Assessment of biofuel feedstock production in South Africa:

Synthesis report on estimating water use efficiency of biofuel crops (Volume 1)

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

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This report (**Volume 1**) 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 biofuels 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. 4th 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 was 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 are not 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)

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". The funding totalled R7.4 million and the project commenced in April 2009, with termination in March 2015. 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 (refer to Volume 2). **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 (this document) 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** 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 (this document) is essentially a summarised version of **Volume 2**. 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**.

2 PRIORITISATION OF FEEDSTOCKS

2.1 Introduction

One of the aims of the project (**AIM 1**) was to specify and prioritise currently grown and potential feedstocks deemed suitable for biofuel production. Although the scoping study report (Jewitt *et al*., 2009a) identified 20 potential feedstocks, this list was reduced by identifying feedstocks with the highest potential for biofuel production in South Africa. This section therefore provides the justification for the list of feedstocks that were:

- studied in field-based experiments and
- considered for water use and yield modelling.

2.2 Approach

The final selection of feedstocks was largely governed by the national biofuels industrial strategy (DME, 2007a). However, a number of other factors were considered, which are given in **Section 2.2** of **Volume 2**. The section provides a timeline of publications and events that were used to shortlist and prioritise feedstocks deemed suitable for the South African biofuels industry. A summary of the feedstocks that were shortlisted in given in **Section 2.3** and **Section 2.4** for bioethanol and biodiesel crops respectively, with the suggested prioritisation given in **Section 2.5**.

2.3 Bioethanol Feedstocks

The bioethanol feedstocks that were shortlisted are divided into perennial, summer and winter crops. No distinction was made between dryland *vs*. irrigated crop production, since the assumptions are made that all biofuel feedstocks should be cultivated under rainfed conditions. However, sugarbeet cultivated in winter is likely to require supplemental irrigation.

2.3.1 Perennial

2.3.1.1 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 (DoE, 2013). 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.

2.3.1.2 Sweet sorghum

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 of may be possible in the hotter and wetter regions of the country (e.g. along the Zululand coast).

2.3.2 Summer

2.3.2.1 Sugarbeet

Since sugarbeet is largely grown in temperate climates, it is not well adapted to the warm and humid growing conditions typically experienced in summer. Although breeding efforts are currently underway to produce a tropical variety, a sub-tropical variety planted in September 2010 at Ukulinga was plagued by a fungal disease (*Cercospera* or Leaf Spot).

2.3.2.2 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). 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 would 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 selection of grain sorghum as a preferred feedstock by two bioethanol producers provided sufficient motivation to shortlist this feedstock. 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.

2.3.2.3 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 was also studied at the ARC's Crop Grains Institute at Potchefstroom, Mpumalanga.

2.3.2.4 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.

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).

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.

2.3.2.5 Cassava

Little information exists on cassava production in South Africa, particularly at a commercial scale. It is believed 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.

2.3.3 Winter

2.3.3.1 Sugarbeet (Irrigated)

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). 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.

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).

2.4 Biodiesel Feedstocks

2.4.1 Perennial

2.4.1.1 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 requiring a permit and 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). Like most biofuel feedstocks, Jatropha is not a wasteland crop as it requires fertiliser, water and good management to provide economically viable yields (Everson *et al*., 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.

2.4.1.2 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.

2.4.2 Summer

2.4.2.1 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).

2.4.2.2 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 predicted 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.

2.4.3 Winter

2.4.3.1 Canola (Dryland)

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.

2.5 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** of **Volume 2**, 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 exhibiting 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 also 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 produced from animal fat (i.e. tallow) and used cooking oil.

2.5.4 Summary

Thus, the final list of prioritised feedstocks considered in this project is summarised in **Table 1**. Sunflower was not included and was replaced with grain sorghum, as agreed to at the reference group meeting on 23rd July 2014. It is assumed that the land suitability map for grain sorghum would be broadly similar to that for sweet sorghum. To re-cap, field work conducted on soybean as part of WRC Project No. K5/2066 (Mengistu *et al*., 2014) was included in this report.

Table 1 Final list of priority feedstocks considered for inclusion in the biofuels project

Feedstock	**Field work**	**Mapping**	**Modelling**
Bioethanol			
Sugarcane	No	Yes	Yes
Sugarbeet	Yes	Yes	Yes
Grain sorghum	Yes	Yes	Yes
Sweet sorghum	Yes	No	No
Biodiesel			
Soybean	K5/2066	Yes	Yes
Canola	No	Yes	Yes

3 FEEDSTOCK WATER USE EFFICIENCY

This chapter addresses **AIM 6**, which is to estimate or quantify the water use efficiency of the prioritised feedstocks. The chapter provides a summary of the water use and yield data derived from the field-based research. Water use efficiency (WUE) and biofuel use efficiency values were estimated for each feedstock.

Jewitt *et al*. (2009a) mentioned that the WUE aspect is considered a critical research need in terms of developing guidelines for farmers, policy and decision makers, towards optimal biofuel feedstock production in potential growing areas. They also stated that in order to be truly informative, studies must consider the amount of biofuel generated per unit of water, not merely crop yield or biomass production.

3.1 Introduction

Before the definition of water use efficiency is given, it is important to first define what is meant by crop water use. In addition, the term crop yield also needs to be clarified.

3.1.1 Definition of water use

Crop water use is defined as the water loss from a cropped surface, accumulated from the planting to harvest and is often termed seasonal water use. Water loss can be defined as:

- transpiration only, or
- transpiration + soil water evaporation (i.e. evapotranspiration), or
- transpiration + soil water evaporation + interception loss (i.e. actual evapotranspiration).

Hence, transpiration represents the lower limit of water used by the vegetation type. Similarly, actual evapotranspiration represents the upper limit of vegetation water use. However, some studies also add percolation loss to actual evapotranspiration, particularly if irrigation is used (Singh, 2005). Owing to the complexity of measuring evapotranspiration over a growing season, the quantity of applied irrigation water is sometimes used as a measure of crop water use. If a significant difference exists between water use based on transpiration only and evapotranspiration, this indicates the need to reduce soil water evaporation by agronomic measures such as mulching covers and conservation tillage (Singh, 2005).

In this study, the definition of water use was governed by the technique used to measure the term. For example, the heat pulse velocity method was used to measure transpiration only for the Moringa trees at Hatfield. Similarly, the same technique was used for the Jatropha trees at Ukulinga. However, a surface layer scintillometer was also used to measure actual evapotranspiration (including interception loss). For the annual crops, the surface renewal and eddy covariance system provided estimates of actual evapotranspiration.

Furthermore, the hydrological and crop yield models used in this study calculated water use over the growing season as evapotranspiration (i.e. transpiration + soil water evaporation), thus neglecting evaporation of intercepted water. It is important to acknowledge these differences in water use estimates when interpreting the WUE results. Finally, crop water use is usually measured as a depth equivalent in mm, which is simply multiplied by a constant (10) to convert to a volume in cubic metres (m^3) per hectare (ha).

3.1.2 Definition of crop yield

The definition of yield is governed by the technology used to produce the biofuel. For example, first generation technologies convert the utilisable portion of the biomass (i.e. stem, tuber, fruit, grain or seed) that contains sugar, starch or vegetable oil) into biofuel. On the other hand, second generation technologies are interested in the entire above-ground biomass for biofuel production and thus, prefer to quantify feedstock yield in volumetric units.

Agronomists prefer to express plant production in units of mass (i.e. kg or tons) and not volume (m^3), the latter requiring knowledge of the plant's density. Mensurationists and forest biometricians also prefer to express timber production in tons (i.e. mass) and not m^3 (i.e. volume). This is advantageous where wood density varies in the trees under study (Jones, 2004).

It is also important to be specific about the nature of the yield (e.g. wet, fresh or dry mass, in-shell, de-husked etc.). Crop yield depends on crop physiology (C_3 *vs*. C_4 crop & variety used), agronomy (planting density & planting date), site conditions (climate, soils and terrain) as well as other management practices (site preparation, irrigation use, fertiliser use & weeding control). This means that water use efficiency is also affected by the above factors.

3.1.3 Definition of WUE

Since many different definitions of WUE exist in the literature, it is important to clarify the specific definition of WUE adopted in this project, as well as the methods (and units) used to quantify this term. The plethora of definitions which exist in the available literature is due to, *inter alia*, the many ways in which water use and yield can be defined. In this study, water use efficiency (kg m^{-3}) is defined as the ratio of yield (kg ha^{-1}) pertaining to the utilisable portion of the total biomass (which contains the sugar, starch or vegetable oil), to the accumulated water (m^{-3} ha^{-1}) that evapotranspired from the crop over the growing season.

The preferred spatial scale is per unit hectare, but can be m^2, or even km^2. The main techniques used to measure actual evapotranspiration from the crop surface was the surface renewal system, calibrated using the eddy covariance technique. The only exception was for the Moringa trees grown at Hatfield research farm. Single tree measurements of transpiration only were made using the heat pulse velocity method, then scaled up to stand level using the planting density. At Ukulinga, a surface layer scintillometer was used to adjust transpiration only measurements to actual evapotranspiration, by accounting for the evaporation of soil water as well as intercepted water.

The project's terms of reference stated that WUE must also be estimated or quantified as biofuel yield, per unit of water consumed. Hence, the term biofuel use efficiency BUE (m^3 m^{-3}) is defined as the theoretical biofuel yield (m^3) relative to the water used to produce the feedstock (m^3). The concept of an "efficiency" implies similar units for the input (actual evapotranspiration) and output (utilisable yield), as is the case for BUE. This is also applicable to second generation feedstocks where both the biomass yield and water use can both be expressed as a volume in m^3.

In an agricultural environment however, production is commonly described as crop yield (kg or tons) per unit area (hectare). Agronomists therefore prefer the term water productivity, which is defined as crop production (as opposed to biomass production) per unit amount of water use (Molden, 1997). The International Water Management Institute (IWMI) proposed a change in nomenclature from water use efficiency to water productivity (WP), particularly for first generation feedstocks (Singh, 2005). To avoid confusion, the term WUE and not WP is used in this study.

The calculation of biofuel yield from feedstock yield was achieved using extraction ratios reported in the local and international literature. For example, the draft national biofuels strategy (DME, 2006a) reported that a ton of sugarcane (fresh), maize (dry) and soybean (dry) could produce 81, 402 and 171 litres of biofuel respectively. Similarly, Meyer *et al*. (2008) reported figures of 76, 402 and 194 litres of biofuel per ton of sugarcane (fresh), maize (dry) and soybean (dry) respectively. The draft position paper on the biofuel pricing framework (DoE, 2014) quoted 80, 417 and 185 L t^{-1} of sugarcane (fresh), grain sorghum (dry) and soybean (dry) respectively. Although there is good agreement regarding sugarcane's extraction rate, the value for soybean varies from 171-194 L t^{-1}. This is discussed further in the results section.

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°40'S; 30°24'E; altitude 809 m) receives an average annual rainfall of 750 mm over 113 rain days, with 23% of the MAP falling during the winter months. 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 Ukulinga's monthly weather data for four seasons is given in **Volume 2**.

3.2.1.1 Soil survey (#1)

Experiments were conducted in two 80 by 80 m 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 in each plot at Ukulinga in August 2010. The soil depth varies from 60 to 100 cm across both plots. The soil texture is predominately a clay loam, with clay content increasing from 29% to 35% with depth (**Table 2**). The particle size distribution was undertaken by the Department of Soil Science at UKZN.

Table 2 Proportion of clay, silt and sand for three depths in each soil survey pit

Plot 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

3.2.1.2 Soil survey (#2)

Three undisturbed soil samples were collected in May 2013 within the study site (Plot #1) for measurements of soil water retention parameters and saturated hydraulic conductivity. The soil samples were collected at three different depths (20, 40 and 60 cm) using six steel cylinders. Three steel cylinders measuring 3 cm in diameter and 6.5 cm in length were used to determine soil water retention parameters using the outflow pressure method (refer to **Volume 2** for details). Another three cylindrical discs measuring 5 cm in diameter and 7.5 cm in length were used to collect samples for determining saturated hydraulic conductivity. The cylindrical discs were inserted at the selected depths in the soil profile and thereafter, they were carefully removed using minimal force so the soil structure would not be disturbed. The discs were labelled according to their depths and analyses were done at the UKZN soil physics laboratory. The results of the soil analysis at three depths in presented in **Table 3**.

Table 3 Soil water retention values representing total porosity (θ_{TPO}), drained upper limit (θ_{DUL}) and permanent wilting point (θ_{PWP}) and saturated hydraulic conductivity (K_{SAT}) for plot#1 at Ukulinga

Depth (cm)	θ_{TPO} (m m^{-1})	θ_{DUL} (m m^{-1})	θ_{PWP} (m m^{-1})	K_{SAT} (mm d^{-1})
20	0.365	0.293	0.157	184.4
40	0.365	0.300	0.175	228.0
60	0.361	0.320	0.208	108.0

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. 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 **Volume 2**.

Two sweet sorghum field experiments were conducted during the 2010/11 summer growing season. The soil for both trials is a sandy clay loam with a permanent wilting point and field capacity of 120-130 and 240-280 mm m^{-1} respectively. The Moringa trial site is a Hutton (SCWG, 1991) soil with a sandy clay texture (**Table 4**) and pH of 5.6.

Table 4 Proportion of clay, silt and sand for soils representing two depths at Hatfield

Soil depth (mm)	Clay (%)	Silt (%)	Sand (%)	Total (%)	Texture
0-150	39	11	50	100.00	Sandy clay
150-300	41	14	45	100.00	Sandy clay

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 Baynesfield Estate receives an average annual rainfall of 839 mm over 129 rain days, with 22% of the MAP falling during the winter months. 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 one season is given in **Volume2**.

3.3 Trial Description

Field experiments were conducted on prioritised biofuel crops at the Hatfield and Ukulinga research farms to establish the water requirements and obtainable yields under local growing conditions. The African Centre for Crop Improvement (ACCI; based at UKZN) managed all agronomy-related aspects of the field-based research undertaken at Ukulinga. 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 summarised next. The reader is referred to **Volume 2** for a full description of the agronomic aspects of each trial.

3.3.1 Ukulinga

At Ukulinga, the following trials were conducted, *viz*. a) three sugarbeet trials, b) two sweet sorghum trials, and c) two grain sorghum trials. In addition, data for the existing Jatropha trial was extended for a further season.

3.3.1.1 Sugarbeet

The sugarbeet trial (variety EB 0809) was established for three consecutive growing seasons at Ukulinga research farm on an 80 × 80 m plot. Drip irrigation was used to maintain optimum soil water conditions in order to maximise crop yield. The irrigation was switched off prior to the expected harvest date. This allowed the tubers to dehydrate, and consequently increased the overall sugar content of the sugarbeet.

Summer planting: For the first season, the sugarbeet trial was planted over a two-week period starting in mid-September 2010 and harvested in early April 2011. The seed was sown at the beginning of July 2010 in seedling trays (undertaken by Sunshine Seedlings) and planting of the seedlings commenced on the 14th September 2010. Seedlings were transplanted with an inter-row spacing of 50 cm and a between plant spacing of 30 cm (i.e. 66 667 plants per hectare). In early April 2010, nine sugarbeet samples plots were identified and harvested. The beets were harvested in each plot with forks using manual labour and placed in labelled bags. The tubers were then weighed and washed and then the general condition of the tuber was recorded. Finally, laboratory samples were taken, thus enabling total Brix (i.e. total sugar) yield to be determined in the ACCI laboratory at Ukulinga.

Winter planting: For the second growing season, transplanting of sugarbeet seedlings 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, after 7 months of growth. The harvesting of the trial was very similar to that undertaken in the first season and thus, the description is not repeated here.

Autumn planting: Seed was treated with *Trichoderma* prior to germination to help improve soil disease tolerance. Transplanting commenced in late May 2013 and seedlings were placed in between the drippers (30 cm apart) to reduce the risk of root rot. For the previous two trials, weeds were manually cleared. However, a registered sugarbeet herbicide (Goltix) was used in the third season. In addition, the trial was sprayed with a micro-nutrient foliar feed to improve growth. The trial was harvested on mid-December 2013 after seven months of growth.

3.3.1.2 Sweet sorghum

The sweet sorghum (variety Sugargraze) trial was conducted over two growing seasons on an 80 × 80 m plot. For the first season, the trial was planted over a two-week period in early December 2010 and finally harvested in early May 2011. 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). A total of 10 sweet sorghum sample plots were selected and harvesting process began on 19th May 2011. The portion of leaves and heads as a percentage of the total biomass on a fresh mass basis was determined, as well as the stem weight. Samples were then oven dried at 80°C and re-weighed to determine the total dry matter yield of each component (stalks, leaves & heads). A total of 20 sugar yield analyses were undertaken using stalks not damaged by stalk borer by the ACCI laboratory at Ukulinga.

The second growing season was from mid-December 2011 to the first week of 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 to 125 000 sph. Again, the harvesting of the trial was very similar to that undertaken in the first season.

3.3.1.3 Grain sorghum

On 27th November 2012, a zero tannin grain sorghum variety (PAN8816) seed was 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 and thus, portions of the trial were replanted up to 18th December. A total of six sample blocks were demarcated and each grain head was protected with two mesh bags. In April 2013, three of the six sample plots were unfortunately damaged by bushpig when the electric fence failed. This resulted in the trial being prematurely harvested on Friday 10th May 2013. The grain heads were harvested from the three remaining sample blocks and stored in bags for subsequent analysis. Finally, the heads were manually threshed and grain samples were sent to Stellenbosch University for moisture content and starch analysis.

Planting of the second grain sorghum trial began at Ukulinga on 5th December 2013. The establishment of this trial was plagued by feeding birds and thus, seed was re-planted several times which resulted in staggered growth. The trial survived a significant thunderstorm on the 24th February 2014 and was finally harvested on 4th June 2014.

3.3.1.4 Jatropha

The Jatropha trial was planted in February 2005 at a density of 1 100 plants ha^{-1}, with six treatments each replicated three times. In September 2007, the trees were pruned to a height of 1.0 m to stimulate branching and increase seed production. Flowers are typically produced at the apex of each branch and pruning increases branching. Although the pruning resulted in many new branches and luxuriant growth in 2008, there was no large increase in seed production. The trees were pruned again in September 2009 and despite the good growth exhibited by the plants, a similar drop in seed production in the season subsequent to pruning was recorded in May 2010. For the 2010/11 season, seed was harvested from the weed-free (i.e. Jatropha only) treatments in March 2011. 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.

3.3.2 Hatfield

At Hatfield in Pretoria, the following trials were conducted, *viz*. a) two sweet sorghum trials, b) two sweet sorghum drought trials and c) one grain sorghum trial. In addition, data for the existing Moringa trial was extended for a further season.

3.3.2.1 Sweet sorghum

Two 80 × 80 m plot trials were also established during early December for the 2010/11 and 2011/12 summer growing seasons. The same sweet sorghum variety used at Ukulinga (i.e. Sugargraze) was used in both trials. Drip irrigation was installed to supplement rainfall when needed in order to ensure optimal growing conditions. Plant rows were spaced 0.9 m apart, with an in-row spacing of about 0.20 m, giving a plant population of about 55 000 plants per hectare. Plants from 10 blocks, each 20 m long and about 10 m wide, were harvested when the crop reached the hard dough stage in May 2011. The same post-harvest procedure carried out at Ukulinga was followed, in order to determine the fresh mass of stalks, leaves and heads. Samples were then oven dried at 70°C and re-weighed to determine the total dry matter yield of each component (stalks, leaves & heads). 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.

3.3.2.2 Sweet sorghum (drought)

This trial was planted on 7th December 2010 with sweet sorghum variety (Sugargraze) and consisted of four different irrigation treatments. A detailed description of the trial layout and design is given in **Volume 2**. Drip irrigation was used to irrigate the experiment, with water meters to record the exact amounts of water applied to each treatment. Destructive growth analyses were conducted once every two weeks to monitor growth in response to water treatments. The plants were finally harvested when the sweet sorghum crop was in the hard dough stage in early May 2011. This trial was repeated in the following season from December 2011 to May 2012.

3.3.2.3 Grain sorghum (drought)

This trial was planted on 4th December 2012 with the same grain sorghum variety used at Ukulinga (i.e. PAN8816; about 100 000 plants ha^{-1} at an inter-row spacing of 0.9 m). The trial consisted of four different irrigation treatments, similar to that used for the sweet sorghum drought trial. Plant population was substantially lower than the target due to seedling death caused by phytotoxic damage. Assessments of growth and biomass production were done on 24, 64, 87, 115, 149 and 178 days after planting (DAP). The Hatfield trial was finally harvested on 30th May 2013.

3.3.2.4 Moringa

The two-factorial Moringa trial had irrigation (irrigated or dryland) and tree density (high or low) as treatments. *Moringa oleifera* seedlings, developed directly from seeds, were planted at two densities (1 × 3.5 m and 3 × 3.5 m) in October 2006. The Moringa trial was designed as a complete randomised block design consisting of 12 plots (about 110 m^2 in size) and divided into three blocks. In each block there were four plots, two for each density treatment. Each plot consisted of 240 plants in the high density treatment and 96 plants in the low density treatment. The plants were regularly watered using a drip irrigation system. 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 the end of the experiment. Data was collected every two or four weeks, depending on the season and performance of the plants.

3.3.3 Baynesfield

As part of WRC Project K5/2066 (Mengistu *et al*., 2014), water use and yield of yellow maize and soybean was determined at the Baynesfield Estate in KwaZulu-Natal. The agronomy of these two trials is described next.

3.3.3.1 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 maize crop (yellow maize variety PAN3Q222) was planted on the 22nd October 2012 and started emerging 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 eddy covariance equipment needed for this trial was provided by project K5/2066 (Mengistu *et al*., 2014). 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.

3.3.3.2 Soybean

The soybean crop (variety PAN1666) was planted on the 15th of October 2012 and started emerging 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). Flux measurements at the soybean site were also 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 Summary

A summary of the trials conducted at Ukulinga and Hatfield for this project are summarised in **Table 5**. The trials undertaken at Baynesfield as part of WRC project K5/2066 (Mengistu *et al*., 2014), are also included.

Table 5 Summary of the planting and harvest dates for each trial conducted over four seasons, together with the plant spacing (Row x Inter-Row distance) and target population

Feedstock	Site	Season	Planting date	Harvest date	Spacing (R x IR cm)	Planting density
Sugarbeet	UKU	2010/11	Sep 2010	Apr 2011	50 x 30	66 667
Sugarbeet	UKU	2011/12	Jul 2011	Jan 2012	50 x 30	66 667
Sugarbeet	UKU	2012/13	May 2013	Dec 2013	50 x 30	66 667
Sweet sorghum	UKU	2010/11	Dec 2010	May 2011	90 x 14	80 000
Sweet sorghum	UKU	2011/12	Dec 2011	May 2012	90 x 09	130 000
Sweet sorghum	HAT	2010/11	Dec 2010	May 2011	90 x 20	55 000
Sweet sorghum	HAT	2011/12	Dec 2011	May 2012	90 x 10	100 000
Sweet sorghum	DRO	2010/11	Dec 2010	May 2011	90 x 12	90 000
Sweet sorghum	DRO	2011/12	Dec 2011	May 2012	90 x 12	90 000
Grain sorghum	UKU	2012/13	Nov 2012	May 2013	50 x 20	100 000
Grain sorghum	UKU	2013/14	Dec 2013	Jun 2014	50 x 20	100 000
Grain sorghum	DRO	2012/13	Dec 2012	Jun 2013	90 x 20	55 000
Yellow maize	BAY	2012/13	Oct 2012	May 2013	76 x 22	60 000
Soybean	BAY	2012/13	Oct 2012	May 2013	76 x 3.6	365 500
Jatropha	UKU	2010/11	Feb 2005	May 2011	300 x 300	1 100

3.4 Approach

A summary of the approach used to estimate water use efficiency of selected feedstocks is presented in this section.

3.4.1 Water use

Water use was estimated as the total water that evapotranspired from the cropped surface. Water use was accumulated from planting date to harvest date, which is equated to seasonal water use. Therefore, it is expressed as the total evaporation (soil water evaporation + transpiration + interception) in mm or m^3 over the growing period. For the Jatropha and Moringa trees, annual water use was estimated for the hydrological year.

As noted in the introduction (**Section 3.1.1**), the two main techniques used in this study were a) heat pulse velocity (transpiration only), and the b) surface renewal method (actual evapotranspiration) to measure crop water use over the growing season. The eddy covariance system was used to calibrate the surface renewal technique (i.e. to obtain the α coefficient). Water use estimates for the Moringa trees were determined using sap flow measurements (HPV technique) and the soil water balance equation, with drainage simulated using the *SWB* model simulations. A surface layer scintillometer was used to measure total evaporation for the Jatropha trees. The theory governing each measurement technique is detailed in **Volume 2** (**Section 3.3.2**). A summary of the method used for each feedstock is presented in **Table 6**.

Table 6 Summary of technique adopted to measure feedstock water use at three trial sites

Feedstock	Location	Surface renewal	Eddy covariance	Surface layer scintillometer	Heat pulse velocity	Soil water balance
Sugarbeet	Ukulinga	Yes	Yes	Yes		
Sweet sorghum	Ukulinga	Yes	Yes			
	Hatfield	Yes	Yes			
Grain sorghum	Ukulinga	Yes	Yes			
	Hatfield					Yes
Jatropha	Ukulinga			Yes	Yes	
Moringa	Hatfield				Yes	Yes
Soybean	Baynesfield	Yes	Yes			
Yellow maize	Baynesfield	Yes	Yes			

3.4.2 Crop yield

Crop yield was determined at harvest in fresh tons of utilisable yield (e.g. stem, tuber, grain or seed) in fresh tons per hectare. Samples were the oven dried to determine the dry mass of certain allometric components of the biomass (e.g. stem, leaves, panicles etc.). In addition, the sugar content of stems or tubers was determined in the laboratory, as well as the starch content of grain.

3.4.3 Water use efficiency

Water use efficiency was estimated as the ratio of the utilisable portion of the total biomass (i.e. stem, tuber, fruit, grain or seed yield in kg), to the unit amount of transpiration or total evaporation (m^3). Since transpiration only was measured for the Moringa trees at Hatfield, transpiration use efficiency and not water use efficiency was calculated. For all other trials, total evaporation was measured, allowing for the calculation of water use efficiency.

3.4.4 Biofuel use efficiency

The equations used in this study to calculate theoretical biofuel yield are presented in **Volume 2**. For sugar crops (e.g. sugarbeet & sweet sorghum), the sugar content was determined by measuring Brix (i.e. total soluble sugars) at the ACCI laboratory at Ukulinga. This meant that the samples of sweet sorghum grown at Hatfield were couriered overnight to Ukulinga for Brix determination.

In general, sweet sorghum stalks (or stems) damaged by stalk borer were not used for the Brix analysis. If stalks are damaged by pests, it makes it impossible to compare samples with each other as the Brix varies considerably. Hence, screened stalks (i.e. no stalk borer damage) were analysed, allowing for the comparison of results obtained from Ukulinga and Hatfield. 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. The samples were kept cool by refrigeration to delay the reduction in sugar properties after harvesting.

For starch crops (e.g. grain sorghum & maize), the extractable starch content and the moisture content are required for the estimation of bioethanol yield. These parameters were determined at the University of Stellenbosch. Finally, the estimation of biodiesel yield from oil-based crops (soybean, Jatropha & Moringa) requires the oilseed content as well as the oil's density value.

An alternative method of estimation biofuel yield from the crop yield involves the use of extraction rates in litres of biofuel per ton or crop yield. Although this method is much simpler, the results are deemed less accurate compared to the biofuel yield equations.

3.5 Results and Discussion

3.5.1 Water use

A summary of the water use of each feedstock considered for field-based research is presented in **Table 9** for a total of four seasons.

3.5.1.1 Sugarbeet

The total seasonal water use of the sugarbeet crop was 562 mm in season #1, 556 mm in season #2 and 411 mm in season #3. Hence, the winter planting (season #3) used less water compared to the summer planting (season #1). These seasonal water use values are low when compared to those given in the literature.

Sugarbeet has long tap roots cable of exploiting water from the deeper soil profile. Evapotranspiration requirements of 350 to 1 250 mm have commonly been reported for sugarbeet (e.g. Allen *et al*., 1998). Draycott (2006) reported seasonal water use values ranging from 385 mm (1967-1991 in the UK; Dunham 1993) up to 1 043 mm (1986 in California, US; Pruitt *et al*., 1986). Draycott (2006) concluded that sugarbeet can use 350 mm of water in temperate areas to over 1 000 mm in arid areas. Dunham (1993) reported water use values of 900 to 1200 mm for sugarbeet grown at different locations.

3.5.1.2 Sweet sorghum

The total seasonal water use estimate for the sweet sorghum crop at Ukulinga was 436 mm for the 2011/12 growing season. The maximum total evaporation of 8.5 mm estimated on 28th February 2012 (**Figure 1**) was due to advective conditions on that day when a hot, dry Berg wind prevailed. The water use figures obtained at Ukulinga and Hatfield are lower than values reported by Dercas *et al*. (2001) for two sweet sorghum varieties (MN1500 and Keller). They gave a water use range of 601 to 609 mm for high irrigation conditions and 449 to 487 mm for low irrigation conditions.

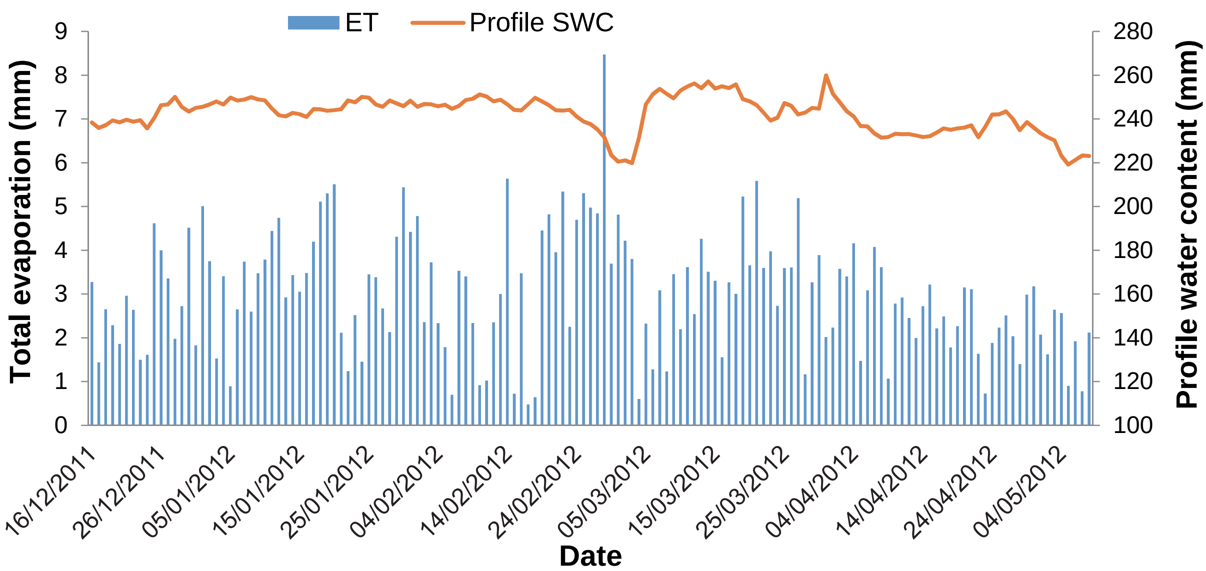


Figure 1 Total evaporation estimates from the sweet sorghum canopy along with profile volumetric soil water content at Ukulinga research farm for the 2011/12 growing season

3.5.1.3 Sweet sorghum (drought)

The drought trial conducted at Hatfield over two consecutive seasons showed that it is better to irrigate in the early vegetative growth stage than compared to the late vegetative stage. In other words, water savings can be achieved by applying supplementary irrigation in the early vegetative stage only, if needed.

According to Reddy *et al*. (2007), sweet sorghum [*Sorghum bicolor* (L.) Moench] is well adapted to the semi-arid tropics. Mastrorilli *et al*. (1999) indicated that sweet sorghum is most sensitive to water stress at the "leaf stage", which corresponds to approximately 40 to 60 days after emergence. However, Zegada-Lizarazu and Monti (2012) suggested that the most sensitive stage was between 60 and 100 DAP.

3.5.1.4 Grain sorghum

The seasonal water use for grain sorghum from December 2012 to May 2013 was 436 mm at Ukulinga. This compares favourably to the water used by the sweet sorghum trial in the previous season (2011/12). However, the grain sorghum growing season (165 days) was longer than that for sweet sorghum (145 days).

Stewart *et al.* (1983) investigated the water use of grain sorghum in Texas, USA and found that the average seasonal water use under irrigation varied between 591 and 647 mm, compared to 289 to 300 mm per season for dryland conditions. These values are higher than those reported by Piccinni *et al*. (2009) for irrigation, which ranged from 481 to 533 mm per season. According to Piccinni *et al*. (2009), sorghum daily water use ranged from as low as 1 mm d^{-1} early in the season to 13 mm d^{-1} during flowering stage. The latter water use values compared well to those recorded for the control in the present study.

3.5.1.5 Jatropha

The Jatropha trees were planted in February 2005 at the Ukulinga research farm. Everson *et al.* (2012) measured daily estimates of total evaporation (soil water evaporation plus plant transpiration) from November 2005 to August 2006 for five selected periods using the Surface Layer Scintillometer (SLS) technique. Eddy covariance measurements of ET was undertaken for two full seasons, namely 2006/07 and 2007/08 (**Figure 2**).

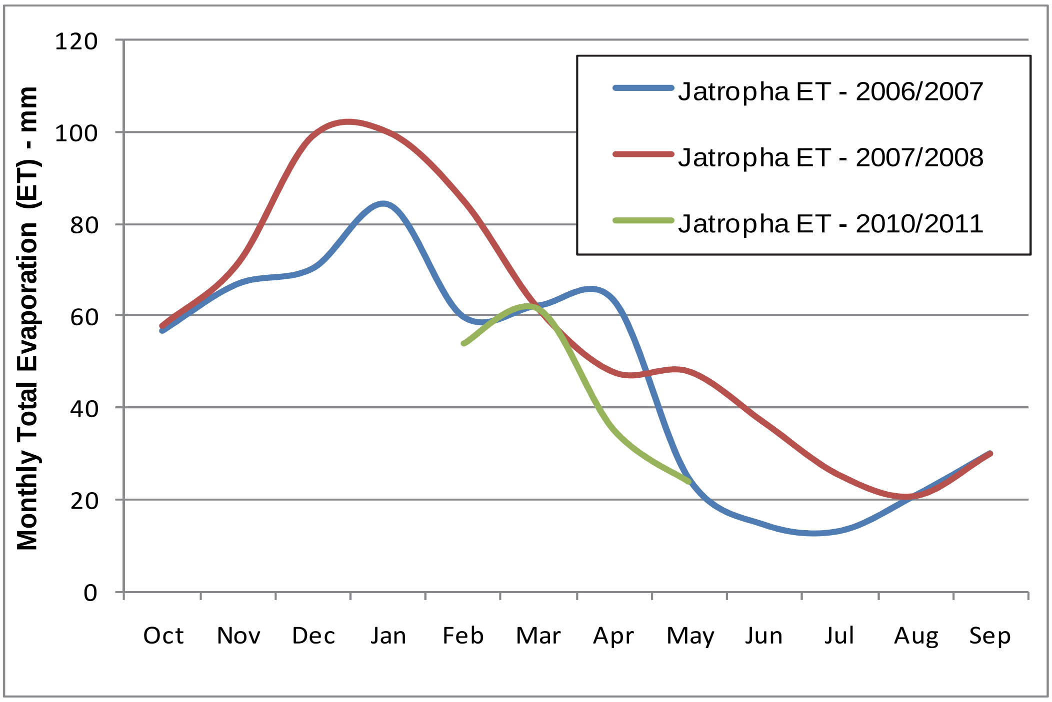


Figure 2 Monthly total evaporation (ET) measured above the Jatropha trial during the 2006/07, 2007/08 and 2010/11 seasons

This project contributed another four months of continuous ET data from February to May 2011, obtained using an SLS (**Figure 2**). It is evident from the ET data that overall water use rates increased from the 2006/07 season (when the trees were 2 years old), to the 2007/08 season when the trees were 3 years old.

Figure 3 shows the daily variation of total evaporation estimates above the Jatropha trees at Ukulinga. Daily water use of Jatropha varied between 0.0 and 4.3 mm. Everson *et al.* (2012) measured daily total evaporation for the one-year old Jatropha trees (weed-free plots) using an SLS. Values ranged between 3-4 mm d^{-1} of water on a clear summer day, which is similar to that shown in **Figure 3**. Reference evaporation during this period was higher than total evaporation, varying between 5-7 mm d^{-1} in summer (when the daily solar radiation exceeded 25 MJ d^{-1}). In winter, the total evaporation rate averaged only 0.5 mm d^{-1} when the available energy was low. Since the trees were completely leafless at this time, total evaporation comprised only of soil water evaporation. It is important to note that this trial is not irrigated (i.e. rainfed only), which explains why the daily total evaporation estimates are typically lower than that of sugarbeet and sweet sorghum.

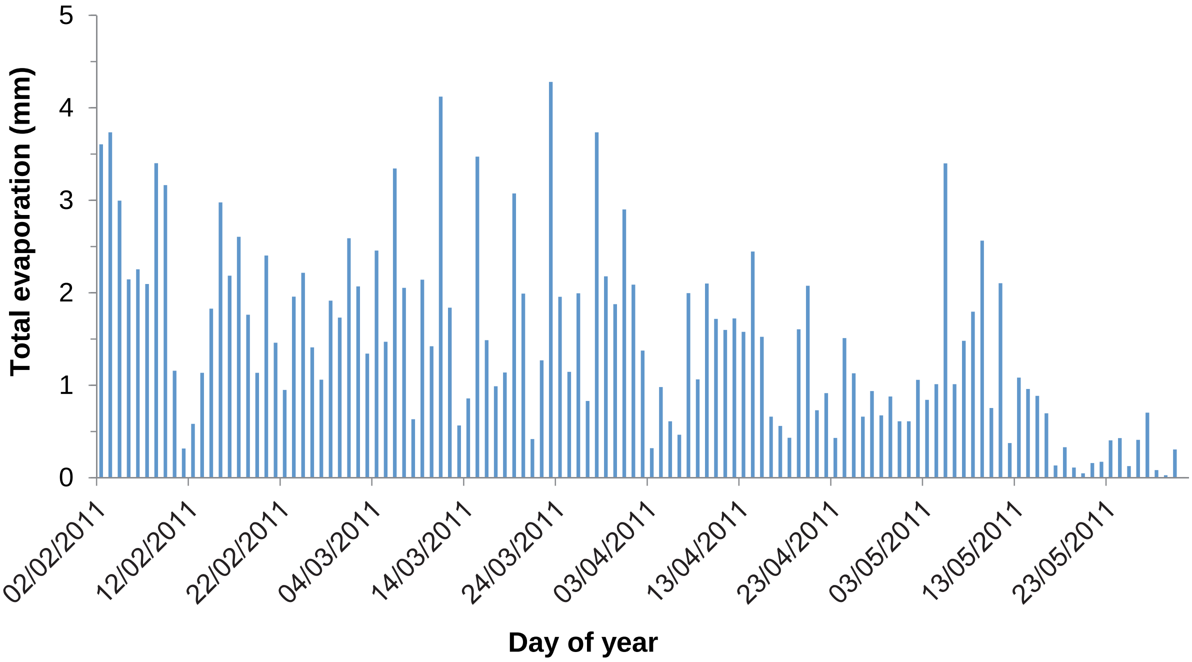


Figure 3 Total evaporation estimates from February to May 2011 for *Jatropha curcas* at Ukulinga research farm

Everson *et al.* (2012) also showed that total evaporation from the Jatropha only plots (≈4 mm d^{-1}) was less than that for kikuyu (≈5.5 mm d^{-1}) during the summer of 2007. The same trend was noticed in winter when total evaporation from the Jatropha only plots dropped below 1 mm d^{-1}, compared to 1-1.15 mm d^{-1} for kikuyu. Hence, Jatropha trees consume less water than kikuyu grass, especially in winter when the leafless tree lies dormant (i.e. *Jatropha* is deciduous).

Sap flow measurements which began in March 2010 and continued until June 2011. Fairly shortly after the monitoring began in March 2010, the deciduous trees lost their leaves for the winter. A relationship between transpiration only *T* (i.e. sap flow measurements) and total evaporation *ET* (SLS measurements) was derived for this four-month period. In addition, reference crop evaporation (ET_o) was used to calculate crop coefficient (K_c) and basal crop coefficient (K_{cb}) values, for *ET* and *T* respectively. These crop coefficients, combined with ET_o, were used to model ET over subsequent periods when *ET* data was absent but *T* data was available. Hence, the four months of *ET* data were extrapolated to derive an additional full year of ET data.

Five years of daily observed and simulated *ET* data exists for the Jatropha trial (**Table 7**). The low water use in year 5 was due to the trees being pruned in the spring of 2009. The trees lost significant leaf area due to the pruning, thus reducing their water use. In the 2010/11 season, the water use approached that of the 2006/07 year. It is anticipated that subsequent increases in leaf area would result in higher water use.

Table 7 Comparison of Jatropha water use obtained at Ukulinga from 2006/07 to 2010/11

Tree age	Season	Annual rainfall (mm)	Water use (mm)	Water use (m^3 ha^{-1})
0	2004/05	577		
1	2005/06	831		
2	2006/07	792	566.2	5 662
3	2007/08	925	684.3	6 843
4	2008/09	803	715.0	7 150
5	2009/10	591	478.0	4 780
6	2010/11	860	507.1	5 071

3.5.1.6 Moringa

Seasonal transpiration amounts for Moringa were established from sap flow measurements. In 2009/10, sap flow equipment was only installed in the high density treatments, while in the following season (2010/11), sap flow was measured for both low and high density trees under dryland and irrigated conditions. The results for the 2009/10 and 2010/11 seasons are displayed in **Table 8**.

Table 8 Moringa water use (transpiration only) for different irrigation and density treatments at Hatfield in 2009/10 and 2010/11

Season	Tree density*	Dryland / Irrigated	Annual rainfall (mm)	Transpiration (mm)	Water use (m^3 ha^{-1})
2009/10	High	Irrigated	779	407	4,070
	High	Dryland	779	336	3,360
	Low	Irrigated	779	-	-
	Low	Dryland	779	-	-
2010/11	High	Irrigated	897	502	5,020
	High	Dryland	897	456	4,560
	Low	Irrigated	897	423	4,230
	Low	Dryland	897	374	3,740

* Note: High density = 2,857 trees ha^{-1}; Low density = 952 trees ha^{-1}

The irrigated treatment had higher water use than dryland in both years. Similarly, high density trees used more water per season than low density. Interestingly, individual trees in the low density treatment used more water per day than high density trees due to thicker stem diameters, which allowed for higher stem sap flow rates per day. However, since there were more trees per hectare under high density, the total use was slightly higher than the low density treatment. Water use per treatment was higher in 2010/11 than in 2009/10, presumably because trees were a year older and therefore bigger in the latter season.

3.5.1.7 Summary

A summary of the water use (i.e. actual evapotranspiration) accumulated over the growing season for each of the feedstocks prioritised for field-based research. When interpreting the results, the following points must be noted:

- In general, seasonal water use varied according to the length of the growing season.
- The third sugarbeet trial was planted in May 2013 and harvested in December 2013, which is not strictly the 2012/13 season.
- All trials were irrigated to maximise yield, except for the Jatropha trial which was rainfed.
- Since the Jatropha trees were rainfed (i.e. not irrigated), data is given for the dryland (D) plots of Moringa at Hatfield, for both the high (HI) density (2 857 sph) and low (LO) density (952 sph) plantings.
- The 2010/11 season at Hatfield was wet (722 *vs*. 315 mm of rainfall in 2011/12) and thus, it was difficult to determine drainage from neutron probe measurements. Hence, simulations provided by the *SWB* model were used to help estimate drainage. This may also account for the difference in water use measurements.
- The water use of sweet sorghum (main trial) obtained for both seasons at Hatfield compared favourably with the Ukulinga estimates, especially in the first season.
- For the drought trials (DRO) conducted at Hatfield for sweet sorghum and grain sorghum, data is given for the fully irrigated (i.e. control) treatment.
- The fully irrigated treatment used more water (499-522 mm) compared to the larger 80 by 80 m trial (430-436 mm).
- The sweet sorghum drought (DRO) trials at Hatfield in 2010/11 and 2011/12 used the soil water balance technique to estimate crop water use. This technique is less accurate than the surface renewal method.
- The grain sorghum drought (DRO) trial at Hatfield in 2012/13 also used the soil water balance technique to estimate crop water use.
- Hence, the soil water balance method tends to over-estimate crop water use when compared to the surface renewal method.

Table 9 Summary of season length SL (in days) and feedstock water use WU (in m^3 ha^{-1}) measured over four seasons from 2010 to 2014 at three different locations (UKU = Ukulinga; HAT = Hatfield; BAY = Baynesfield)

Feedstock	Site	2010/11 (#1)		2011/12 (#2)		2012/13 (#3)		2013/14 (#4)	
		SL	WU	SL	WU	SL	WU	SL	WU
Sugarbeet	UKU	181	5 620	182	5 560	186	4 110		
Sweet sorghum	UKU	132	3 940	145	4 360				
Sweet sorghum	HAT	139	3 910	140	4 050				
Sweet sorghum	DRO	139	4 990	140	5 220				
Grain sorghum	UKU					165	4 360	169	4 610
Grain sorghum	DRO					187	5 020		
Yellow maize	BAY					172	4 270		
Soybean	BAY					189	4 690		
Jatropha	UKU	242	5 071						
Moringa (DHI)	HAT	273	4 560						
Moringa (DLO)	HAT	273	3 740						

3.5.2 Crop yield

3.5.2.1 Sugarbeet

The undamaged tuber yield declined from 53.1 t ha^{-1} in season #1 to 21.7 t ha^{-1} in season #2 (**Table 10**). It then increased to 45.4 t ha^{-1} in season #3. The low yield in season #2 is likely to be due to infestation by weeds and root rot. The half-summer planting of the crop resulted in a significant increase in below ground disease (root rot) from 5.0% (season #1) to 26.7% (season #2).

Table 10 Comparison of utilisable yield (tuber yield) for sugarbeet at Ukulinga obtained from the 2010/11, 2011/12 and 2013/14 growing seasons

Season	Growing period (days)	Planting density (sph)	Tuber yield (t ha^{-1})	Tuber damage (%)
2010/11	181	66 667	53.1	5.0
2011/12	182	66 667	21.7	26.7
2013/14	186	66 667	45.4	2.4

For seasons #1 and #2, there were no registered herbicides for sugarbeet in South Africa and thus, weeds were controlled manually which became a labour intensive exercise. The manual weeding of the trial, especially from December 2010 to March 2011, resulted in the disturbance of soil directly in contact with the tubers. However, significant manual weeding was still done at the trial site, especially from September to December 2013. This may have contributed to the increased incidence of root rot. Root rot problems may also be attributed to the irrigation dripperlines, which drip water at a rate of a litre an hour directly on top of the growing tuber.

The maximum yield of 67.2 t ha^{-1} in season #3 shows that sugarbeet exhibits potential for bioethanol production. However, the lower performing sample rows produced a minimum yield of 28.0 t ha^{-1}, which reduced the overall mean yield significantly. It is interesting that the disease incidence dropped to 2.4%, which was achieved by limiting the irrigation of the crop and better weed control. In season #3, the regular application of a foliar feed also improved growing conditions. Goltix was also used to combat weed growth.

A number of valuable lessons were learnt from the three sugarbeet trials, all dealing with the agronomy of the crop. The findings suggest that irrigation should be limited as soon as the transplanted seedlings are well established (this avoids the crop turning yellow). It is also recommended that a foliar feed and fertiliser are applied early in the growing season. Goltix should be used as a pre-emergent herbicide for as long as possible and fungicide prevention sprays are necessary, especially in hot and humid growing conditions.

The tuber yields obtained at Ukulinga compare with the range reported by Tohidloo *et al*. (2004) of 13 to 37 t ha^{-1} for irrigated sugarbeet in Iran (2001/02 season). The yield in season #2 was well below the "average" reported by Draycott (2006), who reported at typical commercial sugarbeet yields are between 50 and 100 t clean beet/ha (with sugar concentrations of 17-18% on fresh weight, yielding 8-18 t sugar/ha). Growers in the Imperial Valley of California hold the world record for sugarbeet production, with averages exceeding 90 and 12 t ha^{-1} of roots and sugar respectively. Individual farms sometimes produced over 150 and 18 t ha^{-1} roots and sugar respectively (Draycott, 2006).

The Ukulinga yields for sugarbeet are significantly lower than those obtained in the Cradock region. Maclachlan (2012) mentioned that the bankable yield of sugarbeet in the Cradock region is 95 t ha^{-1}. The obtainable yield ranges from 100 to 120 t ha^{-1}, thus providing 20 t ha^{-1} of sugar. The optimum yield ranges from 130 to 140 t ha^{-1} which can provide 30 t ha^{-1} of sugar (30% Brix). The highest yields reported exceeded 200 t ha^{-1}, with the maximum yield estimated at 320 t ha^{-1}. It is believed that the maximum yield was calculated from 4 kg sugarbeet tubers grown on a small research plot, then scaled up to 80 000 plants per hectare (24% Brix). Kings (2012) reported sugarbeet tubers weighing up to 13 kg being grown in Cradock, which exceeds the typical weight of 1 kg tubers produced in Europe. The high yields were due to the region's good soils and the country's second largest irrigation scheme as well as the 8-month growing season.

3.5.2.2 Sweet sorghum

At Ukulinga, the fresh stalk yield ranged from 24.4 to 41.8 t ha^{-1} as a result of the increase in plant population (**Table 11**). The dry stalk yield was calculated from the product of the fresh stalk yield and the stalk dry matter content (e.g. 20.2 and 22.4% based on mass for the 2010/11 and 2011/12 season respectively).

Table 11 Comparison of utilisable yield (stalk yield) for sweet sorghum at Ukulinga obtained from the 2010/11 and 2011/12 growing seasons

Season	Site	Growing season (days)	Planting density (sph)	Fresh stalk (t ha^{-1})	Dry stalk (t ha^{-1})
2010/11	Ukulinga	132	81 813	24.4	4.89
	Hatfield	139	55 000	34.1	7.95
2011/12	Ukulinga	145	134 609	41.8	9.32
	Hatfield	145	86 000	37.6	8.98

At Hatfield, the stalk damage increased from 5.0% in the first season, to 8.5% in the second season. Although, the portion of stalks damaged by stalk borer was not recorded at Ukulinga, experience shows that stalk borer has a greater impact on Brix than yield. This means pest damage can reduce both sugar and bioethanol yield.

