land use was considered, (Wicke*,* 2011) highlighted that it is also important to recognise the future demand for food and feed production, which may require additional land (due to population growth and dietary changes). This may reduce the availability of land for bioenergy production, assuming that bioenergy should not compete with food production.

7.3.5 Summary

From the four case studies reviewed in the previous section (**Section 7.3**), the following approaches were highlighted:

- weighting of criteria by Holl *et al*. (2007),
- ranking and classification of criteria by Koikai (2008), and

- consideration of present land use by Wicke (2011).

The above aspects were incorporated into the approach used in the study to map regions that are optimally and sub-optimally suited to biofuel feedstock cultivation. The six main steps followed in the land suitability assessment were as follows:

- identification of land suitability criteria,
- acquisition of required spatial datasets,
- determination of feedstock growth criteria,
- ranking of suitability criteria,
- weighting of each criterion, and finally
- consideration of present land use.

7.4 Land Suitability Assessment

7.4.1 Land suitability criteria

The criteria used in this study were seasonal rainfall (index of moisture supply), monthly temperature (index of moisture demand), relative humidity (surrogate index for disease risk), soil depth (index of moisture supply) and slope (minimise risk of soil erosion; consideration of mechanical harvesting). These five criteria were derived from due cognisance of the:

- criteria suggested in **AIM 3** (**Section 1.2**),
- literature review of factors affecting plant growth (**Section 7.2**),
- criteria used to map suitable areas for Jatropha production (**Section 7.3.1**), and
- recommendations of the biofuels scoping study to include other criteria (**Section 7.3.3**).

7.4.2 Data sources

In order to derive land suitability maps for biofuel feedstock production, five important spatial datasets were collected from different sources. These include monthly rainfall totals, monthly means of daily temperature and relative humidity as well as soil depth and slope. The updated South African Atlas of Climatology and Agrohydrology (Schulze, 2007) provided a valuable source of climatic, edaphic and topographic information. The gridded databases of monthly rainfall, temperature, and relative humidity were of particular importance to this study.

Table 75 summarises the various data sources used for land suitability mapping. For additional information pertaining to each data set, the reader is referred to **Volume 3**. The sub-section that follows describes the methodology used in this study to evaluate the suitability of land to grow biofuel feedstocks.

Table 75 Sources of climatic (rainfall, temperature & relative humidity), edaphic (soil depth) and topographic (slope) data used in this study

Datasets	**Description**	**[1]Source**	**Reference**
Rainfall	Monthly rainfall totals	CWRR	Lynch (2004)
Temperature	Means of daily maximum, minimum & average temperature	CWRR	Schulze and Maharaj (2007a)
Relative humidity	Means of daily average & minimum relative humidity	CWRR	Schulze *et al*. (2007a)
Slope	Digital elevation model	ARC	Weepener *et al*. (2011)
Soil depth	Depth of topsoil and subsoil horizons	CWRR	Schulze (2007)
Land use	Land use in South Africa	SANBI	Bhengu *et al*. (2008)
Protected Areas	Formal and informal protected areas in South Africa	SANBI	Bradshaw (2010)

[1] Note: Centre for Water Resources Research (CWRR)
Agricultural Research Council (ARC)
South African National Biodiversity Institute (SANBI)

7.4.3 Feedstock growth criteria

The growth criteria for each selected feedstock were based on rainfall, temperature, relative humidity, slope and soil depth constraints. The growth criteria were derived from a literature review conducted by Khomo (2014) for sugarcane, grain sorghum and soybean. It followed on from the review of literature undertaken for the biofuels scoping study (Jewitt *et al.,* 2009a). Hence, literature was sourced from 2008 onwards and then ranking from highest to lowest applicability to South African growing conditions. Hence, local and newer information sources were ranked higher than older references or international literature. A distinction was made between a primary information source (e.g. Smith, 2006) and a secondary source (e.g. Jewitt et al., 2009a), which cited the primary source. Thus, secondary information sources were ranked lower than the primary source (i.e. Smith). The sources of information that were considered in this study are presented in **APPENDIX D** for each feedstock. From these tables, a final set of growth criteria were derived which are presented in **Section 2.6** and **Section 2.7** for bioethanol and biodiesel feedstocks respectively (refer to the section heading "**Growth criteria**").

7.4.4 Ranking of criteria

The next important step involved ranking the growth criteria to identify optimum, sub-optimum and marginal growth areas. Soybean is used as an example feedstock to explain the methodology that was followed.

An approach developed by Ramirez-Villegas *et al*. (2013) was adopted to identify climatic thresholds that distinguish between suitable (optimum and marginal) *vs*. unsuitable growing areas as depicted in **Figure 49**. When rainfall and temperature conditions are beyond the absolute thresholds, the location is not suitable for crop production (white area in **Figure 49**). If climate conditions are within the optimum range (light grey area in **Figure 49**), the site is highly suitable for crop production. When conditions are between the optimum and absolute thresholds (dark grey area in **Figure 49**), the site is marginally suited to crop growth. A decision was made to include a sub-optimum growing area into the approach. This sub-optimum class introduced a “buffer” zone in-between the optimum and marginal classes.

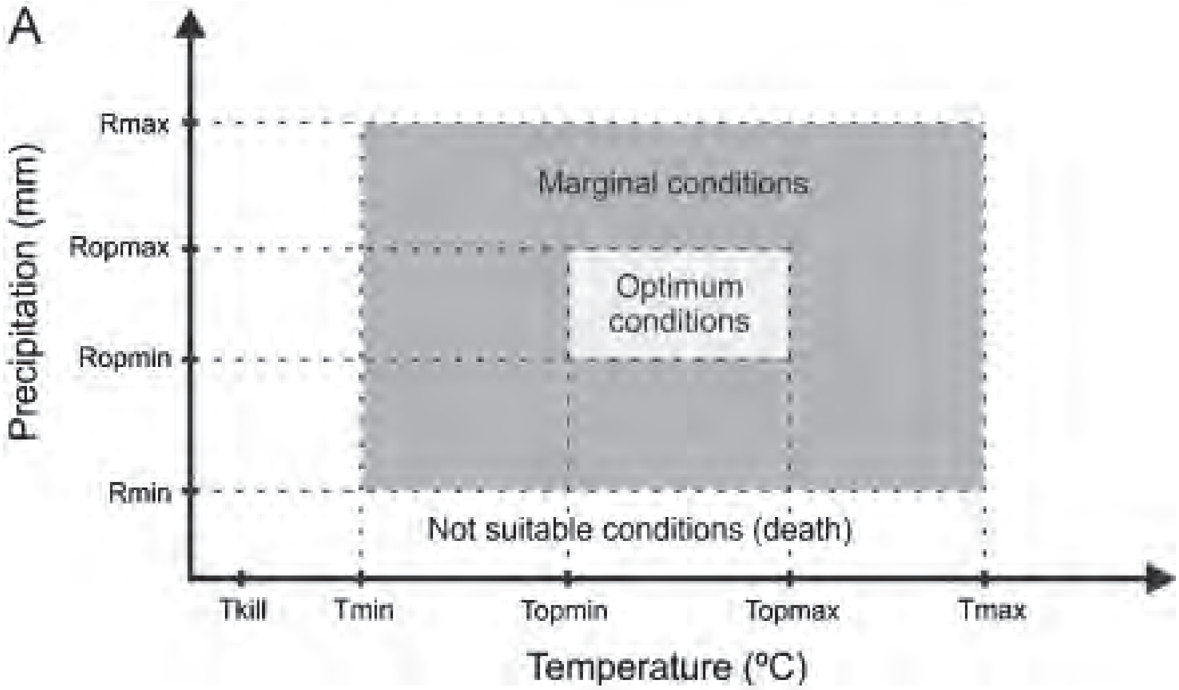


Figure 49 Crop suitability based on rainfall and temperature thresholds for growth (Ramirez-Villegas *et al*., 2013)

7.4.4.1 Rainfall

As shown in **Table 93** in **APPENDIX D**, the recommended seasonal rainfall total for soybean obtained from various sources is as follows:

- 450 to 700 mm (Smith, 1994),
- 550 to 700 mm (Smith, 1998; Smith, 2006), and
- 500 to 900 mm (DAFF, 2010a).

In the scoping study, the range indicated by Smith (1998) and Smith (2006) was selected (i.e. 550-700 mm). However, this optimum range eliminates the Free State as climatically suitable for potential soybean production as shown in **Figure 47** in **Section 7.3.3**. According to **Table 13** in **Section 2.7.1.1**, 26.8% of total soybean production occurred in the Free State in 2010. In order to determine the lower threshold (R_{min} in **Figure 49**) for soybean cultivation, Mokonoto (2012) selected 450 mm, as suggested by Smith (1994), which then highlighted the eastern Free State as being suitable for soybean production. Hence, the absolute rainfall threshold (R_{min}) was set to 450 mm as given in **Table 14** (**Section 2.7.1.3**). The upper threshold (R_{max}) was set to 1 100 mm to avoid waterlogged conditions with high disease incidence.

The seasonal rainfall thresholds chosen to distinguish between optimum (Opt), sub-optimum (Sub) and marginal (Abs) growing conditions are given in **Table 76** for soybean. The inclusion of the sub-optimum class is important if one considers a seasonal rainfall total of 699 mm (or 901 mm), which is now classified as sub-optimal and not marginal. In other words, it solves a practical issue related to using discrete class intervals on continuous datasets. Finally, a ranking was then assigned to each of the four suitability classes as shown in **Table 76**. The higher the ranking, the more suitable the site is for soybean cultivation.

Table 76 Seasonal rainfall thresholds and rankings for each suitability class derived for soybean (Khomo, 2014)

Code	**Seasonal rainfall range (mm)**	**Ranking**
Not	< 450	0
Abs	450 - 550	1
Sub	550 - 700	2
Opt	700 - 900	3
Sub	900 - 1 000	2
Abs	1 000 - 1 100	1
Not	> 1 100	0

Hence, soybean is unlikely to survive, due to severe water stress, if grown in areas where the seasonal rainfall total (i.e. monthly totals accumulated from November to March) is below 450 mm (R_{min} in **Figure 49**). Similarly, survival is deemed low due to high risk of disease incidence (e.g. soybean rust) when soybean is grown in very wet areas (R_{max} > 1 100 mm in **Figure 49**).

As noted by Holl *et al*. (2007), it is important to realise that the growth thresholds were derived from a subjective assessment of values gleaned from a literature review. Thus, these estimates are not absolute and should only be used as a definitive guide to where the crop may be grown in South Africa. In general, such estimates may "improve" with time as more data becomes available on each feedstock, especially if it is grown extensively in South Africa.

7.4.4.2 Temperature

A similar exercise was conducted to develop the ranking metric for temperature. As highlighted in **Section 7.2.2**, all plants have lower and upper temperature limits, beyond which the plant can stop growing. These temperature limits differ with species and from one growth stage to another (Schulze *et al*., 1997). The temperature suitability classes derived for soybean from November to March are summarised in **Table 77**. A distinction is made between the temperature thresholds for germination and those deemed appropriate for the remainder of the growing season.

Table 77 Ranking of each suitability class based on thresholds of monthly means of daily average temperature (ºC) for soybean

Code	**Not**	**Abs**	**Sub**	**Opt**	**Sub**	**Abs**	**Not**
Suitability Class	N1	S3	S2	S1	S2	S3	N1
Ranking	0	1	2	3	2	1	0
Nov	< 10	10 - 13	13 - 15	15 - 18	18 - 25	25 - 33	> 33
Dec-Mar	< 10	10 - 18	18 - 23	23 - 27	27 - 30	30 - 33	> 33

7.4.4.3 Relative humidity

In this study, it was important to assess the risk of disease occurrence using relative humidity as a surrogate climate variable. The relative humidity suitability classes and scores are summarised in the tables below for soybean (**Table 78**). The thresholds were based on evidence presented in **Section 2.7.1.6** for rust, a fungal disease which affects the leaves of soybean plants.

Table 78 Ranking of each suitability class based on thresholds of monthly means of daily average relative humidity (%) for soybean

Code	Suitability class	Average relative humidity (%)	Ranking
Opt	S1	< 60	3
Sub	S2	60 - 75	2
Abs	S3	75 - 80	1
Not	N1	> 80	0

7.4.4.4 Soil depth

According to Camp (1995; cited by Sibanda, 2008), the evaluation and examination of soil factors (e.g. soil depth and slope) should be important criteria in land evaluation studies. However, a lack of spatial data at an appropriate scale is often cited as the reason why soils are excluded in assessments of land suitability (Jewitt *et al*., 2009a). Due to data limitations, only soil depth was evaluated in this study. **Table 79** summarises the soil depth suitability classes and rankings (i.e. scores) used for soybean.