3.5.2.3 Sweet sorghum (drought)

Fresh and dry stalk yields recorded for the Hatfield drought trial in the 2010/11 and 2011/12 growing seasons are shown in **Table 12**. During the 2010/11 season, very high rainfall (722 mm) occurred during the growing season, which interfered with stress treatments. As a result, yields of the control and EVS treatments did not differ much from each other, probably due to sufficient rainfall at critical times during the growing season. EVS produced higher stalk yields than the LVS and dryland treatments in both years, which suggests that supplementary irrigation is most critical in the early vegetative stages.

Table 12 Utilisable yield (i.e. stalk yield) for sweet sorghum at Hatfield, obtained from the drought trial in the 2010/11 and 2011/12 seasons

Season	Treatment	Fresh stalk (t ha^{-1})	Dry stalk (t ha^{-1})
2010/11	CT	41.01	9.36
	EVS	41.27	10.37
	LVS	34.88	8.20
	DL	34.21	8.63
2011/12	CT	44.72	10.29
	EVS	34.82	7.70
	LVS	32.48	8.76
	DL	29.34	7.43

CT - Control, irrigated once per week. The soil profile was refilled to field capacity using neutron probe measurements.

EVS - Supplemental irrigation only during the early vegetative stage.

LVS - Supplemental irrigation only during the late vegetative stage.

DL - Dryland, irrigated only if needed during established and thereafter the crop depended on rainfall.

In order to compare the yields obtained at Ukulinga and Hatfield with those found in the literature, total dry matter (stalk, plus leaf & head) and not stalk dry matter was used. Total dry matter is more appropriate for reporting biomass yields when considering 2nd generation conversion technologies. Regardless of the climate, sweet sorghum yield is sensitive to planting date and low yields can result if the crop is planted too early (not cold tolerant) or too late (short growing season) in the season.

The total dry matter yield of sweet sorghum ranged from 7.3 to 13.1 t ha^{-1} at Ukulinga and 14.2 to 18.1 t ha^{-1} at Hatfield. These values are low compared to those obtained from the available literature. For example, Miller and Ottman (2010) reported a biomass yield range of 23.5 to 26.0 dry t ha^{-1} (average of 25.1 dry t ha^{-1}). In addition, Turhollow *et al*. (2010) reported that forage and sweet sorghums have higher biomass yield potentials of 20 to 40 dry t ha^{-1} compared to grain sorghum. USDoE (2011) reported that sweet sorghum can potentially yield a dry weight of up to 35 t ha^{-1} (15.6 t ac^{-1}). Zegada-Lizarazu and Monti (2012) reported sweet sorghum yields ranging from 8.5 to 20.3 dry t ha^{-1} for temperate, sub-tropical and tropical climates (and sucrose yields from 2.5 to 5.2 t ha^{-1}).

In comparison, energy sorghum produced fresh biomass yields of 80 to 100 t ha^{-1} (36 to 44.6 t ac^{-1}) from a single harvest, with a moisture content of 65%. Dry weight yields ranged from 16 to 30 t ha^{-1} (7 to 13.4 t ac^{-1}), with 22 t ha^{-1} seen as the average for energy sorghum (USDoE, 2011). Breeding programs in Texas (US) are aiming at potential yields of 45 dry t ha^{-1} from energy sorghum (Turhollow *et al*., 2010).

3.5.2.4 Grain sorghum

The grain sorghum yield results were finalised on 22nd July 2013 and are shown in **Table 13**. Unfortunately, only three of the original six sample blocks were measured, which were undamaged by bushpig. Bushpig gained aces to the trial site when the electric fence failed. A total of 12 lines per block were sampled, with the lowest and highest grain yields of 1.7 and 4.3 t ha^{-1} respectively.

Table 13 Comparison of utilisable yield (i.e. grain) for three grain sorghum blocks at Ukulinga during the 2012/13 growing season

Season	Sample block	Growing period (days)	Planting density (sph)	Grain yield (t ha^{-1})
2012/13	Block 1	165	109 167	2.87
2012/13	Block 2	165	103 766	2.61
2012/13	Block 3	165	96 607	2.95
		Average	**103 180**	**2.81**

The average grain yield and plant population was 2.81 t ha^{-1} and 103 180 sph respectively. This grain yield was lower than expected for the following reasons:

- The staggered planting due to bird damage caused significant variations in population levels (ranging from 60 000 to 150 714 sph).
- Yields are sensitive to final population (as shown for with sweet sorghum), with the highest yield of 4.3 t ha^{-1} recorded for the highest population of 150 714 sph. Taller grain sorghum varieties grown on small plots at Ukulinga by ACCI yielded up to 5 t ha^{-1}.
- A high stalk borer infection occurred after flowering due to high levels of plant residue in the adjacent ratooned sweet sorghum plot (this trial was abandoned in December 2012 due to poor regeneration).
- A loss in grain yield occurred due to the early harvesting to avoid further bushpig damage.
- Although the final averaged population of 103 180 sph is comparable with normal practice, higher populations exceeding 125 000 would have improved the overall yield.

The grain sorghum yield results for the 2013/14 season are shown in **Table 14**. These yields are also lower than expected, mainly because the trial was planted several times due to bird damage. Storm damage on 24th February 2014 meant the crop was more susceptible to pest and disease problems.

Table 14 Comparison of utilisable yield (i.e. grain) for two grain sorghum blocks at Ukulinga during the 2013/14 growing season

Season	Sample block	Growing period (days)	Planting density (sph)	Grain yield (t ha^{-1})
2013/14	Block 1	169	102 000	1.66
2013/14	Block 2	169	96 000	2.41
		Average	**125 000**	**2.11**

Birds caused significant problems during the establishment of the sorghum trials at Ukulinga, in particular for grain sorghum. The second trial in 2013/14 was re-planted several times which significantly affected the final yield. Birds also ate the grain produced by sweet sorghum. For example, the un-threshed heads removed from sweet sorghum stems in 2010/11 at Ukulinga comprised only 3% of the total fresh mass (stalks + heads + leaves). This figure should be nearer to 10% and is low because birds removed most of the grain.

Almost all the grain was removed from the heads of grain sorghum planted in both seasons at Ukulinga. The need to protect the developing grain heads using a fine mesh mag added to the overall cost of trials, with R23 000-00 spent to protect only 25% of the total trial area. According to Coleman (2012), the risk of planting sorghum is higher than that of maize. Sorghum is prone to diseases such as bollworm, leaf spot and rust. Possible damage from red-billed Queleas (*Quelea Quelea*) is also a serious threat. Steyn (2011) reported that an average Quelea flock can rapidly decrease sorghum yields from 5 to 1 t ha^{-1}.

Bird damage to small stands of zero tannin (or tannin free) varieties of grain sorghum is thus cause for concern. Tannin free varieties of grain sorghum are preferred because they reduce the cost of bioethanol production.

3.5.2.5 Jatropha

The Jatropha trees were planted in February 2005 at Ukulinga research farm. The first Jatropha seeds were harvested during the 2006/07 season. Data on the seed production of Jatropha (number and mass of seeds per plot) and time taken to harvest and de-husk the seeds (labour costs) were collected from March 2007 to July 2009 (Everson *et al*., 2012). Jatropha yield data for water use efficiency estimation consisted of annual totals of de-husked seed (kg ha^{-1}), obtained from records kept after harvesting the plots and de-husking the nuts

The three weed-free plots were harvested at the end of March 2011 for the 2010/11 season. An additional seed 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.

Table 15 shows the seed yield harvested from March to May each year. The oilseed yields are much lower than those reported elsewhere in the literature. For example, Jongschaap *et al*. (2007) estimated that in areas such as southern India, where two harvests per year are possible, 3 m spaced Jatropha trees can produce annual seed yields of 3 to 5 t ha^{-1}. Jongschaap *et al.* (2009) reported that 4-year old Jatropha (non-irrigated and unfertilised) in

South Africa yielded 1.286 t ha^{-1} of dry seeds. In assessing the yield from the trial, it is important to remember that the Jatropha trees were heavily pruned during September of 2007 and 2009. This had a severe impact on yield in the subsequent two harvests (2009/10 and 2010/11), as the trees were still recovering from the pruning exercise. In the first year, the trees were severely damaged by insects which could have had negative impacts on seed production.

Table 15 Comparison of utilisable yield (seed yield) for Jatropha at Ukulinga from 2006/07 to 2010/11

Tree age	Season	Growing period (days)	Planting Density (sph)	Seed yield (t ha^{-1})
0	2004/05			
1	2005/06	242	1 100	
2	2006/07	242	1 100	0.0899
3	2007/08	242	1 100	0.1044
4	2008/09	242	1 100	0.3488
5	2009/10	242	1 100	0.0010
6	2010/11	242	1 100	0.0717

Based on the LAI data, the Jatropha stand at Ukulinga senesces between July and October. Hence, the growing season is considered November to June, which is approximately 242 days. This is supported by the basal crop coefficients which clearly illustrate that transpiration rates are typically lower in November and June (compared to December and May), and zero from July to October (when the tree sheds all its leaves).

3.5.2.6 Moringa

Seed yield was measured after harvesting all the pods per plant. In 2010/11, the highest seed production per tree was observed in the low density irrigated treatment and the lowest in the high density non-irrigated treatment. However, total highest yield extrapolated to per hectare was recorded for the high density irrigated treatment (52 kg ha^{-1}) and the lowest was for the low density non-irrigated treatment (24 kg ha^{-1}). These seed yields in 2010/11 were much lower than those recorded in the 2009/10 season (**Table 16**). Based on the LAI and PAR data, the Moringa stand at Hatfield senesces between July and September. Hence, the growing season is considered October to June, which is approximately 273 days.

Table 16 Comparison of utilisable yield (seed yield) for Moringa at Hatfield from 2009/10 to 2010/11

Tree age	Season	Growing period (days)	Planting density	Seed yield (t ha^{-1})	
				Irrigated	Dryland
4	2009/10	273	High	0.259	0.223
4	2009/10	273	Low	0.150	0.144
5	2010/11	273	High	0.052	0.034
5	2010/11	273	Low	0.030	0.024

This seed yield is low in relation to high yielding varieties recently identified in India which produce up to 60 tons of pods ha^{-1}, i.e. 220 pod^{-1} $tree^{-1}$ $year^{-1}$ (Kutti, 2010). Although trees grew well at Hatfield, it seemed that pod and seed yields were hampered under the specific climatic conditions of this locality. Young pods often died due to low winter temperatures, resulting in a low number of pods and seed yield at harvest. In years with high rainfall and hailstorms during the flowering months, a high degree of flower abortion and pod shedding was also observed. In addition, the seed yields (and thus Transpiration efficiency) obtained in this study were very low when compared to typical values for other oil plant species proposed for biofuels. Based on our experience with Jatropha at Ukulinga, the 2010/11 Moringa seed yield was higher than that for Jatropha, except for the 2008/09 season.

3.5.3 Water use efficiency

3.5.3.1 Summary

Yield water use efficiency (WUE_Y) was determined as the ratio of utilisable yield (i.e. stem, tuber, grain & seed at harvest) to seasonal water use (i.e. actual evapotranspiration accumulated over the growing season). The results are presented next in a summarised table (**Table 17**).

Table 17 Water use efficiency (kg m^{-3}) per feedstock derived from field measurements, with the ranking from highest to lowest

Feedstock	Site	Season	Crop yield (t ha^{-1})	Water use (m^3 ha^{-1})	WUE_Y (kg m^{-3})	Rank
Sugarbeet	UKU	2010/11	53.1	5 620	9.448	3
		2011/12	21.7	5 560	3.903	9
		2012/13	45.4	4 110	11.046	1
Sweet sorghum	UKU	2010/11	24.4	3 940	6.193	8
		2011/12	41.8	4 360	9.587	2
Sweet sorghum	HAT	2010/11	34.1	3 910	8.721	5
		2011/12	37.6	4 050	9.284	4
Sweet sorghum	DRO	2010/11	41.0	4 990	8.218	7
		2011/12	44.7	5 220	8.567	6
Grain sorghum	UKU	2012/13	2.8	4 360	0.572	13
		2013/14	2.1	4 610	0.405	14
Grain sorghum	DRO	2012/13	5.7	5 020	1.024	11
Yellow maize	BAY	2012/13	9.6	4 270	1.967	10
Soybean	BAY	2012/13	3.5	4 690	0.751	12
Jatropha	UKU	2010/11	0.072	5 071	0.014	15
Moringa (DHI)	HAT	2010/11	0.034	4 560	0.007	16
Moringa (DLO)	HAT	2010/11	0.024	3 740	0.006	17

Of all the feedstocks studied in the field, sugarbeet exhibited the highest water use efficiency. However, the results show that sugarbeet's WUE is highly dependent on the agronomic practice. If disease occurs due to humid conditions or over-irrigation (as in the 2011/12 season), the WUE decreases rapidly. The autumn planting (2012/13) was more WUE than the summer planting (2010/11), suggesting the crop is better suited to cooler and drier conditions. In the literature, sugarbeet is reported as a drought resistant plant that can

produce economic yield, even with deficit irrigation and therefore exhibits high water use efficiency. However, the crop's water use efficiency is strongly dependent on weather conditions, irrigation management and growth period, plant density, genotype and nitrogen application rate.
In general, the bioethanol feedstocks are more water use efficient than the biodiesel feedstocks.

When interpreting the results, the following points must be noted:

- The low ranking (09) of sugarbeet in 2011/12 was due to over-irrigation, which resulted in high below-ground disease incidence. The result suggests that determining the WUE of crops where the agronomy is not well understood, is not recommended.

- The low ranking (08) of sweet sorghum in 2010/11 was due to low planting density of 81 800 sph. When the planting density was increased to 134 600, the WUE increased substantially. This result highlights the sensitivity of WUE to agronomic practices.

- The drought trials conducted at Hatfield used the soil water balance method to estimate crop water use. This technique may over-estimate feedstock water use, resulting in lower WUE values.

- The grain sorghum yields at Ukulinga for two seasons are lower than expected, which resulted in lower WUEs. The low yields were due to a number of unavoidable problems experienced in the field (e.g. bird damage at establishment, bushpig damage, storm damage etc.).

- The WUE of Moringa in 2010/11 is strictly speaking, an indication of transpiration use efficiency. The heat pulse velocity measures sap flow only (i.e. transpiration rate) and not actual evapotranspiration.

- The low Jatropha seed yield is due to a heavy pruning of the trees in 2009. The trees were pruned to facilitate easier seed collection by hand, without the need for ladders.

- Overall, the results show that the WUE metric is highly sensitive to agronomic practice.

3.5.3.2 Is WUE a useful metric?

Water use efficiency depends 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 and weeding control). Using sorghum as an example feedstock, these aspects are discussed next in further detail.

<u>Water use definition</u>

If plant water use considers only the transpiration component of total evaporation, this will result in higher WUE estimates compared to calculations which also consider soil water evaporation (i.e. transpiration + soil water evaporation). Similarly, WUE is even lower if water use also incorporates interception loss (i.e. transpiration + soil water evaporation + interception loss). Transpiration therefore represents the lower limit of water used by the vegetation type. Similarly, actual evapotranspiration represents the upper limit of vegetation water use. However, some studies also add percolation loss to total evaporation, particularly if irrigation is used (Singh, 2005).

Yield variation

From **Table 17**, sweet sorghum's WUE from the 2010/11 trial at Ukulinga ranked 8th out of 17. However, when the plant population was increased from approximately 80 000 to 134 000 sph in 2011/12, the WUE improved considerably to the second highest value estimated from field experimentation. This was despite the 2011/12 trial using more water than compared to the first season (436 vs. 394 mm). The improvement in water use efficiency was due to the large increase in yield (24.4 *vs*. 41.8 t ha^{-1}) due to the higher planting density.

Experiments conducted in Zambia to evaluate sweet sorghum potential showed that stem yield varied with variety, time of planting, population, production practices, level of fertiliser applied as well as the control of pests and diseases. Highest yields (and tallest stems) were obtained with an intra-row (i.e. within row) spacing of 10 cm, which corresponds to a planting density of about 133 000 sph (COMPETE, 2009).

Sorghum is a fast growing C_4 plant native to tropical zones, but can be grown in sub-tropical as well as temperate zones (Zegada-Lizarazu and Monti, 2012). In subtropical and tropical environments, 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 WUE of sorghum grown in tropical climates will differ to that grown in temperate climates.

Vapour pressure deficit

The biomass production and transpiration rate of a vegetation type are related to the diffusion rates of CO_2 and H_2O molecules through the stomatal apertures of leaves. Assuming that plant growth is not limited by energy or water availability, plant transpiration is dependent on the vapour pressure deficit (VPD) gradient between the inside of the leaf and the ambient air. Water use efficiency improves with lowering vapour pressure deficits. In other words, WUE is highest for feedstocks grown in regions exhibiting high relative humidity. For example, Mediterranean climates are ideal where the majority of feedstock production occurs in the cooler winter and spring months. Hence, WUE estimates for different climatic conditions may need to be "normalised" for better comparisons.

Tanner and Sinclair (1983) normalised WUE by multiplying values by the saturation vapour pressure deficit of the air (i.e. g kPa kg^{-1}). They presented standard and normalised values of WUE for both maize and alfalfa. Their results showed that without normalisation, the two crops exhibited similar WUE. However, the WUE of maize (C_4 crop) with normalisation was about twice that of alfalfa (C_3 crop). This corresponds with the notion that under idealised conditions, C_4 crops are more water use efficient than C_3 crops (Squire, 1990), due to their higher efficiency of photosynthetic conversion.

In the *AQUACROP* model, the biomass water productivity term is normalised using reference crop evaporation (ET_o) instead of VPD. Using ET_o is considered superior, as it accounts for advective energy transfer, which is ignored when *VPD* is used. After normalisation, the water productivity term can be used to distinguish C_4 crops (30-35 g m^{-2}; 0.30-0.35 t ha^{-1}) and C_3 crops (15-20 g m^{-2}; 0.15-0.20 t ha^{-1}) as reported by Raes *et al*. (2011).

Biofuel *vs*. bio-energy
The water use efficiency of sorghum is based on total evaporation accumulated over the feedstock growing season (expressed in m^3 or mm). As a first generation feedstock, WUE is sensitive to sorghum's grain and/or stem yield. As a second generation feedstock, WUE is sensitive the total above-ground biomass yield of energy sorghum varieties. Therefore, the WUE of second generation feedstocks will be higher than that of first generation feedstocks (i.e. more "crop per drop").

3.5.4 Biofuel use efficiency

3.5.4.1 Summary

Product water use efficiency (WUE_P) is defined as the ratio of:

- fermentable sugar yield (i.e. sugar yield as tons of Brix per ha),
- extractable starch (i.e. starch yield in t ha^{-1}), or
- vegetable oil (i.e. bio-oil in t ha^{-1})

to seasonal water use. Finally, biofuel use efficiency (WUE_B) was also determined as the ratio of biofuel yield (i.e. bioethanol or biodiesel) to seasonal water use. The results of these two metrics are summarised in **Table 18**.

Table 18 Biofuel use efficiency (L m^{-3}) per feedstock derived from field measurements, with the ranking from highest to lowest

Feedstock	Site	Product yield (t ha^{-1})	WUE_P (kg m^{-3})	Biofuel yield (L ha^{-1})	WUE_B (L m^{-3})	Rank
Sugarbeet	UKU	7.91 (14.9%)	1.408	4 050	0.721	3
		3.67 (16.9%)	0.660	1 879	0.338	9
		7.76 (17.1%)	1.889	3 978	0.968	1
Sweet sorghum	UKU	2.17 (08.9%)	0.551	1 075	0.273	11
		5.27 (12.6%)	1.208	2 606	0.598	6
Sweet sorghum	HAT	4.16 (12.2%)	1.064	2 059	0.526	7
		5.72 (15.2%)	1.411	2 828	0.698	4
Sweet sorghum	DRO	3.36 (08.2%)	0.674	1 664	0.333	10
		6.86 (15.3%)	1.313	3 392	0.650	5
Grain sorghum	UKU	1.63 (65.2%)	0.373	1 062	0.244	12
		1.17 (62.5%)	0.253	762	0.165	13
Grain sorghum	DRO	3.57 (69.4%)	0.710	2 323	0.463	8
Yellow maize	BAY	5.64 (67.1%)	1.321	3 681	0.862	2
Soybean	BAY	0.634 (18.0%)	0.135	654	0.140	14
Jatropha	UKU	0.025 (35.0%)	0.005	26	0.005	15
Moringa (DHI)	HAT	0.011 (31.0%)	0.002	11	0.002	16

Feedstock	Site	Product yield (t ha^{-1})	WUE_P (kg m^{-3})	Biofuel yield (L ha^{-1})	WUE_B (L m^{-3})	Rank
Moringa (DLO)	HAT	0.007 (31.0%)	0.002	8	0.002	17

In terms of WUE_B, sugarbeet is the most water efficient crop, producing the most biofuel per unit of water consumed by the crop. Although the autumn planting (2012/13 season) produced a lower yield compared to the summer planting (2010/11), this was compensated by the higher Brix and thus sugar yield. This was confirmed in the literature which stated that although water deficits decrease sugarbeet tuber yield, sugar yield increases which offsets the reduction in root mass and results in higher bioethanol yield.

When interpreting the results, the following points must be noted:

- In general, the biofuel use efficiency of bioethanol crops was higher than that for biodiesel crops. This trend is similar to that noted for yield water use efficiency (WUE_Y).

- The exception is the high WUE_B estimated for yellow maize at the Baynesfield Estate. This is due to the high yield of 9.6 t ha^{-1} produced under dryland conditions, which is double the country's national average of 4.63 t ha^{-1} (5-year mean from 2007-2012; Lemmer and Schoeman, 2011).

- Yellow maize ranked low (10th) in terms of WUE_Y, but much higher (2nd) using WUE_B. This significant improvement is due to the high extraction rate of yellow maize. The crop produces 402 litres of bioethanol per dry ton of feedstock, which is much higher than sugar-based crops (e.g. 80 Lt^{-1} for sugarcane).

- The biofuel yield is based on the theoretical value, which may not be achieved in a processing plant due to a number of inefficiencies. For example, the biodiesel estimates for oil-based crops assumes that all of the vegetable oil can be extracted from the seed, which is not the case for mechanical crushing (only chemical extraction).

- For starch-based crops, the production of bioethanol is very sensitive to the extractable starch content and moisture content of the crop. These figures were determined from a laboratory analysis for grain sorghum. However, a value of 12.5% moisture content and an extractable starch content of 67.1% were assumed for maize. Thus, the figures for maize are less reliable than those for grain sorghum.

- The bioethanol yield from grain sorghum at Ukulinga in 2012/13 is based measured values of 11.2% moisture content and a starch content of 65.2%.

- Similarly, the bioethanol yield in the following season was determined from a measured moisture content of 11.5% and a starch content of 62.5%.

- The Hatfield drought trial had a lower moisture content of 9.00% and higher extractable starch content of 69.4%, which resulted in higher bioethanol product compared to Ukulinga.

- A fermentation efficiency of 90.9% was used for starch-to-bioethanol conversions, which was based on laboratory measurements of grain samples taken from Ukulinga and Hatfield.

- The estimation of biodiesel from bio-oil content is dependent on the conversion efficiency (set at 95%), the oil content of the seed and the density of the extracted oil.

- An oil content of 18, 35 and 31% was assumed for soybean, Jatropha and Moringa respectively. The value for Moringa was based on laboratory measurements.

- Similarly, and oil density of 0.92 kg L^{-1} was used for soybean and Jatropha, and a slightly lower value of 0.90 kg L^{-1} for Moringa.

3.5.4.2 Sugar degradation

The Brix determination was conducted by ACCI soon after the samples were prepared from the harvested tubers (sugarbeet) and stalks (sweet sorghum). To delay the reduction in sugar properties after harvesting, samples were kept cool by refrigeration. Hence, the sweet sorghum stalks harvested at Hatfield by Pretoria University were cut into 1 m lengths and bundled, then refrigerated prior to their overnight courier to Ukulinga for Brix analysis. It was important that the stalks were not cut into smaller lengths (i.e. < 1 m) or shredded, prior to transport to Ukulinga, as this would drastically affect the sugar content. Finally, only healthy stalks were used for Brix determination.

The self-fermentation of sugary juice in sweet sorghum stalks (as well as sugarbeet tubers) prior to juice extraction (for bioethanol production) is a major concern. This will occur if juice extraction is delayed after harvest due, for example, to transport problems between the field and the bioethanol processing plant. Srinivasa Rao *et al*. (2009) reported that preliminary results indicated a reduction in sugar yield by 16.8% if the juice extraction process is delayed by 48 hours. Srinivasa Rao *et al*. (2009) therefore suggested that further research should address the post-harvest losses in terms of juice quality and quantity.

3.5.4.3 Extraction rates

As noted in the approach, the theoretical biofuel yield was estimated using equations given in **Volume 2** for sugar, starch and seed oil crops. To simply this estimation, the biofuel yield can also be calculated from the product of the crop yield and the biofuel extraction rate. A table of biofuel extraction rates for selected feedstocks was gleaned from the available literature and compared to the average values derived from the equations field trials (**Table 19**).

Table 19 Biofuel production in litres per ton of crop yield

Feedstock	Extraction rate (L t^{-1})		Source
	Equation	Suggested	
Sugarcane	78	80[a]	DoE (2014)
Sugarbeet	84	75[a]	Maclachlan (2012)
Sweet sorghum	60	69[a]	Prasad *et al*. (2007)
Yellow maize	383	402[b]	DME (2006a)
Grain sorghum	383	417[b]	DoE (2014)

Feedstock	Extraction rate (L t^{-1})		Source
	Equation	Suggested	
Canola	413	413[b]	This study
Sunflower	392	398[b]	Meyer *et al*. (2008)
Soybean	186	185[b]	DoE (2014)
Jatropha	361	380[b]	Jongschaap *et al*. (2009)
Moringa	327	327[b]	This study

[a] multiply by crop yield in fresh (i.e. wet) tons
[b] multiply by crop yield in dry tons

The extraction yield represents the quantity of biofuel that can theoretically be produced per ton of utilisable crop yield. In order to determine the biofuel yield per hectare, the crop yield is multiplied by the extraction rate provided in **Table 19**. For canola, the yield extraction of 413 litres of biodiesel per dry ton of crop yield is based on an oilseed content of 40% (Fouché, 2015), an oil density of 0.92 kg L^{-1} and a conversion efficiency (bio-oil to biodiesel) of 95% (Nolte, 2007). The assumption is made that the majority of the bio-oil can be extracted from the seed, which is not necessarily the case.

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 more detailed description of the parameters is provided in **Volume 2**. This section therefore pertains to **AIM 4** and **AIM 5** of this project's terms of reference.

4.1 Introduction

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 Approach

4.2.1 Reference evaporation

The FAO56 (Penman-Monteith) equation is widely accepted as the best-performing method for E_r estimates. The equation provides reference evaporation estimates for a well-watered hypothetical grass surface having a fixed crop height, albedo, and surface canopy resistance. Other reference evaporation standards used in this study include the ASCE-EWRI approach.

4.2.1.1 FAO56 method

The Penman-Monteith equation (**Equation 1**) was used to calculate reference evaporation for a hypothetical grass surface ET_o (in mm day^{-1}) 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). 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).

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

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 ($\gamma = 0.0016286P/\lambda$, where $\lambda = 2.501-0.002361T$; Shuttleworth, 2007).

4.2.1.2 The ASCE-EWRI approach

The equation developed by the Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) was also used in this study. **Equation 2** estimates reference evaporation for a hypothetical alfalfa surface ET_r (in mm day^{-1}) of uniform height (0.50 m). The units in this equation are identical to those in **Equation 1** above.

$$ET_r = \frac{0.408\Delta(R_n - G) + \gamma\frac{1600}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.38u_2)}$$ **Equation 2**

4.2.1.3 *PENPAN* approach

The form of the *PENPAN* equation given by McMahon *et al.* (2013) and Roderick *et al.* (2007) for unscreened A-pan evaporation (**Equation 3**) 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 3**

where E_a is the aerodynamic term $f(u_2) \cdot D$. **Equation 4** from Thom *et al*. (1981) was used for the wind function:

$$f(u_2) = 1.201 + 1.621u_2$$ **Equation 4**

where $f(u_2)$ is in mm day^{-1} kPa^{-1} and u_2 is the daily averaged wind speed in m s^{-1}. The vapour pressure deficit (D) was calculated as per Allen *et al.* (1998) in kPa. Since u_2 is set to 2 m s^{-1} in this study, $f(u_2)$ equates to 4.44 mm day^{-1} kPa^{-1}. Parameter a in **Equation 3** was set to 2.4. Net radiation (R_n in MJ m^{-2} day^{-1}) was estimated according to the procedure determined by Linacre (1994):

$$R_n = 0.71H \cdot R_s - R_{nl}$$ **Equation 5**

Hence, the version of R_n adopted by Rotstayn *et al*. (2006) was not used in this study, i.e. $R_n = 0.86H \cdot R_s - R_{nl}$. R_s is the incoming solar radiation in MJ m^{-2} day^{-1}. The factor 0.86 is based on an albedo of 0.14 for the water in the A-pan (i.e. 1-0.14). Furthermore, the version differs from Linacre's (1994) version of $R_n = 0.71H \cdot R_s - 3.46$, which assumes a constant net longwave radiation loss (R_{nl}) of 3.46 MJ m^{-2} day^{-1} (or 40 W m^{-2}). This over-simplification of R_{nl} is discussed further in **Section 4.3.1**.

The term H is an augmentation factor which Linacre (1994) developed to account for the additional sources of heat (i.e. the direct, diffuse and reflected solar radiation) which are absorbed through the A-pans outer walls:

$$H = F \cdot P + 1.42(1 - F) + 0.42\alpha_s$$ **Equation 6**

The three terms in the above equation account for direct [$F \cdot P$], diffuse [$1.42(1 - F)$] and reflected [$0.42\alpha_s$] radiation respectively. Thus, the incoming solar radiation is augmented by the above term H.

The term α_s is the albedo of the A-pan's surroundings which is assumed to be well-maintained short grass (i.e. α_s = 0.22). It accounts for the radiation that is reflected onto the pan wall from the ground below. In order to estimate the contribution of direct solar 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 7**

P ranges from 1.37 to 1.43 for the latitude (*A*) range 22°S to 35°S. The term *F* accounts for the diffuse radiation from the sky onto the pan wall. The equation used by used by McMahon *et al*. (2013) and Rotstayn *et al.* (2006) is as follows:

$$F = -0.11 + 1.31 \cdot R_s / R_a$$ **Equation 8**

The term R_s/R_a is the ratio of incoming solar (R_s) to extra-terrestrial (R_a) radiation. R_a is the radiation received at the top of the atmospheric layer. In this study, the range of R_s/R_a was limited to 0.23 (i.e. completely cloudy) to 0.75 (clear sky) and thus, *F* ranges from 0.22 to 0.87.

When the sky is completely overcast, R_s/R_a is about 0.25, *F* is 0.22 and the radiation augmentation factor *H* equates to 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. A histogram of *H* values across all quinary sub-catchments is given in **Section 4.3.1**.

Linacre (1994) also proposed an additional longwave irradiance from the ground into the sides of the pan in "dry" months. When Rotstayn *et al*. (2006) applied this adjustment, they found that the *PENPAN* equation tended to over-estimate A-pan evaporation. 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, this suggested augmentation of longwave radiation was also ignored.

4.2.2 Rainfall/runoff response

Schulze and Horan (2011) noted that runoff response in *ACRU* 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 20**.

Table 20 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).

Variable	Definition
QFRESP	Storm flow response fraction for the catchment (set to 0.30).
COFRU	Base flow recession constant (set to 0.009).

4.2.2.1 CORPPT

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). The monthly rainfall adjustment factors used in this study were derived from the original quinary sub-catchment database and range from 0.50 to 2.00 (Schulze *et al*., 2011).

4.2.2.2 CORPAN

The *PENPAN* (c.f. **Section 4.2.1.3**) equation was used to derive monthly APAN-equivalent evaporation estimates for an unscreened evaporimeter. These values were then used the calculate pan factors (K_p), defined as the ratio of reference crop evaporation (ET_o) to A-pan evaporation (E_p). Pan factors allow evaporation from pans to be used for estimating reference crop evaporation for periods of 10 days or longer (but preferably every 30 days, i.e. monthly). In this study however, pan factors were used to adjust daily ET_o evaporation estimates to APAN-equivalent evaporation. Hence, *CORPAN* is set to the reciprocal of K_p (i.e. *CORPAN* = 1/ K_p). Daily ET_o estimates were calculated using the FAO56 equation (c.f. **Section 4.2.1.1**). A distribution of values calculated for all 5 838 quinaries is given in **Section 4.3.2**.

4.2.2.3 EFRDEP

The effective rooting depth (*EFRDEP*) 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).

4.2.2.4 SMDDEP

For all hydrological simulations in this project, *SMDDEP* was set to 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. Hence, the effective soil depth from which storm flow is generated from is the topsoil depth. Stream flow generation is sensitive to *SMDDEP*, particularly if the parameter is under-estimated in drier sites, as it results in over-estimated stream flow (Schulze, 1995).

4.2.2.5 QFRESP

QFRESP was increased from 0.21 (used in previous studies) to 0.30. Schulze (2011) recommended the latter value as being typical at the spatial scale of quinary sub-catchments and is based experiment evidence. Thus, for all simulations of feedstock water use, 30% of the storm flow generated from a rainfall event is assumed to exit the sub-catchment on the same day.

4.2.2.6 COFRU

The *ACRU* parameter *COFRU* (base flow recession constant) was set to 0.009 for both the baseline land cover types and the biofuel feedstocks. This value was suggested by Schulze (2011) as being typical for southern Africa, based on experimental evidence. A slightly different value of 0.010 was used in previous studies.

4.2.3 Water use (*ACRU*)

This section lists the parameters and variables used to model the water use of prioritised feedstocks using the *ACRU* hydrological model. Where possible, the selected values are justified with field-based evidence or from information gleaned from the available literature.

4.2.3.1 Sugarcane (averaged)

Typical values for FAO56-based crop coefficients for three different sugarcane production areas in KwaZulu-Natal, as shown in **Table 21**, were obtained from the SFRA project (Jewitt *et al*., 2009b). The city of Durban provides the boundary between North and South coastal production regions. Quinary sub-catchments with an average altitude of 400 m are classified as Inland.

The K_c values for the inland region were derived from experiments conducted at Eston in the KwaZulu-Natal Midlands for the period 2001/02-2004/05. Similarly, experiments conducted from 2004/05 to 2006/07 at Kearsney Manor and Umzinto represent the northern and southern coastal areas respectively (Jewitt *et al*., 2009b).

Table 21 Representative values for FAO56-based crop coefficients (K_c) for unstressed ratoon sugarcane for the three main production areas in KwaZulu-Natal (Jewitt *et al*., 2009b)

Region	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
sci	1.08	1.15	1.17	1.01	0.99	0.83	0.85	0.77	0.84	0.81	0.97	0.99
scs	1.12	1.16	1.16	0.99	1.03	0.85	0.88	0.82	0.98	0.89	1.06	1.01
scn	1.14	1.16	1.16	1.01	1.05	0.90	0.93	0.88	0.99	1.00	1.10	1.05

sci=sugarcane (Inland); scs=sugarcane (South Coast); scn=sugarcane (North Coast)

The above regional crop coefficients were averaged to obtain one set of monthly values. Monthly averaged values for the vegetation interception loss (*VEGINT*) and rooting distribution for the topsoil horizon (*ROOTA*) were also obtained as shown in **APPENDIX A**.

The average root colonisation values for the B-horizon (*COLON*) derived for each sugarcane region are also shown in are shown in **Table 73** in **APPENDIX A**. The values indicate that the maximum root colonisation of the subsoil is 65%. The root colonisations were based on work originally reported by Glover (1967) and interpreted by experts at SASRI in 2008 (e.g. Van den Berg, Van Antwerpen and Lecler). They coincide with a fractional light interception value of 0.87 (i.e. leaf area index, LAI ≈ 3).

Instead of averaging the root colonisation values for each sugarcane production region, Schulze (2014) suggested that a typical value of 60% should be used for all months. He added that this variable should not be varied monthly for ratoon sugarcane. However, Ball-

Coelho *et al*. (1992) reported that root die-back during a two-week period after ratoon harvest was estimated to be about 17% of the total root mass.

The *ACRU* model was then run for a subset of quinary sub-catchments using the parameters given in **Table 73** (**APPENDIX A**) for the four scenarios (Inland, South Coast, North Coast & Averaged). The model was run for a total of 134 quinary sub-catchments were selected using the procedure described next.

The sugarcane mill areas represent the farm boundaries that contribute feedstock to each sugar mill. The assumption was made that the entire farm is planted to sugarcane, which may be invalid, especially if the farm produces other crops. The mill areas that are supplied with rainfed sugarcane were overlaid with the quinary sub-catchments. This approach therefore excluded the mills that receive irrigated cane (e.g. Komatipoort, Pongola, Felixton & Umfolozi).

A total of 185 quinaries were identified that contain sugarcane farms produced under dryland conditions. Sugarcane farms that occupied less than 10% of the total quinary area were then excluded from further analysis. This reduced the number of sub-catchments from 185 to 134, of which 47 (or 35.1%) are located in in the inland growing region. Similarly, 35.1 and 29.8% of the sub-catchments are located along the South and North Coast respectively (**Table 22**).

Table 22 Distribution of sub-catchments which contain sugarcane mill supply farms that occupy more than 10% of the total quinary area

Number of quinaries with sugarcane farms	185
Number of quinaries where cane farms occupy 10% or more of quinary area	134
Number of 134 cane quinaries located inland	47
Number of 134 cane quinaries located on the South Coast	47
Number of 134 cane quinaries located on the North Coast	40

An analysis was then conducted to ascertain if any major differences existed between mean annual runoff simulated with each different set of monthly *ACRU* parameters and variables values. The results of this exercise are discussed in **Section 4.3.3.1**.

4.2.3.2 Crop coefficients

Optimal crop water use (E_m) is commonly estimated using grass (or alfalfa) reference evaporation (E_r) multiplied by crop-specific coefficients (K_c). K_c is derived from the ratio of E_m to E_r where E_m can be measured using one or more well-documented methods (**Section 3.4.1**). These methods include *inter alia*, lysimeters, soil water balance approach, eddy covariance method, Bowen ratio energy balance system or surface renewal method (Ortega-Farias *et al*., 2009).

The monthly crop coefficients (called CAY in *ACRU*) also 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 given in **Table 23** below.

Table 23 Monthly crop coefficients (with FAO56 as the reference) used in *ACRU* to derive estimates of feedstock water use

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
sca	1.11	1.16	1.16	1.00	1.02	0.86	0.89	0.82	0.94	0.90	1.04	1.02
ssu	0.92	0.97	0.90	0.74	0.64							0.68
ssh	0.79	0.76	0.62	0.45	0.36							0.51
grs	0.97	0.97	0.89	0.80							0.51	0.89
sbs	1.06	0.85	0.84						0.77	0.78	1.05	1.07
sbw						0.81	0.85	0.75	0.76	0.73	0.76	0.86
syb	1.00	1.03	0.84								0.72	0.72
snf	1.15	0.70	0.35								0.35	0.85
cnw				0.80	1.00	1.15	0.80	0.60				

sca=sugarcane (Averaged); ssu=sweet sorghum (Ukulinga averaged); ssh=sweet sorghum (Hatfield averaged); grs=grain sorghum (Averaged); sbs=sugarbeet (Summer); sbw=sugarbeet (Winter); syb=soybean; snf=sunflower; cnw=canola (Winter)

It is important to note the following:

- All crop coefficients used in this study are based on FAO56 as the reference.

- The values presented above were multiplied by the monthly pan coefficient (or divided by *ACRU*'s *CORPAN* value) which was calculated for each quinary, in order to adjust them to PAN-equivalent crop coefficients.

- For sugarcane, it is assumed that each "farm" is made up of equal portions of fields cut in April, June, August, October and December.

- The crop coefficients for each sugarcane growing region (e.g. Inland, S. Coast & N. Coast) were averaged and used to estimate sugarcane water use, which reduced the total number of national runs required (allowing other feedstocks to be considered, e.g. sunflower). The justification is provided in **Section 4.3.3.1** (and **Section 5.2.2**).

- For sweet sorghum, the crop coefficients (K_c) obtained at the Ukulinga and Hatfield research farms differ significantly. Thus, two national runs were undertaken to emphasise the impact of management practice on crop coefficients as well as the importance of using locally determined K_c values and the *ACRU* model's sensitivity to this input. Hatfield-based values are representative of growing conditions in the **interior** or a higher planting density, whilst Ukulinga-based values better represent growing conditions **inland** of coastal areas or lower planting density.

- The crop coefficients for grain sorghum were averaged for two growing seasons based on estimates derived at Ukulinga.

- Two national runs for sugarbeet were also undertaken to represent a summer and winter planting. In Cradock (Eastern Cape), sugarbeet will likely be grown in winter (i.e. May-June planting), whilst farmers in other areas may decide to plant sugarbeet in summer (as a rotational crop).

- The crop coefficients for soybean were estimated under dryland conditions and not irrigated (i.e. no water stress) conditions as prescribed by Allen *et al*. (1998). Ideally, these values should be adjusted upwards to account for the effects of soil water stress which may have occurred during the growing season.

- The coefficients given in the above table are based on good management practices i.e. unstressed crops, pest/disease free, no planting in riparian areas, contour banks are in place etc.

- For annual crops, a monthly crop coefficient of 0.35 (as suggested by Schulze, 1995 and Piccinni *et al*., 2009) was used to represent fallow conditions. This value was decreased to 0.25 in the case of sweet sorghum grown in the interior (Hatfield) and for sunflower. However, Allen *et al*. (1998) suggested that the minimum K_c for bare soil ranges from 0.15 to 0.20.

- The assumed planting date for summer crops is November, except for sugarbeet (September) and sweet sorghum (December).

- Where possible, K_c values derived for South African growing conditions were used, with the exception of canola (sourced from international literature).

- Locally derived K_c values based on only one growing season pertain to sugarbeet (summer and winter) and soybean.

Table 24 Location of trials from which crop coefficients deemed represented of local growing conditions were derived

Feedstock	Abbr.	Trial location	Start period	End period
Sweet sorghum	ssu	Ukulinga	2010/11	2011/12
Sweet sorghum	ssh	Hatfield	2010/11	2011/12
Grain sorghum	grs	Ukulinga	2012/13	2013/14
Sugarbeet (Summer)	sbs	Ukulinga	2010/11	2010/11
Sugarbeet (Winter)	sbw	Ukulinga	2012/13	2012/13
Soybean	syb	Baynesfield	2012/13	2012/13

ssu=sweet sorghum (Ukulinga averaged); ssh=sweet sorghum (Hatfield averaged); grs=grain sorghum (Averaged); sbs=sugarbeet (Summer); sbw=sugarbeet (Winter); syb=soybean

<u>Adjustment of crop coefficients</u>

Since the crop coefficients given in **Table 23** were derived using FAO56 as the reference, they must be adjusted before being used as *ACRU* model input. In general, FAO56 reference evaporation is less than APAN evaporation, which means APAN-based K_c values are smaller than FAO56-based values.

Shuttleworth (2010) stated that the ratio of PAN to FAO56 evaporation is within the range 1.1 to 1.2 “for the majority of likely conditions”. He therefore suggested a “default” value of

1.15 is usually a reasonable assumption. However, based on evidence provided by Rotstayn *et al*. (2006) and McMahon *et al*. (2013) using the *PENPAN* equation, Shuttleworth (2010) may have under-estimated the energy balance of an A-pan. This means that the adjustment of 1.15 (or 1.20) is deemed conservative and results in an under-estimation of APAN equivalent evaporation (and an over-estimation of stream flow response). For this study, new monthly factors to convert FAO56 to APAN evaporation were derived using a modified version of the *PENPAN* equation (c.f. **Section 4.2.1.3**).

Upper limit of crop coefficients

Even under extreme advection, there is an upper limit of evaporation, caused by limitations on aerodynamic transport and on equilibrium forces above the evaporating surface. According to Allen *et al*. (2011a), the upper limit of reference evaporation is relatively well represented by the tall reference crop (i.e. alfalfa) that has been defined by ASCE-EWRI (Allen *et al*., 2005) (see **Section 4.2.1.2**).

Allen *et al*. (2011a) stated that the tall (alfalfa) reference represents sufficiently low surface resistance and sufficiently high aerodynamic roughness to approximate *near maximum rates* of total evaporation expected from large expanses of well-watered vegetation cover, even under conditions of strong regional advection. For example, Allen *et al.* (1998) suggested a surface resistance (r_s) of 70 s m^{-1} for short grass, whereas Allen *et al*. (2005) recommended an r_s value of 45 s m^{-1} for “tall” alfalfa (for daily time-step calculations of E_r).

Allen *et al*. (2011a) provided a critical appraisal of crop coefficient values calculated for humid as well as arid/semi-arid climatic conditions. In humid climates, regional advection is relatively minor and hence, the majority of available energy for the evaporation process is derived from net radiation. K_c values should not exceed 1.0 to 1.05 and 1.2 to 1.3 relative to the alfalfa and grass references respectively, for large expanses (> 100 m fetch or > 200 m diameter) of similar vegetation. In arid and semi-arid climates, K_c values of 1.0 to 1.1 for the alfalfa reference are typical, with values approaching 1.2 for the grass reference. Exceptionally high K_c values of 1.4 are rare but obtainable for tall, well-watered vegetation. Hence, Allen *et al*. (2011a) suggest limiting K_c values according to the thresholds provided in **Table 25**.

Table 25 Upper threshold of crop coefficient values suggested by Allen *et al*. (2011a) based on the two most common reference crops

Climate type	Upper limit of crop coefficients (Kc)	
	Alfalfa reference	Grass reference
Arid/semi-arid	≈1.0	1.2-1.4
Humid	≈1.0	≈1.2

Allen *et al.* (2011b) stated that the limits presented above should serve as guidelines for review of data accuracy and representativeness as well as to indicate the potential for bias in measurement procedures. These comparisons are necessary because many of the erroneously high total evaporation estimates reported in the literature violate the conservation of energy law that governs the conversion of liquid water to vapour during the transpiration and soil water evaporation processes.

4.2.3.3 Interception loss

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). For the final *ACRU* model runs, the monthly interception loss values given in **Table 26** were used for each feedstock.

Table 26 Monthly interception loss values (mm per rain day) used in *ACRU* to derive estimates of feedstock water use

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
sca	2.1	2.2	2.2	1.9	1.9	1.6	1.7	1.5	1.8	1.7	2.0	1.9
ssu	1.0	1.5	2.0	1.0	0.5							0.5
ssh	1.0	1.5	2.0	1.0	0.5							0.5
grs	1.0	1.5	1.5	1.0							0.5	0.5
sbs	1.0	1.0	0.5						0.5	0.5	1.0	1.5
sbw						0.5	0.5	1.0	1.5	1.5	1.0	0.5
syb	2.0	2.0	1.0								0.5	1.0
snf	2.0	2.0	2.5								0.5	1.5
cnw				0.5	1.0	2.0	2.5	1.0				

sca=sugarcane (Averaged); ssu=sweet sorghum (Ukulinga averaged); ssh=sweet sorghum (Hatfield averaged); grs=grain sorghum (Averaged); sbs=sugarbeet (Summer); sbw=sugarbeet (Winter); syb=soybean; snf=sunflower; cnw=canola (Winter)

These values are similar to those used in the SFRA project (Jewitt *et al*., 2009b) for sugarcane as well as those used in the biofuels scoping study (Jewitt *et al*., 2009a) for the annual feedstocks. However, values were adjusted to account for different planting dates assumed in this project as well as for crops with high leaf area indices (LAI). For example, interception loss is deemed to approach 2.5 mm per rain day for feedstocks with LAIs of 7, such as sunflower (Jovanovic *et al*., 2000) and canola. Thus, the high interception loss for canola in July reflects the large LAI values reported by Tesfamariam *et al*. (2010) for canola planted in May 2003 at Hatfield. For LAIs of 0-3 and 4-5, VEGINT was limited to 1.5 and 2.0 mm per rain day, respectively. A typical value of 0.5 mm per rain day was assumed for the fallow period. Based on research by de Villiers (1975), interception losses are capped at 3 mm per rain day for most vegetation types (excluding mature forest plantations).

4.2.3.4 Rooting distribution (sweet sorghum)

A sample of sweet sorghum plant roots at the end of the 2010/11 trial were excavated from the field after the stalks were harvested. A pit was carefully dug along a row of eight plants. The pit bordered the centreline of the row and care was taken not to damage the roots. An image of the exposed roots in the pit is shown in **Figure 4**. The roots were then removed from the field and washed to remove any soil from the roots and maintain the structure of the rooting system. **Figure 5** shows the rooting structure after all the soil had been removed.

Figure 4 Sweet sorghum rooting distribution partially exposed by the soil pit at Ukulinga in 2010/11

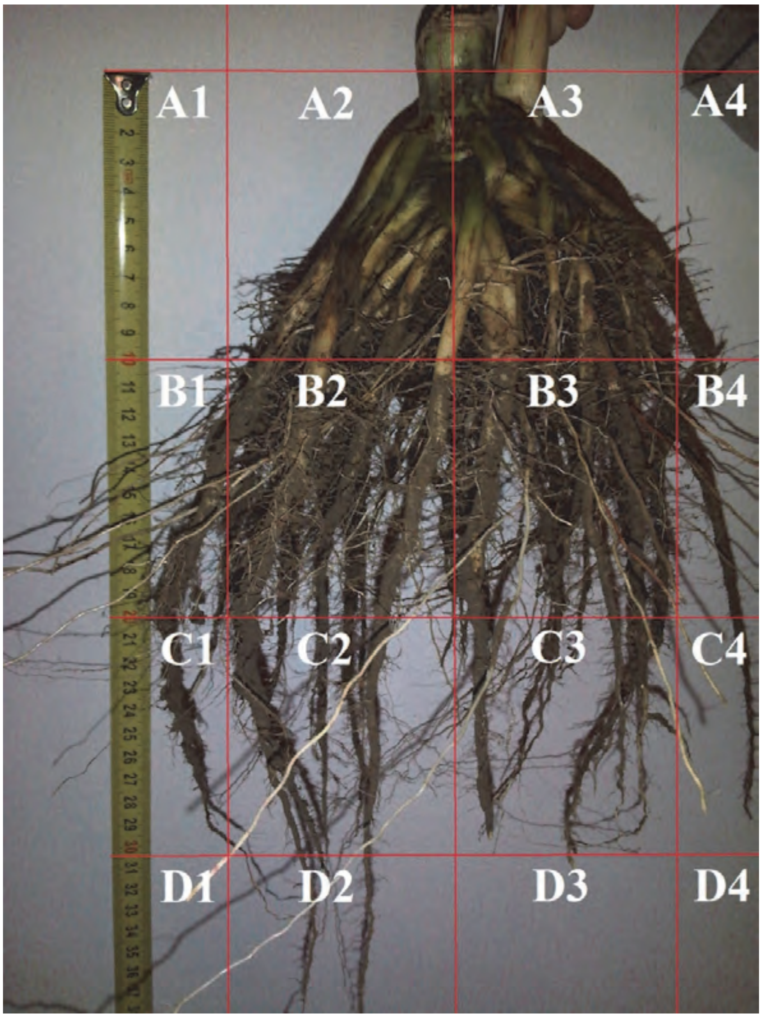


Figure 5 A 10 by 10 cm grid (16 blocks in total) superimposed onto each photograph of a washed sweet sorghum root system

Once the root structures were completely removed from the soil and washed, a grid was superimposed onto a photograph of each root system as shown in **Figure 5**. Within each 10 by 10 cm block, the roots were divided into four categories in terms of their average diameter. Hence, a single tapering root passing through more than one grid block may fall into different diameter categories. The root diameters were measured at their midpoint in each block using a vernier calliper.

The roots were then categorised into one of four diameter classes, namely 0.0 to 1.0 mm, 1.1 to 2.0 mm, 2.1 to 3.0 mm and 3.1+ mm. The fine roots (≤ 1.0 mm) and the large roots (≥ 3.1 mm) were easier to categorise than the medium thickness roots (i.e. 1.1 to 3.0 mm). The percentage of total roots and all diameter classes per horizontal row were first estimated. This made the estimation of each specific block more accurate. The percentage of roots for each diameter class per block was then estimated and the results of this analysis are shown in **Section 4.3.3.1**

4.2.3.5 Rooting distribution (summary)

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 (**Table 27**). 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).

Table 27 Monthly fraction of roots in the A-horizon (*ROOTA*) that were used in *ACRU* to derive estimates of feedstock water use

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
sca	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72
ssu	0.80	0.75	0.75	0.75	0.75							0.85
ssh	0.80	0.75	0.75	0.75	0.75							0.85
grs	0.80	0.75	0.75	0.75							0.85	0.80
sbs	0.85	0.85	0.85						0.85	0.85	0.85	0.85
sbw						0.85	0.85	0.85	0.85	0.85	0.85	0.85
syb	0.85	0.85	0.85								0.85	0.85
snf	0.40	0.40	0.40								0.80	0.60
cnw				0.80	0.60	0.40	0.40	0.40				

sca=sugarcane (Averaged); ssu=sweet sorghum (Ukulinga averaged); ssh=sweet sorghum (Hatfield averaged); grs=grain sorghum (Averaged); sbs=sugarbeet (Summer); sbw=sugarbeet (Winter); syb=soybean; snf=sunflower; cnw=canola (Winter)

The *ROOTA* values used in the SFRA study (Jewitt *et al*., 2009b) for three production areas (Inland, South Coast & North Coast) are given in **Table 73** in **APPENDIX A**. The values for each production area reflect the assumption that growth below ground (i.e. root elongation) "mimics" that above ground (i.e. stalk elongation). This assumption may be challenged if one considers that more carbon is generally allocated below ground (i.e. to root development) during times of stress (Smith *et al*., 2005). Baran *et al*. (1974) showed the percentage of root biomass decreasing in the upper soil layer (and increasing in the deeper soil) as irrigation frequencies increased from 1 week to 3 weeks. Based on this argument, it is intuitive that the *ROOTA* values for the Inland and North Coast regions should be "switched".

Blackburn (1984) stated that approximately 50% of sugarcane's root biomass typically occurs in the top 20 cm of soil and 85% in the top 60 cm. Thus, the root fraction (Y) and depth (d in cm) is given by $Y = 1 - 0.967^d$, where 0.967 represents the root "extinction coefficient" (Gale and Grigal, 1987). Since the average topsoil depth for all quinaries is 27.2 cm (only 10 sub-catchments exhibiting an A-horizon depth shallower than 20 cm), a value of 63% for *ROOTA* is was calculated using the above equation. However, in the interest of consistency, the *ROOTA* values for sugarcane used in this study represent an average of values derived for three production areas (as was done for the crop coefficients).

Jackson *et al.* (1996) reported that 70% of the roots of annual plants are found in the top 30 cm of the soil. Hence, an end-season value of 70% for *ROOTA* is feasible for most crops since the average topsoil depth for all quinaries is approximately 30 cm. However, this value was increased to 75% for the sorghum feedstocks in order to mimic a slightly shallower rooting system at harvest. This was based on field observations at Ukulinga where the majority of sorghum's (both sweet & grain) fine root system was found in the top 20 cm of the soil profile. This infers that a high value of *ROOTA* should be selected. However, it is important to remember that the field trials were well irrigated and rooting depths are typically shallower for irrigated crops compared to crops grown under dryland conditions. Hence, the fraction of roots in the A-horizon was decreased to 75% considering that the majority of biofuel feedstock will be grown under dryland conditions.

For sugarbeet, the value of *ROOTA* is held constant at 85% to reflect a shallow rooting system. This is representative of the growing conditions in Cradock, where the majority of sugarbeet production is likely to take place under irrigated conditions. Furthermore, Brown and Biscoe (1985) found that most of the sugarbeet's fibrous root system was found in the top 30 cm (i.e. in the plough layer). This concurs with in-field observations at Ukulinga. Draycott (2006) also mentioned that water uptake preferentially occurs near the soil surface.

Soybean plants stop root development at the "green bean" stage, when the first pod containing a single green seed is produced. Although soybean's tap root can extend to around 1.5 m, the majority of the plant's extensive lateral root system occurs within the 30 cm of the soil surface (DAFF, 2010a). Hence, *ROOTA* was set to the same value as that used for sugarbeet.

Anderson *et al*. (2003) and Jovanovic *et al*. (2000) reported maximum rooting depths of 1.35 and 1.50 m for sunflower. Anderson *et al*. (2003) stated that sunflower extracts water from the deeper soil layers, resulting in less available soil water for the succeeding crop. Canola also has a taproot system, with secondary roots growing laterally off the taproot and thus, is able to extract water from the deeper soil layers. An initial *ROOTA* value of 80% was used for canola, since DAFF (2010d) reported that root "growth is rapid after establishment with 85% of the root dry matter in the top 25 cm of soil". According to Evans (1964), drought tolerance is higher for those crops with a tendency to develop deep root systems.

For the fallow period (or during periods of plant senescence), *ROOTA* was set to 1.00 (Smithers and Schulze, 1995). In these months, total evaporation is computed as soil water evaporation occurring from the topsoil layer only. It is therefore assumed that good management practices are followed in that, the farmland is kept free of weeds during the fallow period. If weed growth is prolific during fallow, or crop rotation is undertaken, then *ACRU* will under-estimate the total evaporative demand during this period.

4.2.3.6 Root colonisation

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. 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). Colonisation of the subsoil is difficult to characterise given the paucity of root data under farming conditions in South Africa. The values used for the final *ACRU* runs are given in **Table 28** and are largely based on experience. As a general rule, *COLON* increases as *ROOTA* decreases.

Table 28 Monthly fraction of root colonisation of the B-horizon (*COLON*) that were used in *ACRU* to derive estimates of feedstock water use

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
sca	60	60	60	60	60	60	60	60	60	60	60	60
ssu	20	40	60	60								10
ssh	20	40	60	60								10
grs	40	60	70	70							10	20
sbs	25	25	25						10	15	20	25
sbw						10	15	20	25	30	30	30
syb	20	25	25								10	15
snf	80	80	60	30							10	40
cnw				10	20	40	60	60				

sca=sugarcane (Averaged); ssu=sweet sorghum (Ukulinga averaged); ssh=sweet sorghum (Hatfield averaged); grs=grain sorghum (Averaged); sbs=sugarbeet (Summer); sbw=sugarbeet (Winter); syb=soybean; snf=sunflower; cnw=canola (Winter)

Schulze (2014) suggested that a *COLON* value of 60% should be used for all months and for all sugarcane production areas. He added that this variable should not vary monthly for ratoon sugarcane. Hence, an average of the three growing regions was not used in this study. A constant monthly value may not be justified considering that Ball-Coelho *et al*. (1992) reported that root die-back during a two-week period after a ratoon harvest was estimated to be about 17% of the total root mass. A maximum value of 60% at harvest was set for other tall crops such as sweet sorghum, to help prevent lodging.

COLON was increased to 25% (summer) and 30% (winter) owing to the length of the tuber at harvest. Draycott (2006) reported that root density is greatest in the upper 30-50 cm of soil, but roots are sparse in comparison with grain crops. Sugarbeet compensates for the lack of root colonisation by high rates of water absorption. For sugarbeet planted in winter, it is assumed that supplemental irrigation will only be used to establish the crop. Thereafter, irrigation should be withheld in order to prevent below-ground disease incidence, as well as to “encourage” the plant to develop a deeper root system. Hence, slightly higher values of COLON were used for winter sugarbeet than compared to sugarbeet planted in summer.

For canola, *COLON* was increased to account for its deep root system. Nielsen (1997) reported that canola extracted 92-95% of its water use from depths up to 1.2 m. Similar (i.e. high) colonisation values would be used for sunflower. Anderson *et al*. (2003) noted that due to sunflower’s high water use, there is less available water for the succeeding crop.

A *COLON* value of 10% was used for the fallow periods, in order to mimic root dieback and/or root destruction during the harvesting process. However, it is important to note that feedstock water use is insensitive to *COLON* values during the fallow period, considering *ROOTA* is set to 1, i.e. soil water evaporation only occurs from the topsoil. The average depth of the B-horizon for all 5 838 quinaries is approximately 34 cm.

4.2.3.7 Surface cover fraction

The *ACRU* model is particularly sensitive to this variable, 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 values used in final model runs for *PCSUCO* are shown in **Table 29**.

Table 29 Monthly fractions (expressed as a %) of the soil surface covered by crop residue that were used in *ACRU* to derive estimates of feedstock water use

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
sca	90	95	95	80	70	50	30	30	50	60	75	85
ssu	10	20	30	30	80	60	50	40	30	20	10	0
ssh	10	20	30	30	80	60	50	40	30	20	10	0
grs	20	30	30	60	50	40	30	20	10	10	0	10
sbs	20	20	30	50	40	30	20	10	0	5	10	10
sbw	50	40	30	20	10	0	5	10	10	20	20	30
syb	10	10	10	30	30	30	30	20	10	5	0	5
snf	20	40	60	30	20	10	10	10	10	10	0	10
cnw	10	10	10	0	20	40	60	80	60	40	20	10

sca=sugarcane (Averaged); ssu=sweet sorghum (Ukulinga averaged); ssh=sweet sorghum (Hatfield averaged); grs=grain sorghum (Averaged); sbs=sugarbeet (Summer); sbw=sugarbeet (Winter); syb=soybean; snf=sunflower; cnw=canola (Winter)

It is important to note that the surface cover fraction does not take into consideration the shading effects of the vegetative canopy. The values for ratoon sugarcane were obtained from the SFRA project (Jewitt *et al*., 2009b). For the annual crops, values were set to zero at the time of planting to indicate the crop was established in fields where crop residue was minimal (i.e. incorporated into the soil during ploughing). This variable is slowly increased over the growing season as crop residue builds up (i.e. due to leaf dieback caused by senescence). The value peaks at harvest time due to the accumulation of residue from the harvesting process.

The percentage of soil surface cover is deemed negligible for sugarbeet for most of the growing season. However, field observations show that the bottom leaves tend to die off in the latter months which increases the surface cover fraction. The value peaks after harvest as the beets are topped (or scalped) in the field to remove the upper crown and attached leaf biomass. This defoliation method (known as ground topping) removes invert sugars which are typically concentrated in the crown tissue (Draycott, 2006).

In the case of sweet sorghum, it is assumed that the leaves will be stripped from the main stem in-field as left as a stover to suppress weed formation as well as aiding nutrient recycling. Tesfamariam *et al*. (2010) reported a decline in LAI from 8.0 to 2.4 for unstressed canola from 125 to 150 DAP which explains why *PCSUCO* is high in August (at harvest). Both *PCSUCO* and *COLON* are only considered in the ACRU model with the parameter *EVTR* is set to 2. For most situations, Schulze (1995) recommends that transpiration and soil water evaporation are calculated as separate components (i.e. *EVTR* = 2).

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 that *CONST* is typically set to 0.50 for most vegetation types.

CONST was set to 0.50 for conventional cane after consultation with Singels (2014), who also suggested a value of 0.30 for energy cane. A value of 0.60 was used for crops that are deemed to be sensitive to soil water stress, e.g. sugarbeet (**Table 30**).

Table 30 Values of *CONST* used in *ACRU* to model feedstock water use, together with suggested values for the depletion fraction (*p*) from the literature

Feedstock	***CONST***	***p* (Allen *et al*., 1998)**
Sugarcane	0.50	0.65
Sugarbeet	0.60	0.55
Sweet sorghum	0.50	0.50
Grain sorghum	0.45	0.55
Soybean	0.50	0.50
Sunflower	0.45	0.45
Canola	0.40	0.60

Grain sorghum is able to withstand water deficit better than most other grain crops. This can be attributed to its 1) relatively small leaf area which limits transpiration, 2) the waxy leaf coating which suppress transpiration and improves desiccation, and 3) the ability of the stomata to close rapidly which limits water loss (ARC-GCI, 1999). Hence, *CONST* was set to 0.45 to account for its drought tolerance (as for sunflower).

According to DAFF (2010a), soybean seed yield is maximised when water in the root zone is kept above 50% of plant available water. Hence, *CONST* was set to 0.50 for soybean (**Table 30**). For canola, *CONST* was set to 0.40 because the crop is reportedly very drought tolerant (Fouché, 2015).

Allen *et al*. (1998; p 163-164) provided values for the depletion fraction (p; **Table 30**) for a range of crops, where p is equivalent *CONST* by definition. Although p is often held constant for a specific growing period, Allen *et al*. (1998) noted that the fraction is a function of the evaporation demand of the atmosphere as well as varies soil type. The authors provided an equation for adjusting p based on the crop's evapotranspiration rate (ET_c) as follows:

$$p = p + 0.04(5.0 - ET_c) \qquad \textbf{Equation 9}$$

Values of p given in **Table 30** apply for ET_c = 5 mm day^{-1} and can be adjusted using the above equation, but with p limited to the range 0.1 to 0.8. Hence, p is up to 20% higher than the values listed in **Table 30** when ET_c is low (i.e. < 3 mm day^{-1}) and 10-20% lower when ET_c is high (i.e. < 8 mm day^{-1}).

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.

In this study, *COIAM* values ranging from 0.25 to 0.35 were used. During the fallow period, *COIAM* was set to *ACRU*'s default value of 0.20. The assumption was made that crops with a high leaf area inferred higher *COIAM* values. Similarly, crops that produce large residues or exhibit high leaf turnover (i.e. dropped leaves) inferred higher *COIAM* values. A value of 0.35 was used for both sugarcane and sweet sorghum as shown in **Table 31**.

Table 31 Monthly coefficient of initial abstraction (*COIAM*) values that were used in *ACRU* to derive estimates of feedstock water use

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
sca	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
ssu	0.30	0.35	0.35	0.30	0.25							0.25
ssh	0.30	0.35	0.35	0.30	0.25							0.25
grs	0.30	0.30	0.30	0.20							0.25	0.30
sbs	0.25	0.25	0.30							0.25	0.25	0.25

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
sbw						0.25	0.25	0.25	0.25	0.25	0.25	0.30
syb	0.25	0.25	0.25								0.25	0.25
snf	0.35	0.35	0.30								0.25	0.30
cnw				0.25	0.25	0.25	0.30	0.30				

sca=sugarcane (Averaged); ssu=sweet sorghum (Ukulinga averaged); ssh=sweet sorghum (Hatfield averaged); grs=grain sorghum (Averaged); sbs=sugarbeet (Summer); sbw=sugarbeet (Winter); syb=soybean; snf=sunflower; cnw=canola (Winter)

4.2.4 Water use (*SWB*)

4.2.4.1 Sweet sorghum

The seasonal crop coefficients required by the FAO model in *SWB* were derived from the drought trial conducted at Hatfield during the 2010/11 season.

4.2.4.2 Moringa

The FAO model parameters calculated for Moringa from the irrigated high tree density treatment at Hatfield are shown in **Table 32** below. These parameters are required by *SWB* to estimate a reduction in yield caused by water stress.

Table 32 FAO model parameters for Moringa, calculated from the irrigated high tree density treatment at Hatfield

Parameter	Growth stage			
	Initial	Development	Mid-season	Late season
Period (days)	30	70	85	80
K_{cb}	0.15	→	0.65	0.45
Root depth (m)	0.75	→	1.2	1.2
Height (m)	2.5	2.5	2.5	2.5

4.2.5 Yield (*AQUACROP*)

It was envisaged that the *AQUACROP* model would provide regional estimates of sugarcane, sugarbeet and soybean yield. Similarly, the *SWB* model would be used to simulate yield of grain sorghum, sweet sorghum and canola at the regional level. However, owing to limitations of *SWB* regarding batch processing, use of this model for regional yield forecasts was therefore abandoned. The parameters in this study to develop regional estimates of yield for selected crops is summarised next, using the new terminology proposed by Augusiak *et al*. (2014).

4.2.5.1 Model evaluation: terminology

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 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.

The reader is referred to **Volume 2** (Chapter 4) for further detail regarding the new terminology used to describe model evaluation (or performance). The *AQUACROP* model defined by Steduto *et al*. (2009) is a canopy-level model capable of simulating the attainable crop biomass and harvestable yield in response to available soil water. It is important to note that the level of calibration undertaken for each feedstock was not consistent. Where possible, the calibrated model was validated against observed data. This was done to test whether the assumptions made are considered reasonable with regard to the real world system. Furthermore, a model verification was also undertaken to ascertain whether *AQUACROP* implements these assumptions correctly.

4.2.5.2 Data evaluation

Sugarcane yield data for eight different planting dates (from 1990 to 1991) was obtained from SASRI. 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.

4.2.5.3 Model output verification

The crop parameters files used in this study were obtained from different sources as indicated in **Table 33**. 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 33 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. **Volume 2** describes in detail the crop 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, more detailed calibrations were carried out for sugarbeet and sugarcane.

4.2.5.4 Model output corroboration

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. The results of this validation are present in **Section 4.3.5.2**.

4.2.5.5 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.

It is evident (but not surprising) that *AQUACROP* is sensitive to climate and soils input. 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.

4.2.6 Yield (*SWB*)

The crop-specific parameters required by *SWB*'s growth model 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 *SWB* model calculates the following statistical parameters for testing model prediction accuracy:

- Willmott's (1982) index of agreement (D index),
- root mean square error (RMSE),
- mean absolute error (MAE) and the
- coefficient of determination (r^2).

According to De Jager (1994), D and r^2 values above 0.8 and MAE values below 0.2 indicate reliable model predictions. In this case, a high degree of agreement between simulated and measured values is confirmed by high r^2 and D values (> 0.8), as well as low RMSE (< 0.2%) and MAE (< 20%) for all variables.

4.2.6.1 Sugarbeet

The FAO model in *SWB* was used to simulate yield reduction due to water stress for sugarbeet.

4.2.6.2 Sweet sorghum

For this study, growth parameters were determined for sweet sorghum from the drought trial conducted at Hatfield during the 2010/11 season. The *SWB* crop growth model was then run and simulated yields were compared to measured crop yields from Ukulinga.

Growth data collected from the control treatment was used to determine sweet sorghum's growth parameters for the *SWB* model. The model was then validated on the other three treatments (refer to **Volume 2** for a description of each treatment). Data collected for each treatment included plant height, leaf area measurement, fresh and dry leaf, stalk and head mass. Since the irrigation trial consisted of different water regimes, model performance with regard to water use and dry matter production under different water supply conditions could also be established.

All data were statistically analysed using the SAS package (Statistical Analysis System Institute Inc. 1999; 2001). The statistical analysis and interpretation was based on comparison of treatment means.

4.2.6.3 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 Hatfield 2002/03 trial are presented in **Volume 2**.

4.2.6.4 Moringa

The FAO model in *SWB* was also used to simulate yield reduction due to water stress for Moringa.

4.3 Results and Discussion

As highlighted in the previous section, *ACRU* requires 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. The values used in this study to assess the water use of the prioritised biofuel feedstocks are summarised next.

4.3.1 Reference evaporation

4.3.1.1 Solar radiation augmentation factor

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 34**. 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 34 Histogram of monthly averaged solar radiation augmentation (H) across all 5 838 quinaries calculated using **Equation 6** 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 in this study had a significant impact the calculation of *ACRU*'s *CORPAN* variable.

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. 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 of 1.10 -

1.20 proposed by Shuttleworth (2010). It is also higher than the value of 1.31 measured during the autumn of 1979 by Thom *et al.* (1981) for an A-pan at the University of Grenoble (France).

4.3.1.2 Outgoing longwave radiation

The histogram of R_{nl} values across all quinary sub-catchments is given in **Table 35**. The results show that there are no negative net longwave radiation values as this was corrected. 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.

Table 35 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**	

Based on the above analysis, a decision was made to ignore the "default" value of 3.46 MJ m^{-2} in **Equation 5** (in **Section 4.2.1.3**) 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".

4.3.1.3 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. 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 6**, which highlights the tendency of the *PENPAN* equation to over-estimate A-pan evaporation. Rotstayn *et al*. (2006) as well as Johnson and Sharma (2010) also reported that the *PENPAN* equation tends to over-estimate A-pan evaporation, particularly for lower monthly evaporation totals.

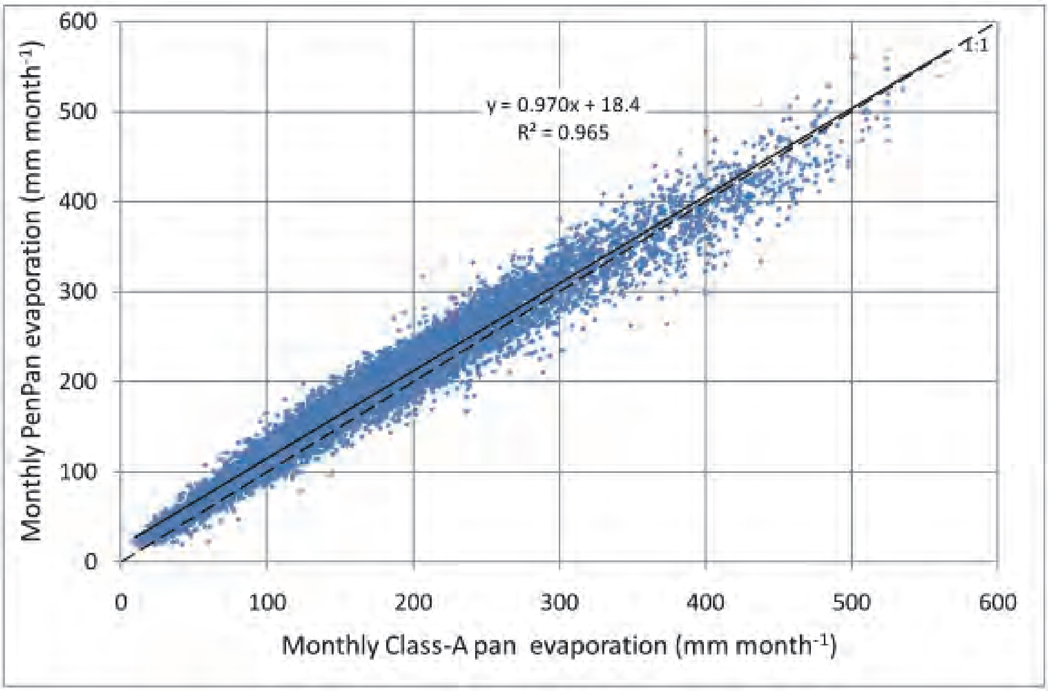


Figure 6 Comparison of monthly *PENPAN* evaporation and Class-A pan evaporation for 68 climate stations in Australia (McMahon *et al*., 2013)

However, the Australian 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. $R_n = 0.71H{\cdot}R_s - R_{nl}$). The value of 0.71 proposed by Linacre (1994) is based on the available energy "halfway" between the respective values for a lake ($0.80R_s$) and green vegetation ($0.63R_s$). Thus, it is assumed that the modified version of the PANPAN equation used in this study will have less tendency to over-estimate A-pan evaporation.

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).

4.3.2 Rainfall/runoff response

The modified *PENPAN* equation (c.f. **Section 4.2.1.3**), with parameter *a* set to 2.4 and $R_n = 0.71H{\cdot}R_s - R_{nl}$ was used to estimate monthly APAN-equivalent evaporation (E_p). This was compared to FAO56-based evaporation (ET_o) to calculate *CORPAN* as E_p/ET_o. The results show that 75.5% of the *CORPAN* values used in this study range from 1.32 to 1.42 as shown in **Table 36**. The empirical equation provided by Allen *et al*. (1998) in **APPENDIX B** 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 74**). 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 36 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**	

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 37**, E_p exceeds ET_o by a factor ranging from 1.28 to 1.60. 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).

Table 37 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

4.3.3 Water use

4.3.3.1 Rooting distribution

The distribution of sweet sorghum roots at harvest time is an indication of the availability of water and nutrients throughout the growing season. For the sweet sorghum crop of 2010/11, the percentage of total roots per 10 by 10 cm block (c.f. **Figure 5**) for each diameter class showed that the majority (70%) of fine roots (≤ 1.0 mm diameter) are found 10 to 20 cm below the soil surface (Block B in the B-horizon). The majority (i.e. 90%) of roots are concentrated in the tilled soil layer (upper 20 cm of the soil), with 30% concentrated in the A-horizon and the remaining 70% in the B-horizon (c.f. **Table 38**).

Table 38 Proportion (expressed as a %) of the total sweet sorghum (Ukulinga) root mass per 10 by 10 cm block as shown in **Figure 5**

Block identifier	Soil depth (cm)	Block number				Subtotal
		1	2	3	4	
A	0 - 10	1	13	13	3	30
B	10 - 20	10	20	20	10	60
C	20 - 30	1	3	3	1	8
D	30 - 40	0	1	1	0	2
					Total	**100**

The concentration of roots in the upper 20 cm of soil profile indicates that the plant available soil water was maintained at near to field capacity throughout the growing season. In other words, the upper horizon always provided sufficient water for the crop and thus the roots did not need to grow deeper in order to access soil water in the deeper soil horizons. This is also suggested by the concentration of very fine roots in the upper 20 cm. This is significant because the location of the very fine roots is indicative of the most reliable depth at which water occurs.

Portmann *et al.* (2010) produced rooting depths under rainfed and irrigated growing conditions for 26 crop classes using the MIRCA2000 data set. Their results showed that a 37% (on average) reduction in rooting depth under irrigation than compared to dryland crops. For example, the rooting depth for soybean was 0.60 m (irrigated) versus 1.30 m (rainfed) which represents a 54% reduction. The rooting depth for rye (and wheat) was 1.25 m (irrigated) versus 1.60 m (rainfed) and appears least affected by irrigation (i.e. only 22% reduction in rooting depth).

4.3.3.2 Sugarcane (Averaged)

The mean annual runoff was determined using the *ACRU* variables for each sugarcane growing region (i.e. Inland, South Coast & North Coast as given in **Table 73** in **APPENDIX A**). The results showed that 23.1% of the 134 quinaries exhibited a reduction in runoff (relative to the baseline) of 10% or more (**Table 39**). A very similar result (26.1%) was obtained using the mean annual runoff derived from the averaged crop-related variables given in **Table 73** (**APPENDIX A**).

Table 39 Analysis of simulated runoff based on preliminary *ACRU* runs (i.e. original quinary climate database), for sub-catchments in which 10% of more of the sugarcane mill supply areas are located

Location of quinaries	**Percentage of 134 quinaries with a reduction in mean annual runoff ≥ 10%**			
	Inland parameters	S. Coast parameters	N. Coast parameters	Averaged parameters
Inland	23.13			26.12
South Coast		0.00		0.00
North Coast			0.00	0.00
Total	**23.13**	**0.00**	**0.00**	**26.12**

Table 39 also shows that the quinaries where sugarcane production may be declared a SFRA are located in the inland growing region only (i.e. KZN Midlands). In other words, no quinaries located along the South or North Coast of KwaZulu-Natal are deemed SFRA areas. This trend was also observed in the original SFRA project undertaken by Jewitt *et al*. (2009b). Thus, the use of averaged parameters increased the number of quinaries flagged as potential SFRAs from 31 to 35 (out of 47) in the inland region. Due to this similarity in results, the decision was made to complete only one national run using averaged variables to represent sugarcane production. This reduced the number of national runs required for sugarcane from three down to one.

4.3.3.3 The need for localised crop coefficients

Crop coefficients 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. Rana and Katerji (2008) highlighted the complexity of the crop coefficient, which actually integrates several functions, *viz*.:

- aerodynamics linked to the height of the crop,
- biological factors linked to the growth and senescence of the surface leaves,
- physical factors linked to the evaporation from the soil,
- physiological factors linked to the response of the stomata to the vapour pressure deficit of the air, and
- agronomy-related factors linked to the crop management (distance between rows, use of a mulch, irrigation system etc.).

Therefore, locally “calibrated” crop coefficients are recommended for crop water use estimation. Hence, one of the many outcomes of this project was the derivation of monthly crop coefficients for various biofuel crops, which were obtained from two different sites over multiple seasons. By definition, crop coefficients require no water or other stresses (e.g. disease) that may reduce crop water use. Hence, experiments designed to estimate crop coefficients should be irrigated and well managed. This highlights the importance and value of the research trials conducted at both the Ukulinga and Hatfield research farms, in meeting the overall objectives of the biofuels project.

4.3.4 Water use (*SWB*)

The *SWB* model growth parameters that were determined for sweet sorghum (see **Section 4.3.4.1**) and Moringa (see **Section 4.3.4.2**) from the well-watered control treatments at Hatfield were used to run the model. The results of the simulated water use are presented next.

4.3.4.1 Sweet sorghum

The *SWB* model simulation results for sweet sorghum are presented in **Figure 7** and **Figure 19**. According to the soil water balance graph (**Figure 7**), a total of 722 mm rainfall was recorded, while an additional 216 mm of irrigation water applied during the sweet sorghum growing season in 2010/11.

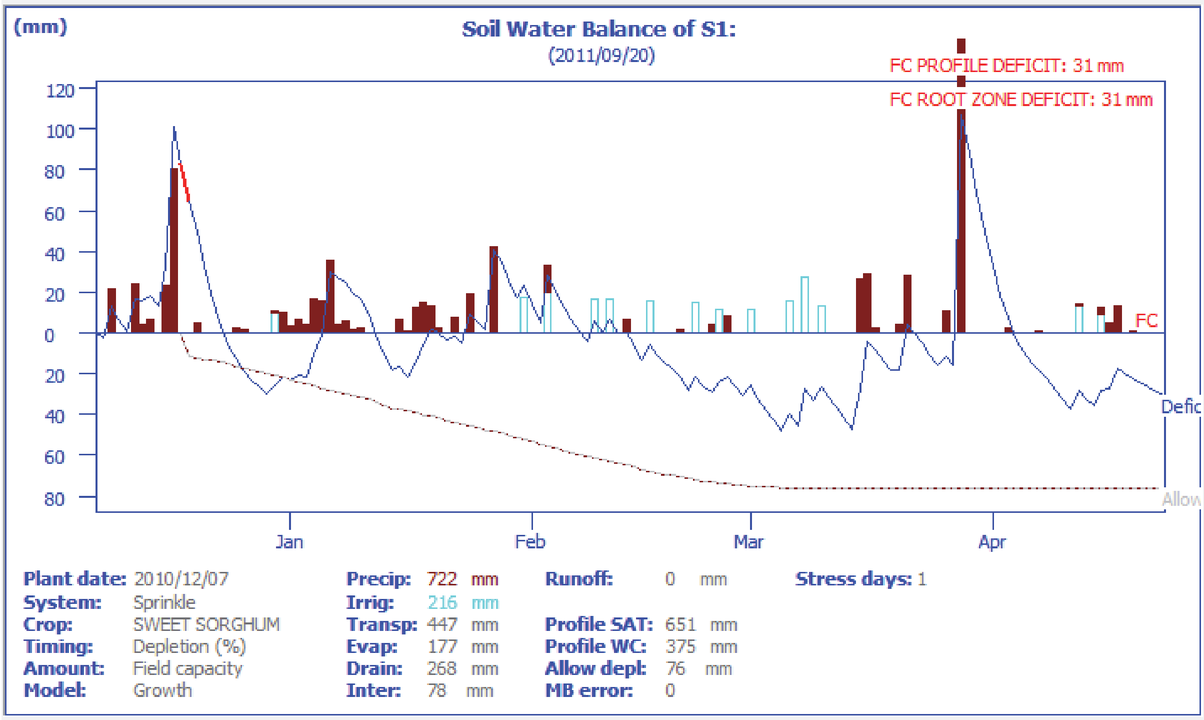


Figure 7 Soil water balance output graph for sweet sorghum at Hatfield based on the calibration data set for the well-watered control treatment in the 2010/11 season

Several large rainfall events were recorded during the growing season, resulting in substantial drainage losses (simulated at 268 mm). These large rainfall events complicated daily or weekly soil water balance calculations from measurements, which made it difficult to determine actual drainage losses, and therefore actual water usage. However, since measured and simulated soil water contents were in general agreement (**Figure 7**), it was assumed that the model simulations gave a true estimation of the actual soil water balance components, and therefore also of drainage losses and seasonal crop water usage. Total crop water use for the growing season was estimated at 624 mm (447 mm of transpiration, plus 177 mm of soil water evaporation).

4.3.4.2 Moringa

The FAO crop parameters determined for Moringa from the high tree density irrigated treatment at Hatfield were used to simulate water use for the same treatment. Some of the *SWB* model simulation results for Moringa are presented in the next three figures. A total of 889 mm of rainfall was recorded for the summer growing period (1st September 2010 to 31st May 2011). In addition, 416 mm of irrigation water was applied during the growing season (**Figure 8**).

SWB model simulations indicated that 506 mm of water was transpired during the growing season, which is in agreement with the value of 502 mm determined from sap flow measurements for the same treatment. A further 348 mm of water evaporated from the soil surface, while the simulated drainage was 386 mm for the season. The seasonal ET for the nine-month summer growing season therefore totalled 854 mm.

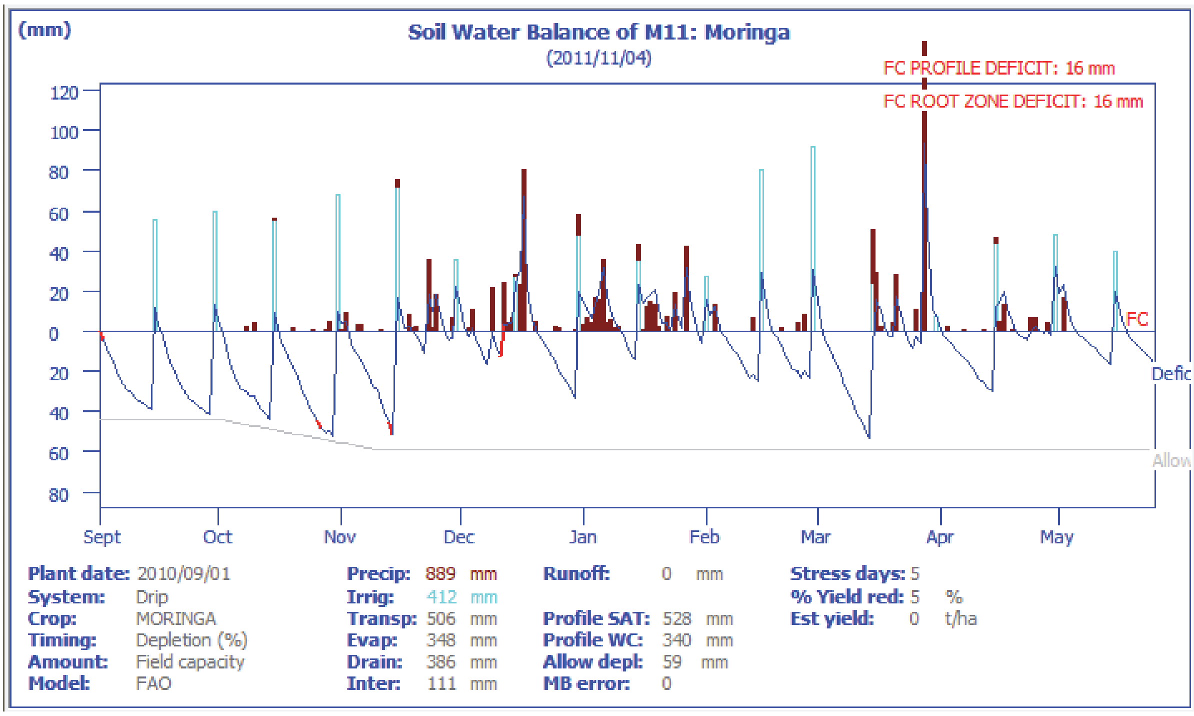


Figure 8 Soil water balance output graph for the high density, irrigated Moringa treatment at Hatfield in 2010/11

4.3.5 Yield (*AQUACROP*)

4.3.5.1 Model output verification

The model was extensively calibrated for both sugarbeet and sugarcane by Mokonoto (2015) in order to better simulate local growing conditions. The results of the calibration for these two crops is given next. A simple verification was conducted by Moyo and Savage (2014) at Baynesfield for soybean.

Sugarbeet

The initial simulation (using the default parameter file) of canopy cover for sugarbeet (**Figure 9**) over-estimated the canopy cover measured at Ukulinga. However, the simulation of canopy cover using the calibrated version was more accurate. In the first 100 days after planting (DAP), the model slightly under-estimated the measured values but after that, simulated values were closely matched with observations. This was especially the case when the crop approached maximum canopy cover after 140 DAP.

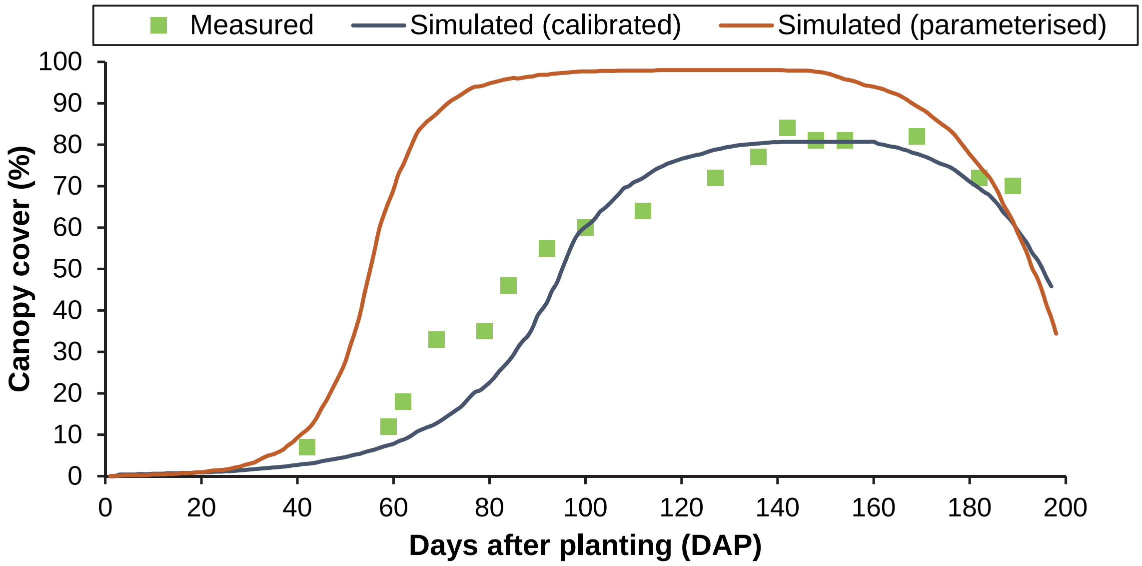


Figure 9 Differences between the parameterised (i.e. default parameters) and calibrated (i.e. modified parameters) sugarbeet canopy cover simulations in relation to measured values at Ukulinga in 2013 (Mokonoto, 2015)

The statistical indicators shown in **Table 40** also indicate improvements in the simulations between the calibrated and parameterised model. Both the R^2 and IoA approach unity (i.e. 1) for the calibrated model, thus indicating a relatively high "goodness of fit". Similarly, all RMSE values are lower for the calibrated version, than compared to the parameterised model simulation. The assumption is made that if the model predicts the development of the canopy cover well, then the yield estimation should be accurate and robust.

Table 40 Statistical indicators for the calibrated and parameterised simulations of percentage canopy cover for sugarbeet (Mokonoto, 2015)

Statistical indicators	Calibrated	Parameterised
R^2	0.945	0.368
IoA	0.972	0.621
RMSE (%)	9.217	35.537
RMSEs	6.085	31.054
RMSEu	6.922	17.279

Sugarcane

Cultivar NCo376 was used in the calibration. A relatively poor goodness of fit and agreement (**Figure 10**) between the parameterised simulation and observed canopy cover was obtained for seven of the eight treatments. Treatment 5 (T5) was the only exception in which an R^2 of 0.882 and IoA of 0.828 were obtained.

The calibration improved the simulations, with higher R^2 and IoA values. However, the relatively high RMSE values indicate the model did not perform well in simulating the percentage canopy cover. The reason for this is due to the lack of crop experimental data (e.g. LAI) in the early phase of the growth cycle which would have allowed the determination of the initial canopy size (CC_o). This parameter affects the time to maximum canopy cover (Steduto *et al*., 2012). Furthermore, the time to canopy senescence could not be derived. This resulted in the model not being able to simulate the onset of canopy senescence as indicated in treatments 6 to 8.

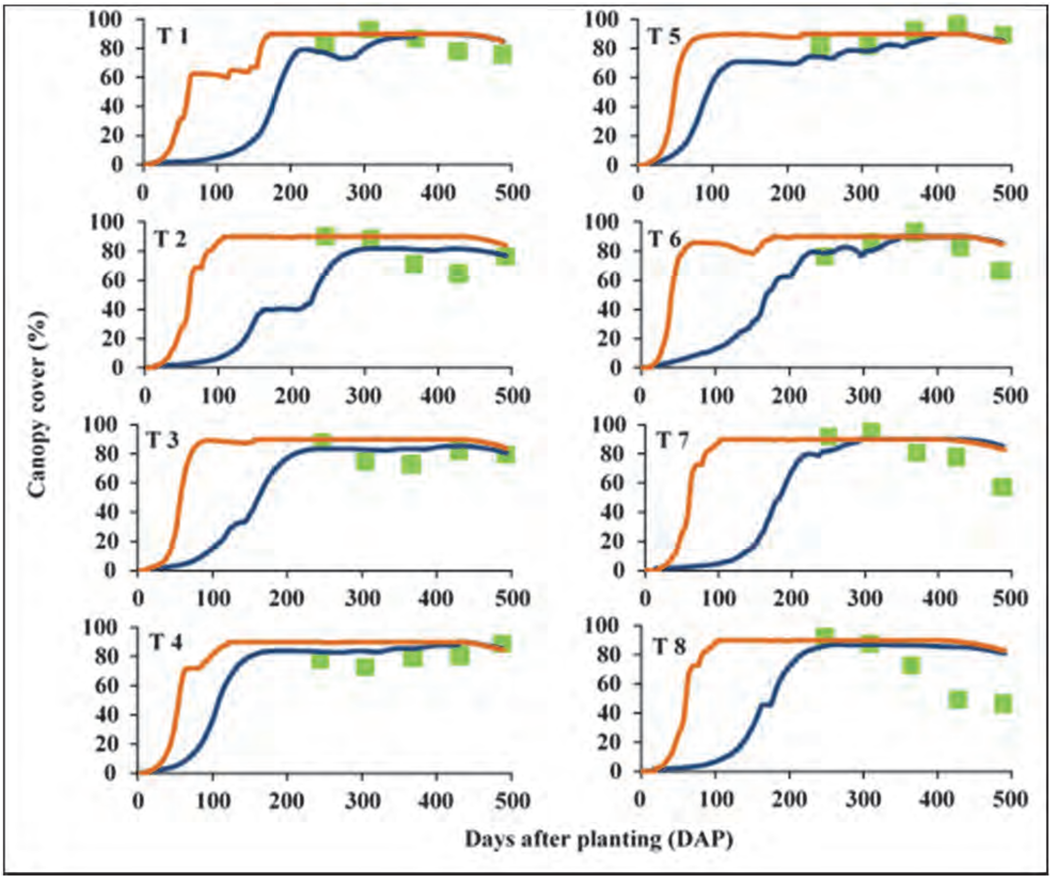


Figure 10 Comparison of the calibrated (blue) and parameterised (orange) sugarcane canopy cover simulations with reference to measured values (green) for eight different planting dates or treatments (T1 to T8) (Mokonoto, 2015)

<u>Soybean</u>

The water use of soybean measured over the 2012/13 season of 189 days at Baynesfield Estate was 469 mm. This compares favourably with the figure simulated by *AQUACROP* of 423 mm by Moyo and Savage (2014). The observed and simulated yields for 2012/13 season at Baynesfield Estate were 5.28 and 5.40 t ha^{-1} respectively, which again shows good agreement as the model over-estimated the yield by 2.3% (Moyo and Savage, 2014). Overall, the model over-estimated WUE by 13.4% for soybean (WUE_{obs} = 1.13 and WUE_{sim} = 1.28 kg m^{-3}). The observed yield reported by Moyo and Savage (2014) of 5.28 t ha^{-1} is higher than the 3.52 t ha^{-1} which was the average yield from 42.46 ha using a combine harvester. This comparison highlights the yield loss that results from mechanical harvesting *vs*. manual harvesting.

4.3.5.2 Model output corroboration

<u>Sugarbeet</u>

A final fresh yield of 45.4 t ha^{-1} was measured at Ukulinga during the 2013 season. According to Raes *et al*. (2012c; c.f. Annex I), a general conversion factor of 20 to 25%, in terms of kg of dry matter per kg fresh weight, may be used. This concurs with measurements at Ukulinga where dry matter percentage ranged from 19.4 to 21.4% (average of 20.3% based on eight samples in the third trial). Therefore, the dry yield is 9.22 t ha^{-1}, which was compared with the simulated yields of 13.81 and 18.80 t ha^{-1} for the calibrated and parameterised versions respectively. Although the model over-estimated the observed yield, the calibrated version produced lower RMSEs than the parameterised version.

The water use of sugarbeet measured over the 2013 season of 186 days at Ukulinga was 411 mm. This compares favourably with the figure simulated by *AQUACROP* of 413 mm by Mokonoto (2015). This equates to a simulated WUE of 3.34 kg m^{-3}, which is somewhat higher than the observed range of 2.21 to 2.76 kg m^{-3}.

AQUACROP was further tested (i.e. validated) using an independent dataset for Komatipoort from October 2011 to May 2012. The experiment consisted of two treatments, with 50 and 100% of the irrigation demand being satisfied. The same parameter file developed for Ukulinga was used, with only the soil and climate files changed to represent Komatipoort. *AQUACROP* slightly over-estimated the final yields for both treatments. The result illustrates the robustness of the model, showing its ability to predict yields at other locations (**Figure 11**).

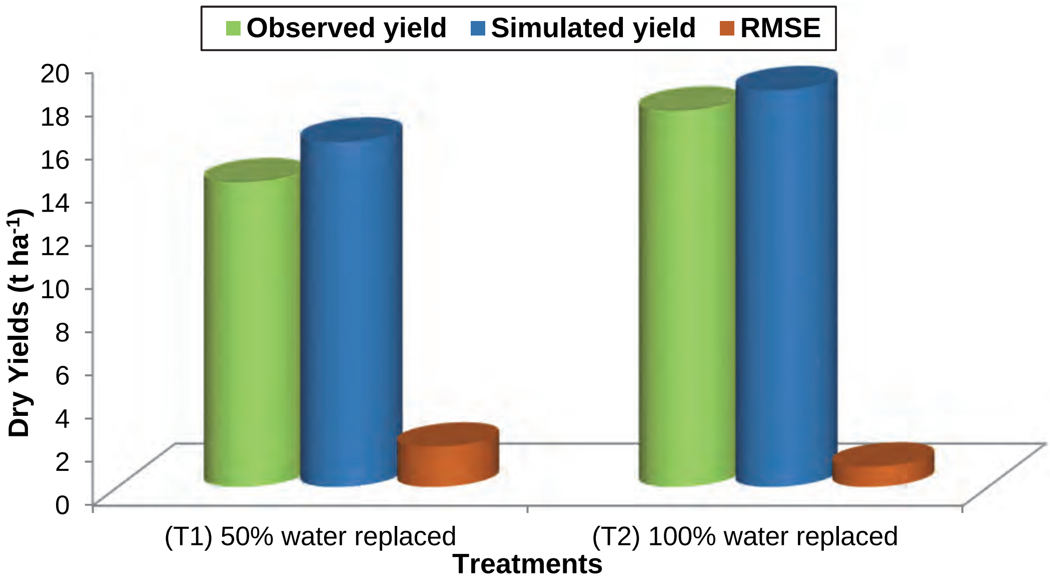


Figure 11 Difference between observed and simulated sugarbeet dry yields at Komatipoort in 2012 for two treatments (Mokonoto, 2015)

Sugarcane

Parameterised (i.e. default parameter) model simulations mostly under-estimated the final yields, except for treatment 2 (**Figure 12**). This figure illustrates how the calibration improved the prediction of final cane yield for each of the eight treatments, especially for treatments 5 and 6. However, final yields were over-estimated in five of the eight treatments resulting in a mean dry yield (of all eight treatments) that was 1.2 t ha^{-1} over the observed. Low RMSE values ranging from 1.67 (T6) to 5.59 (T8) further indicate that the model performed well in simulating the final yields compared to the parameterised simulations.