Table 79 Ranking of each suitability class based on soil depth (mm) for soybean

Code	Suitability class	Soil depth (mm)	Ranking
Opt	S1	> 500	3
Sub	S2	300 - 500	2
Abs	S3	200 - 300	1
Not	N1	< 200	0

7.4.4.5 Slope

McRae and Burnham (1981) identified slope, aspect and elevation as important topographical features for consideration in land suitability evaluations. As noted in **Section 7.2.6**, altitude was excluded as a mapping criterion in this study. Slope is an important land characteristic that influences its use for agricultural purposes. Usually, steeper areas are not cultivated due to high risk of soil erosion from increased runoff. Furthermore, steeper slopes are more difficult and costly to cultivate than flat land (Santos *et al.,* 2000; cited by Sibanda, 2008).

TABLE 80 summarises the slope suitability classes and rankings used in this study for all feedstocks.

Table 80 Ranking of each suitability class based on slope (%) for each feedstock (Russell, 1997)

Code	Suitability class	Soil slope (%)		Ranking
		Sugarcane	All other crops	
Opt	S1	< 10	< 4	3
Sub	S2	10 - 15	4 - 8	2
Abs	S3	15 - 30	8 - 10	1
Not	N2	> 30	> 10	0

The maximum slope for cultivation allowed by the Department of Agriculture, Forestry and Fisheries (DAFF) is 30% (Holl *et al*., 2007). Due to the erosion hazard, all areas with a slope exceeding 30% must be excluded as non-arable for sugarcane and commercial forestry. Russell (1997) stated that a slope greater than 10% is considered too steep for production of annual row crops, assuming conventional methods of cultivation and conservation.

7.4.5 Weighting of criteria

Based on the above approach, five suitability criteria were selected for use in the mapping approach. These five criteria were then assigned weightings according to their relative importance in determining feedstock survival at a particular location. These subjective weightings were based on expert opinion (Bertling and Odindo, 2013) and ranged from most important (40%) to least important (10%), as shown in **Table 81**. The weightings are similar to those used by Holl *et al.* (2007) in the Jatropha study (c.f. **Section 7.3.1**).

According to Bertling and Odindo (2013), rainfall is most important to crop survival, because plants cannot grow without an adequate water supply. Temperature and slope are not as important as rainfall but are more important than relative humidity and soil depth. Relative humidity and soil depth are least important because diseases can be prevented (by spraying with fungicides) and soil depth can be modified using tillage. These weightings were then normalised (i.e. dividing by the summed weightings) to create a decimal weighting for each criterion. This approach is similar to that used by Koikai (2008) as given in **Section 7.3.2**.

Table 81 Weighting assigned to each suitability criterion (Bertling and Odindo, 2013)

Suitability criteria	Relative weighting (%)	Decimal weighting
Rainfall	40	0.4
Temperature	20	0.2
Relative humidity	10	0.1
Soil depth	10	0.1
Slope	20	0.2
Total	**100**	**1.0**

7.4.6 Total suitability score

FAO's Land Evaluation Guidelines for Dryland Agriculture (FAO, 1983) recommends four methods to combine individual suitability ratings as follows:

- Subjective combination: defines overall suitability based on an understanding of the interaction between different land qualities.

- Limiting combination: overall suitability is defined mostly by limitations in one land quality.

- Arithmetic procedures: overall suitability is obtained by multiplying or adding values assigned to each suitability class.

- Modelling method: uses models to predict crop yields, based on the relationship between crop requirements and land qualities.

In this study, the arithmetic procedures method was used to determine the overall land suitability score. In **Table 82**, the suitability score is the product of the ranking and the decimal weighting. The five suitability scores are then summed to derive the overall land suitability score. Hence, if a particular site is ideally suited to the optimum growth of a feedstock, it is assigned an overall suitability score of 3. Similarly, a ranking of 1 assigned to each suitability criteria would produce an overall suitability score of 1.

Table 82 Total suitability score obtained when each suitability criteria is ideally ranked

Suitability criteria	**Ranking**	**Decimal weighting**	**Suitability score**
Rainfall	3	0.4	1.2
Temperature	3	0.2	0.6
Relative humidity	3	0.1	0.3
Soil depth	3	0.1	0.3
Slope	3	0.2	0.6
Total		**1.0**	**3.0**

7.4.7 Normalised suitability score

As highlighted in **Section 0**, the total suitability score is the sum of five suitability scores and ranges from 0 (not suitable) to 3 (optimally suited). The final step involved the normalisation of the total suitability score (i.e. dividing by 3) to produce a range from 0 (not suitable) to 1 (ideally suited to feedstock cultivation). The normalised values were then grouped into four classes for mapping purposes as shown in **Table 83**. For the mapping of sugarbeet, the lower threshold was increased from 0.60 to 0.63, to eliminate unsuitable areas in the Northern Cape Province.

Table 83 Normalised total suitability score used for mapping purposes (Khomo, 2014)

Normalised suitability score	Suitability for feedstock cultivation	FAO (1976) classification
0.00 - 0.60	Not suitable	N1 or N2
0.60 - 0.65	Marginally suitable	S3
0.65 - 0.75	Moderately suitable	S2
0.75 - 1.00	Highly suitable	S1

These class intervals were derived by comparing observed soybean yields collated at magisterial district level from commercial soybean producers under dryland conditions. This was done to adjust the highly suitable class interval so that the majority of the optimum growing areas were located within the boundaries of magisterial districts that reported high soybean yields. Similarly, the marginally suitable class interval was modified so highlighted areas coincided with low yielding farms (Khomo, 2014).

Each suitability class was then equated to the land suitability classification proposed in 1976 by the Food and Agriculture Organisation of the United Nations (FAO). According to FAO (1976), land suitability ""is the fitness of a given type of land for a defined use". Land can be classified as suitable (S) or unsuitable (N) for a particular use. Suitable means sustained use is expected to give positive results. Similarly, not suitable means land qualities are considered inappropriate for a particular use.

The degree of suitability is reflected by different land suitability classes. The classes are numbered in a sequence where the highest number represents the least suitable and the lowest number represents the most suitable. According to FAO (1976), the relationship between inputs and benefits mainly determines the differences in the degree of suitability. The FAO recommends three suitability classes, with the following denominations:

- Class S1: Highly suitable
- Class S2: Moderately suitable
- Class S3: Marginally suitable

The land can be classified as not suitable based on, for example, environmental considerations (e.g. potential damage to biodiversity), technical considerations (e.g. soil depth and slope) or economic considerations (e.g. revenues). There are normally two classes for not suitable as follows:

- Class N1: Currently not suitable
- Class N2: Permanently not suitable

7.4.8 Summary

The main aim of the mapping component of this project was to complete a land suitability assessment at a national and provincial scale, in order to produce maps showing areas optimally and sub-optimally suited to the production of biofuel feedstocks. However, the sub-optimal areas were split into two classes, namely moderately suitable and marginally suitable.

7.5 GIS Approach

7.5.1 Rainfall distribution

Table 81 in **Section 7.4.5** considered rainfall as the most important suitability criterion. As noted in **Section 7.2.1.2**, the timing or distribution of rainfall over the growing season can affect crop growth. For example, the optimum seasonal rainfall range for soybean is 700 to 900 mm (accumulated from November to March) as given in **Section 7.4.4.1**. However, soybean yield would be significantly different if the seasonal rainfall 1) was evenly distributed over the 5-month growing season (i.e. 140 to 180 mm per month), compared to 2) the majority of rainfall occurring over a 2-month period.

Based on this evidence, a decision was made to apply an additional weighting factor to monthly rainfall over the growing season. The monthly rainfall weightings are based on crop coefficients values, as opposed to using the rainfall concentration index. The largest monthly crop coefficient indicates the month in which crop water use is highest. Thus, a lack of rainfall in this month could result in a significant yield reduction. This approach is further explained using soybean as an example feedstock.

The single crop coefficients derived at Baynesfield Estate as shown in **Table 16** (**Section 2.7.1.4**) for each month were normalised (i.e. division by the sum of 4.31) and then multiplied by each of the seasonal rainfall thresholds given in **Section 7.4.4.1**. For example, a minimum of 450 mm of seasonal rainfall is required for soybean cultivation. Based on peak water use (K_c of 1.03 mid-season), 105 of the 450 mm should fall in February. Similarly, 90 mm of rainfall is ideal in March, with 75 mm required in November for germination.

Table 84 Preferred distribution of seasonal rainfall in each month of the growing season for soybean

Month	Growth stage	K_c	K_c norm	Monthly rainfall thresholds (mm)					
				Abs	**Sub**	**Opt**	**Opt**	**Sub**	**Abs**
November	Ini	0.72	0.167	75	90	115	150	165	185
December	Dev	0.72	0.167	75	90	115	150	165	185
January	Mid	1.00	0.232	105	130	160	210	230	255
February	Mid	1.03	0.239	*105*	*135*	*175*	215	*245*	*260*
March	End	0.84	0.195	90	105	135	175	195	215
Total		**4.31**	**1.000**	**450**	**550**	**700**	**900**	**1 000**	**1 100**

For simplicity, the monthly rainfalls shown in the above table were rounded to the nearest 5 mm. The values were then summed to ensure that the rainfall thresholds assigned to each suitability class remained unaltered. If discrepancies occurred, the monthly values representing peak water use (i.e. in February) were adjusted accordingly, as highlighted by italicised values in **Table 84**.

In this study, a seasonal rainfall range of 700 to 900 mm is considered optimum for soybean cultivation. Based on the single crop coefficient approach, the majority of seasonal rainfall should occur in February to satisfy the peak water requirements of the crop. Hence, a ranking of 3 is assigned to areas where February's rainfall total ranges from 175 to 215 mm.

If February's total is in the range 135-175 mm or 215-245 mm, the location is considered sub-optimal for soybean cultivation and assigned a ranking of 2. Marginal sites (ranked 1) exhibit monthly rainfall totals of 105-135 mm or 245-260 mm. Finally, the location is considered unsuitable for soybeans if February's rainfall is below 105 mm or above 260 mm (**Table 85**).

Table 85 Ranking of seasonal rainfall in each month of the growing season for soybean

	Monthly rainfall ranges (mm) per suitability class						
Ranking	**0**	**1**	**2**	**3**	**2**	**1**	**0**
November	< 75	75- 90	90-115	115-150	150-165	165-185	> 185
December	< 75	75- 90	90-115	115-150	150-165	165-185	> 185
January	< 105	105-130	130-160	160-210	210-230	230-255	> 255
February	< 105	105-135	135-175	175-215	215-245	245-260	> 260
March	< 90	90-105	105-135	135-175	175-195	195-215	> 215
Seasonal total (mm)	**< 450**	**450-550**	**550-700**	**700-900**	**900-1 000**	**1 000-1 100**	**> 1 100**

This approach produces a ranked value for each month in the growing season. Khomo (2014) then used the monthly crop coefficient (again) to weight the relative importance of each month's ranking. Thus, the rainfall suitability score is the ranking multiplied by the decimal weighting, then summed to give a total score for the five-month growing season (**Table 86**). February was assigned the highest weighting because crop water use is highest in this month. If the rainfall total is within the ideal range for each of the five months in the growing season, a ranking of 3 assigned to each month which produces a maximum rainfall suitability score of 1.2 out of 3 (since rainfall contributes 40% tot the total suitability score).