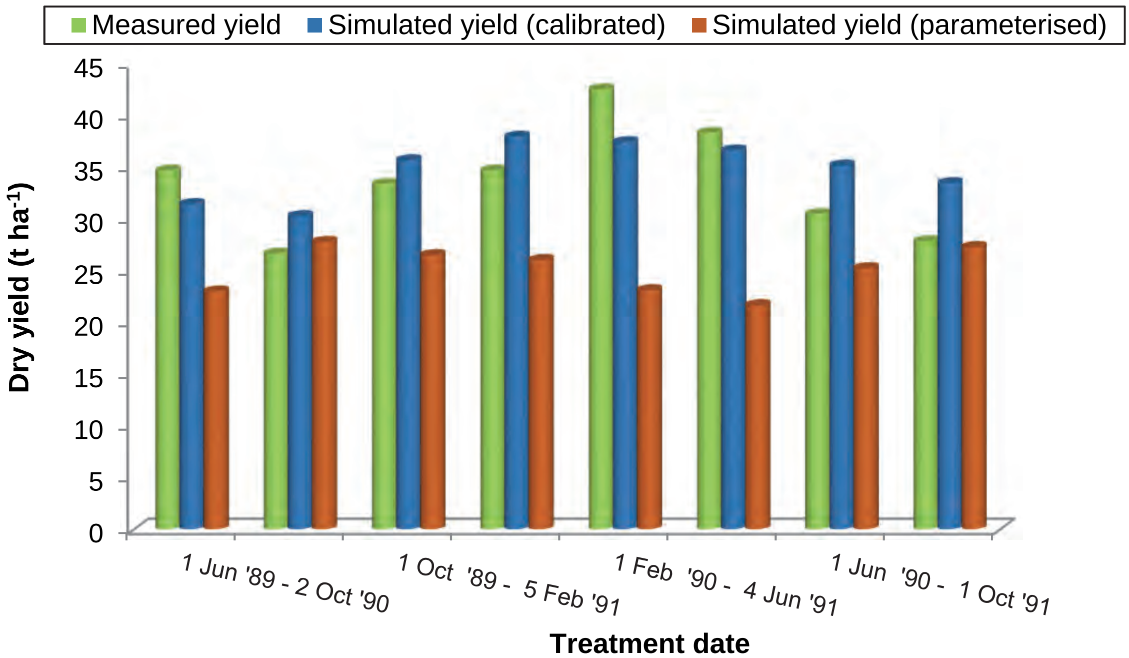


Figure 12 Difference between calibrated (blue) and parameterised (orange) sugarcane simulated dry yields in relation to the measured yields shown in green (Mokonoto, 2015)

AQUACROP was also tested (i.e. validated) using an independent dataset for Pongola from December 1968 to May 1971. The experiment consisted of eight treatments, which represented eight different planting dates. The same parameter file developed for La Mercy was used, with only the soil and climate files changed to represent Pongola. *AQUACROP* slightly under-estimated the final yield for six of the eight treatments at Pongola, with low RMSE values further indicate the model performed fairly well (**Figure 13**). This result again illustrates the robustness of the model.

As noted earlier, cultivar NCo376 was used to calibrate sugarcane at La Mercy. Based on an experiment conducted at Komatipoort in 2012 involving two irrigation treatments and three cultivars, *AQUACROP* predicted final yields well for cultivar N31, followed by cultivar's N19 and 04G0073 (Mokonoto, 2015).

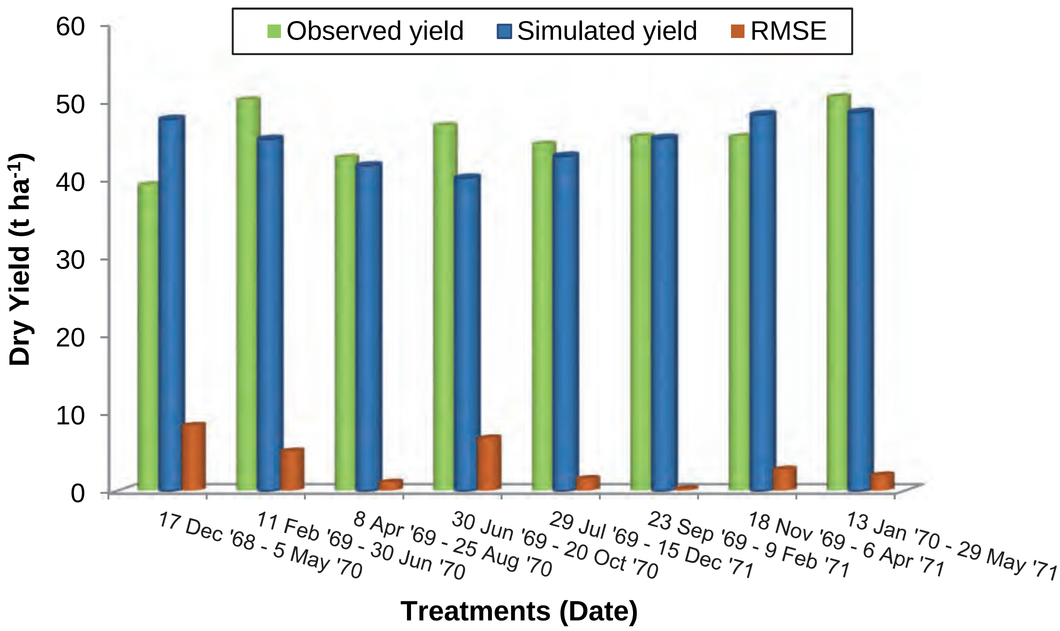


Figure 13 Differences between observed and simulated sugarcane dry yields at Pongola from 1968-1971 (Mokonoto, 2015)

4.3.5.3 Water use estimation

From the results presented above, *AQUACROP* adequately estimated the crop water use (i.e. total evaporation accumulated over the growing season) for both sugarbeet and soybean. However, Mokonoto (2015) noted that although the totals are comparable, the model does not adequately predict the daily variation in ET. *AQUACROP* under-estimated ET during the development growth stage (< 100 DAP) when soil water evaporation is dominant. The model then tended to over-estimate ET from 100 DAP to maturity when transpiration becomes dominant. These findings concur with those of Paredes *et al*. (2014), stating that *AQUACROP* tended to under-estimate soil water evaporation and over-estimate transpiration for maize. This implies that soil water content will be over-estimated during the early season (due to insufficient soil water evaporation) and under-estimated from the mid- to late-season. This concurs with findings by Mokonoto (2015) and by Nyakudya and Stroosnijder (2014), who also noted that *AQUACROP* over-estimated soil water content or maize.

4.3.5.4 Implementation verification

The inter-seasonal yield and WUE of sugarcane is given in **Figure 48** and **Figure 49** (**APPENDIX C**) respectively. The figures show the low yield and WUE simulated by the model in the first season (1950/51), which cannot be explained. The average yield (over 40 seasons) is higher for the April transplanting (27.50 dry t ha^{-1}) compared to the February transplanting (23.63 dry t ha^{-1}). However, the yield variation is slightly higher for February (30.14%) compared to April (27.94%). The February transplanting was affected more by the severe droughts which occurred in 1953, 1968 and from 1982 to 1984. According to Du Toit (1954), the rainfall in KwaZulu-Natal was deficient from March to August 1953 when "an exceptionally severe drought was experienced". However, the 1992/93 drought resulted in low yields for both transplanting dates. Based on these simulated results, an April transplanting is preferred for quinary 4 719, yet the observed yields recorded at La Mercy in

1990 were highest for the February treatment. The same trends were observed for WUE. However, the coefficient of variation of WUE is lower than that for yield.

4.3.6 Yield (*SWB*)

The *SWB* growth model has been parameterised for sweet sorghum using the Hatfield experimental data set. The model was then to estimate both total and stalk dry matter yields at Hatfield as well as Ukulinga. Hence, the Ukulinga data set for sweet sorghum was used to validate the *SWB* crop growth model. These results are presented in **Section 4.3.6.2.**

4.3.6.1 Model output verification

The results of the model parameterisation for sugarbeet, sweet sorghum, canola and Moringa are presented next.

<u>Sugarbeet</u>

SWB model simulation results of sugarbeet water use for the 2010/11 Ukulinga trial are shown in **Figure 14** and **Figure 15**. Since the FAO model does not simulate growth, measured *LAI* values could not be plotted against simulated *LAI*. However, canopy cover (or fractional interception, *FI*) could be calculated from measured *LAI* values, assuming a canopy extinction coefficient of 0.6. Simulated canopy cover followed the same trend as calculated *FI* values, but substantial differences occurred early and late in the season. This probably resulted in the poor correlations observed between measured and simulated soil water deficits.

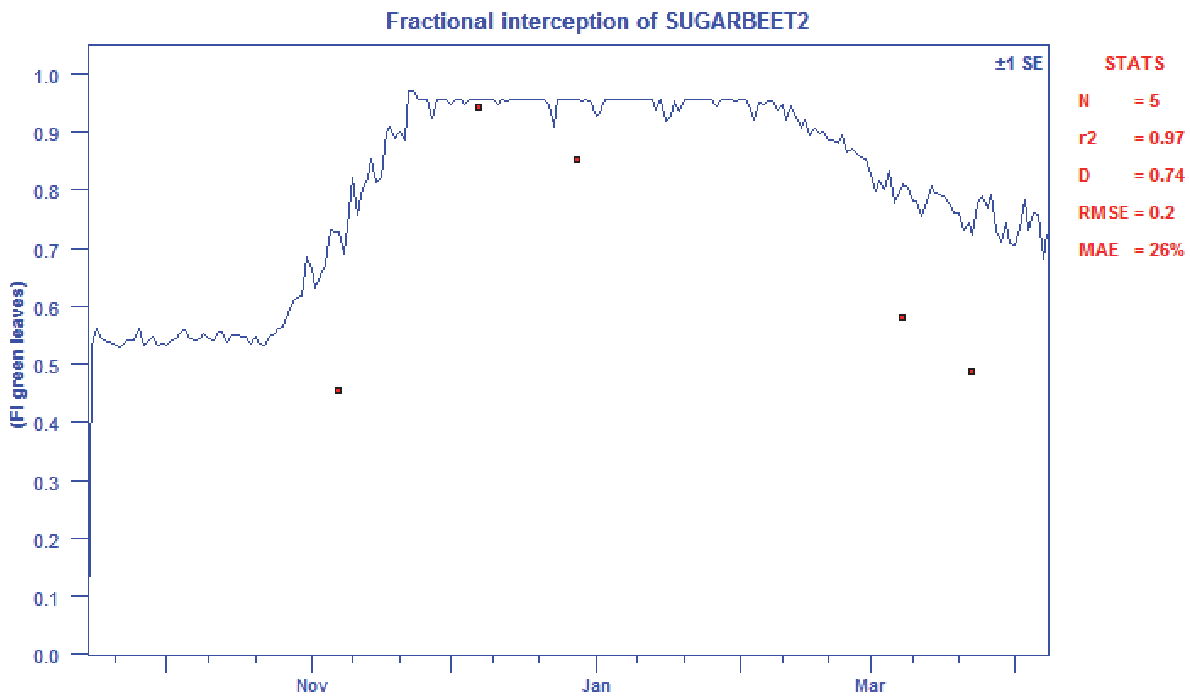


Figure 14 *SWB* model simulation results of sugarbeet fractional interception (*FI*; top) for the 2010/11 season at Ukulinga (line = simulated; point = measured value)

A total dry matter root yield of 12 t ha^{-1} was simulated, while the observed yields ranged between 7.2 and 12.2 t ha^{-1}. Only one water regime was applied in the trial (i.e. well-water conditions) and therefore, model performance could not be evaluated under varying water supply conditions. These observed yields compared well with yields reported by Farley and Draycott (1974), who also found root dry mass yields of 12 t ha^{-1}. Other authors generally obtained higher yields than this. For example, Refay (2010) reported dry mass root yields ranging between 16 and 21 t ha^{-1}.

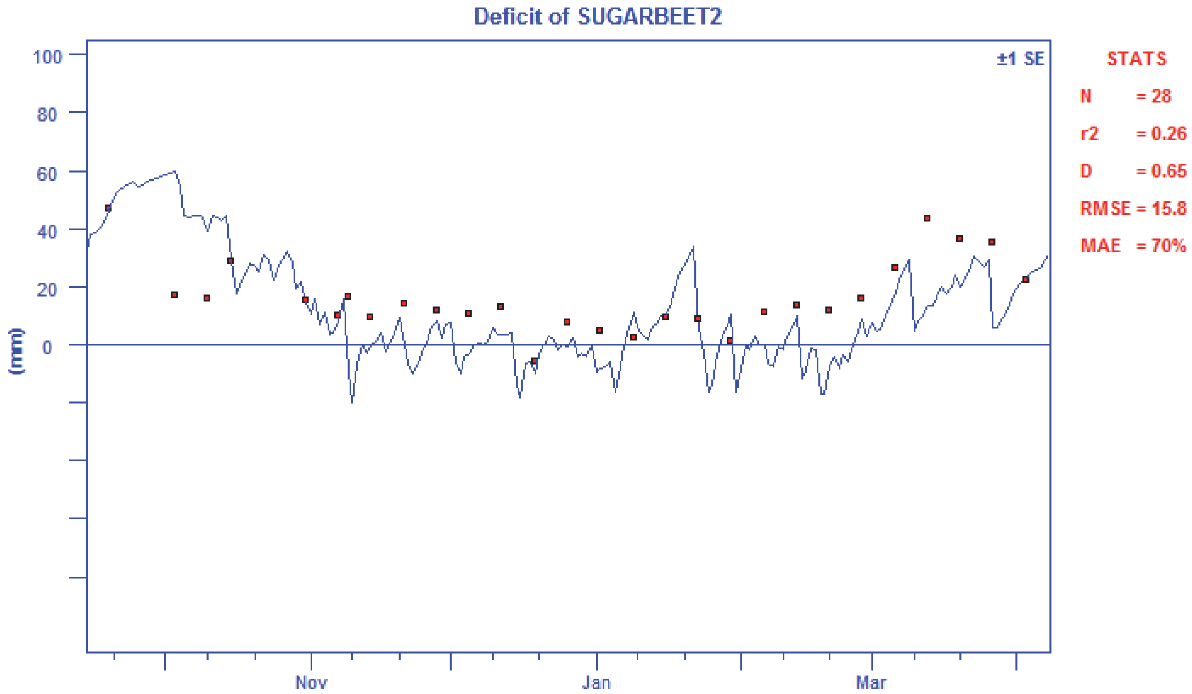


Figure 15 *SWB* model simulation results of sugarbeet soil water deficits for the 2010/11 season at Ukulinga (line = simulated; point = measured value)

<u>Sweet sorghum</u>

Weather and frequent growth analysis data were used to determine crop-specific growth model parameters for sweet sorghum. These included the canopy radiation extinction coefficient, radiation use efficiency, specific leaf area, leaf-stem partitioning parameter, vapour pressure-corrected dry matter/water ratio and thermal time requirements for different developmental stages (Jovanovic *et al*., 1999).

A T_{bse} value of 10°C, as recommended by Curt *et al*. (1995), was used in this study for sweet sorghum. Parameters that could not be determined from data are typically obtained from the literature or through calibration. Parameter values derived for the sweet sorghum growth model are presented in the results.

Growth parameters for the *SWB* model were determined for sweet sorghum from the Hatfield 2010/11 trial and are given in **Volume 2**. The relationships between some of the parameters are shown in **Figure 16** to **Figure 18** below. These were determined for sweet sorghum from the well-watered control treatment at Hatfield. The relationship between leaf area index (*LAI*) and fraction of intercepted solar radiation (*FI*) for sweet sorghum is shown in **Figure 16**.

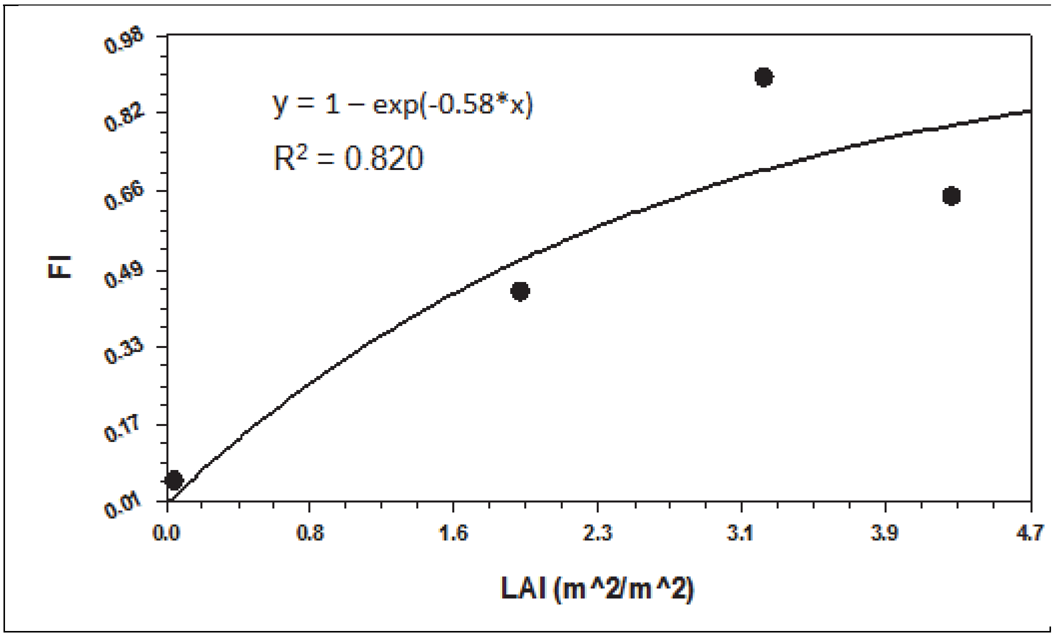


Figure 16 Relationship between the leaf area index (*LAI*) and fraction of intercepted solar radiation (*FI*) for sweet sorghum at Hatfield

In **Figure 17**, top dry matter (*TDM*) production of sweet sorghum is a function of the cumulative product of fractional interception (*FI*) and total solar radiation (R_s). The fitted model is *TDM* = 0.002 * ∑(*FI**R_s), with an R^2 value of 0.92. The slope represents radiation conversion efficiency (E_c).

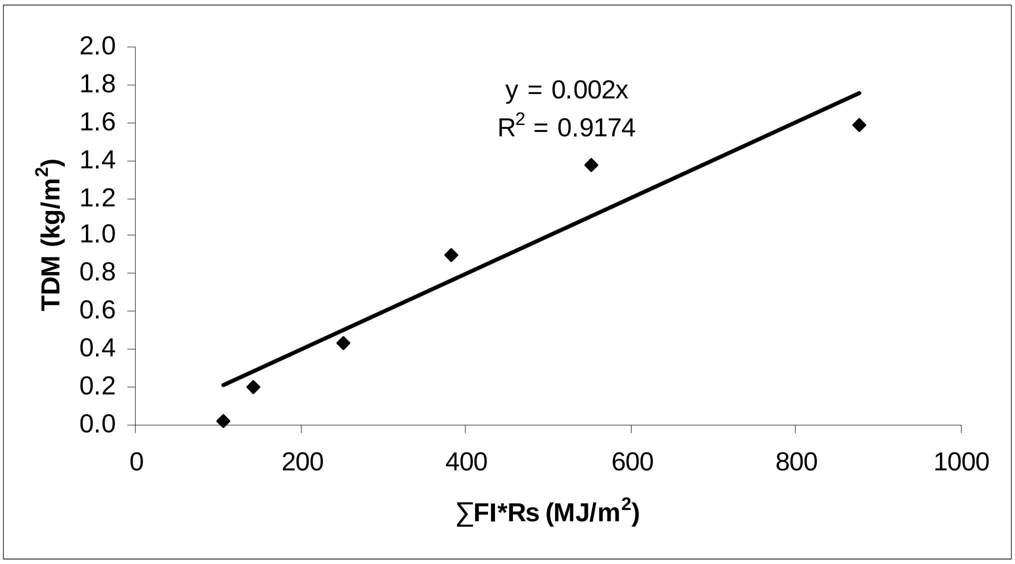


Figure 17 Top dry matter (*TDM*) production of sweet sorghum at Hatfield as a function of the cumulative product of fractional interception (*FI*) and total solar radiation (R_s)

The relationship between sweet sorghum canopy dry matter (*CDM*), specific leaf area (*SLA*) and leaf area index (*LAI*) is shown in **Figure 18**. The slope of the regression line represents the leaf-stem dry matter partitioning parameter (p in m^2 kg^{-1}).

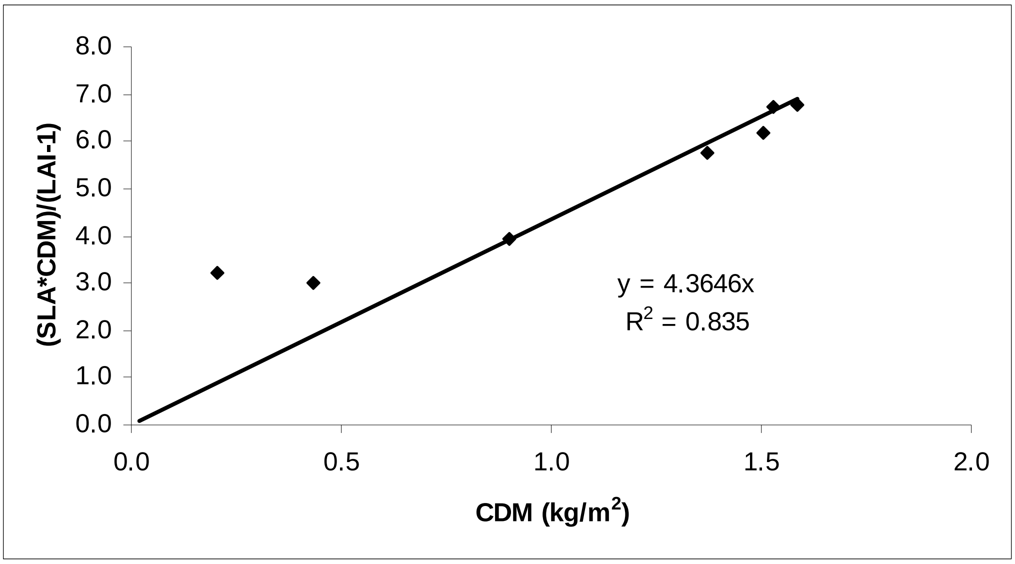


Figure 18 Relationship between sweet sorghum canopy dry matter (*CDM*), specific leaf area (*SLA*) and leaf area index *(LAI*) at Hatfield research farm

Figure 19 illustrates simulated (lines) and measured values (points) for root depth, leaf area index, total dry matter yield and soil water deficits. Measured dry biomass yields recorded in the 2010/11 season at Hatfield (15.8 Mg ha^{-1}) fall within the range (12.6 to 27.6 Mg ha^{-1}) recorded by Vasilakogloua *et al*. (2011) under Mediterranean conditions. In general, simulated above-ground dry matter production, canopy development (leaf area index) and daily soil water deficits agreed well with measured values.

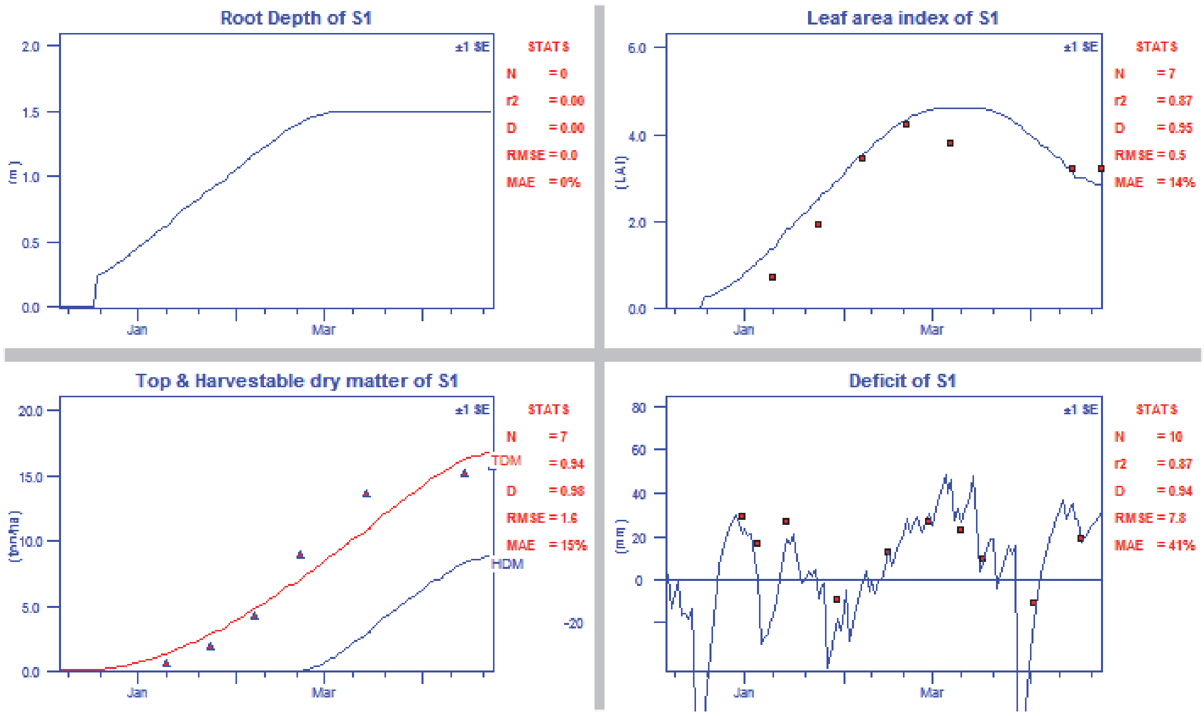


Figure 19 Simulated (lines) and measured data (points) of sweet sorghum root depth (top left), leaf area index (top right), top dry matter yield (bottom left) and soil water deficits (bottom right) for the 2010/11 growing season at Hatfield

It can therefore be concluded that the model was successfully calibrated for sweet sorghum. The next step was to validate the model against independent data sets, e.g. other treatments in the Hatfield trial, as well as the 2010/11 Ukulinga data set. These results are presented in **Section 4.3.6.2**.

Canola

Field data collected at Hatfield during the winter of 2002 was used to determine specific crop parameters for canola as well as to calibrate the *SWB* model. The crop parameters are given in **Volume 2**. Output from the *SWB* model simulation is shown in **Figure 20** for the unstressed treatment. The graphs show the simulated *vs*. measured root depth (top left) and *LAI* (top right). The bottom two graphs show the simulation of top and harvestable dry matter and the water deficit from field capacity (with measured valued based on neutron probe readings). Overall, the simulation performed well against measured data for the unstressed treatment in 2002. However, water deficit was over-estimated by the model as indicated by a poor coefficient of determination. The over-estimation of water deficit began at the flowering stage or 76 days after planting when the roots ere 1 m deep. The vertical bars are one standard error of the measurement (Tesfamariam, 2004).

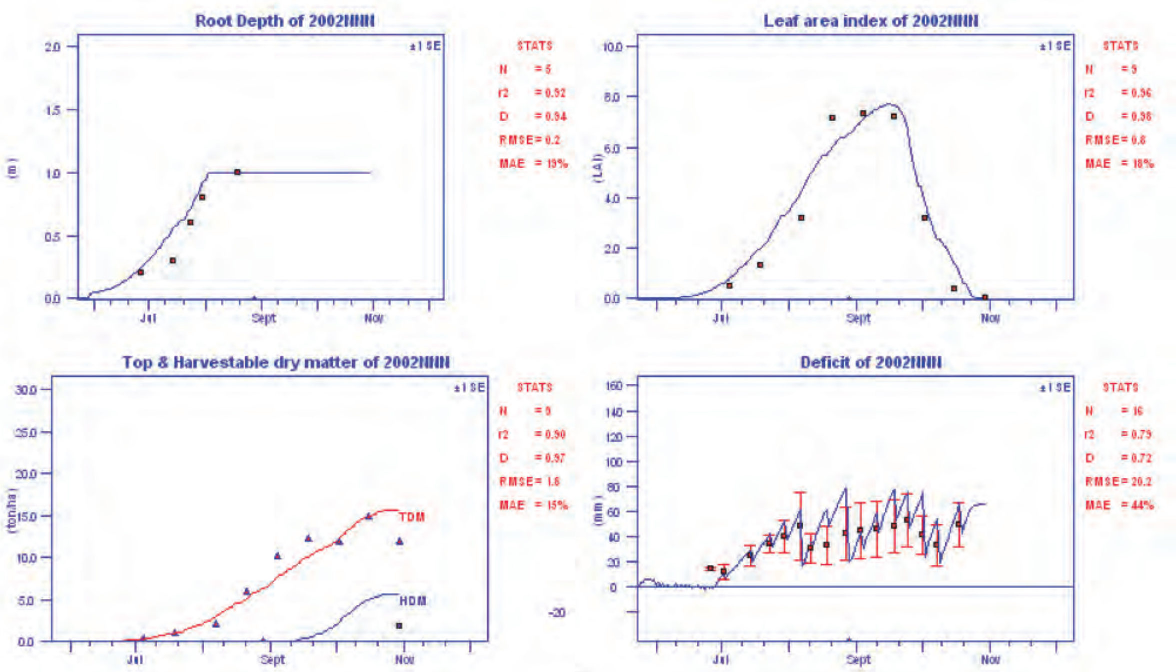


Figure 20 Simulated (lines) and measured data (points) of canola root depth (top left), leaf area index (top right), top dry matter yield (bottom left) and soil water deficits (bottom right) for the 2002 growing season at Hatfield (Tesfamariam, 2004)

Moringa

Simulated soil water deficits over the growing season are shown in **Figure 21**. Measured and simulated values agreed reasonably well, with r^2 value of 0.72, a D index of 0.9 and RMSE of 17.4. The MAE was, however 28%, which is slightly higher than the acceptable norm of below 20%. Measured and simulated values for fractional interception of solar radiation (*FI*) for Moringa are presented in **Figure 22**. A good agreement between measured and simulated values was generally observed, with r^2 and D-index values above 0.9 and MAE of 8%.

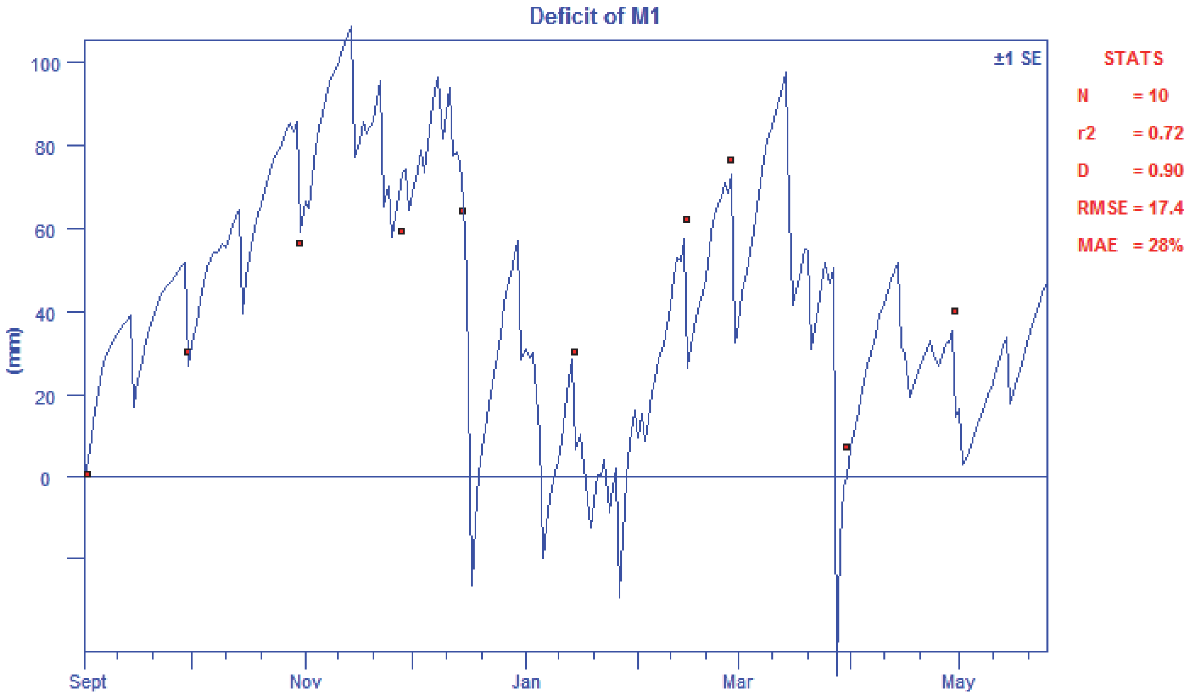


Figure 21 Measured data (points) and simulated (lines) soil water deficits for Moringa. Calibration data set: high density irrigated treatment during the 2010/11 season at Hatfield

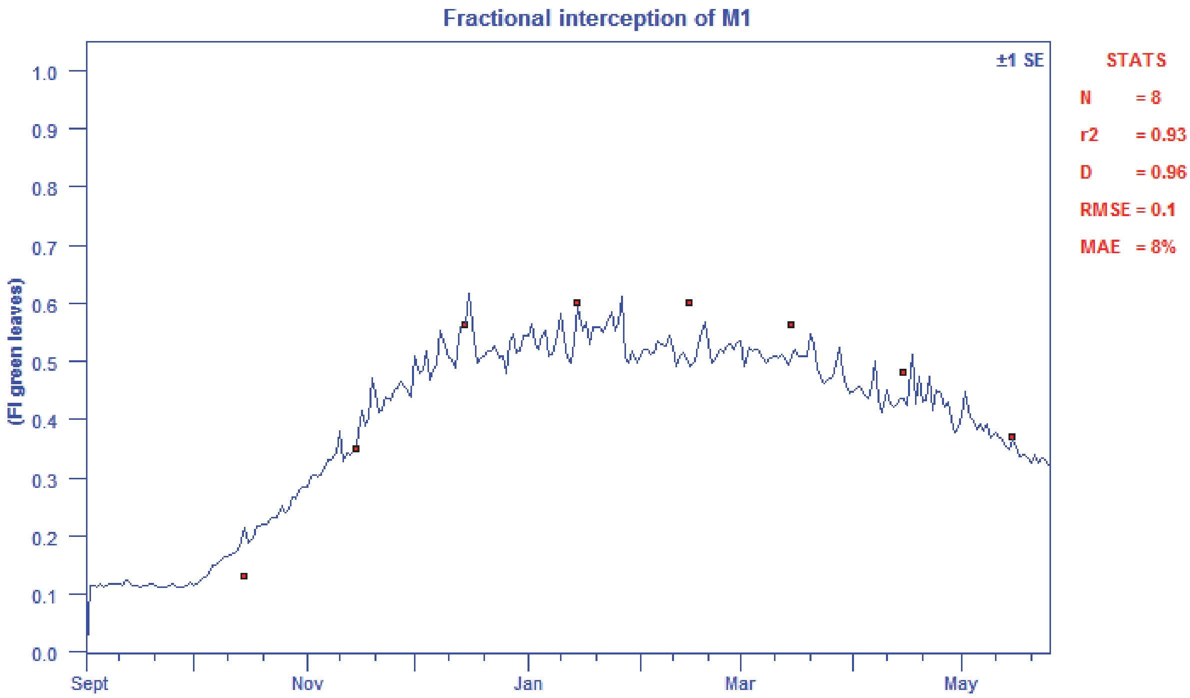


Figure 22 Measured data (points) and simulated (lines) fractional interception of solar radiation (*FI*) for Moringa. Calibration data set: high density irrigated treatment during the 2010/11 season at Hatfield

The general good agreement between simulated and measured values of both soil water deficit and fractional interception of solar radiation suggests that the model simulations are reliable, using the parameters generated from the same trial. The model still needs to be validated on independent data sets from different seasons before scenario simulations for different parts of the country can be run.

Tree growth and production are complex processes and cannot easily be simulated with a generic crop model such as *SWB*. Pretoria University are investigating the possibility of including tree growth in the *SWB* growth model. However, this option is not yet available. Therefore, *SWB* can only be used to simulate water use (and potential yield reduction) from FAO crop factors (c.f. **Section 4.3.4.2**). Although this approach is less mechanistic and will probably not be able to simulate crop yields accurately, is can still give useful indications of yields that could be expected under specific climatic, soil and water supply conditions.

SWB model simulation results of total dry leaf production for the 2010/11 season at Hatfield are given in **Table 41**. Based on water use and water balance simulations, a dry matter leaf yield of 2.53 t ha^{-1} was simulated for the high density irrigated treatment, which compared well with the observed yield of 2.48 t ha^{-1}. Similarly, the simulated dry leaf yield (1.84 t ha^{-1}) for the high density dryland treatment compared well with measured yield (1.73 t ha^{-1}).

Table 41 *SWB* simulation results for total dry matter yield (*TDM*) of Moringa grown under different water supply conditions (2010/11 season), based on a leaf dry matter content of 10% for both treatments

High Density Treatment	Total dry leaf yield (t ha^{-1})	
	Observed	Simulated
Irrigated	2.48	2.53
Dryland	1.73	1.84

These results suggest the *SWB* model is able to simulate water stress effects well, which resulted in a smaller canopy and lower leaf yield. Since pod and seed yields were quite variable between and within seasons, the model could not succeed in simulating these effects. It is hoped that an improved version of *SWB*, that can simulate tree growth realistically, will be available in the near future. Such a model should be able to simulate canopy development and production better than the FAO model which was used here.

4.3.6.2 Model output corroboration

Sweet sorghum

The *SWB* growth model was parameterised using data from the control treatment of the drought trial conducted at Hatfield in 2010/11. The model was then verified by comparing simulated with observed dry matter yields (total & stalk) for the other treatments and experiments. **Figure 23** and **Figure 24** are examples of the output graphs for simulated total (*TDM*) and stalk dry matter (*HDM*) yields. From the graphs, it is clear that total biomass and stalk (harvestable) dry yields were simulated with reasonable accuracy under well-watered and dryland conditions.

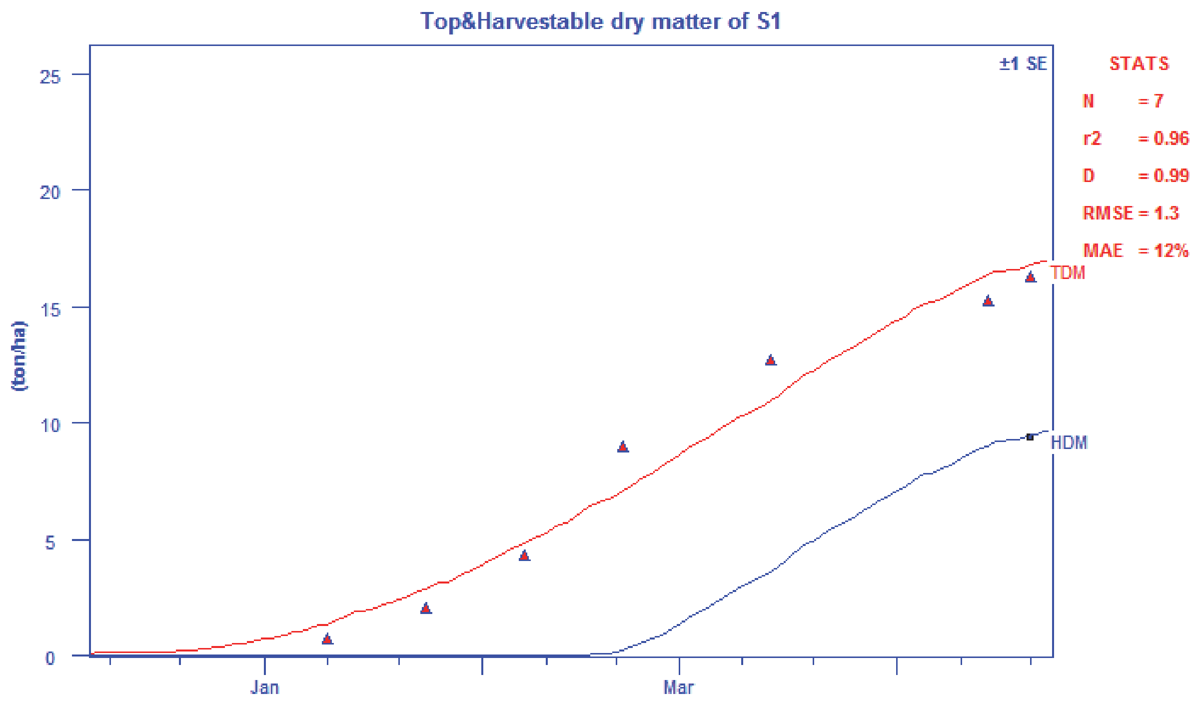


Figure 23 Simulated total (*TDM*; red line) and stalk dry matter (*HDM*; blue line) yield for the sweet sorghum control treatment (at Hatfield in 2010/11 season). Lines represent simulated values from *SWB*, whilst points indicate measured values

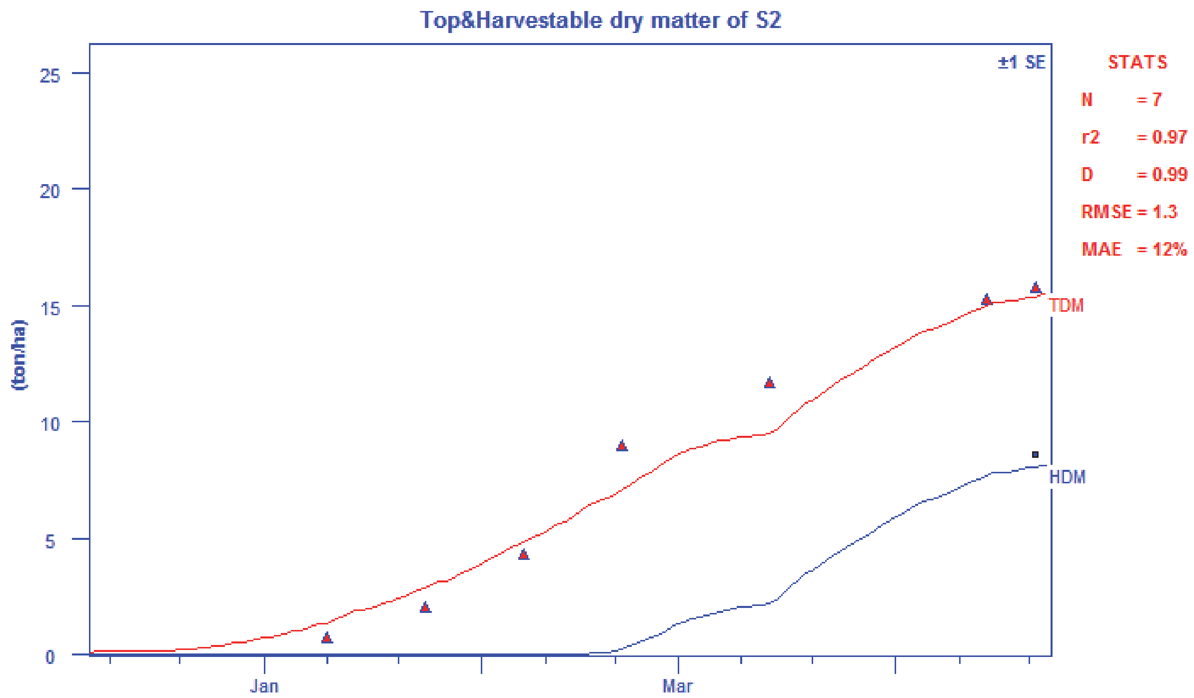


Figure 24 Simulated total (*TDM*; red line) and stalk dry matter (*HDM*; blue line) yield for the sweet sorghum dryland treatment (at Hatfield in 2010/11). Lines represent simulated values from *SWB*, whilst points indicate measured values

Simulation results for the different trials and water supply conditions are summarised in **Table 42**. Stalk yields presented in **Table 42** indicate that sweet sorghum yields were generally simulated well under a range of water supply conditions at Hatfield, with the exception of the LVS treatment, for which yields were over-estimated by about 15%.

Table 42 *SWB* simulation results for total dry matter yield (*TDM*) and stalk dry matter (*HDM*) yields of sweet sorghum at different locations and water supply conditions

Treatment	Trial type	Total dry matter yield (t ha^{-1})		Stalk dry matter yield (t ha^{-1})	
		Observed	Simulated	Observed	Simulated
Control	Drought trial	16.5	16.8	9.4	9.6
Dryland	Drought trial	15.5	15.5	8.6	8.2
EVS	Drought trial	17.7	17.2	10.3	9.9
LVS	Drought trial	14.8	16.5	8.2	9.6
Hatfield	Water use	14.2	16.2	8.0	9.2
Ukulinga	Water use	7.3	9.5	4.9	6.4

EVS = Supplemental irrigation at early vegetative stage
LVS = Supplemental irrigation at late vegetative stage

SWB was also used to simulate water use, growth and biomass production for the larger 80 by 80 m (i.e. water use) uniform plots at Hatfield and Ukulinga. Yields for both these trials were, however, over-estimated by between 15 and 30%. For both these trials, yields from the different harvested sub-plots varied substantially, which suggests that growing conditions were not favourable throughout the larger blocks, and that yields were possibly limited by factors other than climate and water supply.

Canola

Model validation was conducted using an independent dataset collected during the 2003 winter at Hatfield. In general, the model performed well when compared to measurements (**Figure 25**). *LAI* was over-estimated up until the flowering stage. Measured top dry matter was lower than simulated values at the beginning of the vegetative stage, but recovered towards the start of the flowering stage (Tesfamariam, 2004).

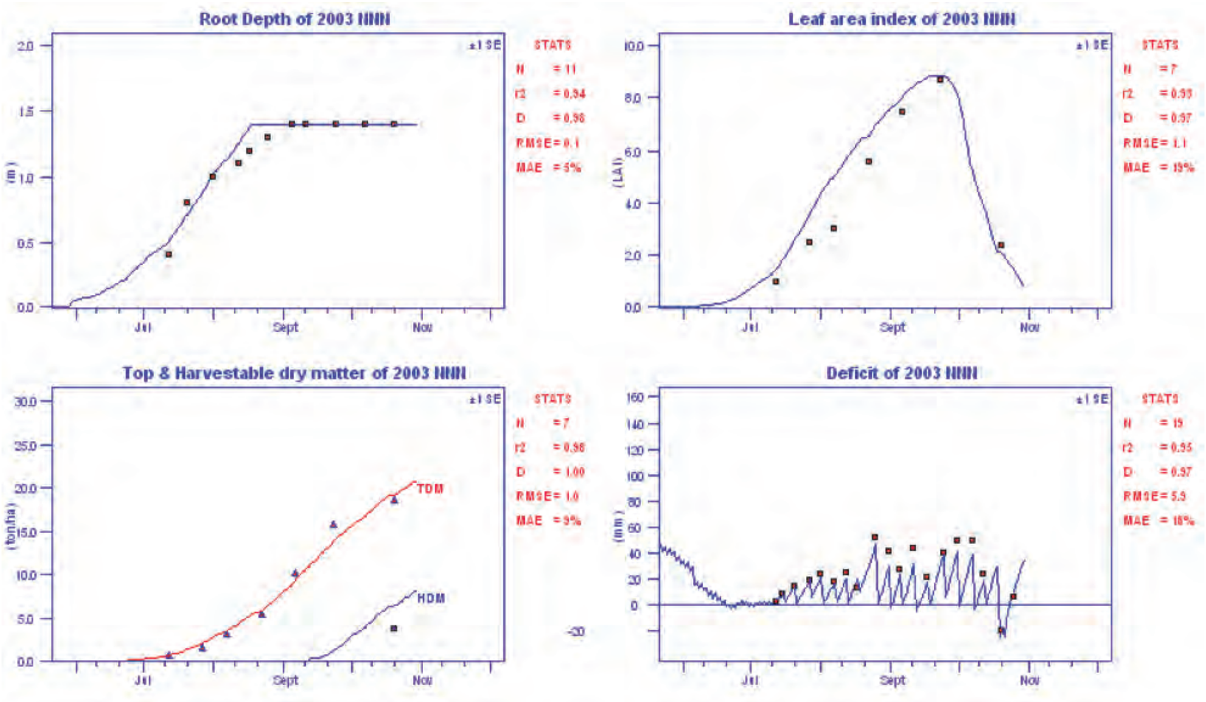


Figure 25 Simulated (lines) and measured data (points) of canola root depth (top left), leaf area index (top right), top dry matter yield (bottom left) and soil water deficits (bottom right) for the 2003 growing season at Hatfield (Tesfamariam, 2004)

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 key 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.

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 on the basis of 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 or actual evapotranspiration, 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.

5.1.2 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.

5.2 Approach

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.

5.2.1 Model selection

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).

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

ACRU is primarily a catchment-scale, daily time-step hydrological rainfall-runoff model. *ACRU* is a physical-conceptual, multi-level and multi-purpose model (**Figure 26**), 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.

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.

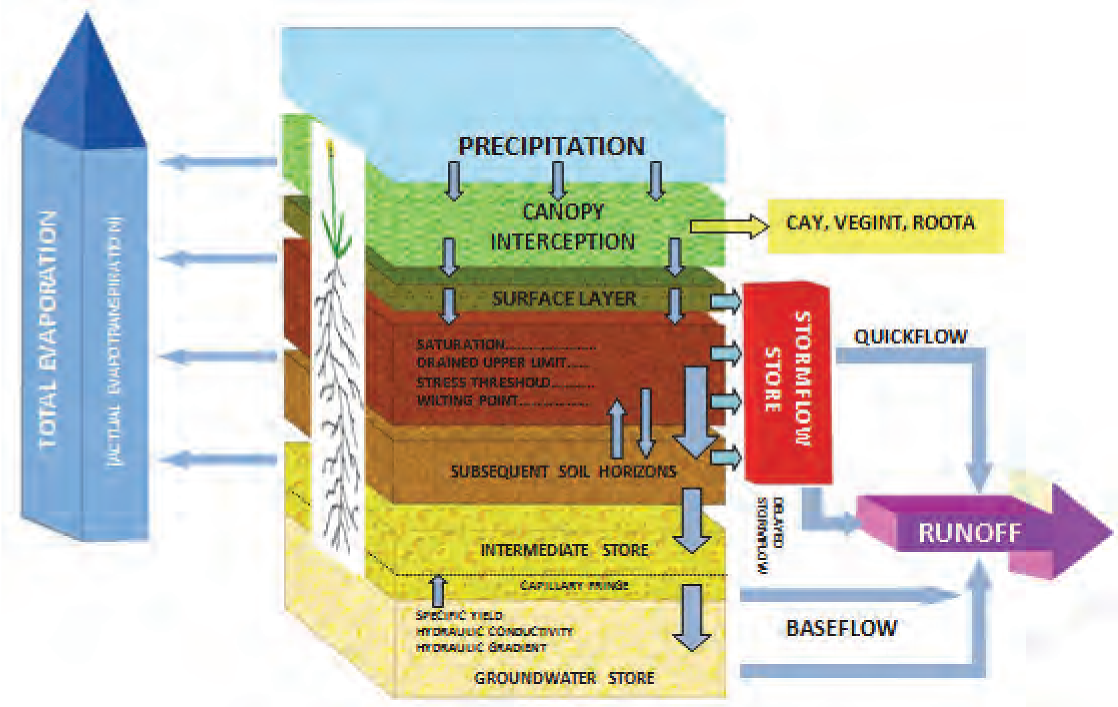


Figure 26 The *ACRU* agrohydrological modelling system: General structure (after Schulze, 1995)

5.2.3 Previous methodology

The approach followed in this project should, where appropriate, be similar to that used in previous studies. Hence, the methodology used in the past to estimate the water use of both commercial forestry and sugarcane (Jewitt *et al*., 2009b) as well as selected biofuel feedstocks (Jewitt *et al*., 2009a), on a national basis, was adopted in this project. A summary of the approach used in previous studies is as follows:

- The original quinary sub-catchment database (Schulze *et al*., 2011), together with the *ACRU* agrohydrological model (Schulze, 1995), was used to assess the impact of biofuel feedstock production on catchment water resources.