Table 86 Maximum rainfall suitability score when each month's rainfall is ideally suited to soybean cultivation

Month	**Optimum range (mm)**	**Rank**	**K_c**	**Relative weighting**	**Decimal weighting**	**Suitability score**
November	115-150	3	0.72	0.67	0.067	0.20
December	115-150	3	0.72	0.67	0.067	0.20
January	160-210	3	1.00	0.93	0.093	0.28
February	175-215	3	1.03	0.96	0.096	0.29
March	135-175	3	0.84	0.78	0.078	0.23
Total	**700-900**		**4.31**	**4.00**	**0.400**	**1.20**

7.5.2 Data manipulation and analysis

New datasets were generated using the Re-classify tool in Spatial Analyst. Each monthly rainfall grid (for November to December) was re-classified to produce five new datasets using the Re-classify tool in Spatial Analyst. The Re-classify tool reads in the class intervals from an ASCII text file. The text file used to classify soybean's monthly rainfall in February is given below as an example:

```
  0 105 : 0
105 135 : 1
135 175 : 2
175 215 : 3
215 245 : 2
245 260 : 1
260 999 : 0
```

The re-classified cell values ranged from 0 (i.e. unsuitable for feedstock growth) to 3 (optimally suited to feedstock growth). The Raster Calculator in Spatial Analyst was then used to weight each new re-classified rainfall grid (called Rfl_Rec_xx; where xx = month). The new grids were then summed to calculate the rainfall suitability score (Rfl_Sum) using the following expression:

```
Rfl_Sum = ([Rfl_Rec_11] * 0.067) +
          ([Rfl_Rec_12] * 0.067) +
          ([Rfl_Rec_01] * 0.093) +
          ([Rfl_Rec_02] * 0.096) +
          ([Rfl_Rec_03] * 0.078)
```

Equation 68

This exercise was repeated for the other raster-based climate datasets (e.g. temperature and relative humidity). The relative temperature weightings assigned to each month indicate soybean is more sensitive to temperature stress early in the season (i.e. November-January). Hence, a total of five new re-classified temperature grids were generated (Tmp_Rec), then weighted and summed to calculate the temperature suitability score (Tmp_Sum) using the following expression:

```
Tmp_Sum = ([Tmp_Rec_11] * 0.050) +
          ([Tmp_Rec_12] * 0.050) +
          ([Tmp_Rec_01] * 0.050) +
          ([Tmp_Rec_02] * 0.030) +
          ([Tmp_Rec_03] * 0.020)
```

Equation 69

A similar approach was followed for relative humidity. Van Niekerk (2009) indicated that risk of soybean rust outbreak increases in January, peaks in February and declines in March. Based on this evidence, the relative weighting assigned to each month shows that the crop is most susceptible to soybean rust in January and February. Finally, a total of five new re-classified humidity grids were generated (Hum_Rec), then weighted and summed to calculate the humidity suitability score (Hum_Sum) using the following expression:

```
Hum_Sum = ([Hum_Rec_11] * 0.010) +
          ([Hum_Rec_12] * 0.010) +
          ([Hum_Rec_01] * 0.030) +
          ([Hum_Rec_02] * 0.030) +
          ([Hum_Rec_03] * 0.020)
```

Equation 70

The soil depth and slope grids were also re-classified, then weighted accordingly. Thereafter, all five re-classified grids were summed and normalised (i.e. division by 3) using the Raster Calculator in Spatial Analyst, to produce a land suitability grid with values ranging from 0 to 1 on a continuous scale.

7.5.3 Present land use

The approach used in this study was further extended by considering existing land use. Land use describes how mankind utilises land, e.g. for urban living and agricultural food production. The legend of the land use dataset obtained from SANBI (c.f. Section 2.8.1 of **Volume 3**) contains explicit classifications which in this study, were divided into two categories, *viz*. absolute “no-go” areas and functional “no-go” areas.

Absolute “no-go” areas comprise of land uses that are physically unsuitable for feedstock production. According to the FAO classification (c.f. **Section 7.4.7**), such areas are classed as N2 (i.e. permanently not suitable) and include mining areas, urban areas and water bodies. Similarly, all formal protected areas identified by SANBI were classified as N2, which includes, *inter alia*, nature reserves, national parks, natural world heritage sites and protected forest areas.

Functional “no-go” areas refer to land uses deemed currently not suitable for feedstock cultivation (c.f. **Section 7.4.7**) and include, *inter alia*, commercial forest plantations, natural and degraded land. These land uses were categorised as N1 (i.e. currently unsuitable for feedstock production).

All areas that were classified as suitable for feedstock cultivation (S1, S2 or S3), but which overlapped with land use areas classified as N2 (permanently unsuitable), were excluded (or filtered out) using GIS. Thus, the consideration of present land use reduced the total arable land available for feedstock cultivation. A decision was made not to exclude land classified as N1 (i.e. currently unsuitable). **Figure 50** highlights areas classified as N1 and N2, which shows a significant portion of the eastern seaboard would be considered unviable for feedstock production.

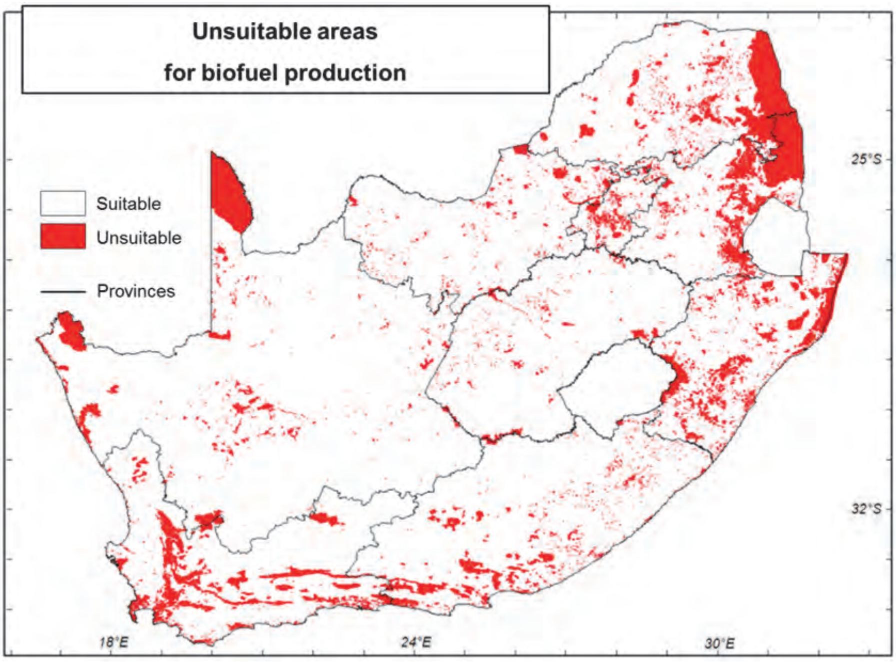


Figure 50 Distribution of areas considered as permanently (N2) and currently unsuitable (N1) for feedstock cultivation in South Africa (Khomo, 2014)

7.5.4 Mapping software and technology

Spreadsheet software developed by Microsoft (Excel Version 2010) was used to develop, test and refine the land suitability model used in this study. The GIS software used to perform the land suitability evaluation was developed by the Environmental Systems Research Institute (ESRI) based in Redlands, California (US). ESRI's ArcGIS (Version 9.3.1) software consists of two components that were used extensively *viz*. ArcMap and Spatial Analyst. The spatial datasets used in this study were projected to the Cape datum using the ArcGIS 9.3.1 project wizard tool in the Toolbox.

7.5.5 Summary

The overall aim was to map areas suitable for selected feedstocks and to improve the mapping approach used in previous land suitability studies. The methodology developed and implemented in this study is broadly similar to that adopted in the four case studies presented in **Section 7.3**. To re-cap, a literature review of feedstock growth criteria added to that undertaken in previous studies (e.g. the biofuels scoping study). Spatial rainfall data were classified into different suitability classes according to each feedstock's crop water requirements, using the crop coefficient concept. Similarly, spatial temperature was also categorised into different classes to separate optimum from sub-optimum growing areas. The rainfall and temperature datasets were then combined and weighted in order to identify land climatically suited to feedstock production.

Holl *et al*. (2007) adopted a two-phase approach to their mapping exercise (c.f. **Section 7.3.1**). Firstly, areas where the MAP < 300 mm and MAT < 11ºC or > 38ºC were eliminated as potential growing areas for Jatropha. Secondly, the remaining suitable areas were then classified as marginal to optimal, based on the selected criteria. In this study, areas considered too dry or too cold (or hot) for crop production were not specifically eliminated and thus, may be classified as marginal (instead of unsuitable). For example, the approach did not eliminate frost-prone areas for sugarcane using the average minimum temperature is June and/or July (c.f. **Section 2.6.1.3**).

The approach then made use of a range of “filters” which were applied to the climatically suitable areas in order to highlight areas realistically suitable for crop production. For example, relative humidity was used (as a surrogate variable) to exclude areas with a high risk of disease incidence, thus minimising the risk of crop failure. Soil depth and slope data were also used to exclude areas with shallow soils and steep slopes that cannot support sustainable agriculture. Land use datasets were used to exclude areas that are classified as built-up, mining and water bodies as well as those areas protected by law for their biodiversity. It was important to eliminate these so-called “no-go” areas in order to identify land area realistically available to feedstock production. This approach helped to obtain a more realistic map of areas that can be planted to biofuel feedstocks. Although the latest available datasets were utilised, small patches of land may have been ignored (i.e. not highlighted as suitable) due to the coarseness of input climate data, which cannot account for microclimate effects.

The approach included relative humidity and soil depth, and is unique in that these two additional sites factors were not considered in previous GIS mapping studies. However, the most innovative aspect of this study is the use of crop coefficients to quantify the feedstock’s optimum distribution of rainfall over the growing season.

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9 APPENDIX A

Petrol, diesel and total (petrol + diesel) consumption in South Africa from 1991 to 2010 in million litres per annum (SAPIA, 2012), as well as the projected demand for petroleum products from 2011 to 2020 (**Table 87**). Diesel is expressed as a portion of the total petroleum consumption, together with estimated values for the future. Refer to **Figure 5** (c.f. **Section 2.1.6.2**) for the linear trend lines that were used to produce the estimates from 2011 onwards.

Table 87 Actual (1991-2010) and projected (2011-2020) demand for petroleum products in South Africa

Year	Million litres per annum				Percentage		Million litres per annum		
	Petrol	Diesel	Total Actual	Total Estimate	Diesel Actual	Diesel Estimate	E2	E10	B5
1991	8 906	5 130	14 036		36.55		178.1	890.6	256.5
1992	9 171	4 950	14 121		35.05		183.4	917.1	247.5
1993	9 202	4 940	14 142		34.93		184.0	920.2	247.0
1994	9 630	5 110	14 740		34.67		192.6	963.0	255.5
1995	10 153	5 432	15 585		34.85		203.1	1 015.3	271.6
1996	10 566	5 759	16 325		35.28		211.3	1 056.6	288.0
1997	10 798	5 875	16 673		35.24		216.0	1 079.8	293.8
1998	10 883	5 959	16 842		35.38		217.7	1 088.3	298.0
1999	10 861	5 993	16 854		35.56		217.2	1 086.1	299.7
2000	10 396	6 254	16 650		37.56		207.9	1 039.6	312.7
2001	10 340	6 488	16 828		38.55		206.8	1 034.0	324.4
2002	10 335	6 831	17 166		39.79		206.7	1 033.5	341.6
2003	10 667	7 263	17 930		40.51		213.3	1 066.7	363.2
2004	10 985	7 679	18 664		41.14		219.7	1 098.5	384.0
2005	11 165	8 115	19 280		42.09		223.3	1 116.5	405.8
2006	11 279	8 708	19 987		43.57		225.6	1 127.9	435.4
2007	11 558	9 755	21 313		45.77		231.2	1 155.8	487.8
2008	11 069	9 762	20 831		46.86		221.4	1 106.9	488.1
2009	11 321	9 437	20 758		45.46		226.4	1 132.1	471.9
2010	**11 874**	**9 298**	**21 172**		**43.92**		**237.5**	**1 187.4**	**464.9**
2011	11 690	9 986		21 677		46.07	233.8	1 169.0	499.3
2012	11 759	10 315		22 075		46.73	235.2	1 175.9	515.8
2013	11 823	10 650		22 473		47.39	236.5	1 182.3	532.5
2014	11 882	10 990		22 871		48.05	237.6	1 188.2	549.5
2015	11 935	11 335		23 270		48.71	238.7	1 193.5	566.7
2016	**11 983**	**11 685**		**23 668**		**49.37**	**239.7**	**1 198.3**	**584.2**
2017	12 026	12 040		24 066		50.03	240.5	1 202.6	602.0
2018	12 063	12 401		24 465		50.69	241.3	1 206.3	620.1
2019	12 096	12 767		24 863		51.35	241.9	1 209.6	638.4
2020	12 123	13 139		25 261		52.01	242.5	1 212.3	656.9

10 APPENDIX B

Table 88 The 2009 per capita consumption of non-animal food groups in South Africa (FAOSTAT, 2009)

Rank	Food group	Production (x 1000 ton)	Consumption (x 1000 ton)	Import (x 1000 ton)	Export (x 1000 ton)	Calorie share (kcal day^{-1})	%	Accum. %
1	*Maize*	12 050	9 599	36	1 887	889	34.9	34.9
2	*Wheat*	1 958	3 148	1 351	162	499	19.6	54.6
3	*Sugar (raw equivalent)*	2 330	1 463	139	952	277	10.9	65.4
4	Sunflower oil	335	396	118	56	149	5.9	71.3
5	Rice	2	738	763	33	146	5.7	77.0
6	Soybean oil	33	213	138	8	104	4.1	81.1
7	Potatoes	1 867	1 910	84	41	57	2.2	83.4
8	Maize germ oil	77	77	0	0	37	1.5	84.8
9	Palm oil	0	417	423	6	24	0.9	85.8
10	Soybean	516	303	2	162	10	0.4	86.2
11	Sorghum	277	271	0	5	14	0.6	86.7
12	Groundnuts	70	69	12	12	11	0.4	87.1
13	Palm kernel oil	0	33	33	0	8	0.3	87.5
14	Groundnut oil	12	16	0	0	7	0.3	87.7
15	Oil crops oil (other)	7	24	23	5	4	0.2	87.9
16	Sweet potatoes	63	60	0	3	3	0.1	88.0
17	Cottonseed oil	11	10	3	13	3	0.1	88.1
18	Olive oil	0	5	5	0	2	0.1	88.2
	Non-animal products (total)					2 544		
	Animal products (total)					473		
	Total					**3 017**		

11 APPENDIX C

Table 89 Summary of decisions made at the biofuels technical meeting in July 2012

Feedstock	Field trial research									
	Season #1 (2010/11)		**Season #2 (2011/12)**		**Season #3 (2012/13)**			**Season #4 (2013/14)**		
	Ukulinga	Hatfield	Ukulinga	Hatfield	Ukulinga	Hatfield	Baynesfield	Ukulinga	Hatfield	Baynesfield
Bioethanol:										
Sugarcane										
Sugarbeet	Done		Done		*Trichoderma* Plant 05/13 Harvest 11/13 Water stressed					
Sweet sorghum (well-watered)	Done	Done	Done	Done						
Sweet sorghum (drought trial)		Done		Done						
Sweet sorghum (ratoon trial)					Cut in 07/12 Irrigate 08/12 Abandon 12/12					
Grain sorghum					Plant 11/12 Harvest 05/13 Well-watered	Plant in 12/12 Harvest 05/13 Drought stressed		Plant 11/13 Well-watered	Plant 11/13 Drought stressed	
Biodiesel:										
Sunflower										
Canola										
Soybean							Plant 10/12 Harvest 05/13 Dryland			Plant 10/13 Dryland
Jatropha	Done		Stopped							
Moringa		Done		Stopped						

12 APPENDIX D

Table 90 Growth criteria for sugarcane cultivation obtained from the literature

Source	Annual rainfall (mm)	Monthly total (mm)	MAT (°C)	T_{ave} (°C)	T_{min} (°C)	T_{max} (°C)	RH_{ave} (%)	Soil depth (mm)	Rank
Jewitt *et al*. (2009a)	850 Min 1300 Opt	120		22-32 Opt 20-34 Abs			< 70		3
Smith (1994)	850-1500			22-30 Opt 10-20 Rip	Jun > 5 Jul > 5			> 1000	3
Smith (1998)	850-1500		> 18 OPT	22-30 Opt 10-20 Rip	Jun > 5 Jul > 5			1000	3
Smith (2006)	850-1500		> 18 OPT	22-30 Opt 10-20 Rip	Jun > 5 Jul > 5			1000	2
FAO (2006)	1500-2000 Opt 1000-5000 Abs				> 24 Opt > 15 Abs	< 37 Opt < 41 Abs		> 1500	4
Schulze *et al*. (2007c)	850 Min 1300 Opt	120		22-32 Opt 10-20 Rip	Jun > 5 Jul > 5		< 70 Rip	1000	2
DAFF (2012c)	1100-1500			20-35			80-85 Opt	1000-1500	1
Watson *et al*. (2008)	1200-1500			26-34 Opt 10-20 Rip	> 15 Abs	< 38 Abs	< 70	> 400	3
Schulze and Kunz (2010b)	850 Min 1300 Opt	120		22-32 Opt 10-20 Rip			< 70	1000	3
Bassam (2010)	1500-1800 Dry 2500 Wet								4
Tammisola (2010)	1500-2500			22-30 Opt 10-20 Rip					4
Muok *et al*. (2010)	1000-1800 Sub 1200-1800 Opt			20-30 Opt 12-38 Sub					4

Note: Min = Minimum criterion; Opt = Optimum criterion; Sub = Sub-optimum criterion; Abs = Absolute criterion; Dry = Ideal for drier regions; Wet = Ideal for wetter regions; Ger = ideal for germination; Flo = ideal for flowering; Rip = ideal for ripening; Jan = Month of January; Jun = Month of June; Jul = Month of July

Table 91 Growth criteria for sugarbeet cultivation obtained from the literature

Source	Annual rainfall (mm)	Seasonal rainfall (mm)	T_{ave} (^{o}C)	RH_{max} (%)	Soil depth (mm)	Rank
Jewitt *et al*. (2009a)	250-1000 Abs 400-700 Opt		15-25 Opt 7-30 Abs		>1500 Opt 500-1500 Abs	3
Fornstrom and Pochop (1976) Went (1957)			OPT20-22 ABS5-30			12
Petkeviciene (2009)			15-25 Opt > 5 Abs			9
FAO (2002)		550-750	7-30 Abs 15-25 Opt		700-1200 Opt	2
Kenter *et al*. (2006)			18-26 Opt			10
Wahab *et al*. (2012)			5-30 Abs 20-25 Opt			8
Morillo-Verlade and Ober (2006)		350-550 Opt 350-1000 Abs	3-48 Abs	< 80		1
Johl (1980)			10-30 Abs 18 - 22 Opt			11
Efetha (2012)		500			500-1000	5
Aminzadeh *et al*. (2014)			16-30 Opt 0-30 Abs			6
Wood *et al*. (1980)			15-20 Opt < 35 Abs	60-70		4
Chegini *et al*. (2010)		524				7

Note: Min = Minimum criterion; Opt = Optimum criterion; Sub = Sub-optimum criterion; Abs = Absolute criterion; Dry = Ideal for drier regions; Wet = Ideal for wetter regions; Ger = ideal for germination; Flo = ideal for flowering; Rip = ideal for ripening; Jan = Month of January; Jun = Month of June; Jul = Month of July

Table 92 Growth criteria for grain sorghum cultivation obtained from the literature

Source	Annual rainfall (mm)	Seasonal rainfall (mm)	T_{ave} (°C)	T_{min} (°C)	T_{max} (°C)	RH_{ave} (%)	Soil depth (mm)	Rank
Jewitt *et al*. (2009a)		450-650 Opt	20-25 Jan > 21					3
Smith (1994)	650-800	450-650 Opt	> 10 Opt > 25 Ger Jan = 21 Ger Jul < 16 Ger	> 15 Flo	< 35 Flo	Not hot/ humid	1 000-1 500	3
Smith (1998)	650-800	450-650	> 25 Opt Jan > 21	> 15 Flo	< 35 Flo	Not hot/ humid		3
Smith (2006)	650-800	450-650	> 25 Opt Jan > 21	> 15 Flo	< 35 Flo	Not hot/ humid		2
FAO (2006)	500-1 000 Opt 300-3 000 Abs	400-600 opt 300-700 abs	27-35 Opt 8-40 Abs	> 8	< 40		500-1 500	4
Schulze and Maharaj (2007c)	> 600	300-1200 600 OPT	25 Opt Jan > 21	> 15 Flo	< 35 Flo	< 60 Not hot/ humid		3
Du Plessis (2008)	> 400 dry > 800 wet		27-30 Opt 20-30 Sub > 21 Sub	7-10 Ger			> 250	1
DAFF (2010b)	300-750		27-30 Opt 20-30 Sub > 21 Sub	7-10 Ger			> 250	1
Bassam (2010)	400-600		27-30 Opt	8-10				4
Schulze and Kunz (2010c)	600	300-1200	25 Opt Jan > 21	> 15 Flo	< 35 Flo	< 60 Not hot/ humid		3
Pannar (2011)		400-800	25-30 Opt > 15 Abs		25-30 Rip	Not cool/humid	Deep	1

Note: Min = Minimum criterion; Opt = Optimum criterion; Sub = Sub-optimum criterion; Abs = Absolute criterion; Dry = Ideal for drier regions; Wet = Ideal for wetter regions; Ger = ideal for germination; Flo = ideal for flowering; Rip = ideal for ripening; Jan = Month of January; Jun = Month of June; Jul = Month of July

Table 93 Growth criteria for soybean cultivation obtained from the literature

Source	Annual rainfall (mm)	Seasonal rainfall (mm)	T_{ave} (^oC)	Frost tolerance	RH_{ave} (%)	HU (GDD) Base 10^oC	Soil depth (mm)	Rank
Jewitt *et al*. (2009a)		550-700 Opt	20-30 Opt 18-35 Sub			> 1500		3
Smith (1994)	> 700	450-700	18-35 Sub Jan > 19 Abs			1100-2400		3
Smith (1998)	> 700	> 450 550-700		Medium			250-400	3
Smith (2006)		550-700					600-1200	2
FAO (2006)	600-1500 Opt 450-1800 Abs		20-33 Opt 10-38 Abs					6
Schulze and Maharaj (2007d)	> 600		Jan > 18			> 1500 1000-2600 (Oct-Mar)		5
Nunkumar (2006)					< 75			4
Schulze and Kunz (2010d)	> 600		Jan > 18			1000-2600 (Oct-Mar)		5
DAFF (2010a)		500-900	13-30 25 Opt				300-500	1
DAFF (2010a) - at planting			15-18					1
Bassam (2010)	500-750		24-25 Opt 20-25 Sub				300-400	7

Note: Min = Minimum criterion; Opt = Optimum criterion; Sub = Sub-optimum criterion; Abs = Absolute criterion; Dry = Ideal for drier regions; Wet = Ideal for wetter regions; Ger = ideal for germination; Flo = ideal for flowering; Rip = ideal for ripening; Jan = Month of January; Jun = Month of June; Jul = Month of July

Table 94 Growth criteria for canola cultivation obtained from the literature

Source	Annual rainfall (mm)	Seasonal rainfall (mm)	T_{ave} (^{o}C)	RH_{ave} (%)	Soil depth (mm)	Rank
Jewitt *et al*. (2009a)	500-1000 Opt 400-2800 Abs	400-560	15-25 Opt 5-41 Abs		500-1500	4
DAFF (2009)		400-500	12-25 Opt 5-27 Abs			6
DAFF (2010d)		> 300	10-30 Opt <10 >30 Abs			2
Tesfamariam *et al*. (2010)		> 300				3
Canola Encyclopaedia (2013a; 2013b)			> 2 Abs > 10 Opt		600-1200	7
Nel (2015)		> 300	0-30 Abs 21 Opt		> 600	1
Bahizire (2007)			15-25 Opt			9
Tesfamarian (2004)		> 300	5-30 Abs 12-30 Opt		< 1800 Abs 600-1200 Opt	5
FAO (2006)			> -4 Abs			11
Cumming *et al.* (2010)		> 300 Abs 400-500 Opt 200-210 Flo	15-20 Ger 20-25 Opt 5-30 Abs			8
Gan *et al.* (2009)					> 600	10
Zeleke and Wade (2012)				20-80		12

Note: Min = Minimum criterion; Opt = Optimum criterion; Sub = Sub-optimum criterion; Abs = Absolute criterion; Dry = Ideal for drier regions; Wet = Ideal for wetter regions; Ger = ideal for germination; Flo = ideal for flowering; Rip = ideal for ripening; Jan = Month of January; Jun = Month of June; Jul = Month of July.

Table 95 Summary of rainfall suitability criteria and ranking used to identify areas suitable for sugarcane cultivation, based on local (averaged) and FAO K_c values

Suitability criteria and ranking									
Rainfall totals apportioned per month using local (averaged) crop coefficients									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative weighting	Decimal weight
Ranking	0	1	2	3	2	1	0		
September	< 65	65- 85	85-100	100-120	120-140	140-155	> 155	0.31	0.031
October	< 65	65- 85	85-100	100-115	115-135	135-150	> 150	0.30	0.030
November	< 75	75- 95	95-115	115-130	130-155	155-175	> 175	0.35	0.035
December	< 70	70- 95	95-110	110-130	130-155	155-170	> 170	0.34	0.034
January	< 80	80-105	105-120	120-140	140-170	170-185	> 185	0.37	0.037
February	< 80	80-105	105-125	125-145	145-175	175-195	> 195	0.39	0.039
March	< 85	85-105	105-130	130-140	140-175	175-195	> 195	0.39	0.039
April	< 70	70- 95	95-110	110-125	125-150	150-170	> 170	0.34	0.034
May	< 75	75- 95	95-110	110-130	130-155	155-170	> 170	0.34	0.034
June	< 60	60- 80	80- 95	95-110	110-130	130-145	> 145	0.29	0.029
July	< 65	65- 80	80- 95	95-110	110-135	135-150	> 150	0.30	0.030
August	< 60	60- 75	75- 90	90-105	105-125	125-140	> 140	0.28	0.028
	< 850	**850-1 100**	**1 100-1 300**	**1 300-1 500**	**1 500-1 800**	**1 800-2 000**	**> 2 000**	**4.00**	**0.400**
Rainfall totals apportioned per month using FAO crop coefficients (mm)									
September	< 60	60- 75	75- 90	90-105	105-125	125-140	> 140	0.28	0.028
October	< 70	70- 90	90-105	105-125	125-145	145-165	> 165	0.33	0.033
November	< 80	80-105	105-125	125-140	140-170	170-190	> 190	0.38	0.038
December	< 80	80-105	105-125	125-140	140-170	170-190	> 190	0.38	0.038
January	< 85	85-110	110-130	130-150	150-180	180-205	> 205	0.41	0.041
February	< 85	85-110	110-130	130-150	150-180	180-205	> 205	0.41	0.041
March	< 80	80-110	110-130	130-155	155-185	185-190	> 190	0.41	0.041
April	< 70	70- 90	90-105	105-120	120-145	145-160	> 160	0.32	0.032
May	< 70	70- 90	90-105	105-120	120-145	145-160	> 160	0.32	0.032
June	< 60	60- 75	75- 90	90-105	105-125	125-140	> 140	0.28	0.028
July	< 60	60- 75	75- 90	90-105	105-125	125-140	> 140	0.28	0.028
August	< 50	50- 65	65- 75	75- 85	85-105	105-115	> 115	0.23	0.023
	< 850	**850-1 100**	**1 100-1 300**	**1 300-1 500**	**1 500-1 800**	**1 800-2 000**	**> 2 000**	**4.00**	**0.400**