- 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 veld types.

- Monthly adjustment factors (i.e. *PPTCOR*) were applied to the observed daily rainfall record to improve the representativeness of the rainfall at the catchment scale.

- Daily estimates of reference evapotranspiration for each quinary were derived using the Penman-Monteith (FAO56) method. Solar radiation was estimated from temperature using the technique described by Chapman (2004) and Schulze and Chapman (2007). Wind speed was assumed to be 1.6 m s^{-1}.

- Monthly adjustment factors (i.e. *CORPAN*) were applied to the Penman-Monteith reference evaporation estimates to ensure that the *ACRU* model was driven by APAN equivalent evaporation and not reference crop evaporation.

- If crop coefficients for a particular land cover were derived using FAO56 as the reference, they were adjusted to APAN equivalent values before being used in the *ACRU* model.

- Where possible, certain parameters and variables were "tweaked" to reflect the current understanding of crop water use.

- The *ACRU* model was then used to simulate mean annual runoff response for baseline conditions (MAR_{base}), i.e. the runoff produced from a land cover of natural vegetation.

- The model was re-run for a 100% land cover change to a particular crop (i.e. biofuel feedstock), in order to simulate mean annual runoff from the crop surface (MAR_{crop}).

- This difference in annual runoff (MAR_{base} - MAR_{crop}) was then expressed as a percentage of the baseline stream flow (MAR_{base}).

- If the difference was above 10%, the crop may be flagged as a possible stream flow reduction activity.

- 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.

As highlighted above, output from the *ACRU* model represents "water use" compared to that of the dominant Acocks veld type in the quinary sub-catchment under consideration. It is not an estimate of consumptive water use (i.e. total evaporation) accumulated over the growth cycle. Hence, 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.

In the following section, changes to the previously used methodology to assess the hydrological impact of land use change are discussed. Thus, it highlights the improvements that were made in this study.

5.2.4 Revised methodology

The main differences in the approach adopted in this study and that used in previous studies are as follows:

- A new approach was developed to calculate pan coefficients which involved a comparison of FAO56-based reference evaporation, with APAN equivalent evaporation estimated using a modified *PENPAN* equation.

- The new pan coefficients (or pan factors) indicate that the difference between FAO56 and APAN reference evaporation is larger than previously thought.

- For sugarcane, crop coefficient values available for each of the three production areas (Inland, South Coast & North Coast) were averaged to produce one set of monthly values deemed representative of all sugarcane growing areas.

- Since all crop coefficients derived from field-based research used FAO56 as the evaporation, they were adjusted to APAN equivalent values using the pan coefficients calculated with the *PENPAN* equation.

- The *ACRU* model was run at the national scale for all 5 838 quinaries, regardless of whether the feedstock could be successfully grown in the quinary.

- The model was run in "distributed" mode and not "lumped" mode, which allowed for the estimation of stream flow that included contributions from upstream sub-catchments.

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. The biofuels assessment utility (c.f. **Volume 3**) can be used to filter out or mask non-suitable quinaries for feedstock production.

In "lumped" mode, stream flow generated from a sub-catchment consists of storm flow and base flow contributions. This output variable is called *SIMSQ* in *ACRU*. Each sub-catchment is considered a single entity and its hydrological response is not influenced by upstream sub-catchments. In "distributed" mode, *ACRU* calculates an additional variable called *CELRUN* for each quinary. In essence, *CELRUN* is the stream flow generated from the sub-catchment (i.e. SIMSQ), but includes the contribution from all upstream sub-catchments. The *CELRUN* output allows for the impact of all upstream land use changes to be assessed at the catchment outlet.

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.

5.2.4.1 Revised quinary climate database

In addition to the changes listed above, the quinary sub-catchment climate database was revised. A number of improvements were made which are summarised as follows:

- A new algorithm was used to select two representative temperature stations for each quinary's centroid location.

- Revised estimates of daily maximum and minimum temperature were then derived for each quinary.

- Incoming solar radiation (R_s) estimates were limited to the range $0.3 \cdot R_{so} < R_s < 1.0 \cdot R_{so}$, where R_{so} represents clear sky radiation.

- Incoming solar radiation (R_s) estimates were also limited to the range $0.23 \cdot R_a < R_s < 0.77 \cdot R_a$, where R_a represents extra-terrestrial radiation.

- The default wind speed used for the estimation of reference evaporation was 2.0 m s^{-1} (and not 1.6 m s^{-1} as in previous studies).

- Finally, revised estimates of FAO56-based reference crop evaporation were derived for all 5 838 quinaries.

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 the calculation of negative net outgoing longwave radiation. Hence, these checks improved the estimates of net radiation used by the FAO56 method. A total of 1 414 579 daily instances affecting the majority of quinaries were finally corrected. These corrections also prevented negative values of net outgoing longwave radiation.

5.2.4.2 Modifications to *ACRU*

ACRU version 3.37 was used to generate the stream flow response from the different land covers. A number of minor modifications were made to this model version which was given in **Volume 2**. However, an important change was made to the generation of base flow as well as a new 64-bit version of the model, which are discussed next.

COFRU 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). *COFRU* controls the rate of base flow from the groundwater store and was set to 0.009 for the *ACRU* runs. A significant modification was made to *COFRU* which results in more base flow store being generated, but less base flow is released.

However, when the base flow store is "full", more base flow is released than compared to before the modification.

The *ACRU* model was re-compiled using Intel's FORTRAN compiler software (v14) to produce a new 64-bit version. 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. This correction resulted in improved model simulations.

5.2.5 National model 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. However, 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. 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).

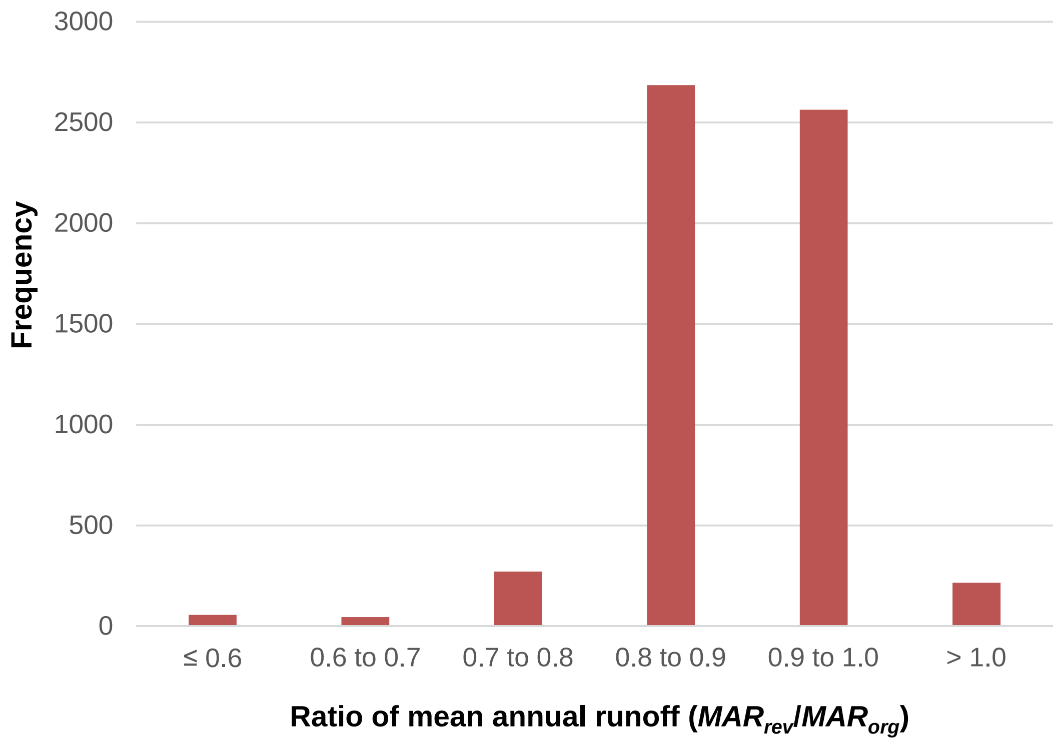
In the past, the model was run manually for each drainage basin which resulted in significant time being "wasted" in between basin runs. However, considerable effort was devoted to automating the procedure whereby *ACRU* runs non-stop for all 21 basins. This effort has significantly improved efficiency by reducing the overall time required to complete a national run. Furthermore, the automation allows for a feedstock to be re-modelled if parameters are refined (e.g. due to new evidence). Thus, much effort was also spent on ensuring the automation procedure runs smoothly and correctly.

5.3 Results and Discussion

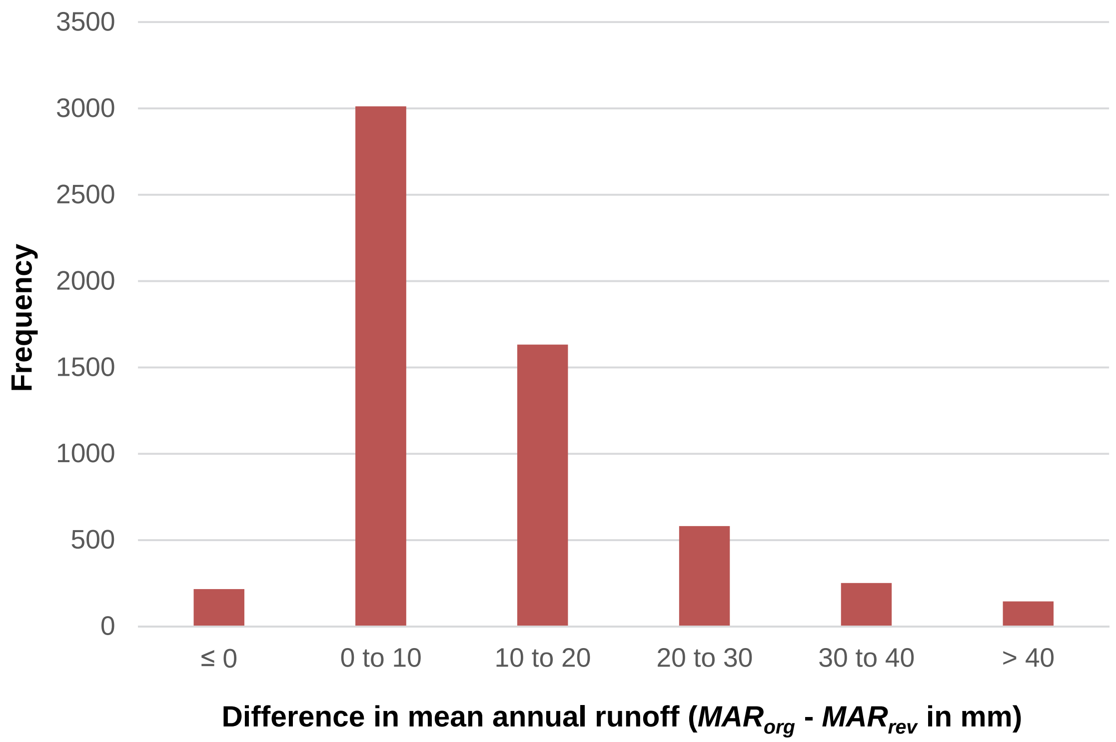
5.3.1 Revised A-pan evaporation

Considerable effort was devoted to updating the temperature and evaporation estimates used to assess the hydrological impact of a change in land use from natural vegetation to biofuel feedstock production. It is evident that, compared to the original quinary climate database (Schulze *et al*., 2011), the A-pan equivalent evaporation estimates are higher, which results in less stream flow being simulated. In this sub-section, the difference in annual and monthly runoff derived from the two climate datasets (i.e. original *vs*. revised) is quantified.

Figure 50a (in **APPENDIX D**) represents the mean annual runoff (MAR; based on the *ACRU* output variable *SIMSQ*) produced from a land cover of natural vegetation using the original quinary sub-catchment climate database (i.e. MAR_{org}). Similarly, **Figure 50b** (in **APPENDIX D**) represents the MAR generated using the revised quinary sub-catchment climate database (i.e. MAR_{rev}). The ratio of mean annual runoff (i.e. MAR_{rev}/MAR_{org}) is presented in **Figure 27a** and the difference (i.e. MAR_{org} - MAR_{rev}) is shown in **Figure 27b**.



(a)



(b)

Figure 27 Frequency distribution of the a) ratio and b) difference in mean annul runoff (MAR) simulated for natural vegetation conditions using the revised (rev) and original (org) quinary sub-catchment climate databases

A comparison of the two figures in **APPENDIX D** reveals a spatial reduction in MAR resulting from the "enhanced" evaporation for 5 622 of the 5 838 quinaries. On average, the reduction is 12.09 mm of MAR, with a range of 0.00 to 171.64 mm. However, more runoff was simulated for 216 quinaries, with the average being 21.25 mm (range 0.03 to 144.83 mm).

Figure 27a shows that for the majority of quinary sub-catchments, less runoff is generated using the revised climate database The MAR_{rev}/MAR_{org} ratio ranges from 0.8 to 1.0 for the majority (i.e. 89.93%) of the quinary sub-catchments. For 6.37% of the quinaries, substantially less annual runoff (i.e. $MAR_{rev}/MAR_{org} \leq 0.8$) is generated due to the increased evaporation. As noted before, only 216 (or 3.70%) quinaries produced more runoff with the revised climate database than compared to the original database (i.e. $MAR_{rev}/MAR_{org} > 1.0$). Furthermore, the difference in annual runoff generated using the original and revised quinary climate databases (i.e. MAR_{org} - MAR_{rev}) shows that in absolute terms, the difference is relatively small, i.e. 0 to 20 mm for the majority of quinaries (**Figure 27b**).

Figure 51a and **Figure 51b** (in **APPENDIX E**) shows that the highest and lowest monthly runoff is generated predominately in February and August respectively. The figures highlight the fact that the majority of the quinaries occur within the summer rainfall region of southern Africa. The same trends were observed (but not shown here) for monthly stream flows generated using the original quinary climate database. Hence, the revised database of enhanced evaporation estimates did not alter the monthly distribution of simulated runoff. However, the difference in February's and August's monthly runoff obtained from both climate databases is below 10 mm for the majority of quinary sub-catchments.

5.3.2 Median *vs*. mean statistic

The mean and median statistic converge (i.e. approximate one another) when there are no outliers (or extreme values, both high and low). This is better understood by considering the ratio of median to mean annual runoff (i.e. *MdAR*/*MAR*) for baseline conditions (i.e. natural vegetation cover).

This ratio is below one (i.e. median < mean, due mainly to flood events) for the majority (5 730 of 5 838) quinaries. The ratio approximates unity (i.e. median within 1% of the mean) for only 83 quinaries. For the remaining 25 quinaries, the ratio is above 1 (i.e. median > mean, due mainly to drought events). The histogram of this ratio is given in **Figure 28** and shows that values range from 0.5 to 1.0 for the majority (89%) of quinary sub-catchments.

The spatial distribution of the median to mean annul runoff ratio is shown in **Figure 29**. In the wetter regions of the country, the mean and median annual runoffs are similar, whereas they differ substantially in the lower rainfall areas. The map highlights "sensitive" sub-catchments where the mean and median statistic differ substantially (i.e. mean is "skewed" by highly variable runoff caused by low rainfall events). The next step involved assessing the hydrological impact of feedstock production using both the mean and median statistics.

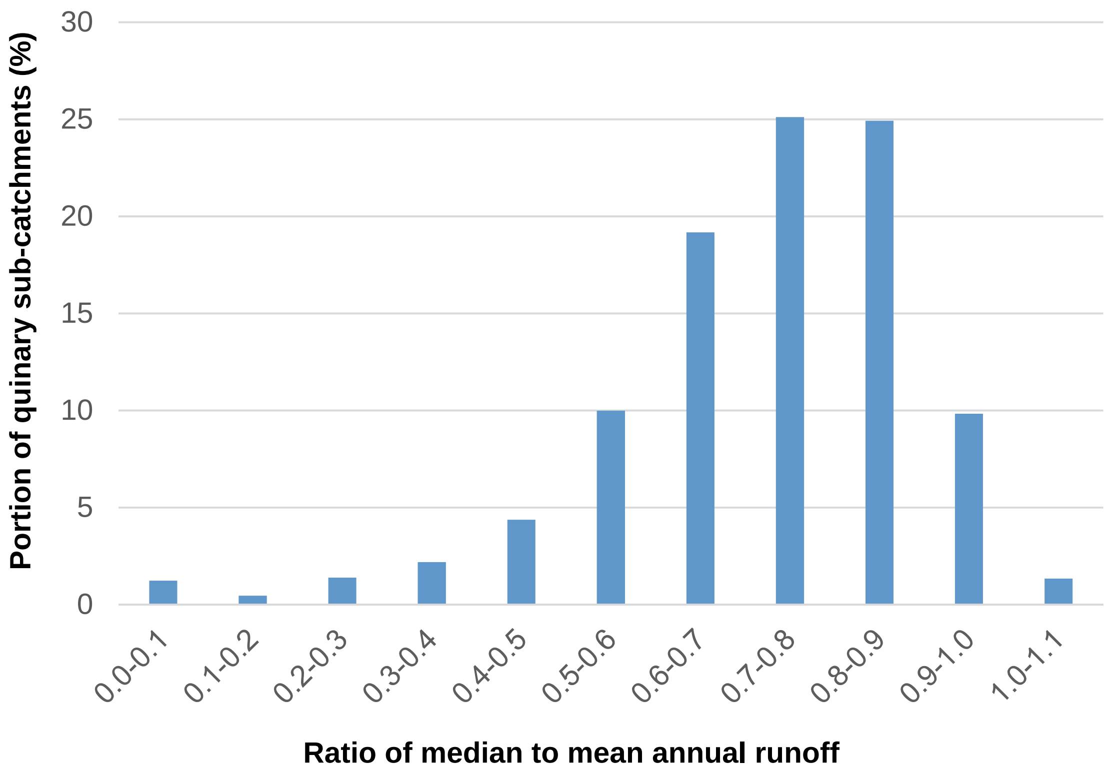


Figure 28 Histogram of the median annual runoff to mean annual runoff ratio across all 5 838 quinaries

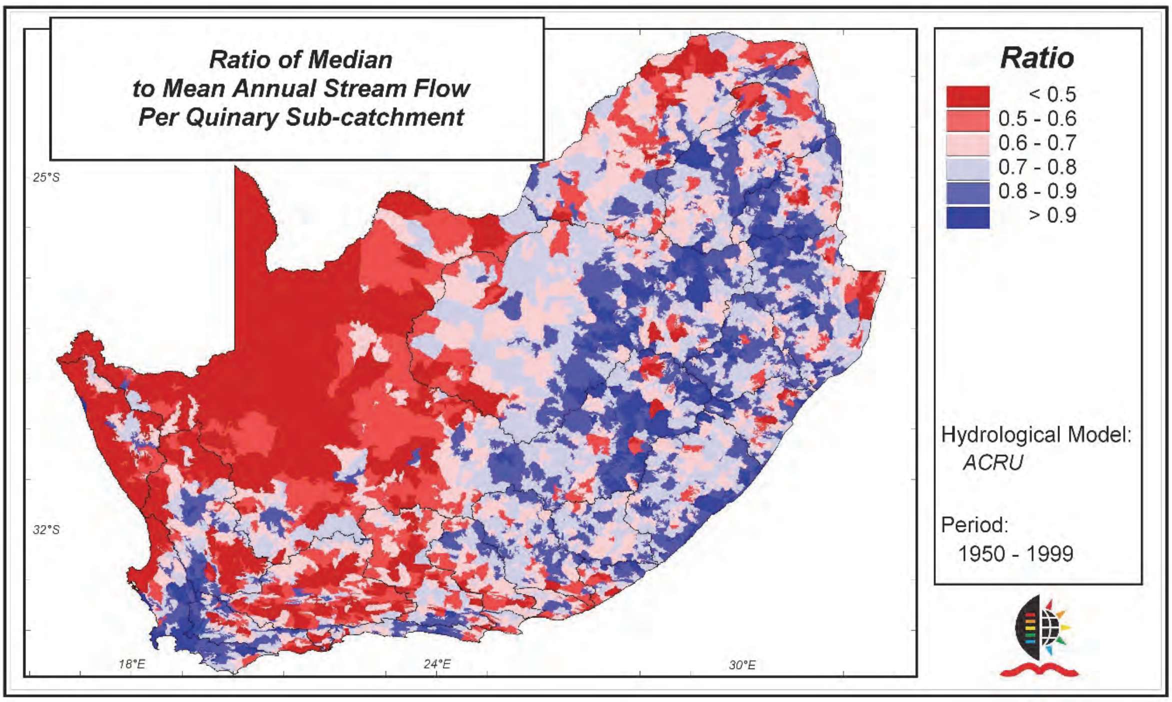


Figure 29 The ratio of median to mean annual runoff for the baseline

5.3.3 Lumped *vs*. distributed mode

When the *ACRU* model is run in "lumped" mode, stream flow generated from a sub-catchment consists of storm flow and base flow contributions. This output variable is called *SIMSQ* in *ACRU*. Each sub-catchment is considered a single entity and its hydrological response is not influenced by upstream sub-catchments. It is important to clarify that *SIMSQ* represents the reduction is stream flow per unit area for each quinary, which is required for current water resources planning approaches.

For this project, the *ACRU* model was run in "distributed mode" and not "lumped mode". In "distributed" mode, *ACRU* calculates an additional variable called *CELRUN* for each quinary. *CELRUN* is the stream flow generated from the sub-catchment (i.e. *SIMSQ*), but includes the contribution from all upstream sub-catchments. Although the distributed mode approach significantly increased the computational complexity of the hydrological modelling, it does allow the end user to assess the impact of changes in land use on the total stream flow from a particular sub-catchment, including contributions from all upstream quinaries. Thus, the accumulated effects on stream flow that may result from a land use change occurring simultaneously in multiple (adjacent) sub-catchments can now be assessed. However, the planted area and location of each feedstock must be known before this type of analysis can be undertaken.

Schulze and Schütte (2015) modelled the impact of land use change in three catchments in KwaZulu-Natal, *viz*. the Mgeni, Mvoti and Mhlatuze. Using key selected quinary outlets for each catchment, the reduction in MAR from actual areas under sugarcane and plantation forestry was determined. The results given in **Table 43** show that reductions in mean annual accumulated stream flows due to actual areas under sugarcane are small. The accumulated reductions at the respective river outlets were simulated as 0.54, 0.35 and 0.17% for the Mgeni, Mvoti Mhlatuze systems respectively. These values were compared against reductions of 3.6, 6.1 and 2.3%, respectively, from actual upstream afforestation in the three catchments. In total, simulations were performed for a total of 90 quinary sub-catchments.

Table 43 Reductions in mean annual accumulated stream flows for selected key quinary outlets of three catchments relative to baseline land cover, for actual areas under sugarcane and plantation forestry

Catchment	Number of quinary outlets considered	Average reduction in MAR at main outlet (Range in MAR for key outlets)	
		Forestry (%)	Sugarcane (%)
Mgeni	4	3.6 (2.0- 9.5)	0.54 (0.00-2.37)
Mvoti	6	6.1 (1.1-15.3)	0.35 (0.00-3.36)
Mhlatuze	6	2.3 (2.4-12.3)	0.17 (0.00-0.34)

The two main reasons given by Schulze and Schütte (2015) for the lower stream flow reductions by sugarcane are that in all three catchments the:

- actual areas under sugarcane are less than those under production forestry,
- unit runoff from sugarcane is considerably less (25-40%) than that of eucalypts (due mainly to differences in the crop coefficient for the two land covers).

The results in **Table 43** are based on accumulated stream flow (i.e. *CELRUN*) simulated at the river estuary. Another reason for the lower impact simulated for sugarcane is that along the KwaZulu-Natal coast, the water use of sugarcane is compared to that of Coastal Forest and Thornveld. Based on the vegetation-related parameters used in *ACRU* to represent these two land covers, results showed that in comparison, sugarcane uses less water (i.e. generates more stream flow). However, inland of the coastal areas, sugarcane is compared to grasses (e.g. Mistbelt Ngongoni Veld and Southern Tall Grassveld) which senesces in winter and thus, uses more water than the natural vegetation it may replace. Consequently, the muted response at the river estuary may be due to the negative impact on stream flow for inland areas being cancelled by the positive impact simulated along the coast.

Based on the evidence presented above, Schulze and Schütte (2015) concluded that "there is little scientific justification with present knowledge that sugarcane actually uses more water in the high production areas along the coastal areas of KwaZulu-Natal", but that "an argument could be made for sugarcane to be declared a SFRA in certain inland areas where it is produced".

Owing to a lack of rainfall recording stations in certain areas, it is inevitable that a single rainfall station may drive the response of multiple, neighbouring quinaries. Even though different adjustment factors are applied to each quinary, a single event results in rainfall occurring simultaneously over numerous quinaries. Consequently, the stream flow produced in each quinary tends to result in an over-estimate of runoff at the catchment outlet. It is important to note this when analysing the *CELRUN* variable from the *ACRU* model.

5.3.4 Potential SFRAs

5.3.4.1 Criteria for SFRA declaration

According to Kruger and Bosch (2002), the criteria used to assess whether a land-based activity qualifies for consideration as a SFRA includes the following:

- Dryland crop production should only be identified a SFRA when substantial scientific evidence exists for a reduction in water availability (i.e. best available scientific evidence).

- The degree to which a given land-based activity may affect water availability requires an estimate of the reduction in catchment annual runoff, calculated from the change in evapotranspiration of the activity, relative to the baseline or virgin condition (i.e. reduction in water availability).

- Based on recommendations by Jewitt *et al*. (2009b; see Figure 4.1), the reduction in runoff (relative to the baseline) is considered significant when the impact is ≥ 10% for annual runoff or ≥ 25% for low flows (i.e. extent of the impact).

- Jewitt *et al*. (2009b) also recommended that if the land-based activity's spatial extent is ≥ 10% of the catchment's area, the impact is considered significant (i.e. the extent of the impact).

5.3.4.2 Mean vs median statistic

The difference in annual runoff between the baseline (base) and each feedstock (crop) was expressed as a percentage relative to the baseline for each quinary. Hence, using mean annual runoff (MAR), feedstock water use is calculated as $100 \cdot (MAR_{base} - MAR_{crop})/MAR_{\mathrm{base}}$. Similarly, water use calculated from median annual runoff (MdAR) is given by $100 \cdot (MdAR_{base} - MdAR_{crop})/MdAR_{\mathrm{base}}$. Quinaries in which the reduction in runoff relative to the baseline is greater than 10% may be considered potential stream flow reduction areas.

The values presented in **Table 44** show that fewer quinaries are flagged as potential stream flow reduction areas when using the mean, rather than the median, of the annual runoff series. The most notable differences occur for feedstocks that can be planted in winter (e.g. sugarbeet and canola). This evidence highlights the difference in impact when the mean and median statistics are used to assess stream flow production potential.

Table 44 Number of quinary sub-catchments in which the reduction in annual runoff (relative to the baseline) is 10% or larger

Feedstock	**Number of quinaries where annual stream flow reduction ≥ 10%**	
	Median	**Mean**
Sugarcane	3 691	3 187
Grain sorghum	2 779	2 423
Sweet sorghum - inland	1 841	1 263
Sweet sorghum - Interior	530	228
Sugarbeet - summer	1 360	561
Sugarbeet - winter	171	27
Soybean	1 855	1 348
Sunflower	812	298
Canola - winter	287	80

Schulze *et al*. (2007b) recommended the median should be preferred to the mean statistic, particularly for annual time series of runoff. Schulze *et al*. (2007b) argued that runoff response is highly influenced by extreme rainfall events. Thus, a few excessive flood events over a 50-year period (e.g. 1984 and 1987 floods in KwaZulu-Natal) can bias the mean annual runoff response, especially in more arid areas. This can create a false impression of what constitutes an "expected" amount of runoff. In the case of runoff, where an excess is typically "lost" to a catchment when flood waters exit that watershed, the median (and not the mean) is the preferred statistic (Schulze *et al*., 2007b). However, for the analysis of low flows, Schulze *et al*. (2007b) recommended that monthly means rather than the medians should be used. The reason for this is that during the low flow period, stream flow comprises mainly of base flow. Base flow constitutes a "store" of water which is gradually "lost" from the catchment, but is beneficially utilised long after the event has occurred which produced that store of water.

However, it must be noted that calculating the difference between two median values is not mathematically sound (Morris, 2015). The median statistic represents the midpoint of a ranked time series of annual runoff values (from smallest to largest) for the period 1950 to 1999, with an equal number of values above and below the midpoint value. As noted earlier, the median effectively "ignores" (i.e. is not influenced by) both low and high runoff values resulting from extreme droughts or floods. Hence, the comparison (i.e. difference) of two medians is strictly speaking, meaningless. In other words, it is unclear what the absolute and percentage difference between two medians actually represents. In contrast, it is much clearer what changes in the absolute or relative (percentage) mean difference represent.

Morris (2015) suggested that a pair-wise comparison is undertaken, where the difference (baseline - feedstock) is calculated on a monthly basis, with the difference then averaged and divided by the average baseline runoff (not the median baseline runoff). Furthermore, any other statistics calculated on the percentage differences is not recommended, as these values are highly influenced by small MAR values. For example, the mean of monthly differences in runoff response that may result from a land cover change to sugarcane (in quinary 4 689) is shown in **Table 45** as 2.14 mm. This equates to a 17.3% reduction relative to the mean monthly runoff for baseline conditions (i.e. 100*2.14/12.32). The same relative reduction is obtained when the mean annual statistic is used. However, very different results are obtained with the median statistic is used as shown in the table below. Furthermore, the assessment using median monthly runoff shows no stream flow reduction potential, in contrast to the result derived from using the median annual values. Finally, the median annual approach produces a much higher impact than compared to that based on the mean annual statistic (as highlighted previously in **Table 44**).

Table 45 Assessment of stream flow reduction potential in quinary sub-catchment no. 4689, assuming a land cover change to 100% sugarcane

Time series	Runoff response		Difference in runoff	
	Baseline (mm)	Sugarcane (mm)	Absolute (mm)	Relative (%)
Mean monthly	12.32	10.19	2.14	17.3
Mean annual	147.89	122.25	25.64	17.3
Median monthly	3.77	3.82	-0.04	-1.2
Median annual	116.74	83.62	33.12	28.4

In sub-catchments where the median annual runoff is very low (or even zero) for the baseline, the calculation of the relative impact cannot be made. Based on the argument presented above, **the mean runoff statistic (and not the median) must be used to assess the impact of feedstock production on downstream water availability**. Hence, the results presented in **Volume 3** are based on an analysis of mean annual and mean monthly flows.

5.3.4.3 Sugarcane (averaged)

The figures provided in **Table 39** (c.f. **Section 4.3.3.2**) are based on the original quinary sub-catchment climate database. As detailed in this report (c.f. **Section 5.2.4**), the quinary climate database was revised with new temperature and reference evaporation estimates. The revised A-pan equivalent evaporation estimates are much higher than the original values, which means that in general, less runoff is generated using the revised climate database. Hence, the analysis discussed in **Section 4.2.3.1** (with results in **Section 4.3.3.2**) was repeated using the latest simulated runoff estimates derived from the revised quinary sub-catchment climate database.

The results presented in **Table 46** show the same trends as those derived using the original quinary climate database (c.f. **Table 39**). In other words, the decision to use averaged parameters for sugarcane to reduce the number of required national runs is well justified. The use of averaged parameters increased the number of quinaries flagged as potential SFRAs from 17 to 24 (out of 47) in the inland region.

However, the increase in evaporative demand resulted in fewer quinaries for which a reduction in stream flow of 10% or more was estimated. In other words, the number of inland quinaries decreased from 35 to 24 (out of 47) based on mean annual runoff determined using averaged crop parameters (and from 31 to 17 using runoff estimates derived with inland parameters).

Table 46 Analysis of simulated runoff based on finalised *ACRU* runs (i.e. revised quinary climate database), for sub-catchments in which 10% of more of the sugarcane mill supply areas are located in

Location of quinaries	**Percentage of 134 quinaries with a reduction in mean annual runoff ≥ 10%**			
	Inland parameters	S. Coast parameters	N. Coast parameters	Averaged parameters
Inland	12.69			17.91
South Coast		0.00		0.00
North Coast			0.00	0.00
Total	**12.69**	**0.00**	**0.00**	**17.91**

5.3.5 Model run time

Even though the national runs have been fully automated, it is important to consider the computational time required to complete the simulations for each feedstock. From **Table 47**, a Core i7 PC completed a national run for each feedstock in approximately 8.5 hours (507 minutes). Thus, the hydrological modelling component took much less time to complete than the crop yield modelling (c.f. **Section 6.3.4**).

The *ACRU* model was initially developed using the FORTRAN 77 programming language. However, it was re-coded in JAVA to create, *inter alia*, a more modular design that is easier to expand and link to other models, as well as being platform independent (Kiker and Clark, 2001; Kiker *et al*., 2006). However, since JAVA is an interpreted language, the JAVA-based model runs much slower than the FORTRAN version, thus making it less suitable for, *inter alia*, climate change studies and national scale simulations.

Table 47 The time required (in minutes) to run the *ACRU* model for each primary drainage basin

Primary catchment	Start quinary	End quinary	No. of quinaries	Run time (minutes)
A	1	417	417	31
B	418	852	435	32
CD	853	2 295	1 443	255
E	2 296	2 520	225	11
F	2 521	2 625	105	4
G	2 626	2 799	174	8
H	2 800	3 006	207	10
J	3 007	3 282	276	15
K	3 283	3 402	120	5
L	3 403	3 576	174	8
M	3 577	3 600	24	1
N	3 601	3 708	108	4
P	3 709	3 756	48	2
Q	3 757	3 969	213	10
R	3 970	4 059	90	3
S	4 060	4 233	174	8
T	4 234	4 635	402	29
U	4 636	4 821	186	8
V	4 822	5 079	258	14
W	5 080	5 526	447	34
X	5 527	5 838	312	18
		Total	**5 838**	**507**

5.3.6 FORTRAN *vs*. JAVA versions

In a recent study conducted by Shabalala (2015), output from the FORTRAN version of the *ACRU* model was compared to that from the JAVA version. The testing was done for a single quinary sub-catchment (4 697) in which the Ukulinga research farm is located. The simulations were undertaken for sweet sorghum using 50 years of revised quinary climate data and quinary soils information. The results showed that the FORTRAN version produced lower estimates (by 14.2% for MAR) of stream flow response when compared to output from the JAVA version (**Figure 30**).

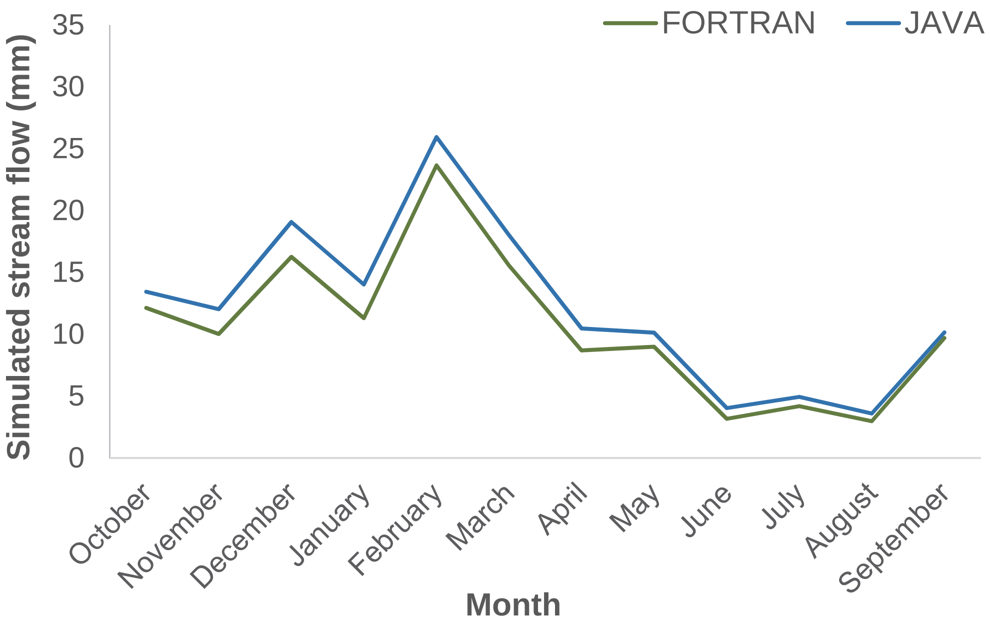


Figure 30 Mean monthly stream flow for quinary 4 697 simulated using the FORTRAN and JAVA versions of the model for sweet sorghum

However, given this discrepancy which is based on a single crop (sweet sorghum) at one location (Ukulinga), it cannot be assumed that the FORTRAN-based model will always produce less runoff than the JAVA version. To test this, a comparison of baseline runoff (generated from a land cover of natural vegetation) was undertaken for quinary 4 697. **Figure 31** highlights the similarity in predicted runoff, with the FORTRAN version producing 1.8% less MAR than the JAVA version.

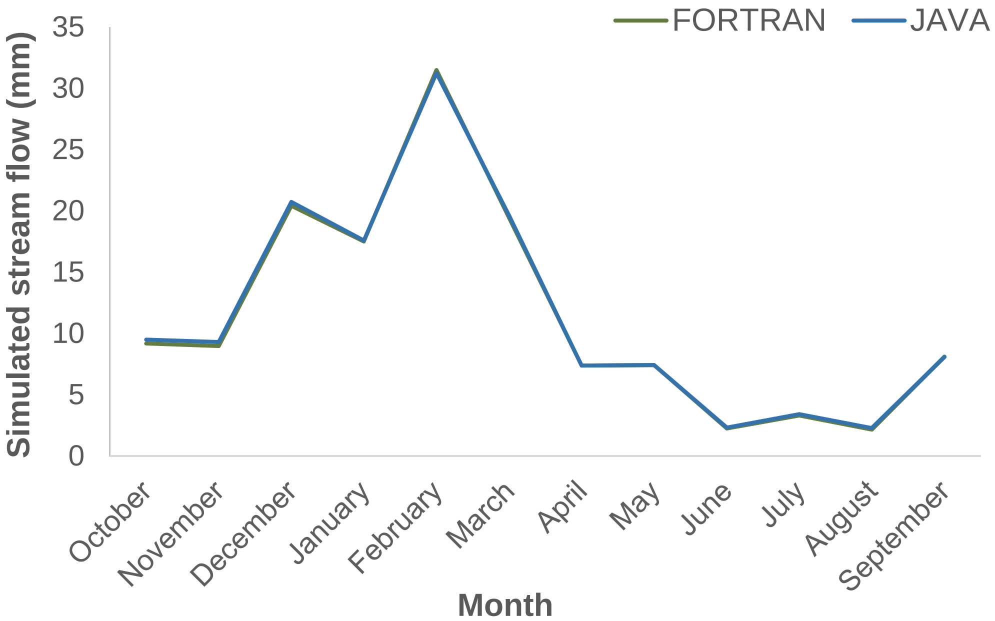


Figure 31 Similarity in mean monthly stream flow simulated for quinary 4 697 using the FORTRAN and JAVA versions of the model for natural vegetation

One of the reasons for the MAR difference (shown in **Figure 30**) is due to the way in which the two versions adjust the daily crop coefficient value within in model. The FORTRAN version was programmed to “reset” the daily crop coefficient (K_c) value to that of the monthly input value, at the beginning of every month. However, this monthly “resetting” procedure was removed in the JAVA version, thus allowing the daily K_c value to continue decreasing until recovery from stress begins when the soil water content rises above a threshold value. Therefore, during the low rainfall months, the JAVA version of the model generates lower crop coefficients than the FORTRAN version.

Since the FORTRAN version produces larger crop coefficient values (especially in the winter months), there is more maximum and total evaporation occurring from the vegetated surface. Hence, the soil water content is lower, which results in less runoff being generated then compared to the JAVA-based simulation. Shabalala (2015) concluded that the FORTRAN version of the model should be modified to mimic the JAVA version, which is echoed in this report. It is speculated that the difference in mean monthly runoff shown in **Figure 30** is also due to other variations in the way each model version separates total evaporation into transpiration and soil water evaporation. Hence, further investigation is required to explore differences in the Ritchie algorithm between the FORTRAN- and JAVA-based models.

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. A more detailed version of the approach is provided in **Volume 2**. 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

According to Steduto *et al*. (2012), there is growing water scarcity, declining water quality and the uncertainties of climate change and climate variability. Hence, improving efficiency and productivity of crop water use, with the simultaneous reduction of negative environmental impact, are of utmost importance in response to the increasing food and (bio)fuel demand of the growing world population. In order to address this need, a large number of crop simulation models were developed over the last four decades. These models often require a large number of input parameter values that are not readily available a particular application. Furthermore, model developers and scientists are more familiar with these parameters than most model end users.

6.2 Approach

6.2.1 *AQUACROP* model

The scientific basis of *AQUACROP* was presented in three papers (Steduto *et al*., 2009; Raes *et al*., 2009; Hsiao *et al*., 2009) that were published in the Journal of Agronomy in 2009 when the model was originally released. A detailed description of the *AQUACROP* model forms part of FAO's Irrigation and Drainage Paper No. 66 titled "Crop Yield Response to Water" by Steduto *et al*. (2012; c.f. Chapter 3). The model's reference manual (Raes *et al*., 2012a; 2012b) also describes the model in detail. However, the following sections represent a summary of the model published by Vanuytrecht *et al*. (2014).

According to Vanuytrecht *et al*. (2014), *AQUACROP* simulates final crop yield by considering:

- green crop canopy cover development,
- crop transpiration rate,
- above-ground biomass production, and
- final crop yield.

Temperature and water stresses directly affect one or more of the above processes. The dotted arrows in **Figure 32** represent the processes affected by water stress (a-e) and temperature stress (f-g). Water stress slows canopy expansion (a), accelerates canopy senescence (b), decreases root deepening but only if severe (c), reduces stomatal opening and transpiration (d), and affects the harvest index (e). Temperature stress reduces biomass productivity (f) and inhibits pollination and reduces the harvest index or HI (g).

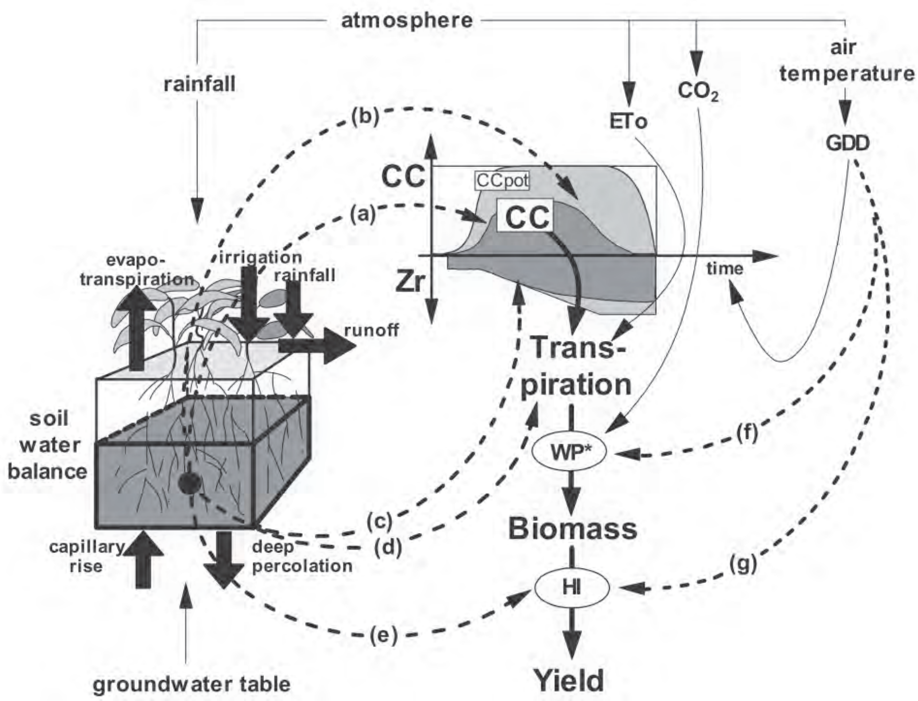


Figure 32 Diagram showing the processes involved in simulating crop biomass and yield and those affected by water stress (a-e) and temperature stress (f-g) (Vanuytrecht *et al*., 2014)

The impact of environmental stress on the crop is simulated using stress coefficients (K_s). In essence, K_s modifies its target parameter and ranges from one (no stress) to zero (full stress). K_s is defined by specifying an upper and lower threshold and by selecting a curve shape (usually convex). Above the upper threshold, stress is non-existent (K_s = 1). At and below the lower threshold, the stress effect is maximum and K_s = 0.

6.2.1.1 Canopy cover development

AQUACROP does not simulate leaf area index, with foliage development expressed as green canopy cover (CC; the fraction of the soil surface covered by the canopy). CC varies between 0 (before emergence) to a maximum (CC_x) which can approximate 100% depending on crop type and planting density. The canopy is a crucial feature of *AQUACROP* and canopy development for non-limiting conditions (CC_{pot}) is simulated using three parameters, *viz*. the 1) initial canopy cover after emergence or CC_o, 2) maximum canopy cover reached or CC_x, and 3) the canopy growth coefficient.

At the start of canopy senescence, the decline in CC is simulated using a canopy decline coefficient. Since *AQUACROP* simulates crop development in GDD, the rate of canopy expansion and decline are modulated by temperature. The crop grows through canopy cover development and biomass accumulation using a daily time step. Crop phenology is simulated in daily increments of growing degree days (GDD) which are accumulated over the season, with the thermal time for each phenological stage specified in the crop parameter file.

6.2.1.2 GDD vs. calendar mode

AQUACROP can run in two different modes to calculate the harvest date. However, when the crop cycle is based on calendar time (i.e. fixed number of days after planting), the model does not account for the effects of temperature on crop growth. Steduto *et al*. (2012) suggested that the model should be parameterised (and calibrated) in the GDD mode to account for different temperature regimes. Thus, setting the correct base and upper (cut-off) temperatures in the crop parameter file is critical. Crop cycles based on GDD, much of the temperature effects on crops, such as on phenology and canopy expansion rate, are accounted for. For example, the model inhibits the conversion of transpiration into biomass at low temperatures when run in GDD model.

6.2.1.3 Simulation of crop transpiration

Crop transpiration is calculated by multiplying ET_o (the evaporating power of the atmosphere) by the crop transpiration coefficient. ET_o is preferably calculated using the Penman-Monteith equation as specified by Allen *et al*. (1998). The crop transpiration coefficient is proportional to CC, with the maximum value typically ranging from 1.0 to 1.2.

6.2.1.4 Soil water balance

AQUACROP is water-driven with biomass production a function of transpiration, so the soil water balance is a critical component of the model. The root zone is considered a "reservoir" in which the water content fluctuates as a result of incoming (e.g. rainfall, irrigation & capillary rise) and outgoing (runoff, evaporation, transpiration & deep percolation) water fluxes at the zone boundaries. The model can handle up to five soil horizons, with each horizon sub-divided into numerous compartments, each with a specific set of physical characteristics. Although the model also simulates a salt balance, this aspect was not considered in this study.

6.2.1.5 Above ground biomass production

In *AQUACROP*, water productivity (WP) is defined as the ratio of biomass produced to water transpired. Daily transpiration is then multiplied by water productivity in order to calculate biomass production, which is accumulated over the growing season. If nutrients are not limiting, water stress has negligible effect on WP, except in extremely severe cases. However, cold temperatures affect biomass production which is accounted for using a stress coefficient for biomass with GDD as the stress indicator.

WP is normalised using the evaporative demand (ET_o) in order to increase model robustness, making it applicable to diverse locations and seasons. Normalisation is obtained by dividing the daily transpiration by ET_o for that day. The effect of ambient CO_2 concentration on biomass production is simulated by altering the normalised (using ET_o) water productivity using a multiplier. Its value is calculated by comparing the ambient CO_2 concentration ([CO_2]) for the year in which the crop is grown, with that for a reference year (i.e. year 2000).

6.2.1.6 Simulation of crop yield

Crop yield is calculated as the product of accumulated biomass product and the harvest index (HI). The actual HI is obtained by adjusting the reference Harvest Index (HI_o) to account for stress effects. Hence, HI depends on the timing and extent of water or temperature stress during the crop cycle. HI_o represents the observed fraction of biomass that is harvestable under non-stressed conditions and is a cultivar-specific parameter.

Finally, nutrient deficiencies and salinity effects are simulated indirectly by moderating canopy cover development over the season, and by reducing crop transpiration and the normalised water productivity.

6.2.1.7 Parameterised crops

AQUACROP is developed by the FAO (Rome, Italy), programmed in Delphi and runs under MS Windows. It was first released in January 2009 (Version 3) and the current version 4.0 was released in August 2012 (Version 4.0 was used in this study). *AQUACROP* is packaged with a set of conservative crop parameters, which are considered general and widely applicable and thus, don't require local calibration. At present, conservative crop parameters are provided for:

- 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).

The thoroughness of the parameterisation and validation process varies with each crop, which is discussed in the model's reference manual (Raes *et al*., 2012a). Several recent papers describe parameterisation and testing of *AQUACROP* for crops not listed above, such as green bean (Coorevits, 2010), canola (Zeleke *et al*., 2011), bambara groundnut (Karunatne *et al*., 2011; Mabhaudhi *et al*., 2013), cabbage (Kiptum *et al*., 2013; Wellens *et al*., 2013), taro (Mabhaudhi *et al*., 2014) and sweet potato (Rankine *et al*., 2015).