Table 96 Summary of other criteria and ranking used to identify areas suitable for sugarcane cultivation

Suitability criteria and ranking									
Monthly means of daily average temperature (ºC)									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative weighting	Decimal weight
Ranking	0	1	2	3	2	1	0		
September	< 15	15-20	20-22	22-30	30-32	32-35	> 35	0.30	0.030
October	< 15	15-20	20-22	22-30	30-32	32-35	> 35	0.10	0.010
November	< 15	15-20	20-22	22-30	30-32	32-35	> 35	0.10	0.010
December	< 15	15-20	20-22	22-30	30-32	32-35	> 35	0.10	0.010
January	< 15	15-20	20-22	22-30	30-32	32-35	> 35	0.20	0.020
February	< 15	15-20	20-22	22-30	30-32	32-35	> 35	0.20	0.020
March	< 15	15-20	20-22	22-30	30-32	32-35	> 35	0.20	0.020
April	< 15	15-20	20-22	22-30	30-32	32-35	> 35	0.20	0.020
May	< 08	08-10	10-12	12-14	14-20	20-24	> 24	0.20	0.020
June	< 08	08-10	10-12	12-14	14-20	20-24	> 24	0.15	0.015
July	< 08	08-10	10-12	12-14	14-20	20-24	> 24	0.15	0.015
August	< 08	08-10	10-12	12-14	14-20	20-24	> 24	0.10	0.010
								2.00	**0.200**
Monthly means of daily average relative humidity (%)									
September	< 30	30-70	70-80	80-85	85-90	90-95	> 95	0.05	0.005
October	< 30	30-70	70-80	80-85	85-90	90-95	> 95	0.05	0.005
November	< 30	30-70	70-80	80-85	85-90	90-95	> 95	0.05	0.005
December	< 30	30-70	70-80	80-85	85-90	90-95	> 95	0.05	0.005
January	< 30	30-70	70-80	80-85	85-90	90-95	> 95	0.10	0.010
February	< 30	30-70	70-80	80-85	85-90	90-95	> 95	0.10	0.010
March	< 30	30-70	70-80	80-85	85-90	90-95	> 95	0.10	0.010
April	< 30	30-70	70-80	80-85	85-90	90-95	> 95	0.10	0.010
May	< 20	20-35	35-45	45-65	65-75	75-85	> 85	0.10	0.010
June	< 20	20-35	35-45	45-65	65-75	75-85	> 85	0.10	0.010
July	< 20	20-35	35-45	45-65	65-75	75-85	> 85	0.10	0.010
August	< 20	20-35	35-45	45-65	65-75	75-85	> 85	0.10	0.010
								1.00	**0.100**
Soil depth (mm)									
All season	< 400	400-700	700-1 000	> 1 000				**1.00**	**0.100**
Slope (mm)									
All season				< 10	10-15	15-30	> 30	**2.00**	**0.200**

Table 97 Summary of suitability criteria and ranking used to identify areas suitable for sugarbeet (summer), based on local K_c values

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative weighting	Decimal weight
Ranking	0	1	2	3	2	1	0		
Rainfall totals apportioned per month using local (Ukulinga) crop coefficients (mm)									
September	<50	50-60	60- 70	70- 95	95-110	110-120	>120	0.48	0.048
October	<50	50-60	60- 75	75- 95	95-110	110-120	>120	0.49	0.049
November	<65	65-80	80-100	100-130	130-145	145-165	>165	0.65	0.065
December	<65	65-85	85- 95	95-140	140-145	145-170	>170	0.67	0.067
January	<65	65-85	85-100	100-130	130-150	150-165	>165	0.66	0.066
February	<55	55-65	65- 80	80-105	105-120	120-130	>130	0.53	0.053
March	<50	50-65	65- 80	80-105	105-120	120-130	>130	0.52	0.052
	< 400	**400-500**	**500-600**	**600-800**	**800-900**	**900-1 000**	**> 1 000**	**4.00**	**0.400**
Monthly means of daily average temperature (ºC)									
September	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.05	0.005
October	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.10	0.010
November	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.10	0.010
December	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.40	0.040
January	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.60	0.060
February	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.70	0.070
March	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.05	0.005
								2.00	**0.200**
Monthly means of daily maximum relative humidity (%)									
September				< 60	60-70	70-80	> 80	0.00	0.000
October				< 60	60-70	70-80	> 80	0.00	0.000
November				< 60	60-70	70-80	> 80	0.00	0.000
December				< 60	60-70	70-80	> 80	0.15	0.015
January				< 60	60-70	70-80	> 80	0.25	0.025
February				< 60	60-70	70-80	> 80	0.50	0.050
March				< 60	60-70	70-80	> 80	0.10	0.010
								1.00	**0.100**
Soil depth (mm)									
All season	< 500	500-700	700-900	> 900				**1.00**	**0.100**
Slope (%)									
All season				< 4	4-8	8-10	> 10	**2.00**	**0.200**
Total								**10.00**	**1.000**

Table 98 Summary of suitability criteria and ranking used to identify areas suitable for sugarbeet (winter), based on local K_c values

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative weighting	Decimal weight
Ranking	0	1	2	3	2	1	0		
Rainfall totals apportioned per month using local (Ukulinga) crop coefficients (mm)									
June	<50	50-65	65-80	80-110	110-125	125-140	>140	0.59	0.059
July	<55	55-70	70-85	85-115	115-130	130-145	>145	0.62	0.062
August	<50	50-60	60-75	75-100	100-115	115-130	>130	0.54	0.054
September	<45	45-65	65-75	75-105	105-125	125-130	>130	0.55	0.055
October	<45	45-60	60-75	75-100	100-110	110-125	>125	0.53	0.053
November	<50	50-60	60-75	75-105	105-115	115-130	>130	0.55	0.055
December	<55	55-70	70-85	85-115	115-130	130-150	>150	0.62	0.062
	< 350	**350-450**	**450-550**	**550-750**	**750-850**	**850-950**	**> 950**	**4.00**	**0.400**
Monthly means of daily average temperature (ºC)									
June	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.05	0.005
July	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.10	0.010
August	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.10	0.010
September	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.40	0.040
October	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.60	0.060
November	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.70	0.070
December	< 5	5-10	10-15	15-20	20-25	25-30	> 30	0.05	0.005
								2.00	**0.200**
Monthly means of daily maximum relative humidity (%)									
June				< 60	60-70	70-80	> 80	0.00	0.000
July				< 60	60-70	70-80	> 80	0.00	0.000
August				< 60	60-70	70-80	> 80	0.00	0.000
September				< 60	60-70	70-80	> 80	0.15	0.015
October				< 60	60-70	70-80	> 80	0.25	0.025
November				< 60	60-70	70-80	> 80	0.50	0.050
December				< 60	60-70	70-80	> 80	0.10	0.010
								1.00	**0.100**
Soil depth (mm)									
All season	< 500	500-700	700-900	> 900				**1.00**	**0.100**
Slope (%)									
All season				< 4	4-8	8-10	> 10	**2.00**	**0.200**
Total								**10.00**	**1.000**

Table 99 Summary of suitability criteria and ranking used to identify areas suitable for grain sorghum cultivation, based on local K_c values

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative weighting	Decimal weight
Ranking	0	1	2	3	2	1	0		
Rainfall totals apportioned per month using local (Ukulinga) crop coefficients (mm)									
November	< 45	45- 50	50- 75	75- 90	90-115	115-140	> 140	0.46	0.046
December	< 90	90-100	100-145	145-180	180-220	220-265	> 265	0.89	0.089
January	< 95	95-105	105-150	150-185	185-235	235-280	> 280	0.93	0.093
February	< 90	90-105	105-150	150-185	185-230	230-275	> 275	0.92	0.092
March	< 80	80- 90	90-130	130-160	160-200	200-240	> 240	0.80	0.080
	< 400	**400-450**	**450-650**	**650-800**	**800-1 000**	**1 000-1 200**	**> 1 200**	**4.00**	**0.400**
Monthly means of daily average temperature (ºC)									
November	< 15	15-20	20-25	25-30	30-32	32-35	> 35	0.50	0.050
December	< 15	15-20	20-25	25-30	30-32	32-35	> 35	0.20	0.020
January	< 15	15-20	20-25	25-30	30-32	32-35	> 35	0.50	0.050
February	< 15	15-20	20-25	25-30	30-32	32-35	> 35	0.30	0.030
March	< 15	15-20	20-25	25-30	30-32	32-35	> 35	0.50	0.050
								2.00	**0.200**
Monthly means of daily minimum relative humidity (%)									
November				< 40	40-60	60-80	> 80	0.10	0.010
December				< 40	40-60	60-80	> 80	0.30	0.030
January				< 40	40-60	60-80	> 80	0.40	0.040
February				< 40	40-60	60-80	> 80	0.10	0.010
March				< 40	40-60	60-80	> 80	0.10	0.010
								1.00	**0.100**
Soil depth (mm)									
All season	< 300	300-500	500-800	> 800				**1.00**	**0.100**
Slope (%)									
All season				< 4	4-8	8-10	> 10	**2.00**	**0.200**
Total								**10.00**	**1.000**

Table 100 Summary of suitability criteria and ranking used to identify areas suitable for soybean cultivation, based on local K_c values

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative weighting	Decimal weight
Ranking	0	1	2	3	2	1	0		
Rainfall totals apportioned per month using local (Baynesfield) crop coefficients (mm)									
November	< 75	75- 90	90-115	115-150	150-165	165-185	> 185	0.67	0.067
December	< 75	75- 90	90-115	115-150	150-165	165-185	> 185	0.67	0.067
January	< 105	105-130	130-160	160-210	210-230	230-255	> 255	0.93	0.093
February	< 105	105-135	135-175	175-215	215-245	245-260	> 260	0.96	0.096
March	< 90	90-105	105-135	135-175	175-195	195-215	> 215	0.78	0.078
	< 450	**450-550**	**550-700**	**700-900**	**900-1 000**	**1 000-1 100**	**> 1 100**	**4.00**	**0.400**
Monthly means of daily average temperature (ºC)									
November	< 10	10-13	13-15	15-18	18-25	25-33	> 33	0.50	0.050
December	< 10	10-18	18-23	23-27	27-30	30-33	> 33	0.50	0.050
January	< 10	10-18	18-23	23-27	27-30	30-33	> 33	0.50	0.050
February	< 10	10-18	18-23	23-27	27-30	30-33	> 33	0.30	0.030
March	< 10	10-18	18-23	23-27	27-30	30-33	> 33	0.20	0.020
								2.00	**0.200**
Monthly means of daily average relative humidity (%)									
November				< 60	60-75	75-80	> 80	0.10	0.010
December				< 60	60-75	75-80	> 80	0.10	0.010
January				< 60	60-75	75-80	> 80	0.30	0.030
February				< 60	60-75	75-80	> 80	0.30	0.030
March				< 60	60-75	75-80	> 80	0.20	0.020
								1.00	**0.100**
Soil depth (mm)									
All season	< 200	200-300	300-500	> 500				**1.00**	**0.100**
Slope (%)									
All season				< 4	4-8	8-10	> 10	**2.00**	**0.200**
Total								**10.00**	**1.000**

Table 101 Summary of suitability criteria and ranking used to identify areas suitable for canola cultivation, based on K_c values from Majnooni-Heris *et al*. (2012)