According to Vanuytrecht *et al*. (2014), these new crops and their parameters will only be packaged with the model once the conservative crop parameters (i.e. those essentially constant and applicable in diverse environments) have been tested across various sites. *AQUACROP* was parameterised by Hsiao *et al*. (2009) for maize using extensive datasets collected in different field experiments at Davis (California, USA), then the parameterised model was tested (i.e. validated) with datasets from Spain, Texas and Florida (Heng *et al*., 2009). According to Vanuytrecht *et al*. (2014), the crop parameters for maize have also been applied in Pennsylvania (USA) as well as Belgium and Serbia.

6.2.2 *SWB* model

SWB is a mechanistic, generic crop growth and soil water balance model, which was developed by Annandale *et al*. (1999) as an irrigation management tool. *SWB* is a field-scale crop growth model which has been developed for a number of crops as well as different irrigation system and management options. The model is pre-packaged with climate and soils data for South Africa, thus reducing the time required to develop a base run. The "scenario generator" allows multiple crop and irrigation scenarios to be easily configured. A number of modifications have been made to the original *SWB* model (Annandale *et al*., 2002) and is now referred to as the *SWBPro* model which can also be used for planning purposes (Pott *et al*., 2008). In *SWB*, the user has the option to choose between the FAO crop factor model and the more mechanistic crop growth model. As *SWB* is a generic crop model, determination of crop-specific model parameters for each crop is crucial to simulate growth and water use. Crop-specific model parameters are the reflection of a 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 growing conditions. The parameterisation of *SWB* model for selected biofuel feedstocks is presented in **Chapter 4**.

6.2.3 Model evaluation

A summary of the methodology developed to produce yield estimates of selected crops at the national level is provided next. The headings for each sub-section are in accordance with the new terminology for model performance as proposed by Augusiak *et al*. (2014) in **Section 4.2.5.1.**

6.2.3.1 Model output verification

The *AQUACROP* is packaged with a set of conservative parameter values for a number of different crops (as indicated in **Section 6.2.1.7**. The parameters are widely applicable without the need for local calibration. Steduto *et al*. (2012) provided a summarised description of these conservative crop parameters (Table 1; p 44) as well as a list of parameters likely to require adjustment (Table 2; p 44) in order to account for different cultivars, local conditions and management practices. This information helped to identify the important parameters to change in order to improve yield simulations for local growing conditions.

Mokonoto (2015) calibrated the *AQUACROP* model for sugarcane and sugarbeet, which involved the "tweaking" of all sensitive crop parameters listed by Steduto *et al*. (2012). Moyo and Savage (2014) evaluated the performance of the model for soybean. For additional information, the reader is referred to **Section 4.3.5.1**. For grain sorghum, *AQUACROP*'s default parameter file was used, which was initially calibrated using growth data from Texas (USA). Similarly, canola was calibrated using data from Alberta (Canada). Slight "tweaks" were made to the latter two crop parameter files.

6.2.3.2 Model output corroboration

Mokonoto (2015) performed a validation of the sugarcane and sugarbeet calibrated using independent datasets. For sugarbeet, the model was tested against two irrigation treatments at Komatipoort in 2012. Similarly, *AQUACROP* was tested using an independent dataset for sugarcane obtained at Pongola from December 1968 to May 1971. For additional information, the reader is referred to **Section 4.3.5.2**.

6.2.3.3 Model analysis

A sensitivity analysis was conducted in order to standardise the input options for the national scale simulations. The crop season length was calculated using both thermal time and calendar time. A comparison was then undertaken to better understand the difference in model output produced for both input options. The results of this comparison are presented in **Section 6.3.5**. 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.

6.2.4 National model runs

6.2.4.1 Soils input

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) for the entire sub-catchment (Schulze *et al*., 2011). A utility was developed in FORTRAN to extract the soil water retention parameters as well as soil depths from the quinary sub-catchment soils database and re-format them to that required by the *AQUACROP* model.

6.2.4.2 Saturated hydraulic conductivity

AQUACROP also requires the saturated hydraulic conductivity (K_{SAT}) which is not available in the quinary soils database. Hence, a pedotransfer function was developed to estimate K_{SAT} from 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 10**

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 11**

where θ_{PWP} is the soil water content at the permanent wilting point (in m m^{-1}). The two constants 33 and 1500 represent the matric potentials at the drained upper limit (DUL) and permanent wilting point (PWP) respectively (in kPa). 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. A validation of the above equations is provided in **Section 6.3.1**.

The saturated hydraulic conductivity estimated for the A-horizon was used to derive the curve number input for *AQUACROP*. Similarly, the readily evaporable water input parameter was derived using an equation provided by Raes *et al*. (2013), which requires as the A-horizon's soil water content at field capacity and permanent wilting point. These values were stored in the soils (.SOL) file for each quinary sub-catchment.

6.2.4.3 Soil textural classes

The *AQUACROP* model also requires the soil texture 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. Histograms of the estimated textual class are provided in **Section 6.3.2** for both the topsoil and subsoil. The reader is referred to **Volume 2** for a detailed description of the methodology used.

6.2.4.4 Climate input

The *AQUACROP* model was linked to the revised quinary sub-catchment climate database in order to derive regional estimates of crop yield at the national scale. The quinary climate database was revised in order to improve estimates of daily temperature and reference evaporation for each sub-catchment. 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. A total of 46 704 input files (climate and soils) were generated to run *AQUACROP* for each of the 5 838 quinary sub-catchments.

6.2.4.5 Verification of ET_o

Two quaternary catchments in KwaZulu-Natal were selected, each comprising of three quinary sub-catchments namely 4 696 to 4 698 and 4 717 to 4 719. These quaternaries were selected since UKZN's Ukulinga research farm and SASRI's La Mercy research farm are situated in quinary 4697 and 4 719 respectively. The ET_O *CALCULATOR* program was used to generate daily reference (i.e. FAO56 or Penman-Monteith) evaporation data using *AQUACROP*'s 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 5.2.4.1**. The results of this comparison are presented in **Section 6.3.3**.

6.2.4.6 Multiple project file

In order to run the crop 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). Considerable effort was spent on checking the .PRM file against those generated by *AQUACROP*. For each feedstock, a representative planting date was chosen (**Table 48**) and the harvest date was determined for each sub-catchment based on the GDD method.

Table 48 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

The maximum season length was limited to 730 days. For certain feedstocks, two planting dates were modelled. For example, a summer (i.e. September) and winter (i.e. June) planting of sugarbeet was considered, together with a seven month growing season The winter planting should be the "norm" for the Cradock region in the Eastern Cape. The PRM file also instructs the model which crop parameter file to use for the multiple simulations.

6.2.4.7 Standalone version

AQUACROP, like other crop growth models, is designed to predict crop yield at the single point (i.e. field or farm scale). The simulation of crop yield at the regional level requires a large number of simulations runs. This involves the generation of large amounts of input data and project files as well as for complex analysis and interpretation of results (Vanuytrecht *et al*., 2014). Owing to the large number of model runs (i.e. 5 838 at the national scale), the plug-in version of the *AQUACROP* model was used extensively in this study. This stand-alone version runs without a graphic user interface. The process was fully automated to reduce its computational complexity, thus minimising the time required to complete a national run.

6.2.4.8 Model run time

The process of running the model 5 838 times for 50 consecutive seasons was computationally, both complex and very time consuming. This was exacerbated by the need to perform the national runs for multiple crops, some with two planting dates. Considerable effort was devoted to automating this procedure, which required to development of thousands of lines of computer code.

An unexpected anomaly occurred when the model was run for quinaries not ideally suited to crop growth. *AQUACROP* generated a "division-by-zero" error which halted the automation procedure, thus requiring the national-scale model runs to be manually re-started. The automation procedure was modified to automatically re-start the model in the event of a "crash" being detected. The length of time required to complete each national run is discussed further in **Section 6.3.4**.

6.2.4.9 GDD *vs*. calendar mode

In **Section 0**, there are clear advantages of running *AQUACROP* in GDD mode and not calendar mode. In GDD mode (i.e. crop cycles based on thermal time), much of the temperature effects on crops, such as on phenology and canopy expansion rate, are accounted for. For example, the model inhibits the conversion of transpiration into biomass at low temperatures when using thermal time. However, the model runs much slower in GDD mode than compared to calendar mode. The difference in both run modes is illustrated using soybean as an example in **Section 6.3.5**.

6.2.4.10 Yield and WUE statistics

AQUACROP was run nationally to estimate the attainable yield and water use under dryland conditions for a single season. This exercise was then repeated to obtain simulated data for for 50 consecutive seasons from 1950 to 1999. From the time series of seasonal output, a number of variables were extracted and statistics such as the mean, median and coefficient of variation were then calculated. For each season, the crop was planted (or transplanted) on a specific date, but harvested when the crop reached physiological maturity according to thermal time. In other words, the length of each consecutive season varied, depending on the time required to accumulate sufficient growing degree days to reach maturity.

6.3 Results and Discussion

6.3.1 Saturated hydraulic conductivity

"Typical" particle size distributions (e.g. sand % and clay %) for 11 soil textural classes were used to estimate soil water retention values using various other 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. From these estimated soil water retention values, K_{SAT} was determined using the two equations (**Equation 10** & **Equation 11**) provided by Saxton and Rawls (2006). These estimates were then compared to values provided by Schulze *et al*. (1995) for 11 soil textural classes as shown in **Table 49**.

Table 49 Comparison of saturated hydraulic conductivity (K_{SAT}) calculated using equations provided by Saxton and Rawls (2006) and compared to values provided by Schulze *et al*. (1995)

Typical percentages of:		Binomial classification (MacVicar *et al*. 1977)	K_{SAT} (mm d^{-1})	
Sand	Clay		Saxton and Rawls (2006)	Schulze *et al*. (1995)
31	50	Clay	11	14
13	50	*Silty clay*	33	22
21	33	*Silty clay loam*	55	36
65	27	Sandy clay loam	175	103
55	40	Sandy clay	24	29
46	32	*Clay loam*	74	55
93	03	Sand	3 292	5 040
86	07	Loamy sand	1 983	1 464
75	10	Sandy loam	1 259	624
57	18	*Loam*	417	312
27	18	Silty loam	216	163

The calculated K_{SAT} values 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}). However, calculated 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.

6.3.2 Soil textural classes

Using the area-weighted soil water retention parameters for each quinary, the textural class was derived for the A- and B-horizon as shown in **Table 50** and **Table 51** respectively. The majority (79.9%) of A-horizons were classified as a sandy loam and 15.1% as a sandy clay loam. No topsoil in all 5 838 quinaries was classified as a pure clay, loam or silt.

Similarly, the majority of subsoils were classified as a sandy loam or a sandy clay loam. The increase in sandy clay loams from the A- to the B-horizon illustrates the higher clay content of the subsoil. No subsoil horizon was classified as a clay or loam. The results show that the area-weighting of land types located in each quinary tends to produce a similar "averaged" soil. This may suggest that national runs could be simplified by assuming common representative soil for all quinaries.

Table 50 Texture of the topsoil derived using the area-weighted water retention parameters obtained from the quinary sub-catchment soils database

A-horizon texture	Number of quinaries	Percentage of total quinaries	Accumulated percentage
Clay	0	0.00	0.00
Loam	0	0.00	0.00
Sand	2	0.03	0.03
Loamy sand	12	0.21	0.24
Sandy loam	4 663	79.87	80.11
Silty loam	59	1.01	81.12
Sandy clay loam	881	15.09	96.21
Clay loam	69	1.18	97.40
Silty clay loam	2	0.03	97.43
Sandy clay	147	2.52	99.95
Silty clay	3	0.05	100.00
Silt	0	0.00	100.00
Total	**5 838**	**100.00**	

Table 51 Texture of the subsoil derived using the area-weighted water retention parameters obtained from the quinary sub-catchment soils database

B-horizon texture	Number of quinaries	Percentage of total quinaries	Accumulated percentage
Clay	0	0.00	0.00
Loam	0	0.00	0.00
Sand	1	0.02	0.02
Loamy sand	8	0.14	0.15

B-horizon texture	Number of quinaries	Percentage of total quinaries	Accumulated percentage
Sandy loam	2 566	43.95	44.11
Silty loam	120	2.06	46.16
Sandy clay loam	2 563	43.90	90.07
Clay loam	94	1.61	91.68
Silty clay loam	1	0.02	91.69
Sandy clay	341	5.84	97.53
Silty clay	15	0.26	97.79
Silt	129	2.21	100.00
Total	**5 838**	**100.00**	

6.3.3 Verification of ET_o

FAO's ET_o calculator utility was used to derive daily ET_o data for six quinaries and accumulated over the 50-year period from 1950 to 1999. The ET_o totals were then compared to those obtained from the revised quinary climate database. The slight differences in totals ranging from -104.8 to +3.8 mm as shown in **Table 52** 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. The exercise was undertaken to validate the FAO56 reference evaporation (ET_o) estimates derived for the revised quinary climate database.

Table 52 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

6.3.4 Model run time

From **Table 53**, *AQUACROP* ran for a total of 1 100 hours (or 46 days continuously) and required almost 1 500 model re-starts to provide yield estimates for five crops (some with two planting dates). The model required an automated re-start when a division-by-zero error occurred. By comparison, *ACRU* took approximately 9 hours for each national water use run (c.f. **Section 5.3.4.3**).

Table 53 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**

6.3.5 GDD vs. calendar mode

As noted previously, the AQUACROP model can be run in two different modes, where the length of the crop cycle is:

- fixed for each simulation (based on calendar days from planting date), or
- varies according to accumulated GDD from planting date to crop maturity (i.e. thermal time).

In this sub-section, output from the AQUACROP model based on thermal time is compared to that derived from calendar time. The comparison of undertaken for soybean only. The findings show that where possible, simulations should rather be based on thermal time.

6.3.5.1 Run time

The advantages of calculating the crop maturity date using thermal time compared to a fixed season length were discussed in **Section 0**. 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 run times shown in **Table 54** 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 54 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

Run time (HH:MM:SS)	Number of quinaries	Maturity date
02:00:39	5 838	Calendar
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

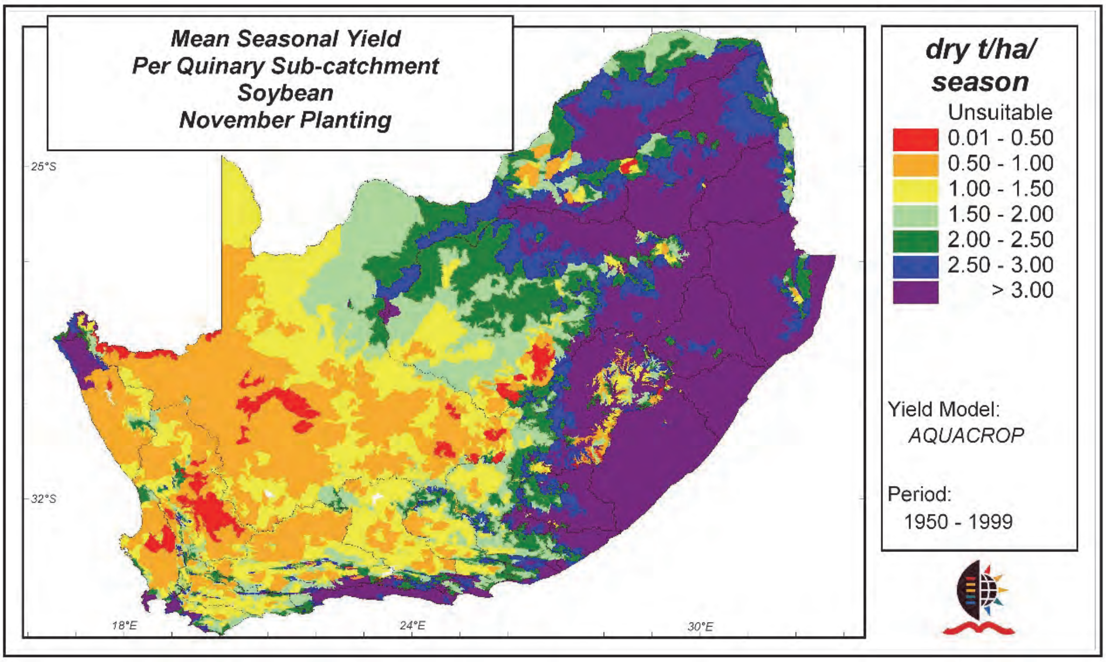
seconds (thermal) to complete each quinary. However, there is also a difference in the output produced by the model which is discussed next.

6.3.5.2 Seasonal yield

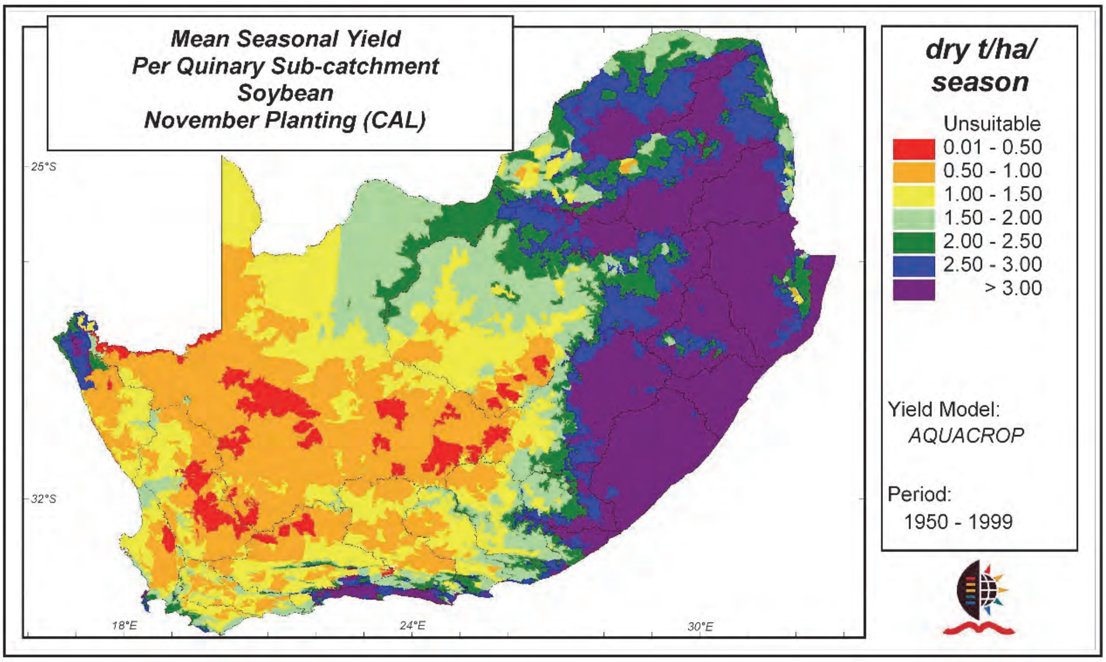
Figure 33 illustrates differences in mean seasonal yield derived from crop cycles based on thermal and calendar time. As noted by Steduto *et al*. (2012), the model inhibits the conversion of transpiration into biomass at low temperatures when using thermal time. This is clearly evident from the quinaries at high altitudes (i.e. cooler temperatures) such as those in Lesotho and those in the Drakensberg region.

In GDD mode, *AQUACROP* predicted lower yields in the high lying areas as shown in **Figure 33a**. Hence, these areas are too cold for soybean growth, whereas the calendar-based run simulated yields > 3 t ha^{-1} for the Lesotho highland areas (**Figure 33b**). A similar trend exists for median seasonal yield derived from crop cycles based on thermal and calendar time as sown in **APPENDIX F**.

Furthermore, *AQUACROP* will under-estimate the yield in all areas where the GDD-based season is longer than 130 days. In other words, the attainable yield will not be realised due to the colder temperatures. Steduto *et al*. (2012) added that for simulation of production and water use under different yearly climates or different times of the season, *AQUACROP* must be run in the GDD mode. Therefore, the results obtained from GDD-based crop cycles are deemed superior to those based on a fixed crop cycle (i.e. calendar days).



(a)



(b)

Figure 33 Differences in mean seasonal yield derived from crop cycles based on thermal (a) and calendar (b) time

6.3.6 Yield and WUE statistics

The output from the *AQUACROP* model is presented as maps in **Volume 3**.

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

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 (e.g. an additional 215 000 ha of grain sorghum production). 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.

Since an expansion of agricultural production is required, it is important to identify areas where feedstock cultivation can realistically occur. A land suitability assessment is therefore needed to identify areas suitable for the cultivation of biofuel feedstocks. Land suitability assessments require geo-referenced information to characterise and optimise land use by location. The following types of spatial data, *inter alia*, are typically required:

- climatic (e.g. rainfall & temperature),
- edaphic (e.g. soil texture & depth, acidity level, slope),
- biotic (e.g. relative humidity to assess disease risk),
- land cover (e.g. grasslands, woodlands, natural forests),
- land use (e.g. cultivated, urban & mining areas), and
- biodiversity (e.g. protected areas).

Land suitability assessments are therefore limited by the availability and quality of the required spatial datasets. In some cases, the necessary data sets are not yet available. In addition, the datasets may need to be acquired from a number of different institutions. This leads to compatibility problems and issues related to spatial scale and resolution. Hence, data quality often determines the scale at which such analyses can be conducted. For example, coarse GIS data (in terms of scale and resolution) is only suitable for national-level assessments.

The theoretical and conceptual basis for the approach is explained in **Volume 2**, with a summary of the applied methodology presented in this volume. The reader is also referred to Khomo (2014) if further detail is required on the derivation of the land suitability maps for sugarcane, grain sorghum and soybean. In this volume, the approach is illustrated using two additional feedstocks (one bioethanol and one biodiesel) and highlights the impact of including various criteria on biofuel production potential.

7.2 Approach

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 7.2.4**). These factors were then applied to various spatial datasets (**Section 7.2.3**) using the following methodology.

7.2.1 Case study review

Khomo (2014) reviewed four case studies involving the use of GIS to assess land suitability to crop production. From three case studies, a unique aspect of the methodology was identified as follows:

- 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 this 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.

7.2.2 Mapping criteria

Khomo (2014) identified five criteria that were used to assess the suitability of land to grow feedstocks as follows:

- monthly rainfall (as an index of moisture supply),
- monthly means of temperature (index of moisture demand),
- monthly means of relative humidity (index of disease risk),
- soil depth (index of moisture storage), and
- slope (e.g. eliminate areas with steep slopes).

These criteria were similar to those used by Holl *et al*. (2007), who selected rainfall, temperature, soil fertility, frost, slope and altitude. Altitude was not considered as a mapping criterion in this approach 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. Similarly, Mokonoto (2012) concluded that either monthly temperature or accumulated heat units should be used as mapping criterion, but not both. Finally, surface (and underground) water resources were also not considered in the methodology.

7.2.3 Spatial 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. **Table 55** summarises the various data sources used in the present study. For additional information pertaining to each data set, the reader is referred to the reference provided in the table.

Table 55 Sources of climatic (rainfall, temperature & relative humidity), edaphic (soil depth) and topographic (slope) data used in this study

Datasets	Description	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)

7.2.4 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 **APPENDX D** of **Volume 2** 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** of **Volume 2** for bioethanol and biodiesel feedstocks respectively (refer to the section heading "Growth criteria").

7.2.5 Ranking of criteria

An approach developed by Ramirez-Villegas *et al*. (2013) was adopted to identify climatic thresholds that distinguish between optimum, marginal and unsuitable growing conditions. However, the approach was modified to include a sub-optimum class, which introduced a "buffer" zone in-between the optimum and marginal classes. Rainfall, temperature and relative humidity thresholds were then selected to distinguish between optimum (Opt), sub-optimum (Sub) and marginal (Abs) growing conditions as shown in **Table 56**. In this section, soybean is used as an example feedstock to explain the approach. The reader is referred to **Volume 2** or Khomo (2014) for further information.

Table 56 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			

Soybean is best adapted to summer rainfall regions where more than 450 mm falls in the growing season (Smith, 1998). Similarly, survival is deemed low due to high risk of disease incidence (e.g. soybean rust) when soybean is grown in very wet areas (> 1 100 mm of seasonal rainfall). A distinction is made between the temperature thresholds for germination and those deemed appropriate for the remainder of the growing season. The relative humidity thresholds account for the risk of soybean rust outbreak, which increases in humid environments. Caldwell *et al*. (2002) stated that soybean rust outbreaks are most severe when relative humidity levels are 75 to 80%.

A ranking was then assigned to each class based on an approach used by Koikai (2008) to identify suitable locations for a bioethanol processing plant in Kenya. Thus, growth conditions are deemed optimal for soybean when accumulated monthly rainfall ranges from 700 to 900 mm over the five-month growing season (**Table 57**).

Table 57 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

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 not be used as a definitive guide to where the crop may be grown in South Africa. Such estimates may "improve" with time as more information becomes available on each feedstock, especially if it is grown extensively in South Africa.

7.2.6 Weighting of criteria

Holl *et al*. (2007) mapped areas suitable for Jatropha production by weighting the three main criteria as follows: rainfall (40%), temperature (35% and soil fertility (10%). A similar approach was adopted in this study where the five selected criteria were weighted according to their relative importance in determining feedstock survival at a particular location (**Table 58**). These subjective weightings were based on expert opinion and according to Bertling and Odindo (2013), rainfall is most important to crop survival. Furthermore, 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 to create a decimal weighting.

Table 58 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**

7.2.7 Total suitability score

Based on FAO's guidelines for Land Evaluation Guidelines for Dryland Agriculture (FAO, 1983), the arithmetic procedures method (i.e. overall suitability is obtained by multiplying or adding values assigned to each suitability class) was used to determine the overall land suitability score. In **Table 59**, 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.

Table 59 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**

7.2.8 Normalised suitability score

The total suitability score ranges from 0 (not suitable) to 3 (optimally suited). The final step involved the normalisation of the total suitability score 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 60**. 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 60 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 classes are numbered in a sequence where the highest number represents the least suitable and the lowest number represents the most suitable as follows:

- Class S1: Highly suitable
- Class S2: Moderately suitable
- Class S3: Marginally suitable
- Class N1: Currently not suitable
- Class N2: Permanently not suitable

7.3 GIS Approach

Khomo (2014) introduced an innovative approach which involved the use of monthly crop coefficients to determine the optimum distribution of rainfall over the growing season. The use of basal (K_{cb}) and single (K_c) crop coefficients was evaluated by Khomo (2014), who showed that the Free State is not suitable for soybean production when K_{cb} is used to determine the desired distribution of rainfall over the growing season. Based on this, Khomo (2014) concluded that the use of K_{cb} values is not recommended.

Furthermore, Khomo (2014) also evaluated the use of international (i.e. FAO) *vs*. locally derived K_c values. The results showed that the central region of Mpumalanga is considered unsuitable for soybean production when FAO K_c values were used. Since the majority of soybean is grown in Mpumalanga, Khomo (2014) concluded that the use of locally derived K_c values is recommended. In addition, Allen *et al*. (1998) strongly encouraged the use of crop coefficients deemed appropriate for local conditions. Hence, monthly K_c for Baynesfield were used in this study to determine the optimum distribution of monthly rainfall over the growing season. This procedure is briefly explained next using soybean as the example feedstock.

7.3.1 Rainfall distribution

The single crop coefficients derived at Baynesfield Estate for soybean as shown in **Table 61**. The monthly values were normalised and then multiplied by each of the seasonal rainfall thresholds given in **Table 56**. 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 61 Preferred distribution of seasonal rainfall in each month of the growing season for soybean

Month	K_c	K_c norm	Monthly rainfall thresholds (mm)					
			Abs	Sub	Opt	Opt	Sub	Abs
November	0.72	0.167	75	90	115	150	165	185
December	0.72	0.167	75	90	115	150	165	185
January	1.00	0.232	105	130	160	210	230	255
February	1.03	0.239	105	135	175	215	245	260
March	0.84	0.195	90	105	135	175	195	215
Total	**4.31**	**1.000**	**450**	**550**	**700**	**900**	**1 000**	**1 100**

If February's rainfall total ranges from 175 to 215 mm, it is considered optimal and is assigned a ranking of 3 (**Table 62**). Similarly, if February's rainfall 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 (i.e. too dry) or above 260 mm (i.e. too wet).

Table 62 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 63**). 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 63 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**

The peak K_c value 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 neglects the supply of soil moisture from capillary rise, which can be significant for clay soils above perched (or shallow) groundwater tables. Furthermore, the K_c 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.

7.3.2 Data manipulation and analysis

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 comprises of ArcMap and Spatial Analyst. The latter was used to manipulate the gridded monthly datasets of rainfall, temperature and relative humidity using the methodology briefly described next.

Each monthly rainfall grid (for November to December) was re-classified to produce five new datasets using the Re-classify tool in Spatial Analyst. For example, if the gridded monthly rainfall in February for a particular grid point ranged from 175 to 215 mm, it was re-classified as 3 (i.e. optimum). 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 12

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). 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 reflects the crop is most susceptible to soybean rust in January and February (**Table 64**).

Table 64 Relative monthly weighting assigned to each criterion (Khomo, 2014)

Month	Decimal weighting		
	Rainfall	Temperature	Relative humidity
November	0.067	0.050	0.010
December	0.067	0.050	0.010
January	0.093	0.050	0.030
February	0.096	0.030	0.030
March	0.078	0.020	0.020
Total	**0.400**	**0.200**	**0.100**

The soil depth and slope grids were also re-classified, then weighted accordingly. Thereafter, all five re-classified grids were summed using Raster Calculator in Spatial Analyst, to produce a final land suitability grid with values ranging from 0 to 1 on a continuous scale.

7.3.3 Present land use

Wicke (2011) used a GIS approach to identify areas considered suitable for bioenergy production, by filtering out land that is not available or not suitable for high biomass cultivation. A similar approach was adopted here where the land use dataset obtained from SANBI was re-categorised into 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 7.2.8**), 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 7.2.8**) 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.

7.4 Results and Discussion

A noted earlier, Khomo (2014) developed land suitability maps for sugarcane, grain sorghum and soybean. The same methodology was applied to develop a land suitability map for sugarbeet and canola. The results of the land suitability assessment for these two feedstocks is discussed next.

7.4.1 Suitability for sugarbeet production

7.4.1.1 Rainfall suitability score

The final rainfall datasets incorporating monthly rainfall from September to March for the summer growing season, and June to December (for the winter season) are shown in **Figure 34** and **Figure 35** respectively. From **Figure 34**, the most suitable areas for the cultivation of sugarbeet during summer is the eastern half of the country, as well as the southern Cape in the Knysna region. For the winter growing season, the pattern is similar, but with the addition of suitable areas in the Western Cape as shown in **Figure 35**.

Table 65 shows that the half (50.9%) of the country's land area is not suited to the dryland cultivation of winter sugarbeet. This result indicates that dryland cultivation of winter sugarbeet is unviable and thus, supplemental irrigation is required to establish and growth this crop. On the other hand, 7.4% of the country is well suited to sugarbeet production if the crop is planted in summer.

Table 65 Areas suitable for the cultivation of sugarbeet based on monthly rainfall accumulated over a seven month growing season, starting in September (summer) and June (winter)

Value	Summer			Winter		
	Pixel count	% of total land area	Accum. %	Pixel count	% of total land area	Accum. %
0.00	9 528 320	36.57	36.57	13 256 704	50.88	50.88
0.01-0.05	3 382 016	12.98	49.55	2 003 520	7.69	58.57
0.05-0.10	3 165 504	12.15	61.70	4 055 424	15.57	74.14
0.10-0.15	1 484 864	5.70	67.40	4 166 336	15.99	90.13

Value	Summer			Winter		
	Pixel count	% of total land area	Accum. %	Pixel count	% of total land area	Accum. %
0.15-0.20	1 790 976	6.87	74.28	2 454 464	9.42	99.55
0.20-0.25	2 062 720	7.92	82.19	74 496	0.29	99.84
0.25-0.30	2 706 176	10.39	92.58	25 664	0.10	99.94
0.30-0.35	1 782 656	6.84	99.42	16 384	0.06	100.00
0.35-0.40	149 952	0.58	100.00	192	0.00	100.00

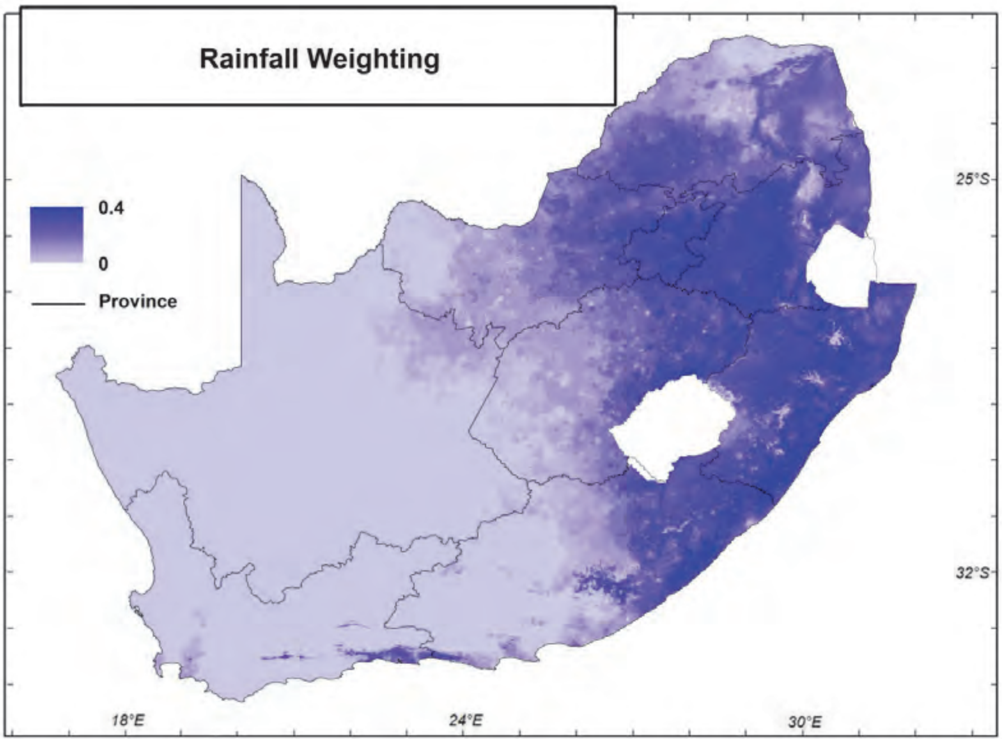


Figure 34 Rainfall suitability map for sugarbeet planted in September

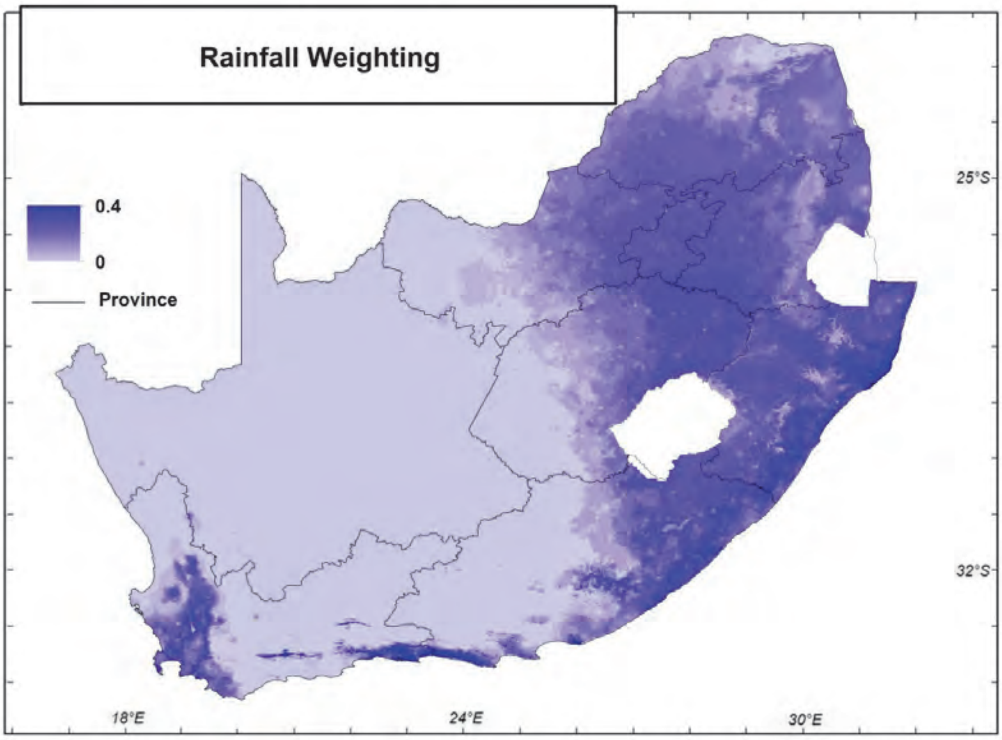


Figure 35 Rainfall suitability map for sugarbeet planted in June

7.4.1.2 Temperature suitability score

The final temperature maps that were used to identify areas where sugarbeet can be cultivated are shown in **Figure 36** and **Figure 37**. Although the same thresholds were used for both planting dates, they were applied to different growing periods (hence the two maps).

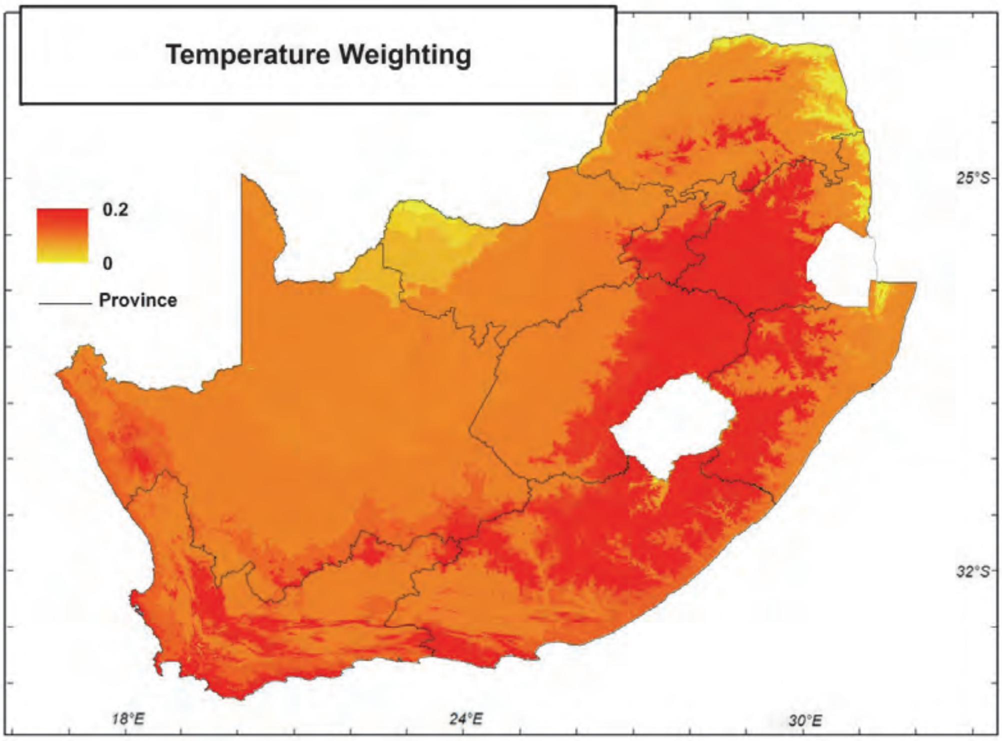


Figure 36 Temperature suitability map for sugarbeet planted in September

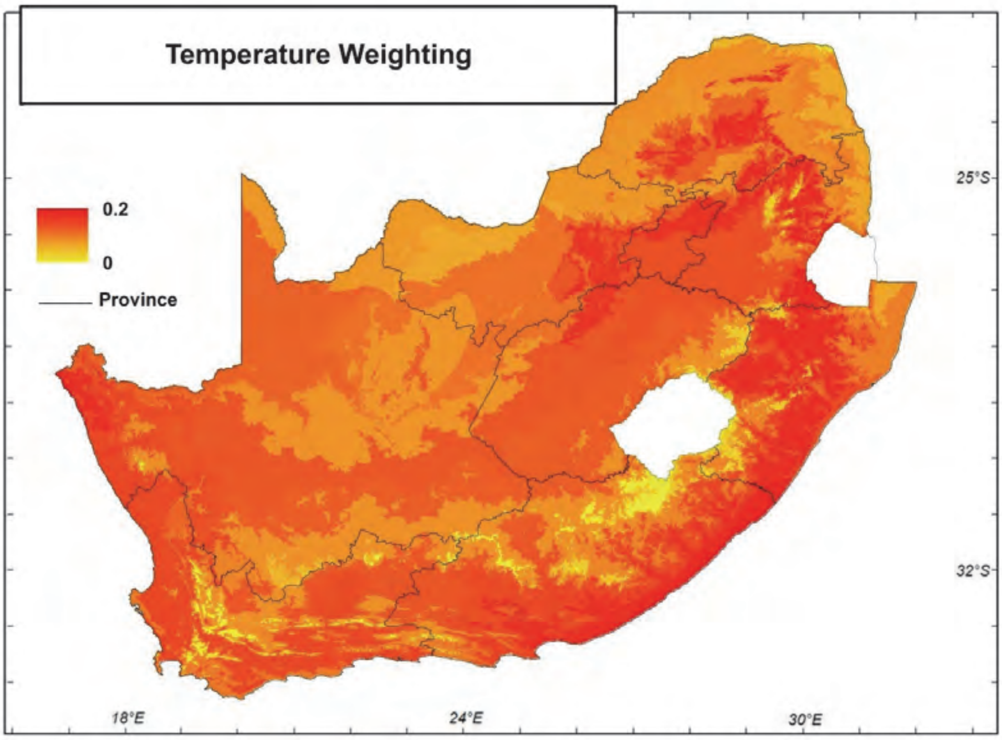


Figure 37 Temperature suitability map for sugarbeet planted in June

In **Figure 36**, areas highlighted in yellow are too hot for sugarbeet growth. However, the yellow areas in **Figure 37** represent mountainous areas that are too cold for sugarbeet growth. The eastern interior of the country and some southern coastal areas are deemed most suitable for sugarbeet planted in September. For the winter growing season, optimal growing areas exist along the eastern seaboard, while the interior is significantly less suitable for cultivation.

Table 66 shows that, in terms of mean monthly temperature, the majority of the country is more suited to a winter planting of sugarbeet than compared to a summer planting. This is not surprising considering the majority of sugarbeet is grown in temperature regions around the world. As noted earlier, a winter planting may require supplemental irrigation to ensure successful establishment of the crop.

Table 66 Areas suitable for the cultivation of sugarbeet based on monthly mean temperature over a seven month growing season, starting in September (summer) and June (winter)

Value	**Summer**			**Winter**		
	Pixel count	**% of total land area**	**Accum. %**	**Pixel count**	**% of total land area**	**Accum. %**
0.00	1 216	0.00	0.00	25 152	0.09	0.09
0.01-0.05	20 032	0.07	0.08	3 584	0.01	0.11
0.05-0.10	407 104	1.51	1.58	233 216	0.86	0.97
0.10-0.15	16 798 208	62.12	63.71	8 345 152	30.86	31.83
0.15-0.20	9 813 824	36.29	100.00	18 433 280	68.17	100.00

7.4.1.3 Humidity suitability score

Figure 38 and **Figure 39** represent the processing of maximum relative humidity raster datasets over a seven-month period. During the summer period, the drier Northern Cape Province is deemed highly suitable for sugarbeet cultivation.

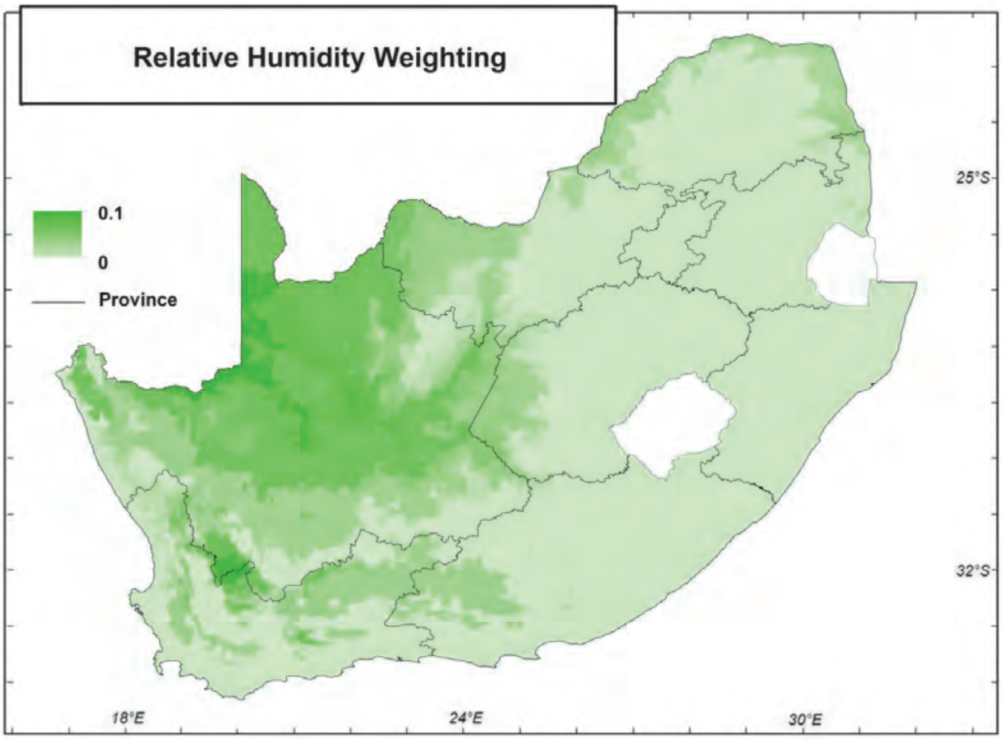


Figure 38 Relative humidity suitability map for sugarbeet planted in September

Although the optimum growing areas expand for a winter growing season, the humid coastal areas of the country are not ideally suited to sugarbeet. The relative humidity constraint favours the western regions, which rarely coincide with the optimum rainfall regions towards the eastern parts of the country.

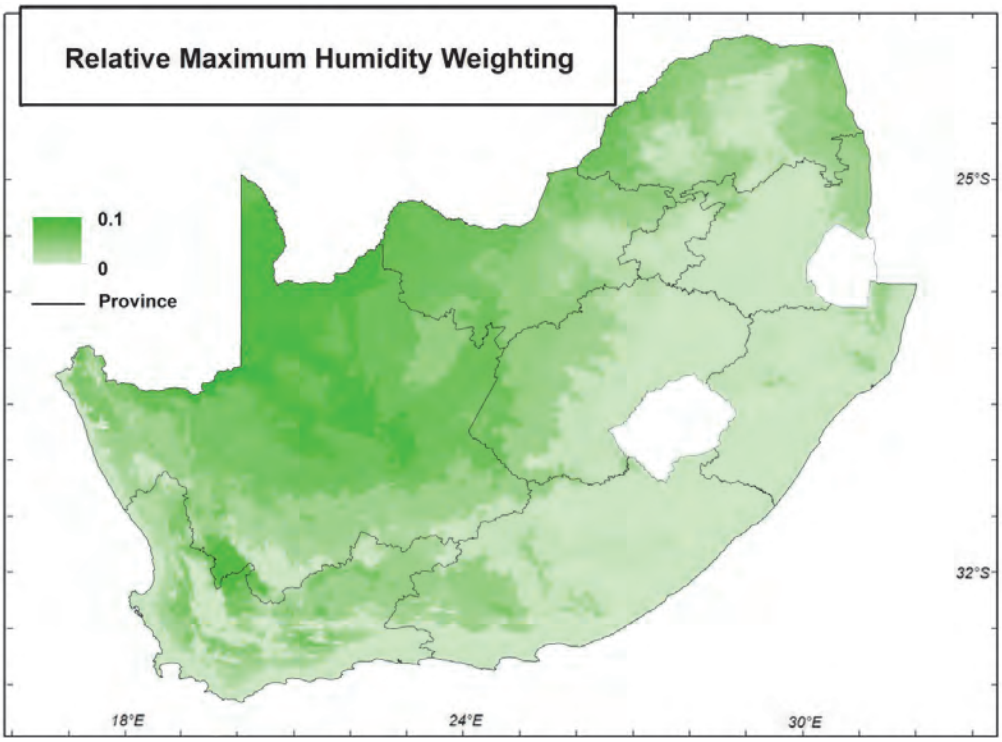


Figure 39 Relative humidity suitability map for sugarbeet planted in June

Table 67 shows that, in terms of maximum relative humidity, the majority of the country is more suited to a winter planting of sugarbeet than compared to a summer planting. This is the same trend noted with mean monthly temperature (c.f. **Section 7.4.1.2**).

Table 67 Areas suitable for the cultivation of sugarbeet based on monthly maximum relative humidity over a seven month growing season, starting in September (summer) and June (winter)

Value	Summer			Winter		
	Pixel count	% of total land area	Accum. %	Pixel count	% of total land area	Accum. %
0.00	14 417 664	53.31	53.31	8 260 416	30.54	30.54
0.01-0.05	8 563 328	31.66	84.97	12 534 080	46.34	76.89
0.05-0.10	4 064 768	15.03	100.00	6 251 264	23.11	100.00

7.4.1.4 Soil depth suitability score

As noted before, soil depth comprises of a single dataset that does not change over the growing season. **Figure 40** highlights areas in yellow that are deemed too shallow for sugarbeet cultivation. Deeper, more suitable soils can be found along the western coastline, the northern (e.g. Northern Cape & North West) provinces and along the KZN coastline.