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative weighting	Decimal weight
Ranking	0	1	2	3	2	1	0		
Rainfall totals apportioned per month using crop coefficients (mm)									
April	< 20	20-55	55-110	110-165	165-220	220-275	> 275	0.74	0.074
May	< 25	25-70	70-140	140-205	205-275	275-345	> 345	0.92	0.092
June	< 25	25-80	80-160	160-240	240-315	315-395	>395	1.06	0.106
July	< 15	15-55	55-105	105-165	165-225	225-280	>280	0.74	0.074
August	< 15	15-40	40- 85	85-125	125-165	165-205	>205	0.55	0.055
	< 100	**100-300**	**300-600**	**600-900**	**900-1 200**	**1 200-1 500**	**> 1 500**	**4.00**	**0.400**
Monthly means of daily average temperature (ºC)									
April	< 5	5-10	10-15	15-25	25-30	30-35	> 35	0.60	0.060
May	< 5	5-10	10-15	15-25	25-30	30-35	> 35	0.60	0.060
June	< 5	5-10	10-15	15-25	25-30	30-35	> 35	0.40	0.040
July	< 5	5-10	10-15	15-25	25-30	30-35	> 35	0.20	0.020
August	< 5	5-10	10-15	15-25	25-30	30-35	> 35	0.20	0.020
								2.00	**0.200**
Monthly means of daily minimum relative humidity (%)									
April				< 80	80-85	85-95	> 95	0.10	0.010
May				< 80	80-85	85-95	> 95	0.10	0.010
June				< 80	80-85	85-95	> 95	0.40	0.040
July				< 80	80-85	85-95	> 95	0.30	0.030
August				< 80	80-85	85-95	> 95	0.10	0.010
								1.00	**0.100**
Soil depth (mm)									
All season	< 500	500-700	700-1000	> 1000				**1.00**	**0.100**
Slope (%)									
All season				< 4	4-8	8-10	> 10	**2.00**	**0.200**
Total								**10.00**	**1.000**

13 APPENDIX E

Table 102 Ukulinga's long-term rainfall statistics based on 26 years of mostly observed rainfall data from 1959 to 1966 and 1974 to 1991 for SAWS station ID 0239700A

Statistic	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**ANN**
Mean	107.87	103.37	93.02	44.29	30.09	10.93	11.65	23.83	50.82	77.78	96.48	99.38	749.51
St. dev	49.48	70.26	53.35	28.15	70.29	15.20	17.58	21.11	75.51	48.61	45.95	57.39	168.76
% C.V	45.87	67.97	57.36	63.57	233.59	139.15	150.88	88.58	148.57	62.50	47.63	57.74	22.52
Minimum	27.80	11.00	9.70	16.80	0.00	0.00	0.00	0.00	1.00	23.90	45.80	17.50	526.40
Maximum	238.40	350.80	195.40	132.40	368.00	64.60	85.20	69.60	397.30	203.60	265.30	274.70	1174.80
No. of obs.	26	26	26	26	26	26	26	26	26	26	26	26	26
Percentile	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**ANN**
10%	49.31	27.67	23.54	18.86	0.04	0.00	0.00	1.08	9.91	28.28	56.8	43.82	576.21
20%	64.08	63.70	40.88	24.89	2.65	0.60	1.16	2.87	12.18	35.41	61.43	57.42	598.47
33%	86.31	69.04	65.19	27.6	7.42	1.65	3.12	8.56	19.88	42.08	80.12	68.52	632.14
50%	97.70	87.55	90.90	39.25	16.25	5.95	5.55	22.8	36.35	67.85	91.00	86.75	733.25
67%	118.88	126.97	111.2	47.64	23.38	12.44	8.46	32.96	45.10	90.63	99.15	122.56	796.90
80%	158.79	139.54	143.86	55.41	30.32	15.89	19.83	43.14	63.95	119.85	107.92	134.63	866.38
90%	163.06	164.78	165.73	59.95	38.92	26.42	23.89	55.40	85.16	153.06	137.35	157.97	1005.62

The percentiles with their equivalent approximations are as follows (Schulze, 1995):

10%: Worst year in 10 (1:10 recurrence value). This value is exceeded 90% of occasions (18 times out of 20).
20%: Worst (driest) year in 5.
33%: Worst (driest) year in 3.
50%: The value exceeded as often as it is not exceeded.
67%: The wettest value occurring once in 3 years.
80%: The wettest value every 5 years.
90%: The wettest value expected every 10 years.

Table 103 Hatfield's long-term rainfall statistics based on 38 years of mostly observed rainfall data from 1960 to 1986 and 1989 to 1999 for SAWS station ID 0513465W (i.e. 1987 and 1988 were missing)

Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	136.99	85.73	80.97	53.77	13.80	7.51	2.53	4.39	16.56	71.17	105.19	123.47	702.06
St. dev	92.98	62.00	60.04	42.33	21.24	16.94	5.49	5.90	18.23	43.83	53.81	47.47	160.95
% C.V	67.88	72.32	74.15	78.73	153.90	225.56	216.67	134.51	110.10	61.60	51.15	38.45	22.92
Minimum	17.30	7.80	5.30	0.20	0.00	0.00	0.00	0.00	0.00	11.80	31.30	46.00	376.60
Maximum	542.80	318.00	327.00	166.20	103.60	84.30	25.50	29.20	82.60	174.70	252.70	219.10	1073.00
No. of obs.	38	38	38	38	38	38	38	38	38	38	38	38	38
Percentile	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**ANN**
10%	46.78	28.31	22.00	5.85	0.00	0.00	0.00	0.00	0.00	19.28	45.07	58.48	504.78
20%	58.06	35.90	34.54	17.38	0.21	0.00	0.00	0.00	0.50	34.99	53.40	71.69	581.81
33%	97.53	52.71	57.30	23.52	1.01	0.00	0.00	0.20	3.59	51.92	68.82	99.76	617.61
50%	113.10	71.70	68.00	47.45	6.45	0.75	0.00	2.50	11.75	58.10	97.00	126.75	704.80
67%	155.40	98.79	85.07	69.24	13.06	2.56	0.90	5.43	22.64	76.45	117.84	142.23	752.46
80%	202.19	121.01	116.95	97.68	21.22	11.33	3.38	9.08	29.13	117.84	154.52	159.12	850.10
90%	233.50	172.86	138.59	115.24	37.34	18.80	9.26	10.96	40.91	143.39	174.43	190.16	921.36

The percentiles with their equivalent approximations are as follows (Schulze, 1995):

10%: Worst year in 10 (1:10 recurrence value). This value is exceeded 90% of occasions (18 times out of 20).
20%: Worst (driest) year in 5.
33%: Worst (driest) year in 3.
50%: The value exceeded as often as it is not exceeded.
67%: The wettest value occurring once in 3 years.
80%: The wettest value every 5 years.
90%: The wettest value expected every 10 years.

Table 104 Baynesfield's long-term rainfall statistics based on 28 years of mostly observed rainfall data from 1974 to 2001 for SAWS station ID 0239585W

Statistic	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Mean	123.82	105.11	101.20	49.47	19.88	13.85	15.00	24.77	59.36	89.34	106.46	130.48	838.73
St. dev	44.51	56.27	49.11	26.07	16.84	15.58	26.67	23.91	86.28	39.26	56.71	68.21	165.67
% C.V	35.94	53.53	48.53	52.70	84.71	112.51	177.83	96.52	145.33	43.94	53.27	52.28	19.75
Minimum	67.80	24.50	33.00	12.50	0.00	0.00	0.00	0.00	0.00	23.00	40.10	51.00	555.10
Maximum	226.50	212.10	218.40	112.50	59.70	58.00	135.00	91.60	464.40	168.80	320.20	354.00	1280.30
No. of obs.	28	28	28	28	28	28	28	28	28	28	28	28	28
Percentile	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**	**ANN**
10%	76.60	39.72	47.94	19.64	1.93	0.00	0.00	0.00	6.33	35.27	47.24	59.60	626.15
20%	84.11	47.19	59.01	29.19	8.14	1.53	0.50	4.88	18.86	53.70	63.43	82.60	688.62
33%	94.52	76.37	73.87	38.15	9.69	3.37	2.27	9.03	25.81	72.70	79.40	93.53	760.24
50%	114.70	96.30	94.55	42.75	12.30	10.75	5.95	18.50	38.90	87.95	97.65	128.20	816.95
67%	136.96	119.54	112.07	50.71	24.26	14.98	11.20	30.71	55.83	105.02	113.86	141.57	899.89
80%	166.89	156.64	130.33	70.42	32.61	20.33	22.59	40.44	76.80	122.59	138.48	161.17	980.57
90%	178.88	201.45	183.07	94.99	49.05	39.10	37.70	61.94	118.63	150.79	167.20	202.72	1030.87

The percentiles with their equivalent approximations are as follows (Schulze, 1995):

10%: Worst year in 10 (1:10 recurrence value). This value is exceeded 90% of occasions (18 times out of 20).
20%: Worst (driest) year in 5.
33%: Worst (driest) year in 3.
50%: The value exceeded as often as it is not exceeded.
67%: The wettest value occurring once in 3 years.
80%: The wettest value every 5 years.
90%: The wettest value expected every 10 years.

14 APPENDIX F

Table 105 Summary of the monthly weather data from September 2010 to May 2014 for the Ukulinga research farm (University of KwaZulu-Natal)

Year	Month	R_s	T_{max}	T_{min}	RH_{max}	RH_{min}	Rain	ET_o
		($MJ\ m^{-2}$)	(^oC)	(^oC)	(%)	(%)	(mm)	(mm)
		Total	Mean	Mean	Mean	Mean	Total	Total
2010	09	468.8	28.0	12.5	87.4	28.9	6.0	99.1
2010	10	474.3	28.0	14.4	88.7	44.3	92.4	91.2
2010	11	500.8	29.0	14.4	91.1	46.8	95.4	97.4
2010	12	545.9	29.9	17.4	96.7	59.0	136.0	88.7
2011	01	585.8	31.5	18.0	97.3	56.1	145.7	96.5
2011	02	553.9	32.4	18.6	99.8	47.3	63.3	99.7
2011	03	515.7	31.4	17.8	96.0	38.5	53.8	109.1
2011	04	405.0	30.4	15.0	96.2	49.3	71.8	66.0
2011	05	348.6	21.3	12.5	86.5	33.4	48.3	56.8
2011	06	333.9	20.7	7.5	89.4	30.6	18.9	56.2
2011	07	340.9	17.8	7.1	87.0	39.4	53.7	57.0
2011	08	436.4	24.7	12.2	85.1	31.6	17.0	85.6
2011	09	476.4	23.8	11.7	91.2	36.2	40.7	94.2
2011	10	527.1	23.9	13.2	98.0	52.4	61.1	101.4
2011	11	512.8	25.1	13.5	96.2	48.6	87.0	95.7
2011	12	534.0	27.0	15.8	97.7	53.2	76.0	101.2
2012	01	587.1	29.3	17.2	96.7	46.8	61.4	116.3
2012	02	478.9	30.1	17.8	96.7	45.5	31.9	98.3
2012	03	480.1	28.4	15.8	96.2	41.8	103.1	97.3
2012	04	430.9	25.4	11.7	94.6	36.3	20.2	80.9
2012	05	338.6	24.9	11.7	91.9	32.0	14.2	64.2
2012	06	318.6	22.1	8.1	85.5	24.9	12.3	58.0
2012	07	370.5	21.9	8.2	86.0	25.3	8.8	68.9
2012	08	392.3	23.7	10.1	85.4	32.5	82.7	81.8
2012	09	424.0	21.8	10.6	95.7	46.4	130.5	74.4
2012	10	411.2	22.6	13.1	97.0	57.6	114.2	72.4
2012	11	466.2	23.6	13.7	97.1	57.1	71.9	83.4
2012	12	631.8	27.4	16.6	96.9	53.1	57.0	115.7
2013	01	578.0	27.9	16.8	97.4	53.7	85.7	110.2
2013	02	542.0	28.9	16.4	97.9	48.2	68.9	103.3
2013	03	476.9	26.6	15.7	97.8	50.5	59.4	90.0
2013	04	455.1	26.6	12.8	92.0	35.9	74.1	85.9
2013	05	385.0	24.2	10.6	87.9	31.5	23.5	68.4
2013	06	346.7	23.0	8.4	80.0	23.3	17.3	63.5

2013	07	351.6	21.9	9.1	92.6	35.4	5.0	60.8
2013	08	467.5	24.0	8.8	87.4	23.8	11.9	95.5
2013	09	477.0	25.7	10.4	92.7	30.3	21.9	93.8
2013	10	522.4	25.2	11.9	93.2	41.9	99.9	101.8
2013	11	575.6	26.4	14.2	96.6	46.2	80.6	112.0
2013	12	526.8	24.9	15.4	97.2	58.9	75.9	100.3
2014	01	632.2	29.5	17.3	98.2	45.6	57.7	131.2
2014	02	571.0	29.8	17.3	98.1	42.1	75.6	116.3
2014	03	513.6	27.6	16.3	97.9	48.7	107.2	101.0
2014	04	476.3	26.0	12.4	94.6	34.0	8.8	87.5
2014	05	386.5	25.9	11.0	91.1	28.5	1.9	72.7

Table 106 Summary of the monthly weather data for three seasons at the Hatfield research farm (University of Pretoria)

Year	Month	R_s (MJ m^{-2}) Total	T_{max} (°C) Mean	T_{min} (°C) Mean	RH_{max} (%) Mean	RH_{min} (%) Mean	Rain (mm) Total	ET_o (mm) Total
2010	12	443.9	28.2	15.9	85.3	32.7	199.2	131.4
2011	01	405.8	27.7	16.9	87.4	41.0	222.6	113.8
2011	02	438.6	28.6	16.2	82.0	25.8	36.3	118.3
2011	03	651.2	29.2	15.9	81.5	29.4	247.5	128.0
2011	04	444.0	23.8	12.4	84.9	35.3	47.4	85.0
2011	05	476.5	22.5	8.1	84.0	26.7	17.7	70.0
2011	12	621.6	28.0	16.3	82.6	30.2	103.7	129.4
2012	01	675.1	29.6	16.5	82.6	25.7	68.3	149.3
2012	02	604.6	30.5	17.1	80.5	23.5	85.0	113.0
2012	03	618.2	30.0	15.1	76.8	15.3	31.5	118.2
2012	04	523.2	26.1	10.2	83.3	20.8	15.4	98.9
2012	05	464.0	25.5	8.7	72.9	12.7	0.0	66.9
2012	12	592.7	28.7	16.2	80.6	26.0	138.5	151.9
2013	01	599.7	30.0	16.9	77.5	24.4	53.5	157.1
2013	02	559.2	31.5	16.3	75.3	16.8	54.9	136.7
2013	03	480.2	29.3	14.9	76.4	18.4	30.8	123.4
2013	04	411.6	25.5	10.3	74.5	20.1	69.6	93.9
2013	05	383.2	23.5	6.7	68.4	13.1	0.4	83.1
2013	06	255.4	22.2	4.7	64.2	10.3	0.0	62.3

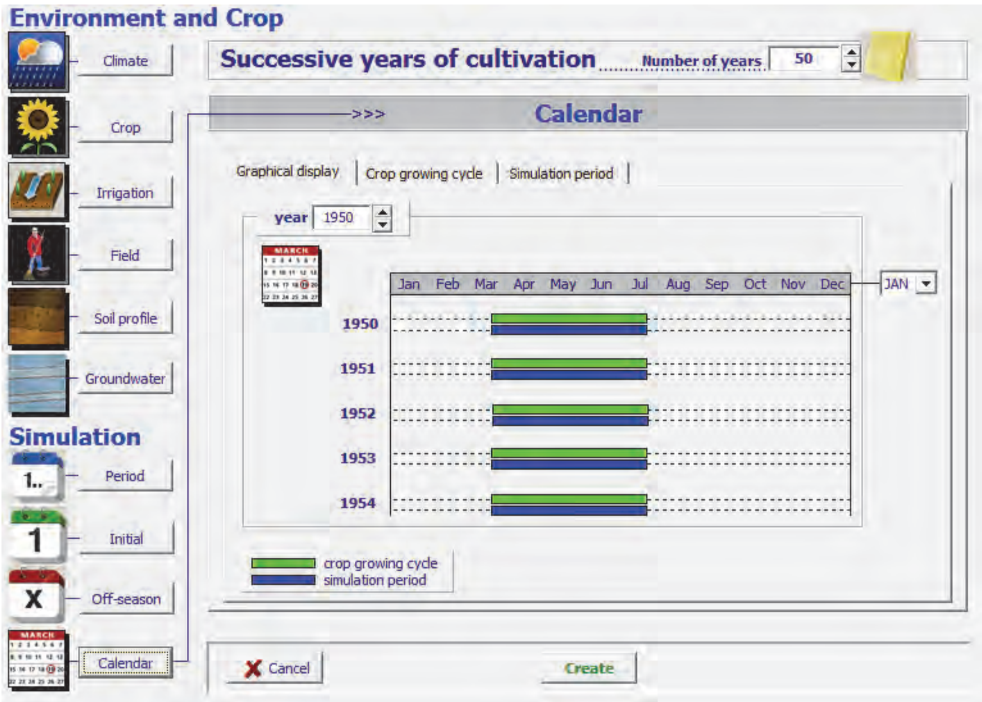
Table 107 Summary of the monthly weather data for one season at Baynesfield Estate (KwaZulu-Natal Midlands)

Year	Month	R_s	T_{max}	T_{min}	RH_{max}	RH_{min}	Rain	ET_o
		(MJ m^{-2})	**(^{o}C)**	**(^{o}C)**	**(%)**	**(%)**	**(mm)**	**(mm)**
		Total	Mean	Mean	Mean	Mean	Total	Total
2012	10	358.5	21.5	12.2	96.6	62.8	119.9	71.5
2012	11	437.3	22.5	12.7	96.9	63.6	94.5	85.5
2012	12	561.9	26.6	15.6	96.5	58.1	74.4	114.4
2013	01	507.3	26.7	16.0	97.0	59.5	122.2	106.3
2013	02	482.8	27.4	15.3	97.2	55.8	80.3	100.0
2013	03	438.6	26.7	14.6	96.9	54.7	53.8	91.0
2013	04	402.7	25.4	10.6	93.3	41.8	99.8	86.5

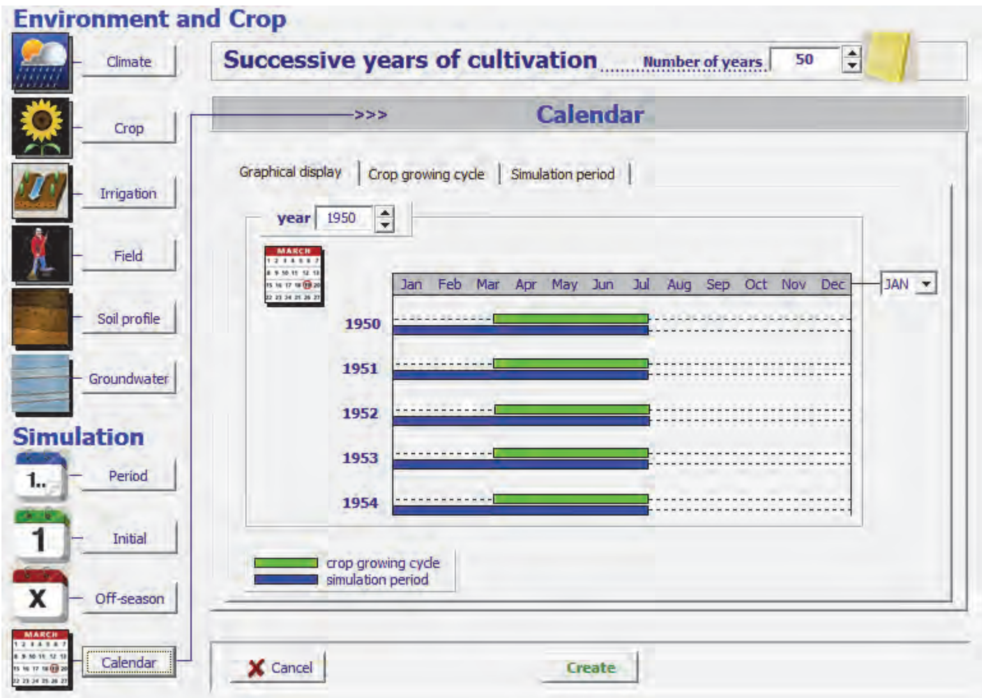
15 APPENDIX G

Table 108 LAI measurements of sugarbeet converted to percentage canopy cover (CC) using two different equations

DAP	LAI	García-Vila *et al*. (2009)	Hsiao *et al*. (2009)
		CC (%)	CC (%)
42	0.2	7.3	7.0
59	0.3	11.5	11.6
62	0.5	17.1	17.8
69	0.8	31.4	33.2
70	0.8	30.0	31.8
79	0.9	33.4	35.3
84	1.2	43.8	45.8
92	1.5	53.2	54.8
100	1.7	58.6	60.0
112	2.0	63.5	64.3
127	2.3	71.6	71.7
136	2.7	78.0	77.4
142	3.3	85.4	84.1
148	3.0	82.4	81.4
169	3.1	83.2	82.1
182	2.4	72.7	72.0
189	2.2	68.9	69.9



(a)



(b)

Figure 51 Option in *AQUACROP* to set the start of the simulation period to a) that of the crop growth cycle (e.g. 22nd March), or b) a fixed date before the crop is planted (e.g. 1st January)

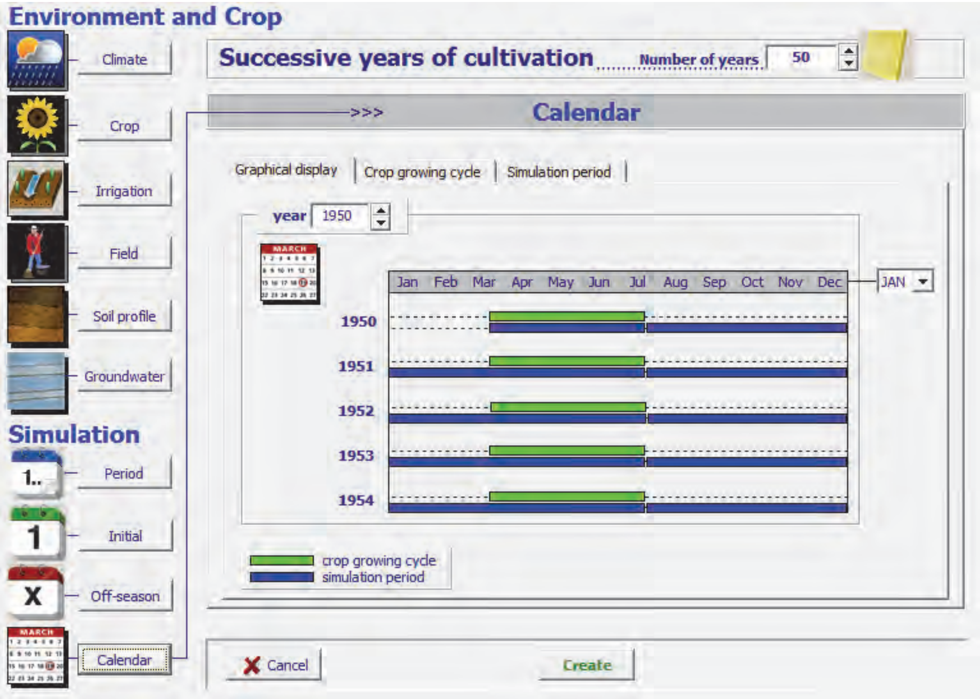


Figure 52 Option in *AQUACROP* to set the start of the successive simulation period to the day after the previous crop maturity date

17 APPENDIX I

Example showing the format of *AQUACROP's* soils (.SOL) file for quinary sub-catchment 4696

```
Quinary sub-catchment 4696
  3.0           : AquaCrop Version (August 2012)
 75             : CN (Curve Number)
   7            : Readily evaporable water from top layer (mm)
   2            : number of soil horizons
 -9.00          : Depth (m) of restrictive soil layer inhibiting root zone expansion - None
    Thickness     SAT   DUL  PWP    KSAT      description
  -----(m)----- ----(vol %)---- (mm/day)   ---------------------------------
      0.30        40.9 26.3 16.2   184.0    Sandy loam
      0.62        42.0 31.1 20.0    77.5    Sandy clay loam
```

where

SAT = saturation (total porosity or TPO) expressed as a volume % (for both soil horizons)

DUL = drained upper limit (field capacity) expressed as a volume %

PWP = permanent wilting point expressed as a volume %

K_{SAT} = saturated hydraulic conductivity (in mm day^{-1}) for both soil horizons

Example showing the format of *AQUACROP's* initial conditions (.SW0) file for quinary sub-catchment 4696

```
Quinary sub-catchment 4696
    3.0         : AquaCrop Version (August 2012)
    0.0         : water stored between soil bunds (if present)
    0           : soil water content specified for specific layers
    2           : number of soil layers considered

  Soil depth (m) Soil water content (vol%)
=========================================
0.30                  21.25
0.62                  25.55
```

where

0.30 = average depth of the A-horizon (m)

0.62 = average depth of the B-horizon (m)

21.25 = initial soil water content of the A-horizon (i.e. $(\theta_{DUL} + \theta_{PWP})/2$) expressed as a volume %

25.25 = initial soil water content of the B-horizon (i.e. $(\theta_{DUL} + \theta_{PWP})/2$) expressed as a volume %

18 APPENDIX J

Table 109 Classification of soil texture using the volumetric water content at saturation (TPO) and at permanent wilting point (PWP), as well as the soil's plant available water (PAW) content