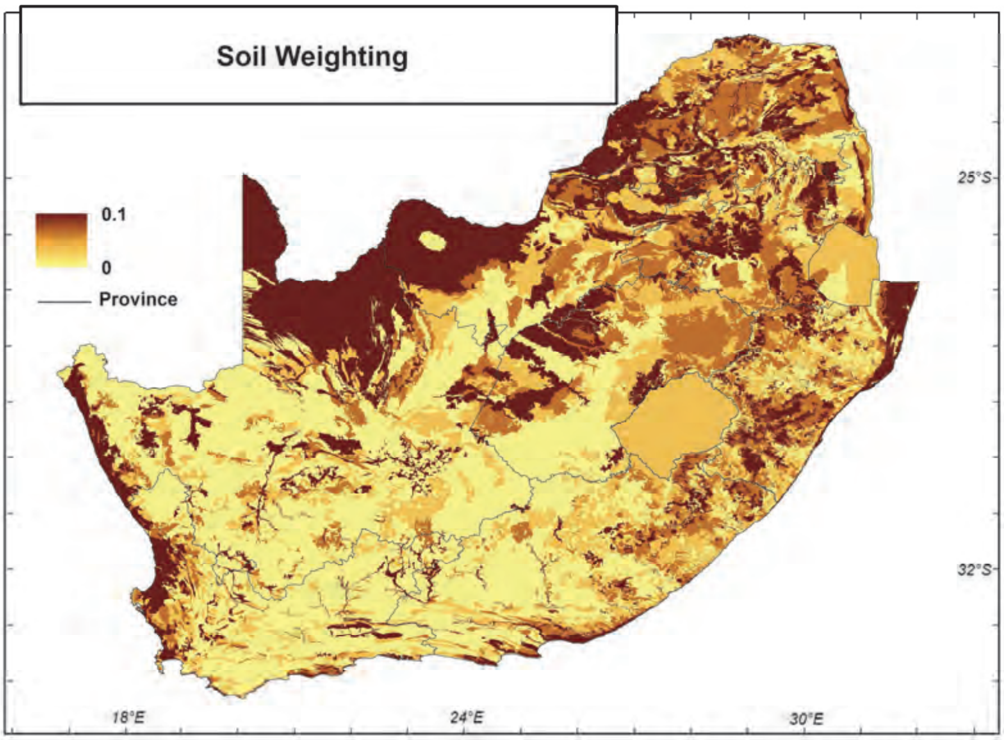


Figure 40 Soil depth suitability map for the cultivation of sugarbeet

Table 68 indicates that for a large portion (≈40%) of the country, soil depths are unsuitable for sugarbeet production. These areas mainly occur in the western parts of the country (**Figure 47**). The same trend was noted for canola, because the minimum soil depth was set to 500 mm for both crops.

Table 68 Areas suitable for the cultivation of sugarbeet based on soil depth

Value	Pixel count	% of total land area	Accum. %
0.00	10 791 582	39.80	39.80
0.01-0.05	6 092 120	22.47	62.26
0.05-0.10	10 232 441	37.74	100.00

7.4.1.5 Slope suitability score

The procedure followed to process slope is similar to that used for soil depth, in that there is only a single dataset. However, the final weighting of this dataset is 0.2, i.e. same influence as temperature. **Figure 41** indicates the area most suited for cultivation is the interior of the country, with less suitable areas located along the coastline. This is due to the steeper terrain normally found in the coastal areas, especially in the western and southern Cape.

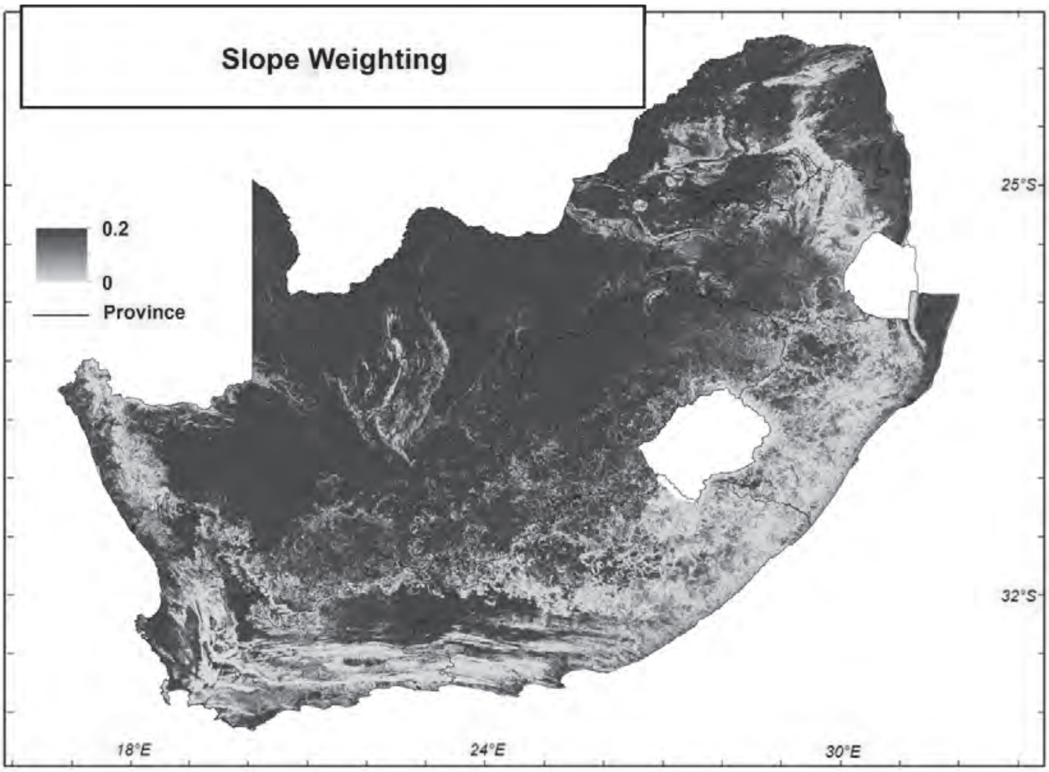


Figure 41 Slope suitability map for the cultivation of canola

With regard to slope constraints, **Table 69** shows that the majority of the country is deemed suitable for cultivation. It is interesting to note that 24.5% of the country is considered unsuitable for cultivation, with the majority (60.4%) being relatively flat for crop cultivation.

Table 69 Areas suitable for the cultivation of canola based on slope

Value	Pixel count	% of total land area	Accum. %
0.00	5 341 942	20.51	20.51
0.01-0.05	0	0	20.51
0.05-0.10	1 041 173	3.99	24.50
0.10-0.15	3 925 460	15.07	39.57
0.15-0.20	15 737 103	60.43	100.00

7.4.1.6 Overall suitability score

The above-mentioned datasets were then summed in order to derive the final weighted raster dataset, with values ranging from 0 to 1. This dataset was then re-classified into four categories, namely unsuitable (≤ 0.63), marginal (0.63 - 0.70), sub-optimal (0.70 - 0.75) and optimal (> 0.75).

7.4.2 Suitability for canola production

7.4.2.1 Seasonal rainfall threshold

Canola farm boundaries were provided by the Western Cape's Department of Agriculture (Roux, 2015), which were then superimposed on the seasonal rainfall map. The total seasonal rainfall was determined by accumulating monthly rainfall from April to August, which represents a typical growing season in the Western Cape. The GIS overlay showed that actual canola farms do exist in areas that receive more than 250 mm of seasonal rainfall. However, it must be noted that some canola farm boundaries also existed in drier areas that receive between 200 and 250 mm of seasonal rainfall. **Figure 42** indicates possible areas within South Africa that may support the dryland cultivation of canola in winter.

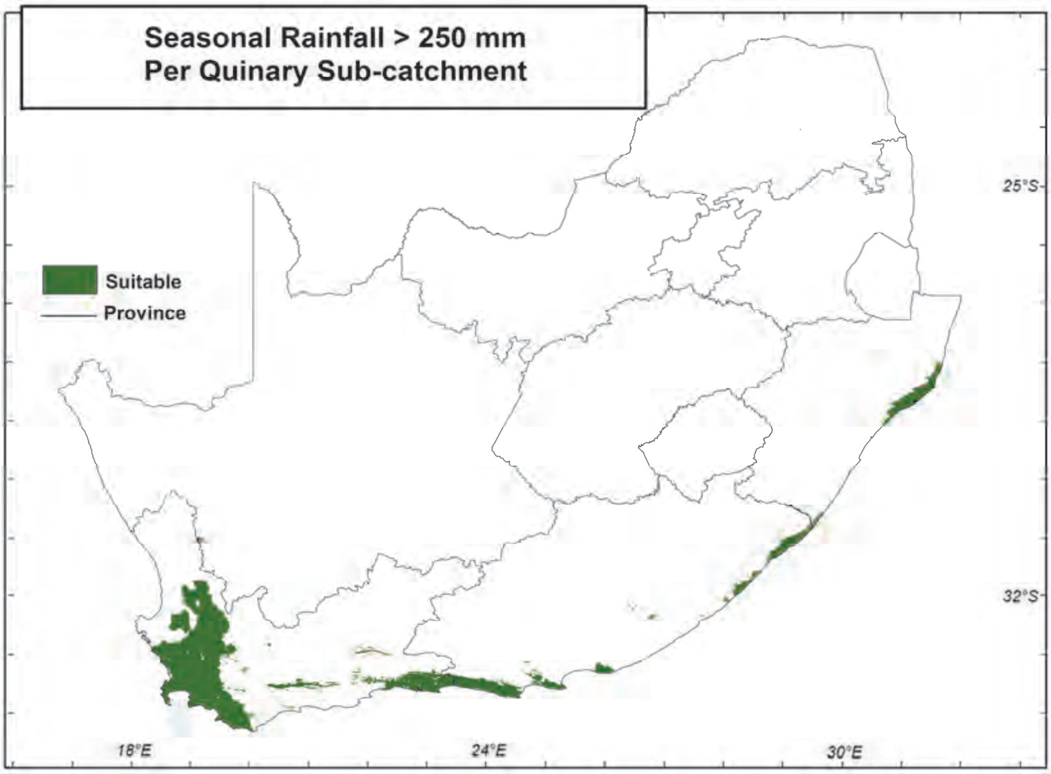


Figure 42 Areas where seasonal rainfall (accumulated from April to August) exceeds 250 mm and thus, canola cultivation may be possible

However, **Figure 42** still does not highlight areas towards the eastern part of the Free State Province that could support winter canola. This may indicate a shortcoming in the approach where it may be argued that the canola season used in this study is too short and should be extended from August to October, as suggested in the canola manual produced by Cumming *et al*. (2010). Fouché (2015) added that for a crop like canola, the available moisture stored in the soil at the beginning of the season is more important than amount of rainfall received over the growing period. This suggests that the rainfall received in March should also be included in the seasonal rainfall total.

This seasonal rainfall threshold was doubled to 500 mm to determine areas in the country that are ideally suited to canola production. **Figure 43** illustrates that the wetter winter rainfall regions only occur in the Western Cape. Since the seasonal rainfall threshold of 250 mm could not be supported by the available literature (Table 94 in APPENDIX_D in **Volume 2**), the threshold was increased to 300 mm to improve the economic viability of canola production.

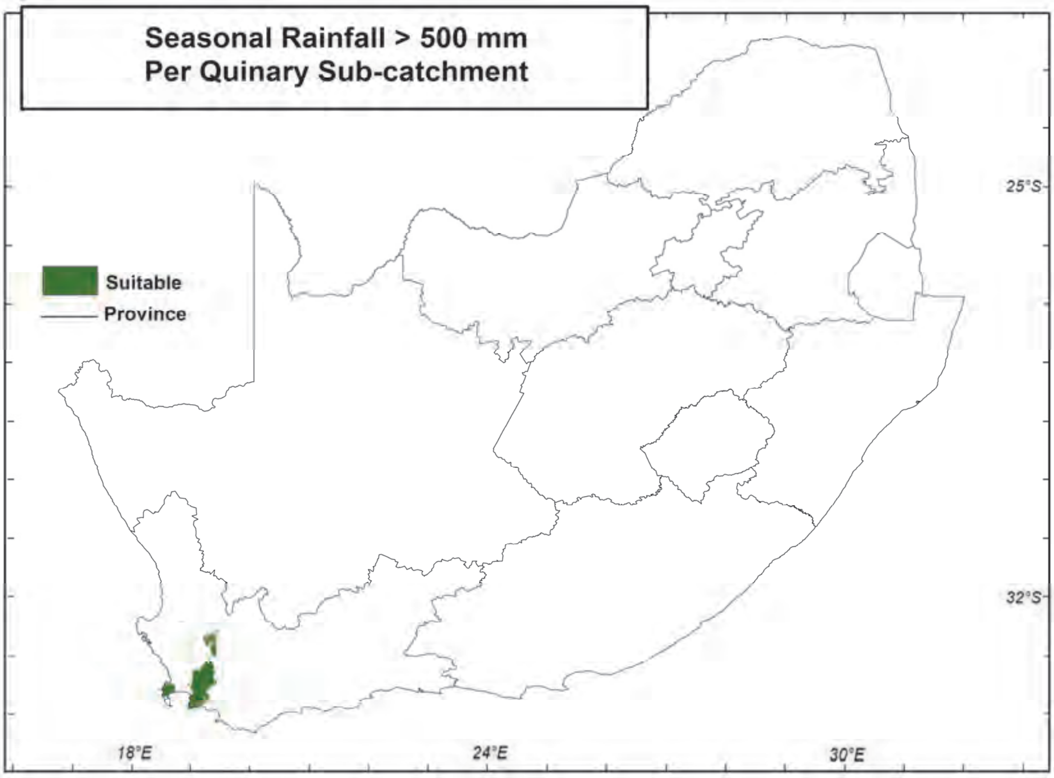


Figure 43 Areas where seasonal rainfall (accumulated from April to August) exceeds 500 mm and thus, higher canola yields are possible

7.4.2.2 Rainfall suitability score

In order to determine areas suitable for the cultivation of canola, a number of algebraic functions were applied to each monthly rainfall raster from April to August. The next step involved the re-classification of each monthly raster into four categories, namely unsuitable (0), marginal (1), sub-optimal (2) and optimal (3). Thereafter, the classified values were normalised to produce a range from 0 to 1. In the final step, the normalised values were then multiplied by a monthly weighting value which is based on the importance of the variable at each growth stage. For rainfall, this weighting factor is based on the crop coefficient, which is normalised to give an overall weighting range of 0.00 to 0.40.

The final rainfall raster incorporates data from April through to August and was created following the method outlined above. The dataset represents the overall suitability of rainfall quantity and distribution over the growing season. The maximum weighted value for rainfall is 0.4, which is considered highly suitable for canola production (0.0 being unsuitable). From **Figure 44**, the most suitable areas for cultivation, based on rainfall, are along the coastal areas in the Western Cape, Eastern Cape and KwaZulu-Natal.

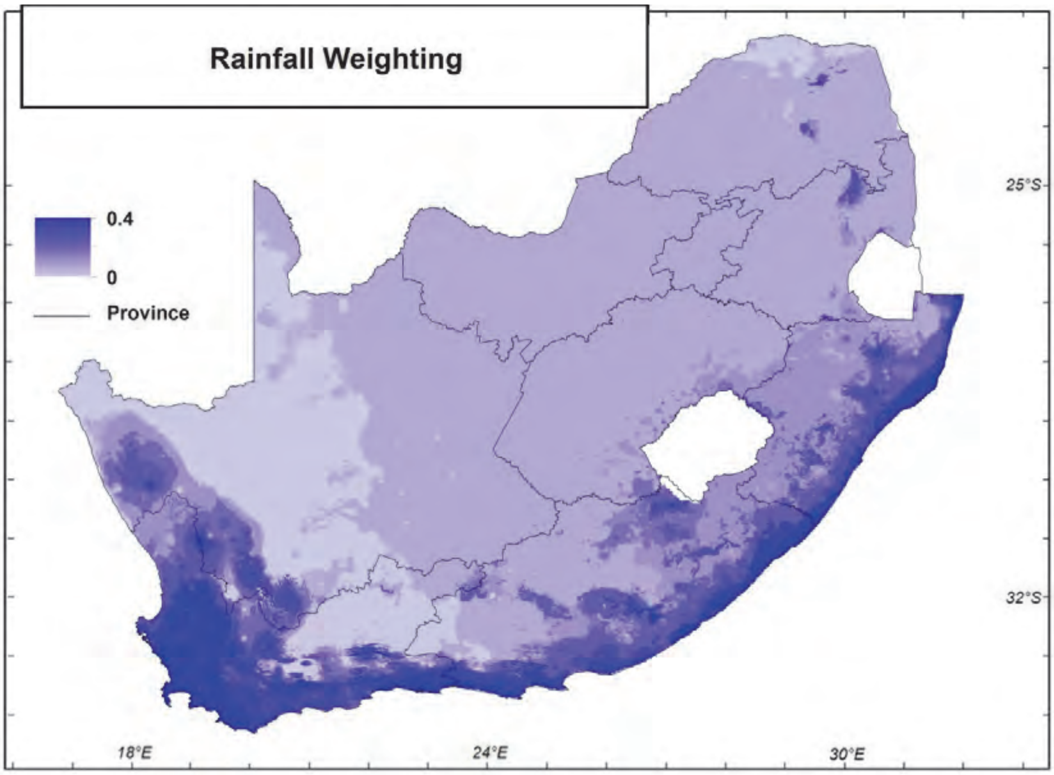


Figure 44 Rainfall suitability map for the cultivation of canola

The interior of the country is not suitable for the cultivation of this winter crop. This is due to the significantly lower winter rainfall occurring in these areas, most of which is below the optimal requirements from the growth of canola. **Table 70** shows that the majority of the country is not suited to the winter production of canola.

Table 70 Areas suitable for the cultivation of canola based on seasonal rainfall

Value	Pixel count	% of total land area	Accum. %
0.00	3 915 008	15.03	15.03
0.01-0.05	16 704 960	64.13	79.16
0.05-0.10	2 419 136	9.29	88.45
0.10-0.15	1 367 552	5.25	93.70
0.15-0.20	1 261 696	4.84	98.54
0.20-0.25	237 888	0.91	99.45
0.25-0.30	93 760	0.36	99.81
0.30-0.35	44 800	0.17	99.98
0.35-0.40	5 184	0.02	100.00

7.4.2.3 Temperature suitability score

The methodology used for to determine the final weighted temperature raster is the same as that used for rainfall. The major difference is that the thresholds used to reclassify the monthly grids are applicable to mean temperature. Furthermore, the overall weighting totals 0.2, i.e. half the importance of rainfall. Hence, a weighting of 0.2 is considered highly suitable for the cultivation of canola. **Figure 45** highlights the coastal and northern regions of South Africa as being most suitable for canola production.

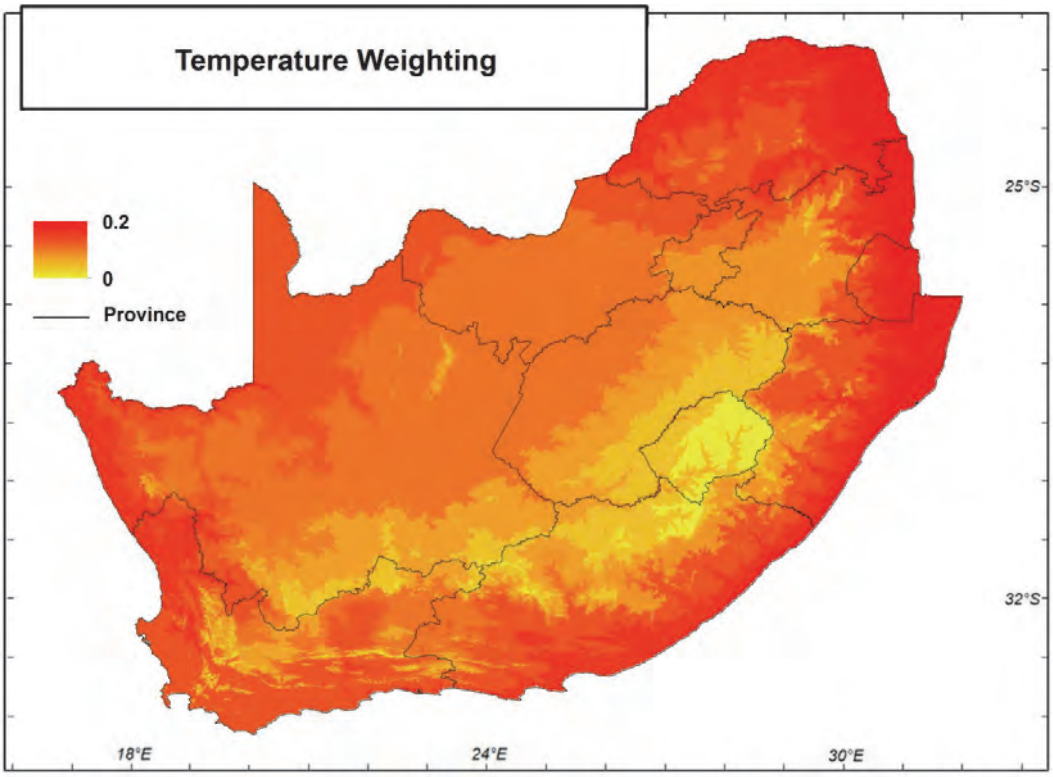


Figure 45 Temperature suitability map for the cultivation of canola

Table 71 shows that the greatest portion (≈59%) of the country is considered sub-optimal (0.00 - 0.15) and thus, 41% is deemed suitable (0.15 - 0.20). Hence, temperature is less of a limiting criterion to canola production than compared to rainfall.

Table 71 Areas suitable for the cultivation of canola based on mean monthly temperature

Value	Pixel count	% of total land area	Accum. %
0.00	86 784	0.32	0.32
0.01-0.05	284 096	1.05	1.37
0.05-0.10	2 174 848	8.04	9.41
0.10-0.15	13 355 840	49.39	58.80
0.15-0.20	11 138 816	41.20	100.00

7.4.2.4 Humidity suitability score

Owing to the scarcity of information available with respect to the potential effects of relative humidity on diseases affecting canola survival, the only information that could be found indicated a range of 20 to 80% as adequate for the cultivation of this crop. **Figure 46** is a result of the processing of five mean monthly relative humidity raster datasets using the same procedure as described for rainfall. The major difference is that the overall weighting is 0.1, i.e. half the importance of temperature. The map indicates that the majority of South Africa is considered highly suitable for canola. The categories used to re-classify these datasets were 30 to 50% as sub-optimal (2), and 50 to 85% as optimal (3). Since the range is mean monthly relative humidity from April to August across southern Africa is 40 to 80%, the majority of the country is deemed optimal as highlighted in the figure below. Hence, canola production is not limited by relative humidity constraints and thus, can be effectively ignored.

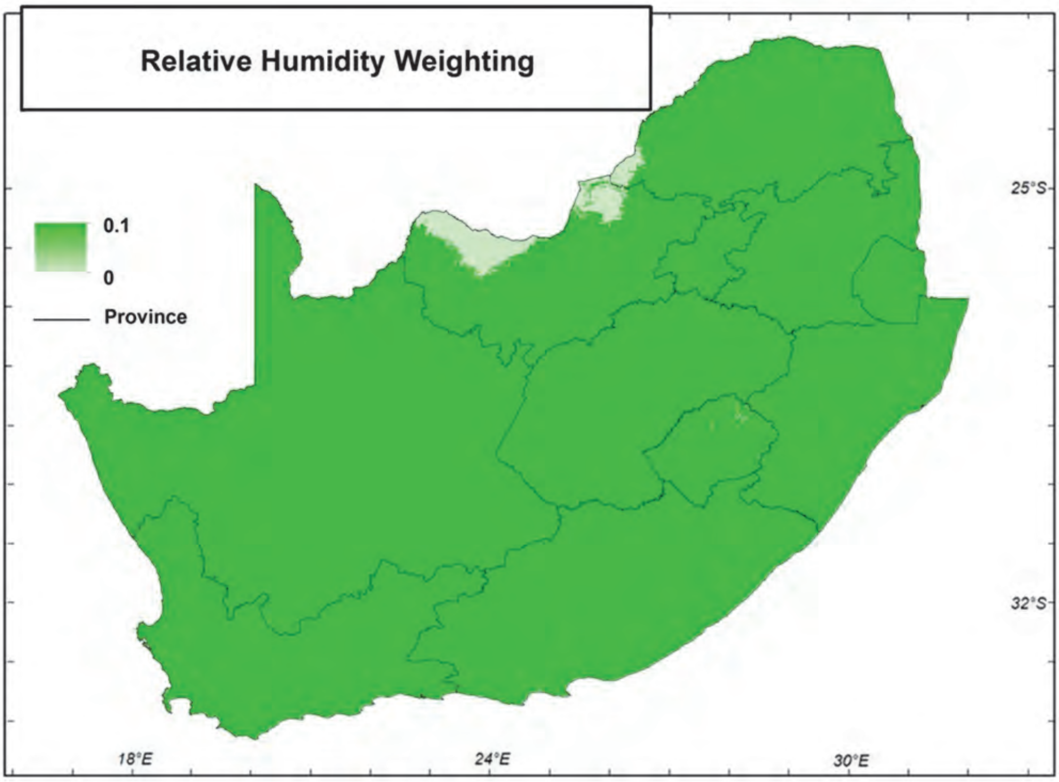


Figure 46 Relative humidity suitability map for the cultivation of canola

7.4.2.5 Soil depth suitability score

Soil depth comprises of a single dataset that does not change over the growing season. The final weighting of this dataset is 0.1, i.e. same importance as relative humidity. **Figure 47** shows the coarseness of the soil depth data available for Lesotho and Swaziland. Deep soils can be found in the coastal regions of the Northern and Western Cape Provinces as well as KwaZulu-Natal. The northern parts of the Northern Cape and North West Provinces are also suitable for canola production. However, these regions are not suitable in terms of rainfall.

Table 72 indicates that for a large portion (≈40%) of the country, soil depths are unsuitable for canola production. These areas mainly occur in the western parts of the country (**Figure 47**).

Table 72 Areas suitable for the cultivation of canola based on soil depth

Value	Pixel count	% of total land area	Accum. %
0.00	10 791 910	39.79	39.79
0.01-0.05	6 090 919	22.46	62.25
0.05-0.10	10 233 310	37.75	100.00

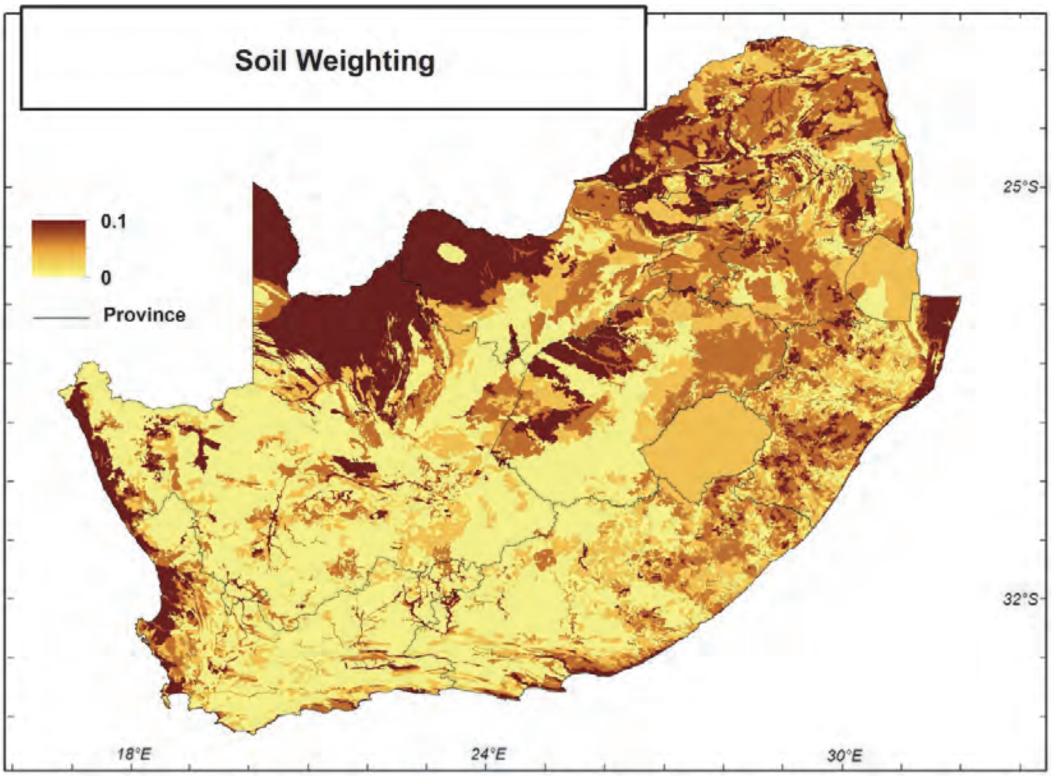


Figure 47 Soil depth suitability map for the cultivation of canola

7.4.2.6 Slope suitability score

Since the slope criteria used for sugarbeet are the same for canola, the reader is referred to **Section 7.4.1.5** for the distribution of suitable cultivation areas.

7.4.2.7 Overall suitability score

In order to determine areas suitable for the cultivation of canola, the above-mentioned datasets were then summed in order to derive the final weighted raster dataset, with values ranging from 0 to 1. This dataset is then re-classified into four categories, namely unsuitable (≤ 0.60), marginal (0.60 - 0.65), sub-optimal (0.65 - 0.75) and optimal (> 0.75).

The final step involved the elimination of "no-go" areas that are deemed unsuitable for crop cultivation, in order to produce the final map. To re-cap, rainfall has the highest weighting (0.4) and thus, the greatest influence on the overall suitability for crop production. Temperature and slope were assigned the next highest weightings of 0.2, with the lowest rating of 0.1 given to relative humidity and soil depth.

7.4.3 Summary

If all other criteria excluding rainfall are considered ideal (i.e. optimum) at a particular location, then the overall weighted score would be 0.60. This score falls in the range ≤ 0.60 and thus, would be considered unsuitable for crop production. However, if the rainfall score was as low as 0.01 out of 0.40, the overall score (including rainfall) would total 0.61, which is considered marginal for crop production. In reality, the risk of crop failure in such areas would be too high due to very low rainfall suitability, even though all other growth criteria are ideal. This highlights a shortcoming of the mapping approach and indicates that the lower threshold of 0.60 should be increased or more weighting is given to the rainfall criterion. It also suggests that the absolute and sub-optimum rainfall thresholds should not be set too low.

As discussed in Section 7.5.2 of **Volume 2**, the mapping approach adopted in the study does not eliminate areas considered too dry or too cold for crop production. Hence, the areas classified as marginal may be unsuitable because they are prone to frost. For example, areas where the average minimum temperature in July is below 7ºC should be eliminated as frost-prone areas for sugarcane cultivation.

8 CONCLUSIONS

8.1 Limitations and Assumptions

Significant improvements were made using locally derived crop coefficients for the hydrological modelling. However, the results are based on the assumption that crop coefficients measured at a single location and sometimes for a single season (e.g. soybean in **Table 24**), are applicable to all feedstock growing areas. Although this situation is not ideal, the high cost of field trials often limits the spatial extent of required research.

The yield and WUE maps (c.f. Section 4.2.3 of **Volume 3**) are based on a number of limitations and assumptions which need to be considered when interpreting the results. Firstly, the level of calibration differed for each crop (c.f. **Section 4.2.5.3**). Hence, yield output for sugarcane and sugarbeet is considered more reliable and applicable to South African growing conditions than yield estimates for grain sorghum and canola.

Secondly, model calibration was undertaken at a single location (e.g. La Mercy or Ukulinga as shown in **Table 33**) and is deemed representative of all other simulated areas. This assumption may not be true if the growing conditions at the location of interest (i.e. each quinary) are very different to that of the calibration point.

Thirdly, *AQUACROP* was run in GDD mode to account for the effects of temperature on biomass production (c.f. **Sections 0**, **6.2.4.9, 6.3.5** & **8.3.2.1**). Thus, setting the correct base and upper (cut-off) temperatures in the crop parameter file is critical.

This study was limited by the availability of spatial data and thus, cannot be applied at the farm level due to the coarse scale of the data used. Only South Africa is considered (not Lesotho and Swaziland) due to lack of soils and land use data (c.f. Sections 2.8 & 2.9 in **Volume 3**) in the neighbouring countries. This is particularly true for the soils data used in this study, which represents the “weakest link” in the methodology.

The soil depth information was derived from the1:250 000 scale land type series available at a national scale for South Africa, i.e. 1.0 cm on the map = 2.5 km on the ground (c.f. Section 2.5 of **Volume 3**). The maximum soil depth is 1 200 m, which is the length of a standard auger. Hence, this depth is not the total soil depth, nor is it the effective rooting depth (which accounts for a root-impeding layer such as a stone line).

The derivation of the crop growth criteria and weightings (c.f. APPENDIX_D in **Volume 2**) is based on a subjective assessment of values gleaned from a literature review as well as expert opinion. Thus, these estimates are not absolute and should not 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 information becomes available on each feedstock, especially if it is grown extensively in South Africa.

The lower threshold used to categorise the overall suitability score as unsuitable was increased to 0.63 for the sugarbeet map (c.f. Section 7.4.7 of **Volume 2**). This modification was made to avoid the scenario where an area with a very low rainfall score, is classified as marginal and not unsuitable, because all other growth criteria are ideal (c.f. Section 7.5.2 of **Volume 2**). Thus, the end-user must bare this in mind when interpreting the land suitability maps.

Another solution is to adopt a two-phase approach. The first phase involves the elimination of areas deemed unsuitable for growth based on climate criteria, in particular rainfall. The second phase involves the classification of remaining areas into marginal to highly suitable (c.f. **Section 8.3.3.6**).

8.2 Summary of Main Findings

The simulation models (both *ACRU* and *AQUACROP*) were not run for a select subset of quinaries in which each feedstock may grow (i.e. based on the land suitability maps). Instead, the approach was to run the model for each of the 5 838 quinaries, irrespective of whether a particular quinary was suitable for feedstock cultivation. Although this approach is more complex and time consuming (c.f. Section 6.5.9.3 of **Volume 2**), it offers a number of advantages as follows:

- If the land suitability maps are incorrect, the models would not be run for areas where feedstock cultivation is possible and thus, required data would be incomplete or missing.

- Since the same level (and type) of data exists for each considered feedstock, the water use, yield, WUE as well as the hydrological impact can be compared to any other crop.

- Results obtained for areas that are unsuitable for crop growth have highlighted issues that certain metrics can be misleading or misinterpreted. For example, high WUE is feasible in marginal areas or when the crop is stressed.

- Output related to crop growth and yield can be used to improve the land suitability maps. This important point is discussed further in the two sub-sections below.

8.2.1 Hydrological impacts

As note previously, the hydrological modelling was undertaken for all sub-catchments in southern Africa (including Lesotho and Swaziland) and not a sub-set of quinaries identified as being suitable for feedstock production.

ACRU's stream flow output is sensitive to changes in crop coefficients. Crop coefficients derived for local growing conditions are recommended for crop water use estimation. Hence, one of the important outcomes of this project was the derivation of monthly crop coefficients for various biofuel crops, which were obtained from two different sites over multiple seasons. This highlights the importance and value of the research trials conducted at both the Ukulinga and Hatfield research farms, in meeting the overall objectives of the biofuels project (c.f. **Table 24**).

McMahon *et al*. (2013) highlight the importance of appropriately specifying the microclimate around a pan in order to estimate representative pan coefficients (c.f. Section 4.2.2.1 of **Volume 2**) and hence, reference crop evaporation estimates. It may be unrealistic to assume that each quinary is represented by an A-pan surrounded by a green fetch of 200 m (c.f. Section 4.2.2.2 of **Volume 2**). Thus, the derivation of monthly *CORPAN* factors by comparing computed A-pan equivalent evaporation (E_p) with reference crop evaporation (ET_o) is deemed more physically-based (c.f. Table 41 in **Volume 2**) than the empirical approach provided by Allen *et al*. (1998).

Revised (and arguably, more realistic) A-pan evaporation estimates were used in this study (c.f. Section 5.5 of **Volume 2**). These evaporation estimates are higher than those used in previous studies which resulted in less runoff generation for the majority of quinary catchments (c.f. **Section 5.3.1**).

It is strongly recommended that the mean runoff statistic (and not the median) must be used to assess the impact of feedstock cultivation on downstream water availability (**Section 5.3.4.2**). The biofuels assessment utility (c.f. **Volume 3**) calculates the reduction in monthly runoff, then expresses this difference as a percentage relative to the mean monthly runoff for the baseline.

A change in land use from natural vegetation to feedstock cultivation has the potential to shift the start of the low flow period (either earlier or later than that for natural vegetation). This shift, which is quantified in **Volume 3** (c.f. Section 3.4.3.8), may exacerbate the impact of the reduction in low flow runoff that may result from the land use change.

Sugarcane exhibits the most potential to utilise more water than the dominant Acocks Veld Type it replaces (c.f. Section 3.4.3.4 of **Volume 3**), particularly in the KwaZulu-Natal Midlands (c.f. Section 3.4.3.2 of **Volume 3**). Furthermore, far fewer quinaries are flagged as potential stream flow reduction areas when low flows are considered (c.f. Section 3.4.3.9 of **Volume 3**). This may indicate that the 25% threshold used for the low flow period is somewhat conservative (c.f. Sections 3.4.3.5 & 3.4.3.7 of **Volume 3**).

A total of 210 quinary sub-catchments were identified where sugarcane may “significantly” reduce both the annual and low flow stream flow (i.e. simultaneously). Of these, 46 were flagged as “cause for concern” because the start of the low flow period may also occur later in the year (c.f. Section 3.4.3.9 of **Volume 3**).

8.2.2 Biofuel yield potential

In this study, the use of a crop model to estimate yield at a national level is deemed superior to previous attempts which made use of simple empirical models that only accounted for climatic effects (mainly rainfall and temperature) on plant growth. The maps presented in this report helped the project to achieve the following objectives, namely:

- To estimate or quantify the WUE of crops with reference to the biomass yield per m^3 water over the full productive cycle.

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

The WUE maps show crop yield (and not biomass yield) per m^3 of water use over the full productive cycle (c.f. Section 4.2.3.5 of **Volume 3**). The reason for this is biofuel production is based on the utilisable portion of the crop which contains sugar, starch or vegetable oil (e.g. stalk or stem; tuber or root; grain or seed). On the other hand, bioenergy production utilises the above-ground plant biomass, but this energy type was not the focus of the biofuels project.

The yield (c.f. Section 4.2.3.3 of **Volume 3**) and WUE maps highlight areas optimally suited to feedstock cultivation. For example, they identified the coastal areas in KwaZulu-Natal as highly suitable to sugarcane production. In addition, the Western Cape is ideally suited to canola production (c.f. Section 4.2.3.2 of **Volume 3**). As noted though, the WUE maps can be misinterpreted and should always be interpreted in conjunction with the yield maps (c.f. Section 4.2.3.5 of **Volume 3**). Other maps of *AQUACROP* output were produced, such as the variability in yield (c.f. Section 4.2.3.7 of **Volume 3**) and WUE (c.f. Section 4.2.3.8 of **Volume 3**) as well as risk of crop failure (c.f. Section 4.2.3.10 of **Volume 3**). These maps can also be used to identify areas not suitable for crop cultivation.

A product of the crop yield estimates and the biofuel extraction figures will provide the biofuel yield potential in any region (c.f. Section 4.2.4 of **Volume 3**). For the crops containing sugar (e.g. sugarcane & sugarbeet), the dry yield must first be converted to fresh (or green) yield. This is due to the rapid deterioration of sugar quality once the crop is harvested. Hence, the crop is typically processed into bioethanol as soon as possible after harvest. In order to determine the biofuel yield per m^3 water over the full productive cycle, the WUE at maturity (i.e. harvest) is also multiplied by the biofuel extraction figure (in litres per kg, not litres per ton). The reader is referred to Section 3.7.4 of **Volume 2** and Section 4.2.4 of **Volume 3** for typical biofuel extraction yields for prioritised feedstocks.

Although the mean is most commonly reported in crop science literature, considerable effort was spent on presenting both the mean and median statistic (Section 4.2.3.4 of **Volume 3**). Since the median is less influenced by extreme values or outliers (c.f. Section 4.2.3.4 of **Volume 3**), it proved useful in identifying areas deemed suitable for feedstock cultivation (by eliminating areas with very low means). In addition, the median may be more representative than the mean in areas with high inter-seasonal variability (i.e. coefficient of variation exceeds 20%).

The use of calendar mode for yield estimation in the *AQUACROP* model is not recommended (c.f. Section 4.2.3.1 of **Volume 3**). Where possible, the model must be run in GDD mode to incorporate the effects of temperature on biomass production (c.f. **Section 8.3.2.1**).

The FAO model in *SWB* is less mechanistic is design and therefore, does not simulate crop yields as accurately as the crop growth model in *SWB* (c.f. Section 6.3. in **Volume 2**). However, the FAO model may still give a good indication of yields that could be expected. However, the growth model in *SWB* shows much potential for application in simulating sweet sorghum yield at the farm level.

8.2.3 Land suitability assessment

The main aim was to map regions that are suited to biofuel feedstock cultivation, taking into account abiotic (climatic, edaphic & topographic) and biotic constraints (disease) that limit plant growth. Furthermore, the emphasis was on identifying land that can realistically be used for feedstock cultivation, by eliminating “no-go” areas that are currently zoned for urbanisation and biodiversity protection (Section 5.3 of **Volume 3**).

A land suitability assessment identifies land area deemed suitable for feedstock production and then assesses the feedstock’s potential yield in such areas. It determines if the identified areas are actually suitable for biofuel production, taking account of competing land use options arising from current and planned agricultural, environmental and socio-economic needs. The research output presented in this report provides a land suitability assessment at the national scale which may assist decision makers in identifying new areas for biofuel production and where agricultural production should be intensified, as well as those areas that should be excluded.

The mapping component highlighted the sensitivity of the innovative rainfall weighting approach (c.f. Section 2.7.1.4 of **Volume 2**). Hence, care must be taken in choosing monthly crop coefficients that adequately reflect the pattern of crop water use for South African growing conditions (c.f. **Section 8.3.1.3**). Where possible, locally derived crop coefficients should be used and not values derived from international studies (c.f. Section 7.3 of **Volume 1**). Furthermore, single (and not basal) crop coefficients should be used (c.f. Section 2.7.1.4 of **Volume 2**).

8.2.4 Water use efficiency

The optimum use of water in agricultural production is one of the most important environmental factors affecting plant growth and development, particularly in arid and semi-arid regions. Water use efficiency and drought tolerance of biofuel feedstocks are two keys aspects which assist in selecting appropriate crops/trees for marginal sites. The higher WUE of C_4 plants gives them an advantage over C_3 plants in hot, dry conditions. Hence, WUE may be increased by selecting C_4 rather than C_3 feedstocks.

This study showed the sensitivity of WUE to planting density (c.f. **Section 3.5.3.2**). Review of the literature revealed that WUE is not only dependent on planting density, but is affected by other factors including the genotype, climatic conditions during the growth period, irrigation management and nitrogen application. Plants grown on fertile soils use water more efficiently and produce deeper rooting systems. In dryland cropping systems, adoption of no-till also increases crop water use efficiency, thus reducing the frequency of summer fallow. Ensuring that planting densities are optimal, tillage is minimal, weeds are controlled and adequate fertiliser is applied at the right growth stage, will ensure a high WUE.

Since WUE is highly influenced by many factors, it is difficult to compare WUE values gleaned from the literature, with those estimated from field trial data. In addition, there are a plethora of WUE definitions that exist in the literature, where applied irrigation water *vs*. crop water use (i.e. total evaporation) is used to calculate efficiencies. In addition, water use is expressed as either a depth (in mm) or a volume (in m^3), thus requiring unit conversions before results can be fully compared.

Biofuel yield can be roughly estimated from the product of crop yield and the biofuel extraction rate (c.f. Section 4.2.4 of **Volume 3**). However, the use of a theoretical biofuel yield equation (c.f. Sections 3.7.1.2, 3.7.2.1 & 3.7.3.1 of **Volume 2**) is recommended as these equations take into account not only crop yield, but other important factors affection biofuel yield such as soluble sugar, extractable starch or bio-oil content. The moisture content of grain starch is another important consideration (c.f. Section 3.7.2.1 of **Volume 2**). Brix levels in hybrids (e.g. sweet sorghum) show large inter-annual variation, thus indicating the use of ripeners. Finally, the impact of feeding birds on small stands of tannin-free grain sorghum is of concern.

8.2.5 Field-based research

A number of lessons have been learnt from the trial series that were conducted at Ukulinga and Hatfield (c.f. **Section 3.5**) as well as the information gleaned from the Baynesfield trials which are summarised below:

- Sugarbeet yields should be higher for autumn plantings (May) than for summer (September) or winter (July) plantings, provided supplemental irrigation is used to establish the autumn crop.
- In order to rotate sweet sorghum (summer) with sugarbeet (autumn), a fast maturing sweet sorghum variety is required, to facilitate a May or June planting of beet.
- Although Syngenta has developed a "sub-tropical sugarbeet" variety (EB 0809), it is not well adapted to hot conditions, particularly when the daily maximum temperature exceeds 26°C.
- A breeding programme is therefore required to produce a genuine "summer sugarbeet" variety suitable for commercial production in South Africa.
- A “Round-up ready” variety of sugarbeet (as used in the USA when permitted) should be considered to aid weed control.
- Sugarbeet is ideally suited to a well-drained soil. If drainage problems occur, root rot becomes a major concern. Root rot is also exacerbated by over-irrigation.

The sweet sorghum drought trials have shown that fresh stalk yields respond significantly to irrigation in the “leaf” predominant stage, i.e. supplemental irrigation during the early vegetative stage (c.f. **Section 3.5.2.3**). Similarly, fresh biomass yields also respond well to irrigation, irrespective of the timing. However, the dry matter yields (both stalk and total biomass) did not show a significant response to supplemental irrigation. It can therefore be concluded that the best stage for saving irrigation water without losing productivity and lowering the WUE is after the fast growing period (i.e. the ‘stem’ predominant stage).

The experience gained at Ukulinga regarding Jatropha supports recent claims in the international literature that without good management, this feedstock produces low yields which are economically unviable (c.f. Section 2.4.4 of **Volume 2**). Furthermore, Jatropha is not a wasteland crop since it is not well suited to marginal sites.

Moringa appears to be a low yielding variety that is not well adapted to the growing conditions experienced at Hatfield (c.f. Section 2.4.5 of **Volume 2**). Seed yields were generally low and variable (c.f. **Section 3.5.2.6**). Heavy rain or hail, high variability among individual plants and low winter temperatures are the main factors that influence production negatively.

8.3 Recommendations for Future Research

The various approaches developed and implemented in this study are by no means considered "exhaustive". Although much effort was spent on producing simulated output that is considered reliable and error-free, the following suggestions would further improve the accuracy of results. These suggestions pertain to the three main research thrusts, namely the hydrological modelling, crop yield modelling and land suitability mapping.

8.3.1 Hydrological impacts

8.3.1.1 The quinary sub-catchment climate database

Stream flow response is most sensitive to rainfall input (c.f. Section 4.2.1.1 of **Volume 2**). Hence, the accuracy of runoff estimates is mostly enhanced by ensuring the representativeness of rainfall data for each sub-catchment. Thus, it is highly recommended that the quinary sub-catchment rainfall database is revised as soon as possible.

This involves extending the daily record beyond 1999, to at least 2013 (i.e. by an additional 14 years). This task is made difficult due to the lack of a single source of quality controlled and infilled rainfall data. Thus, data must first be sourced from various custodians such as the South African Weather Service (SAWS), the Agricultural Research Council (ARC), the South African Sugarcane Research Institute (SASRI) as well as the Department of Water and Sanitation (DWS). The next step would involve quality control and patching of missing data using, *inter alia*, the Expectation Maximisation Algorithm (EMA) used by Lynch (2004). Unfortunately, this exercise is beyond the scope of the biofuels project.

This project thus "echoes" the recommendations made by Lumsden and Schulze (2012). They suggested that sustained and adequate funding (possibly from multiple sources) be made available for one institution in South Africa. This institution would be responsible for the collation (from different sources) and uniform quality control of climate data, and that these data then be made freely available to all *bona fide* researchers. This would save not only the many WRC projects from major duplication of effort in updating climate related databases, but would also ensure that the same datasets be used across the many disciplines in South Africa that utilise climate data.

The selection of two representative temperature stations for each quinary sub-catchment would be improved following additional data quality control of the 973 temperature recording stations. For example, daily temperature data from duplicate stations (i.e. two or more stations at the same location) should be combined to produce a single series for that location. Furthermore, certain stations may need to be removed from the database owing to the lack of observed record. For example, station "0520094 A" has observed data from November 1985 to December 2000. However, the station's record length was extended using patched data obtained from a nearby station from January 1968 to October 1985. Similarly, harmonic data was used to extend the record from January 1950 to December 1967. This means that the first 18 years of daily data are identical.

The algorithm that was developed to select the two most representative temperature stations for each quinary centroid (c.f. Section 5.5.1 of **Volume 2**) may be improved if one station is chosen below the quinary's mean altitude, whilst the other station is situated above the quinary's mean altitude. Hence, further work is required to test if this suggestion would improve the algorithm.

8.3.1.2 Improved soils information

The Land Type soils database at a 1:250,000 scale, developed by the former Soil and Irrigation Research Institute (SIRI, 1987 and subsequent updates), represents the most detailed soils information currently available. This database was used to derive the soil parameters required by *ACRU* for each quinary. Within each land type, there exists five terrain units (crest, scarp, midslope, footslope & valley bottom) and each terrain unit has different soil types. However, the location of each terrain unit within a particular land type is unknown. Hence, the soils information is averaged for each land type, then area weighted according to the number of land types occurring within a quinary.

Research is currently underway at the CWRR (UKZN) to determine which terrain units occur in each quinary. Based on the methodology used to delineate the three quinary sub-catchments within a quaternary, one intuitively expects the crest/scarp to occur mainly in the upper quinary, the midslope/footslope to dominate the middle quinary and the valley bottom to dominate the lower quinary. Once these fractions have been determined using GIS, it will be possible to assign soils information for each terrain unit to a particular quinary. This will spatially improve the accuracy of the soils data and avoid the use of average conditions (and even an "average of averages" scenario). Once this work has been completed, the water use estimates for each feedstock should be revised.

8.3.1.3 The need for local crop coefficients

The results presented in this study highlight the importance of using locally determined crop coefficients to estimate feedstock water use. Hence, it is strongly recommended that the water use of canola (in particular) is measured, from which local K_c values can be estimated. Furthermore, the water use of soybean should be measured for a second season at Baynesfield (c.f. **Section 4.2.3.2**). It is also recommended that the evapotranspiration from bare soil is determined, which will help set the K_c value for the fallow period.

It is important to note that relative to commercial afforestation, very little research has been conducted on the water use of South Africa's indigenous vegetation. Consequently, there are high levels of uncertainty in the hydrological parameters used to provide the baseline estimates of water use. Thus, further research into the water use characteristics of natural vegetation types is highly recommended.

8.3.1.4 Moving to the FAO56 reference

As highlighted in this report, the USWB Class A evaporimeter (or APAN) is used by *ACRU* as the reference evaporation (c.f. Section 5.2.2.2 of **Volume 2**). However, the *de facto* standard for estimating reference evaporation since 1998 is the Penman-Monteith method, also referred to as FAO56 (Section 3.1.2.2 of **Volume 2**). Thus, it is imperative that the reference evaporation used by *ACRU* is changed from APAN to FAO56. This will negate the need to convert:

- FAO56 reference evaporation in *ACRU*'s input data files to APAN equivalent values via the monthly CORPAN factors, and
- FAO56-based crop coefficients to APAN equivalent values by dividing by CORPAN.

This modification involves research to modify any APAN-based methodology in the *ACRU* model. For example, the model uses an equation to estimate LAI from K_c. The equation was derived from LAI and K_c values for grass, barley and sugarbeet. The estimated LAI values are then used to compute interception loss and separate evapotranspiration into its two components (i.e. transpiration and soil water evaporation). This project has acquired a wealth of knowledge on LAI and K_c values from field trials, thus providing sufficient data to modify (and improve) this relationship.

8.3.1.5 FORTRAN *vs*. JAVA version

The FORTRAN version of the *ACRU* model generates slightly less runoff when compared to the JAVA-based version (**Section 5.3.6**). Hence, the FORTRAN version of the model should be modified to mimic the JAVA version. Further investigation is required to explore differences in the Ritchie algorithm between the FORTRAN- and JAVA-based models.

8.3.1.6 Estimation of interception loss

The variable storage Gash model should be incorporated into the *ACRU* model to estimate interception loss (c.f. Section 4.2.3.3 of **Volume 2**). This model requires daily climate data as well as monthly leaf area indices for each land cover. In addition, the *ACRU* output variable AET (i.e. total evaporation) excludes the interception loss component. This needs to be addressed in *ACRU*, so that simulated AET can be compared directly with measured AET (obtained from field trials using the surface renewal technique).

8.3.1.7 Further model optimisation

It is recommended that the *ACRU* model developers determine why the model produces invalid floating point exceptions when executed at the national scale for certain drainage basins. A "division by zero" and un-initialised variables are the most likely causes of such errors. At present, these anomalies affect the irrigation and primary productive routines within the model and thus, does not influence the output presented in this study.

Furthermore, a multi-threaded version of the *ACRU* model would significantly improve its overall performance. At present, the 64-bit version executes as a single thread only. In addition, minor speed improvements can be made by disabling the "echo" of each sub-catchment menu which will prevent 5 838 files from being created during a national run (c.f. **Section 5.3.5**).

8.3.1.8 Additional feedstocks

In this study, model runs have been undertaken for sugarcane, sugarbeet, grain sorghum, sweet sorghum, soybean, sunflower and canola. However, additional feedstocks could be included in the future. For example, the *ACRU* model should be parameterised and run for yellow maize, especially if the current ban which excludes this crop from being used for biofuel production is lifted (c.f. Section 2.3.5 of **Volume 2**).

In addition, much effort was spent on improving the biofuels assessment utility (Section 6.3 of **Volume 3**), which was originally developed as part of the SFRA project. It is recommended that the *ACRU* model is re-run for the forest genera (i.e. eucalypt, pine and wattle) using the revised quinary-catchment climate database. Furthermore, work should be carried out on other land covers of particular interest to DWS, such as bamboo. The outcome would be a single, standardised product that meets the needs of the DWS in terms of assessing the hydrological impact of land use changes.

8.3.1.9 Potential SFRAs

This project identified a limited number of quinary sub-catchments in which a change in land use from natural vegetation to a particular biofuel feedstock may cause the following three impacts:

- Reduction in mean annual runoff of 10% or more.
- Reduction in runoff during the low flow period of 25% or more.
- A shift in the low flow period.

In areas where all three impacts occur simultaneously (c.f. Section 3.4.3.9 of **Volume 3**), biofuel feedstock cultivation is not recommended, even if DWS does not declare the land use a SFRA. Hence, these quinaries should be excluded as potential feedstock production areas.

8.3.2 Biofuel yield potential

In this study, the automation of *AQUACROP* to provide estimates of crop yield and WUE at the national scale is considered an innovative approach. However, the following recommendations would improve the accuracy and reliability of output from the model.

8.3.2.1 GDD mode

It is important to run the *AQUACROP* model in GDD (thermal time) and not calendar mode (c.f. **Section 6.3.5** of this volume). This evokes a number of functions within the model that incorporate temperature effects on phenology and transpiration (c.f. Section 6.4.3.4 of **Volume 2**). Furthermore, it is recommended that, where possible, the model's default options are selected. For example, the option to change the initial soil water content from field capacity to 50% of plant available water had a significant impact on yield results. Similarly, the option to start the simulation period before the crop planting date also resulted in lower yield estimates (c.f. Section 4.3.5.8 of Volume 2 and Sections 4.2.5.5 & 6.2.3.3 of this volume).

8.3.2.2 K_{SAT} for the topsoil

From the experience gained whilst testing *AQUACROP*, it became apparent that the model is particularly sensitive to the saturated hydraulic conductivity (K_{SAT}) of the topsoil. Within the model, this parameter determines the:

- internal drainage in the soil profile,
- losses from deep percolation,
- amount of water infiltrated in the root zone, and
- surface runoff (after an irrigation or rainfall event).

It is therefore recommended that this parameter is measured (c.f. Section 3.4.3.5 of **Volume 2**) and not estimated. In this study, measured values of K_{SAT} are not feasible for each quinary and thus, were inferred from the soil water retention parameters for each soil horizon (c.f. Section 6.5.2.1 of **Volume 2**). Further research is required to improve and validate the pedotransfer function used in this study to estimate K_{SAT} from other soil characteristics.

8.3.2.3 Crop calibration

As noted in this study, a crop parameter file for canola was obtained from Alberta, Canada (c.f. **Section 4.2.5.3**). It is therefore recommended that field work is conducted to parameterise canola for South African growing conditions. Furthermore, the adjusted parameters should be compared to those derived for Australia. In addition, the field data collected to date for grain sorghum should be used to adjust the parameterisation for this crop. In addition, a sweet sorghum parameter file should also be developed for the *AQUACROP* model using data measured in this study.

8.3.2.4 Model validation and verification

Further research is required to validate the output from *AQUACROP* for other sites (c.f. **Section 4.3.5.2**) and thus, to test the model's level of robustness. Similarly, the estimation of crop water use (i.e. accumulated total evaporation over the growing season) needs to be validated against observations (**Section 4.3.5.3**). The Southern Africa Agricultural Model Intercomparison and Improvement Project (SAAMIIP) could assist in providing the necessary data to assist with model validation.

As noted in this study, the crop yield simulated by *AQUACROP* in the first season is sometimes much lower than the following season (**Section 4.3.5.4**). Further work is required to use the full (i.e. GUI) version of the model to determine why this anomaly occurs and to find an acceptable solution. If this anomaly cannot be corrected, then the long-term average yield calculation should be modified to ignore the first season's yield.

It is highly recommended that the statistics utility is modified to calculate the biofuel yield (in L) using the theoretical biofuel equations for sugar, starch and vegetable oil crops. From this, the biofuel WUE (in L m^{-3}) can also be determined. This will facilitate the production of maps showing the spatial variability in biofuel yield and biofuel WUE.

8.3.2.5 Alternative transplanting date for sugarcane

In this study, February and April were selected as transplanting months as these months produced the highest yields observed at La Mercy (c.f. **Section 4.3.5.2**). However, it is acknowledged that sugarcane is not cut in February since the milling season is April to

December. It is therefore suggested that additional national runs are undertaken for sugarcane, starting with an October transplanting date.

The season length for sugarcane can be categorised into a 12, 18 or 24 months and given the target harvest date is typically from March to October, the planting date can be calculated accordingly using an iterative procedure. For this, a list of the most common planting dates could be determined for quinaries in which sugarcane is currently produced.

8.3.2.6 Automation of national model runs

The *AQUACROP* model was run at the national scale in batches according to the number of quinary sub-catchments in each drainage basin (c.f. Section 6.5.8 of **Volume 2**). Since the model is sometimes run for a region not considered suitable for crop growth, a division-by-zero error occurs (c.f. Section 6.5.12.3 of **Volume 2**). The model then stops which requires the batch process to be automatically restarted. Since this procedure is complex and sometimes results in duplicate runs, it should be simplified. It is therefore recommended that the batches are reduced in size to 50 quinaries or even a single sub-catchment.

8.3.2.7 Improvement of land suitability maps

A number of useful maps depicting output from the *AQUACROP* model are presented in this study (c.f. Section 4.2.3 of **Volume 3**). Such data can be used to validate and further improve the land suitability maps (c.f. Section 5.4.3 of **Volume 3**), especially since they attempt to differentiate high from low potential production areas. Due to time constraints, this approach was not followed in this study but is recommended for future research.

The model output should be superimposed (i.e. GIS overlay) to identify sub-catchments where crops are unsuitable for growth. This decision could be based on one or more of the following criteria:

- low mean (or median) crop yield,
- high yield variability,
- low mean (or median) WUE,
- high variability in WUE,
- high risk of crop failure,
- lengthy crop growing season, and
- less than 20 seasonal yield simulations.

Thresholds for each of these criteria could be developed from the available literature and expert knowledge. For example, agricultural economists could advise on the break-even yield, which could then be used to eliminate areas which are considered economically unviable. Thus, the mapping and modelling approach would then incorporate the economics of crop growth.

Furthermore, two WUE estimates were presented in this study. If the maximum WUE (labelled as “at peak”) and the end-season WUE (labelled “at maturity”) differ substantially, the site should also be unsuitable for crop production since the crop yield peaks too early in the growing season. Although this approach was not considered in this study, it is recommended that it is investigated in future research efforts.

Once unsuitable growing areas have been identified, the remaining areas could be used to refine site criteria considered suitable for optimum and sub-optimum growth. For example, a GIS could be used to refine the range in monthly temperature across the suitable growing areas.

8.3.3 Land suitability assessment

8.3.3.1 Food security

The mapping approach facilitated the classification of optimum, sub-optimum and marginal areas. This allows for the differentiation between high productivity areas from low productivity areas and a step towards estimating the productivity capacity of land. However, a comprehensive analysis of productivity capacity requires spatial estimates of feedstock yield. Hence, the crop yield maps can identify high agricultural production areas (c.f. Section 4.2.3 of **Volume 3**) which should be zoned for food production and not biofuel production. Although this approach was not attempted in this study, it is recommended for further investigation.

8.3.3.2 Under-utilised land

The government of South Africa promotes the production of biofuel crops under rainfed conditions using under-utilised arable land, particularly in the North West, Limpopo and Eastern Cape Provinces. Of the total land area deemed suitable for feedstock cultivation, the proportion that exists in these under-utilised areas should be determined. This will help to assess the contribution of such areas in meeting the country's biofuel volume targets.

The use of marginal land for biofuel feedstock production is controversial. Studies have found that feedstock yields (and ultimately biofuel yields) are low when grown on marginal sites. Hence, additional land area is required to meet biofuel volume targets. Marginal lands may have the least economic value, but higher social, environmental or ecological value. Hence, a "cost-benefit" analysis should be undertaken to ascertain if the use of marginal land for feedstock production is sustainable (c.f. Section 7.1 of **Volume 2**).

8.3.3.3 Exclusion of strategic water supply areas

Since South Africa is a water-scarce country, it is evident that water availability will likely limit potential feedstock cultivation and not land availability. SANBI have identified strategic water supply areas, which are defined as areas that supply a disproportionate amount of mean annual runoff to a geographical region of interest. Although these areas make up 8% of southern Africa (South Africa, Lesotho & Swaziland), they supply half of the total water resource. Hence, biofuel feedstock cultivation in these areas is not recommended and thus, should be eliminated as potential growing areas.

8.3.3.4 Future land use

The land suitability maps do not consider the additional land required to support the growing population, the need to expand current mining activities as well as protecting the country's rich biodiversity heritage (c.f. Section 5.5 of **Volume 3**). Optimised land use planning will avoid unnecessary expenses associated with changing the land use back to its preferred and sustainable function. Hence, other land use needs in the future should be given priority over the necessity to produce biofuel. It is therefore recommended that future land use needs are incorporated into the mapping methodology.

8.3.3.5 Growth criteria

It is suggested that growth criteria of selected feedstocks are "reverse engineered" by overlaying current production areas with available climate data sets. For example, actual farm boundaries obtained from the Department of Agriculture were used to assess seasonal rainfall totals across canola farms located in the Western Cape. A similar approach could be used to identify the range in monthly temperature and relative humidity for these farms.

In addition, the sugarcane industry is busy finalising a dataset showing farm boundaries where sugarcane is grown on a commercial scale. This data layer will also facilitate an analysis of climate variability (in particular monthly rainfall & temperature) across the sugarcane-producing farms. Such information could then be used to determine optimum growth criteria for sugarcane, allowing other areas with similar climates to be easily identified using GIS.

It is also recommended that future research examines the use of dew point temperature as a surrogate variable for disease incidence and not relative humidity. Dew formation typically occurs when hot days are followed by cold nights and if dew occurs early in the evening, then prolonged leaf wetness provides ideal conditions for fungal spore germination. Research has shown that soybean is most susceptible to rust disease when the duration of wet leaves exceeds 12 hours.

8.3.3.6 Unsuitable *vs*. marginal

The use of discrete boundaries with continuous datasets is problematic (c.f. **Section 7.4.3**). The lower threshold to categorise the overall suitability score as unsuitable needs revision. This threshold was increased to 0.63 for the sugarbeet map to avoid the scenario where an area with a very low rainfall score, is classified as marginal and not unsuitable, because all other growth criteria are ideal. Furthermore, the weighting of rainfall may also need to be increased from 40% (c.f. Section 5.2.2.3 of **Volume 3**). This modification will help to eliminate marginal areas that are too dry to realistically support crop growth.

Another solution is to adopt a two-phase approach as undertaken by Holl *et al*. (2007; c.f. Section 7.3.1 of **Volume 2**). To re-cape, the first phase involves the elimination of areas deemed unsuitable for growth based on climate criteria, in particular rainfall. The second phase involves the classification of remaining areas from marginal to highly suitable. It is recommended that the mapping approach is modified to incorporate the first (i.e. elimination) phase. This phase should also eliminate frost-prone areas using the average minimum temperature in June and/or July. This suggestion is discussed further in Section 7.5.2 of **Volume 2**.

8.3.3.7 Canola map revision

For canola, seasonal rainfall should be replaced by the amount of moisture stored in the soil profile at the beginning of the season. This may alleviate the problem with the current land suitability map which does not highlight the Free State as a viable canola production area (c.f. Section 5.4.3.6 of **Volume 3**).

Alternatively, the seasonal rainfall thresholds could be set to: < 200 mm (unsuitable); 200-300 mm (marginal); 300-400 (sub-optimum) and 400-900 mm (optimum). In addition, the seasonal rainfall could be summed from March to September (c.f. Section 4.2.3.2 of **Volume**

3). These suggestions may help to identify areas in the eastern Free State that are suitable for canola production.

8.3.3.8 Additional feedstocks

It is further suggested land suitability maps for sunflower and yellow maize are produced in the future.

8.4 The Way Forward

When planning biofuel feedstock production, it is essential to consider other current (i.e. present) and planned (i.e. future) land uses. The starting point is to map out areas suitable for feedstock cultivation, based on climatic, edaphic and biotic constraints which limit plant growth. Initially, the land suitability assessment study considers all identified land as available for feedstock cultivation. According to the German Advisory Council on Global Change (WBGU), this is referred to as the theoretical potential (i.e. upper limit) of biofuel production. This approach was adopted in the biofuel scoping study, which was completed in November 2009. However, only the climatic criteria for optimum growth were considered.

Thereafter, a number of filters can be introduced in order to exclude certain production areas, based on sustainability criteria. Thus, areas that cannot be used for feedstock cultivation (e.g. urban areas, water bodies and mining areas) are eliminated or "filtered out". This approach was adopted in this project and is referred to as the technical potential of biofuel production by the WBGU. As noted previously, areas prone to frost occurrence should also be eliminated, especially for crops sensitive to frost damage (e.g. sugarcane).

In addition, protected areas can also be excluded from biofuel production as was undertaken in this study. According to the WBGU, this approach provides the sustainable potential of biofuel production. However, other sustainability criteria can also be considered. For example, endangered and vulnerable ecosystems could also be excluded for biofuel feedstock cultivation. Areas currently under food production can be excluded for food security reasons. As noted previously, other future land use needs (e.g. land required to house the growing population) should also be eliminated as feedstock production areas.

The last step involves deriving a land suitability index for each location, based on its production capability. This land suitability index can be calculated in a number of different ways. In this study, the suitability index is based on water use efficiency. Maps showing the spatial variability in WUE were developed for prioritised feedstocks. This metric maximises the productive capacity of land by considering feedstock yield (in kg) in relation to its water use (i.e. total evaporation expressed in m^3). In other words, the approach views land use decisions as water use decisions. For example, the sugarcane WUE map identifies the coastal areas of KwaZulu-Natal and the Eastern Cape where sugarcane's water use is most efficient and thus, highlights areas where the crop should be grown.

In addition, the yield of each feedstock can be expressed as a percentage of the maximum attainable yield. The suitability index can then be used to rank the feedstocks from highest productivity to lowest. Another approach involves comparing the feedstock yield of the location to the country's average, in order to decide whether or not the location is suitable for feedstock production.

Another useful metric is biofuel use efficiency, which considers the biofuel yield (m^3) relative to feedstock water use (m^3). Conversion rates or efficiencies (in litres of biofuel per ton of crop) were presented in this report. Similarly, they were estimated using the theoretical biofuel equations used in this study. These conversion rates allow for the estimation of biofuel yield (in m^3) from the simulated feedstock yield (in tons). This is referred to as the conversion potential of biofuel production by the WBGU.

Although not all of the above-mentioned metrics were calculated, the output from this study allows for their determination. Using these new metrics, the land suitability maps could be refined based on the crop yield output. Therefore, it may be argued that the national yield estimates produced in this study represent the most valuable contribution to existing knowledge.

It is fortunate that the biofuels sector in South Africa is still at an early stage of development. Thus, the output from this project can be used to help guide the decision makers within this industry, especially with regard to 1) where to grow biofuel feedstocks, 2) the potential impact of feedstock cultivation on downstream water availability, and 3) quantifying the crop yield and biofuel yield of a region. In South Africa, water (not land) availability will limit the country's biofuel production potential of the country. Competition for limited water resources should be the biofuel industry's major concern, even if biofuel expansion occurs into marginal areas. The WUE maps produced for each biofuel feedstock should assist land use planners in striving towards the most beneficial use of available water resources.

The draft version of the biofuels regulatory framework published by DoE in January 2014 proposed the use of grain sorghum and soybean as the reference feedstock for bioethanol and biodiesel production respectively. However, it is envisaged that sugarcane will represent sugar-based feedstocks in the final version of this policy document. The WRC have recognised the need for additional research to measure and model the water use (and yield) of these reference feedstocks. Hence, they initiated and funded a further five-year study which began in April 2015. This follow-up study allows for the above-mentioned recommendations to be implemented. By March 2020, the WRC would have funded 13 consecutive years of research focussed on the water use impacts of biofuel feedstock production, which is commendable. For more information on this new project, the reader is referred to Project No. 2491 (under KSA4, i.e. water utilisation in agriculture) in the 2015/16 version of the WRC's Knowledge Review (http://www.wrc.org.za/Pages/KH_KnowledgeReviews.aspx?dt=8).

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10 DATA STORAGE

The project has generated over a 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 the large database 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. Contact person: Richard Kunz (kunzr@ukzn.ac.za).

11 CAPACITY BUILDING

11.1 Staff Development

CLULOW, ALISTAIR (2011) Installation of horizontal and vertical fibre optic cables to sense temperature distribution within and above a sugarbeet crop. Ukulinga research farm, Pietermaritzburg, November 2011.

DOIDGE, IAN (2010) Installation and maintenance of a non-pressure compensating drip irrigation system. Ukulinga research farm, Pietermaritzburg, August 2011.

EVERSON, COLIN (2011) Installation of horizontal and vertical fibre optic cables to sense temperature distribution within and above a sugarbeet crop. Ukulinga research farm, Pietermaritzburg, November 2011.

KUNZ, RICHARD (2011) Networking experience at the Bioenergy Australia Conference. Maroochydore, Australia, November 2011.

KUNZ, RICHARD (2014) AquaCrop training course. University of KwaZulu-Natal, Pietermaritzburg, July 2013.

MENGISTU, MICHAEL (2011) Installation of horizontal and vertical fibre optic cables to sense temperature distribution within and above a sugarbeet crop. Ukulinga research farm, Pietermaritzburg, November 2011.

STEYN, MARTIN (2011) Installation, maintenance and use of fine-wire thermocouples to measure crop water use. Hatfield research farm, Pretoria, November 2011.

11.2 Students who Graduated

Over the project's six-year duration, the following two MSc students contributed to the research effort and have graduated:

HLOPE, HANSON (2014) Sweet sorghum (*Sorghum bicolor* (L.) Moench) response to supplemental irrigation in different growth stages. Unpublished MSc (Agric.) Agronomy. Faculty of Natural and Agricultural Sciences, University of Pretoria, RSA. Dissertation available from:
http://repository.up.ac.za/xmlui/bitstream/handle/2263/43352/Hlophe_Sweet_2014.pdf

KHOMO, THOBANI (2014) Spatial assessment of optimum and sub-optimum growing areas for selected biofuel feedstocks in South Africa. Unpublished MSc. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, RSA. Dissertation available from:
http://researchspace.ukzn.ac.za/xmlui/handle/10413/12307

11.3 Students Still to Graduate

The following two students are currently on course for graduation in the near future:

MOKONOTO, OFENTSE (2015) Parameterisation and validation of AquaCrop for sugarcane and sugarbeet in South Africa. MSc dissertation in preparation. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, RSA.

KUNZ, RICHARD (2015) Towards a national-level assessment of South Africa's sustainable biofuel production potential. PhD thesis in preparation. School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, RSA.

11.4 Honours Students

Six hydrology students at UKZN completed their Honours projects using data and information pertaining to this study as follows:

GOVENDER, JEDINE (2014) Estimating the streamflow production potential of sugarcane. Hydrology Honours 790 project, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, RSA.

MOKONOTO, OFENTSE (2012) Mapping of areas potentially suitable for soybean feedstock growth for biodiesel production. Hydrology Honours 790 project, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

MORRIS, FEROZA (2012) The standardised precipitation evapotranspiration index for Cedara. Hydrology Honours 790 project, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

NGUBANE, SANELE (2013) Modelling the potential impacts of climate change on soybean and grain sorghum yields at the Ukulinga research farm. Hydrology Honours 790 project, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, RSA.

PICKLES, ANDREW (2010) Water use of sweet sorghum (*Sorghum bicolor (L.) Moench*) and its potential as a biofuel feedstock. Hydrology Honours 790 project, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

SITHOLE, ZINHLE (2010) Characteristics of sugarbeet and sweet sorghum as potential biofuel crops in South Africa, as well as their possible hydrological implications. Hydrology Honours 790 project, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

In addition to the above, a total of three post-doctorate students assisted the project in meeting its research objectives. Two BSc graduates gained valuable internship experience working with the project team. Finally, one MSc student from the Delft University of

Technology (The Netherlands) gained expertise measuring Bowen ratios using high-resolution vertical dry and wet bulb temperature profiles above sugarbeet grown at Ukulinga in 2011.

12 TECHNOLOGY TRANSFER

12.1 Presentations

EVERSON C, MENGISTU M and GUSH M (2012) Water use and suitability of *Jatropha curcas* as a biofuel feedstock. *Proceedings of the South African National Committee on Irrigation and Drainage (SANCID) Symposium*, Alpine Heath Resort Drakensberg, KwaZulu-Natal. 20-23 November 2012.
http://www.sancid.org.za/conf_proceedings/Session5/22Session5-1110-1130.pdf

JEWITT G (2013) Land and water considerations for biofuel feedstock production. Presentation at the World Biofuels Markets Conference, Rotterdam, The Netherlands. 12-14 March 2013.
http://www.ieabioenergytask43.org/wp-content/uploads/2013/12/8th-WBM-conference-Rotterdam-Jewitt.pdf

JEWITT GPW and EVERSON T (2011) Renewable energy through biofuels and biogas. *Proceedings of the WRC 40 Year Celebration Conference*, Water Research Commission (WRC), Emperor's Palace, Gauteng, RSA. 31st August 2011.

JEWITT G and KUNZ R (2011) Water use of biofuels crops: Is production of biofuels an SFRA? *Proceedings of the 15th SANCIAHS National Hydrology Symposium*, Rhodes University, Grahamstown, RSA. 12-14 September 2011.

JEWITT G, KUNZ R and BERNDES G (2013) Water for food - Water for energy: biofuels at the water-energy-food nexus. Presentation at the 2013 WRC Research Symposium, CSIR International Convention Centre, Pretoria, RSA. 25-27 September 2013.
http://www.wrc.org.za/Knowledge%20Hub%20Documents/Conference%20proceedings/12h05%20-%2012h25%20Graham%20Jewitt.pdf

JEWITT G, MUNISHI S, KUNZ R and VIOLA P (2010) Drivers and dynamics of global environmental change in southern Africa. *Geophysical Research Abstracts* 12: EGU2010-9562. Vienna, Austria. 2-7 May 2010.
http://meetingorganizer.copernicus.org/EGU2010/EGU2010-9562.pdf

JEWITT G, KUNZ R, MUNISHI S, WARBURTON M, JARMAIN C and VIOLA P (2013) Integrating Green and Blue Water Flows to Assess the Impact of Biofuel Feedstock Production on Water Resources in Southern Africa. *Proceedings of the Combined Congress*, University of KwaZulu-Natal, Westville, KwaZulu-Natal, RSA. 21-24 January 2013.

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13 APPENDIX A

Table 73 Comparison of parameters and variables used in *ACRU* to describe the hydrological response from natural vegetation *vs*. sugarcane

Variable	Acocks	Sugarcane			
		Average	Inland	South Coast	North Coast
CONST	0.4-0.5	0.50	0.50	0.50	0.50
CAY_01	0.35-0.85	1.11	1.08	1.12	1.14
CAY_02	0.40-0.85	1.16	1.15	1.16	1.16
CAY_03	0.40-0.85	1.16	1.17	1.16	1.16
CAY_04	0.35-0.85	1.00	1.01	0.99	1.01
CAY_05	0.20-0.85	1.02	0.99	1.03	1.05
CAY_06	0.20-0.85	0.86	0.83	0.85	0.90
CAY_07	0.20-0.80	0.89	0.85	0.88	0.93
CAY_08	0.20-0.85	0.82	0.77	0.82	0.88
CAY_09	0.20-0.85	0.94	0.84	0.98	0.99
CAY_10	0.35-0.85	0.90	0.81	0.89	1.00
CAY_11	0.40-0.85	1.04	0.97	1.06	1.10
CAY_12	0.35-0.85	1.02	0.99	1.01	1.05
VEGINT_01	0.80-3.20	2.09	2.03	2.10	2.14
VEGINT_02	0.80-3.20	2.17	2.16	2.18	2.18
VEGINT_03	0.80-3.20	2.18	2.19	2.18	2.18
VEGINT_04	0.80-3.20	1.88	1.89	1.86	1.89
VEGINT_05	0.90-3.20	1.92	1.86	1.93	1.97
VEGINT_06	0.90-3.20	1.61	1.56	1.59	1.69
VEGINT_07	0.90-3.20	1.66	1.59	1.65	1.74
VEGINT_08	0.90-3.20	1.54	1.44	1.54	1.65
VEGINT_09	0.90-3.20	1.76	1.58	1.84	1.86
VEGINT_10	0.80-3.20	1.69	1.52	1.67	1.88
VEGINT_11	0.80-3.20	1.96	1.82	1.99	2.06
VEGINT_12	0.80-3.20	1.91	1.86	1.89	1.97
ROOTA_01	0.70-0.95	0.72	0.81	0.75	0.60
ROOTA_02	0.70-0.95	0.72	0.81	0.75	0.60
ROOTA_03	0.70-0.95	0.72	0.81	0.75	0.60
ROOTA_04	0.70-0.95	0.72	0.81	0.75	0.60
ROOTA_05	0.70-1.00	0.72	0.81	0.75	0.60
ROOTA_06	0.70-1.00	0.72	0.81	0.75	0.60
ROOTA_07	0.70-1.00	0.72	0.81	0.75	0.60
ROOTA_08	0.70-1.00	0.72	0.81	0.75	0.60
ROOTA_09	0.70-1.00	0.72	0.81	0.75	0.60
ROOTA_10	0.70-0.95	0.72	0.81	0.75	0.60
ROOTA_11	0.70-0.95	0.72	0.81	0.75	0.60
ROOTA_12	0.70-0.95	0.72	0.81	0.75	0.60

COIAM_01	0.15-0.30	0.35	0.35	0.35	0.35
COIAM_02	0.15-0.30	0.35	0.35	0.35	0.35
COIAM_03	0.20-0.30	0.35	0.35	0.35	0.35
COIAM_04	0.25-0.30	0.35	0.35	0.35	0.35
COIAM_05	0.30-0.30	0.35	0.35	0.35	0.35
COIAM_06	0.30-0.30	0.35	0.35	0.35	0.35
COIAM_07	0.30-0.30	0.35	0.35	0.35	0.35
COIAM_08	0.30-0.30	0.35	0.35	0.35	0.35
COIAM_09	0.30-0.30	0.35	0.35	0.35	0.35
COIAM_10	0.25-0.30	0.35	0.35	0.35	0.35
COIAM_11	0.20-0.30	0.35	0.35	0.35	0.35
COIAM_12	0.15-0.30	0.35	0.35	0.35	0.35
PCSUCO_01	40-100	90	90	90	90
PCSUCO_02	40-100	95	95	95	95
PCSUCO_03	40-100	95	95	95	95
PCSUCO_04	40-100	80	80	80	80
PCSUCO_05	40-100	70	70	70	70
PCSUCO_06	40-100	50	50	50	50
PCSUCO_07	40-100	30	30	30	30
PCSUCO_08	40-100	30	30	30	30
PCSUCO_09	40-100	50	50	50	50
PCSUCO_10	40-100	60	60	60	60
PCSUCO_11	40-100	75	75	75	75
PCSUCO_12	40-100	85	85	85	85
COLON_01	100	60	43	53	55
COLON_02	100	60	54	62	63
COLON_03	100	60	60	65	65
COLON_04	100	60	50	52	52
COLON_05	100	60	51	52	53
COLON_06	100	60	39	41	43
COLON_07	100	60	39	43	46
COLON_08	100	60	27	34	38
COLON_09	100	60	29	40	44
COLON_10	100	60	21	35	41
COLON_11	100	60	31	46	51
COLON_12	100	60	30	44	48

14 APPENDIX B

Allen *et al*. (1998) proposed an empirical equation (**Equation 13**) 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.

$$K_p = 0.108 - 0.0286u + 0.0422\ln(FD) + 0.1434\ln(RH_{ave}) - 0.000631[\ln(FD)]^2 \cdot \ln(RH_{ave}) \qquad \textbf{Equation 13}$$

Assuming a fetch of 200 m for a typical A-pan in South Africa (Schulze, 2014), 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 74**). However, 15.4% of all monthly *CORPAN* values exceed 1.29.

Table 74 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**	

15 APPENDIX C

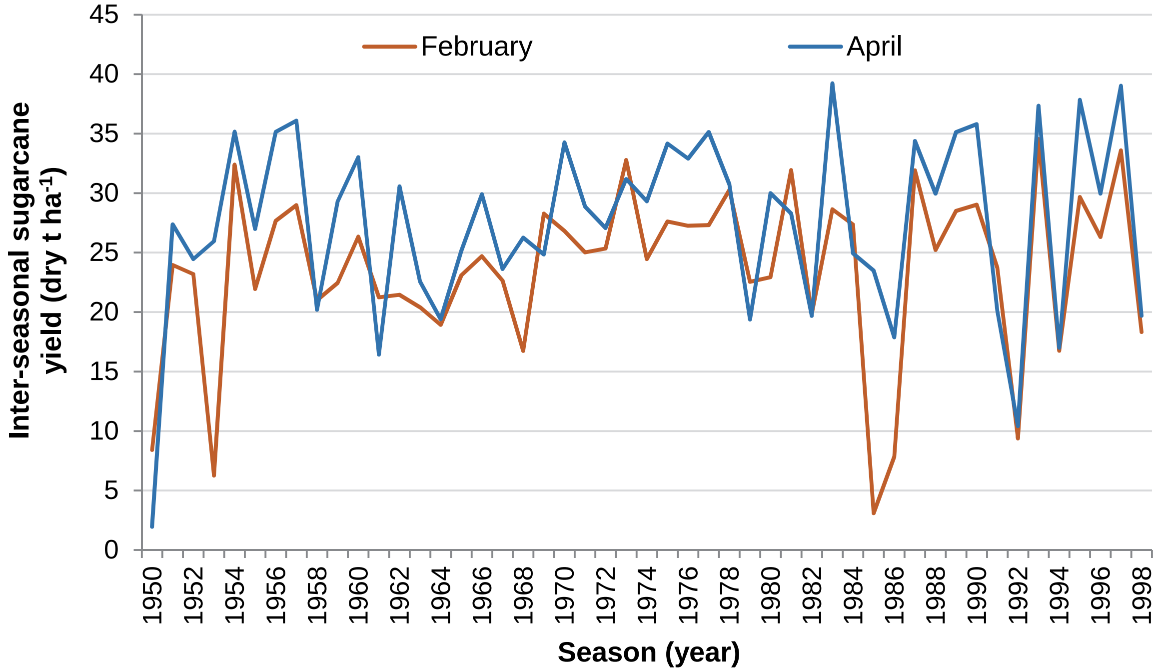


Figure 48 Inter-seasonal yield (in dry t ha^{-1}) of sugarcane simulated using *AQUACROP* for quinary 4719 (La Mercy)

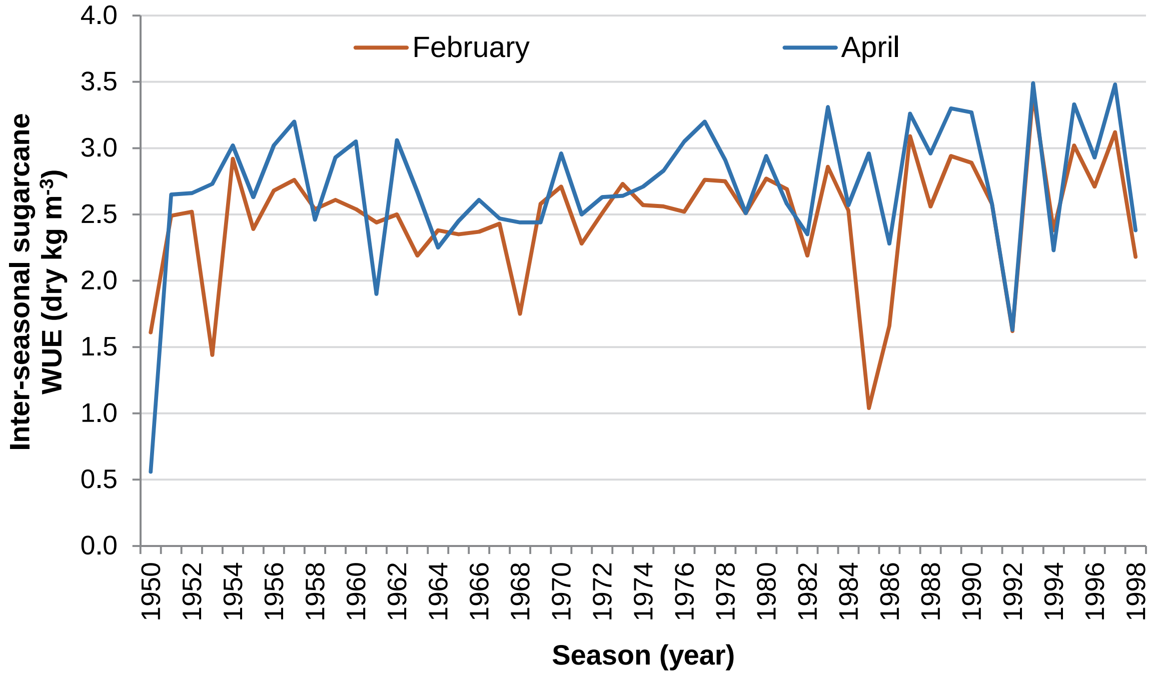
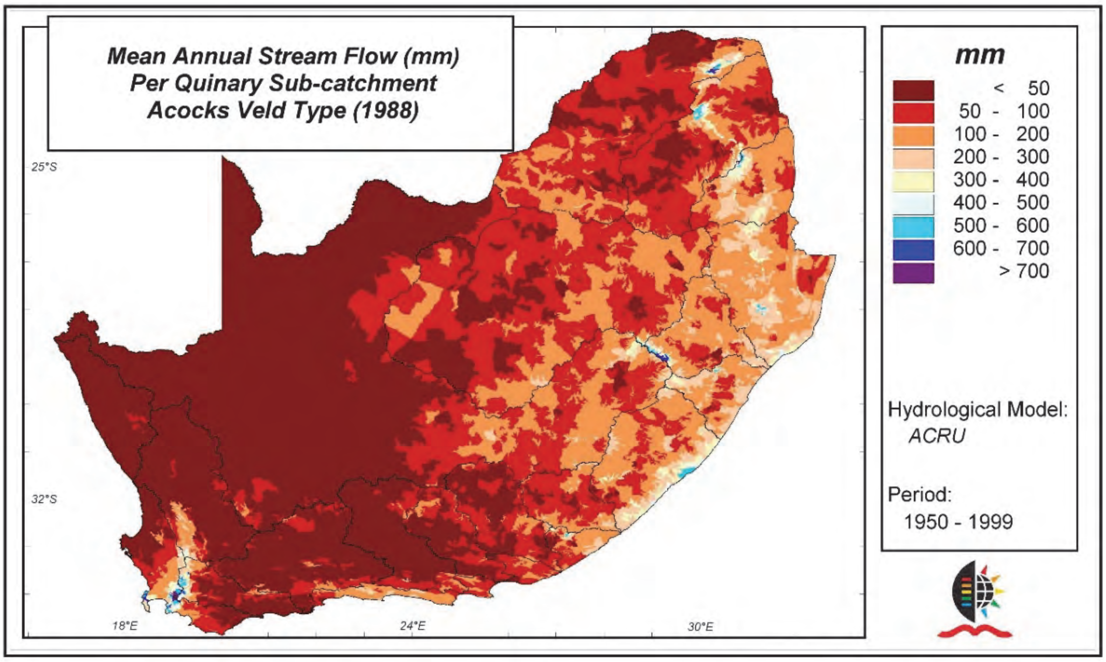
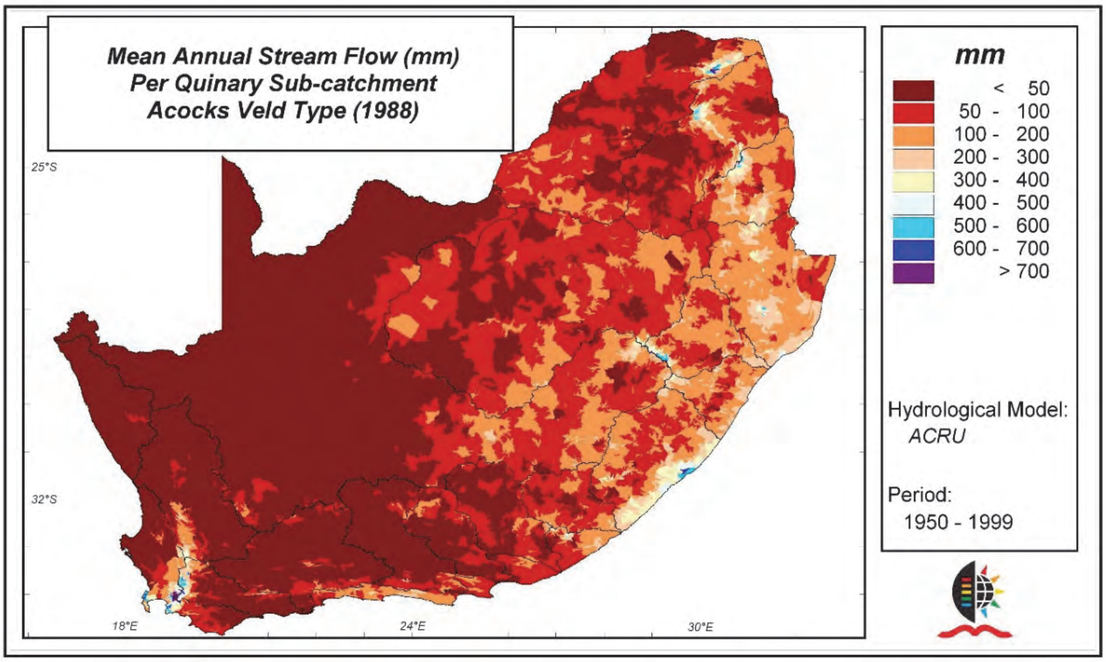


Figure 49 Inter-seasonal WUE (in dry kg m^{-3}) of sugarcane simulated using *AQUACROP* for quinary 4719 (La Mercy)

16 APPENDIX D



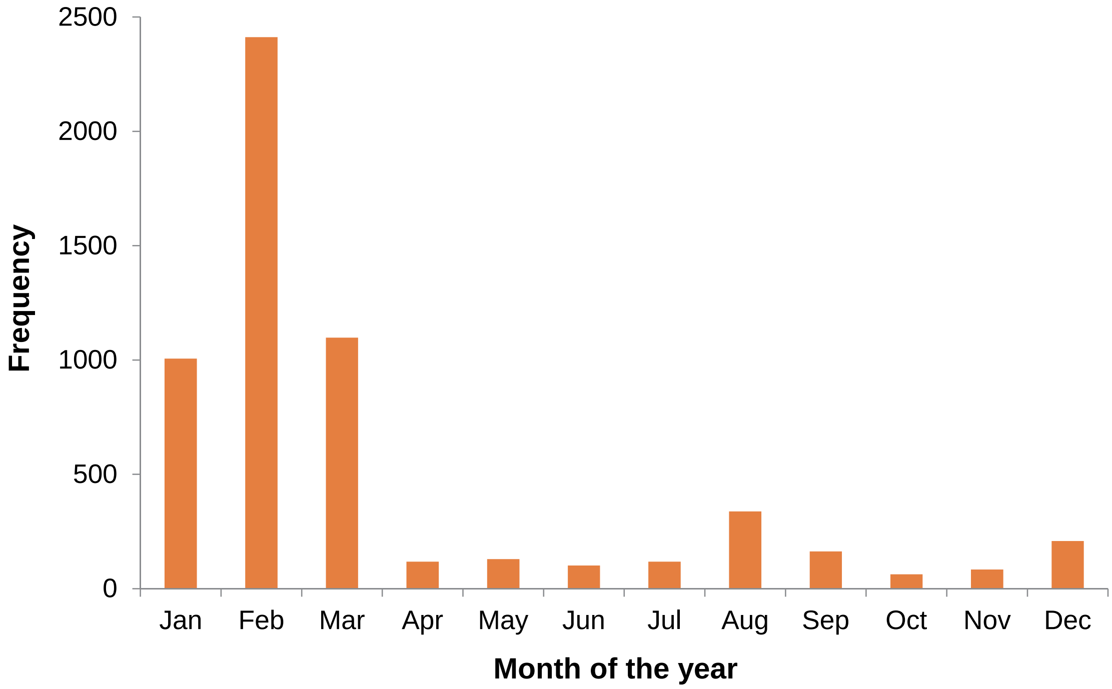
(a)



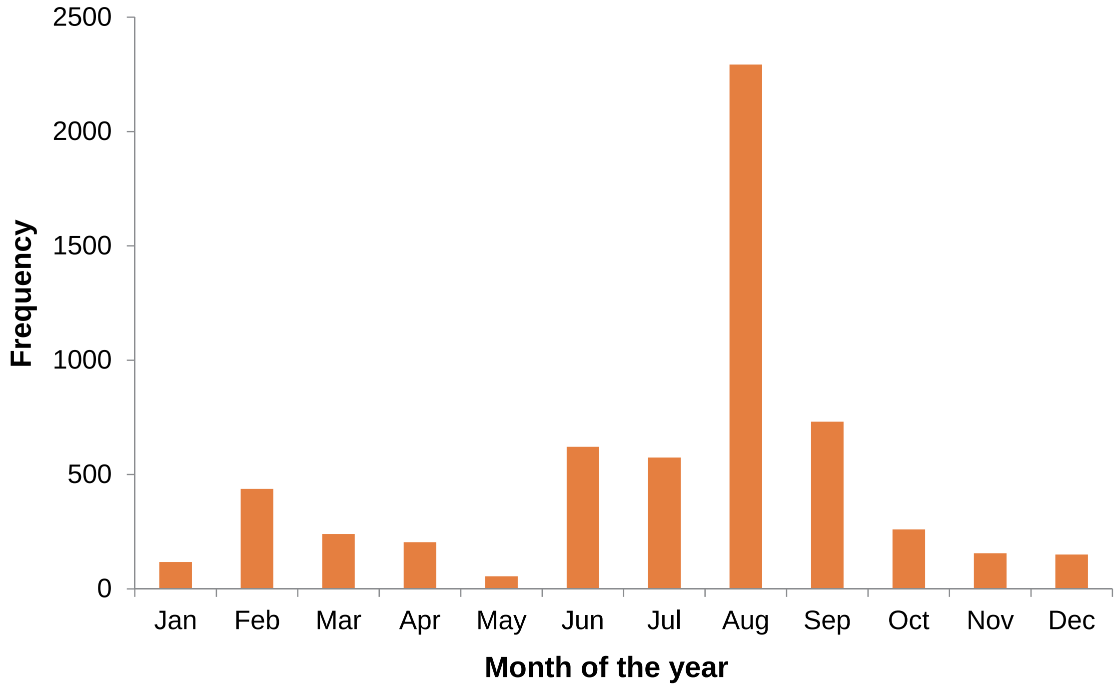
(b)

Figure 50 Mean annual stream flow simulated for each quinary sub-catchment for a land cover of natural vegetation using the a) original and b) revised quinary sub-catchment climate database

17 APPENDIX E



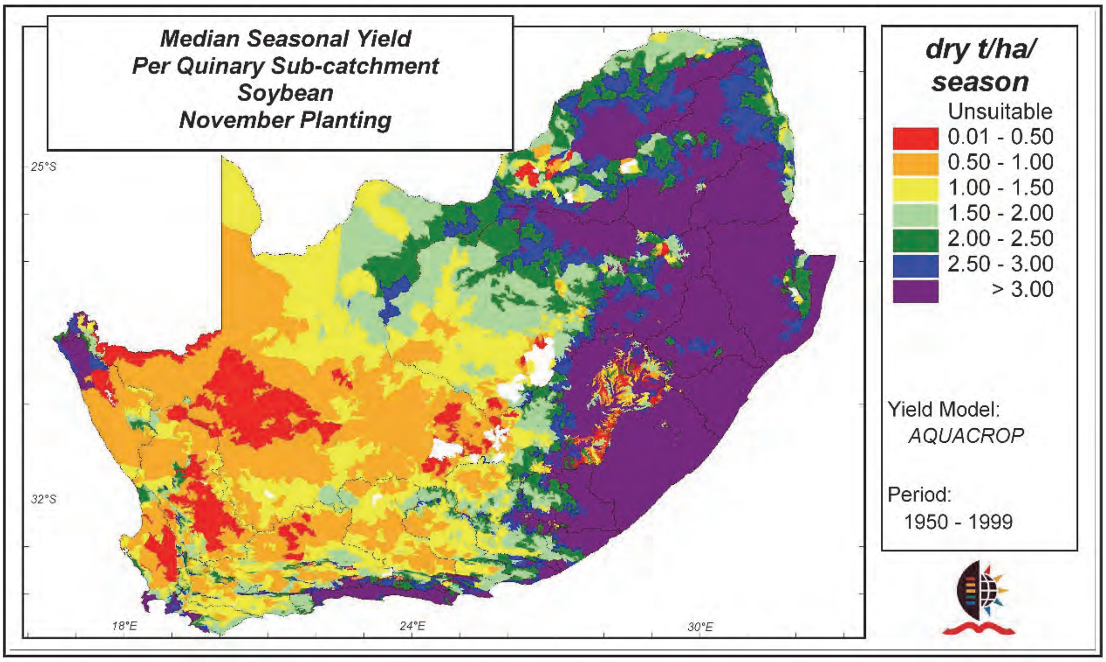
(a)



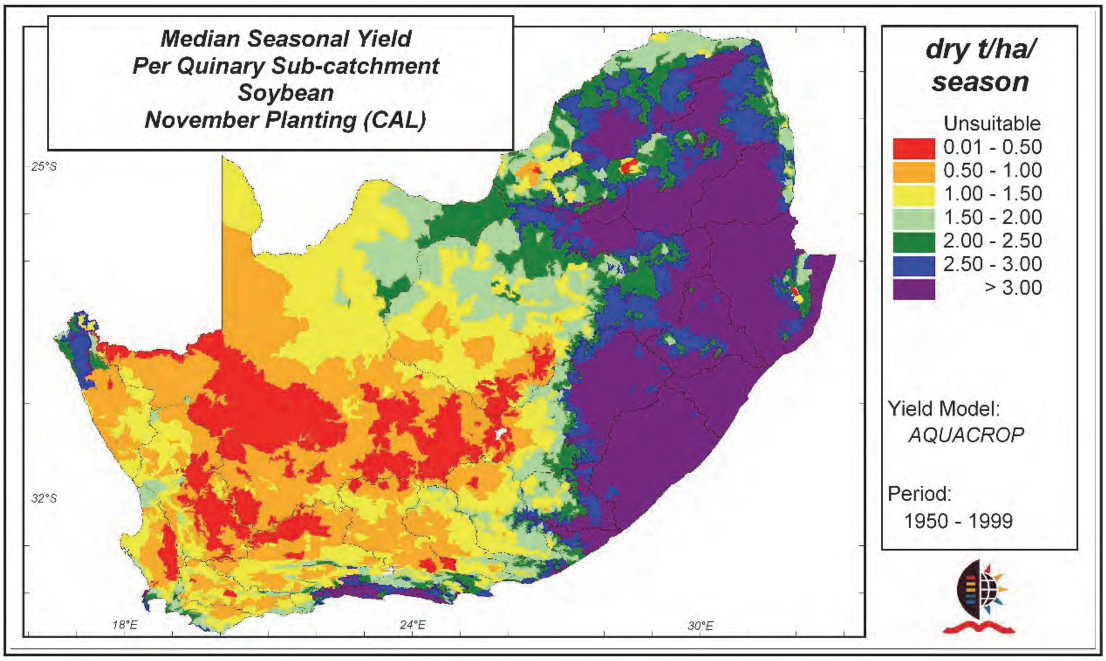
(b)

Figure 51 Frequency distribution showing the month in which the a) highest and b) lowest monthly runoff is generated using the revised quinary climate database

18 APPENDIX F



(a)



(b)

Figure 52 Differences in median seasonal yield derived from crop cycles based on thermal (a) and calendar (b) time