Broad Classification	Textural class	Percentage of:		Organic matter	Volumetric water content (vol %)			PAW
		Sand	Clay	(%)	PWP	DUL	TPO	(mm)
Silty clayey	Clay	0.05	0.95	2.50	52.8	54.0	61.0	1.2
Silty clayey	Clay	0.15	0.85	2.50	48.1	53.9	56.7	5.8
Silty clayey	Clay	0.05	0.85	2.50	47.5	51.3	59.3	3.7
Silty clayey	Clay	0.25	0.75	2.50	43.2	52.3	52.7	9.0
Silty clayey	Clay	0.15	0.75	2.50	42.8	50.5	55.2	7.7
Silty clayey	Clay	0.05	0.75	2.50	42.3	48.7	57.8	6.3
Silty clayey	Clay	0.35	0.65	2.50	38.2	49.1	49.1	10.8
Silty clayey	Clay	0.25	0.65	2.50	37.9	48.1	51.5	10.2
Silty clayey	Clay	0.15	0.65	2.50	37.5	47.1	53.8	9.6
Silty clayey	Clay	0.05	0.65	2.50	37.1	46.1	56.2	9.0
Silty clayey	Clay	0.45	0.55	2.50	33.1	44.4	45.9	11.4
Silty clayey	Clay	0.35	0.55	2.50	32.8	44.2	48.1	11.5
Silty clayey	Clay	0.25	0.55	2.50	32.5	44.0	50.3	11.6
Silty clayey	Silty clay	0.15	0.55	2.50	32.2	43.8	52.5	11.6
Silty clayey	Silty clay	0.05	0.55	2.50	31.9	43.6	54.8	11.7
Sandy clayey	Sandy clay	0.55	0.45	2.50	27.8	38.6	43.5	10.8
Silty clayey	Clay	0.45	0.45	2.50	27.5	39.1	45.4	11.6
Silty clayey	Silty clay	0.35	0.45	2.50	27.3	39.6	47.4	12.3
Silty clayey	Silty clay	0.25	0.45	2.50	27.1	40.1	49.4	13.0
Silty clayey	Silty clay	0.15	0.45	2.50	26.9	40.7	51.4	13.8
Silty clayey	Silty clay	0.05	0.45	2.50	26.7	41.2	53.3	14.5
Sandy clayey	Sandy clay loam	0.65	0.35	2.50	22.3	31.8	41.9	9.5
Sandy clayey	Sandy clay	0.55	0.35	2.50	22.1	32.9	43.6	10.7
Sandy clayey	Clay loam	0.45	0.35	2.50	22.0	34.0	45.2	12.0
Silty clayey	Slity clay loam	0.35	0.35	2.50	21.9	35.2	46.9	13.3
Silty clayey	Silty clay loam	0.25	0.35	2.50	21.7	36.4	48.6	14.7
Silty clayey	Silty clay loam	0.15	0.35	2.50	21.6	37.6	50.3	16.0
Silty clayey	Silty clay loam	0.05	0.35	2.50	21.4	38.8	52.0	17.3
Sandy clayey	Sandy clay loam	0.75	0.25	2.50	16.7	24.2	41.6	7.6
Sandy clayey	Sandy clay loam	0.65	0.25	2.50	16.6	25.9	42.8	9.3
Loamy	Loam	0.55	0.25	2.50	16.5	27.5	44.0	11.0
Loamy	Silt loam	0.45	0.25	2.50	16.5	29.3	45.3	12.8
Loamy	Silt loam	0.35	0.25	2.50	16.4	31.0	46.6	14.6
Loamy	Silt loam	0.25	0.25	2.50	16.4	32.8	47.9	16.4
Loamy	Silt loam	0.15	0.25	2.50	16.3	34.6	49.3	18.3
Loamy	Silt loam	0.05	0.25	2.50	16.2	36.5	50.7	20.2
Loamy	Silt loam	0.05	0.15	2.50	11.0	34.2	49.4	23.2
Loamy	Silt loam	0.15	0.15	2.50	11.0	31.7	48.4	20.7
Loamy	Silt loam	0.25	0.15	2.50	11.0	29.3	47.4	18.3
Loamy	Silt loam	0.35	0.15	2.50	11.0	27.0	46.5	16.0
Loamy	Slit loam	0.45	0.15	2.50	10.9	24.7	45.6	13.8
Loamy	Silt loam	0.55	0.15	2.50	10.9	22.6	44.8	11.6

Sandy	Sandy loam	0.65	0.15	2.50	10.9	20.5	44.1	9.5
Sandy	Sandy loam	0.75	0.15	2.50	10.9	18.4	43.5	7.5
Sandy	Loamy sand	0.85	0.15	2.50	10.9	16.5	43.0	5.6
Loamy	Silt	0.05	0.05	2.50	5.8	32.0	48.3	26.2
Loamy	Silt	0.15	0.05	2.50	5.7	28.9	47.6	23.3
Loamy	Silt	0.25	0.05	2.50	5.6	26.0	47.0	20.4
Loamy	Silt	0.35	0.05	2.50	5.5	23.2	46.6	17.7
Loamy	Silt	0.45	0.05	2.50	5.4	20.5	46.2	15.1
Loamy	Silt loam	0.55	0.05	2.50	5.3	17.9	46.0	12.6
Sandy	Sandy loam	0.65	0.05	2.50	5.2	15.5	45.9	10.3
Sandy	Sandy loam	0.75	0.05	2.50	5.1	13.2	46.0	8.0
Sandy	Sand	0.95	0.05	2.50	5.0	8.8	46.4	3.9

19 APPENDIX K

Example showing the format of *AQUACROP's* climate (.CLI) file for quinary sub-catchment 4 696

```
acrhis_4696: 1779: 1816: 1023 (South Africa) - daily data: 1950/01/01 - 1999/12/31
 4.0       : AquaCrop Version (June 2012)
acrhis_4696.TMP
acrhis_4696.ETo
acrhis_4696.PLU
A2.CO2
```

where

```
acrhis_4696     =    name of the .CLI file
1799            =    latitude of quinary centroid (minutes of a degree)
1816            =    longitude of quinary centroid (minutes of a degree)
1023            =    mean altitude of quinary sub-catchment
South Africa    =    location (or origin) of climate data
Daily data      =    time step of climate data
1950/01/01      =    start date of daily record (YYYY/MM/DD)
1999/12/31      =    end start of daily record (YYYY/MM/DD)
4.0             =    AquaCrop model version number
acrhis_4696.TMP =    name of daily temperature file
acrhis_4696.ETo =    name of daily reference evaporation file
acrhis_4696.PLU =    name of daily rainfall file
A2.CO2          =    name of file containing historical (1902-2009) and
                     projected (2010-2100) atmospheric CO2 concentrations
```

Example showing the format of *AQUACROP's* temperature climate (.TMP) file for quinary sub-catchment 4 696

```
acrhis_4696: 1779: 1816: 1023 (South Africa)
   1       : Daily records (1=daily, 2=10-daily and 3=monthly data)
   1       : First day of record (1, 11 or 21 for 10-day or 1 for months)
   1       : First month of record
 1950      : First year of record (1901 if not linked to a specific year)

 Tmin (dC) Tmax (dC)
=======================
    14.1    18.3
    14.9    23.6
    16.3    26.6
.
.
.
    16.6    26.4
    16.3    24.6
    16.2    26.4

where
acrhis_4696     =    name of the .CLI file
1799            =    latitude of quinary centroid (minutes of a degree)
1816            =    longitude of quinary centroid (minutes of a degree)
1023            =    mean altitude of quinary sub-catchment
South Africa    =    Location (or origin) of climate data
   1            =    time step of climate record (1=daily)
   1            =    first day of record
   1            =    first month of record
 1950           =    first year of record
```

20 APPENDIX L

Example showing the daily climate data available in the quinary sub-catchment database for each quinary

```
swbhis_xxxx.csv  : input climate file for each quinary in SWB model format
where:
     xxxx = the quinary sub-catchment number (SUB_CAT or SUBC)
          = ranges from 2637 to 3324 (113 sub-catchments in total)

     YYYY-MM-DAY, TMAX,  TMIN,  RMAX,  RMIN, WSPD, IRSW, RAIN,FAO56
     1950-01-01, 28.20, 15.50, 82.31, 37.90, 2.00,26.52,  0.0, 5.80
     1999-12-31, 24.40, 13.30, 83.79, 41.87, 2.00,25.75,  0.0, 5.10

where:
     YYYY  = year
     MM    = month
     DD    = day
     TMAX  = daily maximum temperature estimate in °C
     TMIN  = daily minimum temperature estimate in °C
     RMAX  = daily maximum relative humidity estimate in %
     RMIN  = daily minimum relative humidity estimate in %
     WSPD  = daily average wind speed in m/s (unknown, therefore set to 2.0 m s-1)
     IRSW  = daily incoming solar (shortwave radiation) estimate in MJ m-2
     RAIN  = daily rainfall in mm
     FAO56 = daily FAO56 (Penman-Monteith) evaporation estimate
```

Example showing the site information available in the quinary sub-catchment database for each quinary

```
swbhis_xxxx.cli  : site information per quinary for the SWB model

      2637,swbhis_2637.csv,-33.567, 18.950,0141,1950/01/01,1999/12/31
      where swbhis_0001.csv is the name of climate file the quinary, and
            2637 = quinary sub-catchment number (xxxx = 2637 to 3324)
         -25.433 = latitude  of quinary centroid in degrees decimal
          25.817 = longitude of quinary centroid in degrees decimal
            1393 =  average quinary sub-catchment altitude in masl
      1950/01/01 = start date (yyyy/mm/dd) of daily record
      1999/12/31 = end   date (yyyy/mm/dd) of daily record
```

Example showing the soils data available in the quinary sub-catchment database for each quinary

```
swbsoi.csv : soil depth and soil water retention parameters for
        the topsoil (A-horizon) and subsoil (B-horizon)

      SUBC,DEPAH,DEPBH,PWPAH,PWPBH,DULAH,DULBH,TPOAH,TPOBH
      2637, 0.29, 0.24 0.142,0.194,0.224,0.265,0.438,0.432
where:
       SUBC = the quinary sub-catchment number from 2637 to 3324
      DEPAH = Average depth of the topsoil in each quinary (m)
      DEPBH = Average depth of the subsoil in each quinary (m)
      PWPAH = Permanent wilting point or lower limit of the topsoil
               (in m/m, i.e. m of soil water per m of soil depth)
      PWPBH = Permanent wilting point or lower limit of the subsoil (m/m)
      DULAH = Drained upper limit or field capacity of the topsoil (m/m)
      DULBH = Drained upper limit or field capacity of the subsoil (m/m)
      TPOAH = Total porosity of saturated topsoil (m/m)
      TPOBH = Total porosity of saturated subsoil (m/m)
```

21 APPENDIX M

Allen *et al*. (1998) proposed an empirical equation (**Equation 71**) to estimate the pan coefficient (K_p) using the assumed green fetch distance (*FD* in m), wind speed (*u* in m s^{-1} at height 2 m) and the mean relative humidity (RH_{ave}). The latter variable ensures that K_p varies monthly and with location.

$$K_p = 0.108 - 0.0286u + 0.0422\ln(FD) + 0.1434\ln(RH_{ave}) - 0.000631[\ln(FD)]^2 \cdot \ln(RH_{ave}) \quad \textbf{Equation 71}$$

Assuming a fetch of 200 m for a typical A-pan in South Africa (Schulze, 2014; *pers. comm.*), values of E_p/ET_o (i.e. $1/K_p$) were estimated for each quinary sub-catchment using the revised temperature and evaporation database. The histogram of monthly *CORPAN* values across all quinary sub-catchments shows that 79.9% of values range from 1.23 to 1.29 (**Table 110**). However, 15.4% of all monthly *CORPAN* values exceed 1.29.

Table 110 Histogram of monthly *CORPAN* values across all 5 838 quinaries calculated for a green fetch of 200 m using an empirical equation proved by Allen *et al*. (1998)

CORPAN	Count	% of total	Accum. %
1.18	27	0.04	0.04
1.19	0	0.00	0.04
1.20	167	0.24	0.28
1.21	702	1.00	1.28
1.22	2390	3.41	4.69
1.23	5577	7.96	12.65
1.24	8319	11.87	24.53
1.25	9343	13.34	37.86
1.26	9938	14.19	52.05
1.27	9365	13.37	65.42
1.28	7806	11.14	76.56
1.29	5632	8.04	84.60
1.30	3942	5.63	90.22
1.31	2825	4.03	94.26
1.32	1526	2.18	96.44
1.33	1039	1.48	97.92
1.34	654	0.93	98.85
1.35	379	0.54	99.39
1.36	261	0.37	99.77
1.37	116	0.17	99.93
1.38	37	0.05	99.98
1.39	11	0.01	100.00
Total	**70 056**	**100.00**	