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Report to the
WATER RESEARCH COMMISSION

by

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This report (**Volume 3**) 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** represents the biofuels atlas and assessment utility.

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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 aren't well established, is not recommended. The variability in seasonal estimates of water use efficiency derived from measurements for both sugarbeet and sweet sorghum highlight this point.

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

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

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

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

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

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

EXTENT TO WHICH OBJECTIVES WERE MET

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

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

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

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

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

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

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

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

CAPACITY BUILDING AND TECHNOLOGY TRANSFER

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

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

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

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

DATA AND TOOLS

The project has generated over 1 000 gigabytes (Gb) of compressed model output pertaining to the national water use and crop yield simulations. In addition, high frequency measurements of air temperature used to estimate crop water use via the surface renewal method was also generated. The biofuels assessment utility will be used to disseminate a large database (i.e. ≈43.3 Gb) of daily stream flow simulations for natural vegetation as well as selected feedstocks. All raw and processed data is stored and archived on a fileserver located in the ICS Server Room on the main campus of the University of KwaZulu-Natal in

Pietermaritzburg. All project-related data and information was backed up to an external hard drive to be stored for the next five years. Contact person: Richard Kunz (kunzr@ukzn.ac.za).

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LIST OF ABBREVIATIONS

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

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

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

LIST OF SYMBOLS

Roman Symbols (lowercase)

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

Roman Symbols (uppercase)

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

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

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

Greek Symbols

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

***ACRU* parameters and variables**

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

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

AQUACROP parameters and variables

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

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

SWB parameters and variables

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

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1 INTRODUCTION

1.1 Background and Rationale

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

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

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

In November 2008, the WRC initiated and funded a second, more detailed project entitled: “Water use of cropping systems adapted to bio-climatic regions in South Africa and suitable for biofuel production”. 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 three final reports. It is important to note that the majority of the research pertaining to crop yield and water use efficiency (WUE) modelling was conducted in 2015 and thus, was not previously reported.

Volume 1 is a synthesis report which contains the key findings of the project. Hence, this volume is intended for a wider audience, including decision-makers. **Volume 2** 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** (this document) represents the biofuel atlas and assessment utility. It provides the output (as maps, tables, tools etc.) from the modelling and mapping work.

Volume 1 is essentially a summarised version of **Volume 2**. 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 summarised description of the datasets used for derive the maps. The mapping (i.e. land suitability) component of the study is presented in **Chapter 5**, with the water use and yield modelling component provided in **Chapter 3** and **Chapter 4** respectively. The biofuels assessment utility is described in **Chapter 6** and the user manual given in **APPENDIX J**. Finally, the main conclusions drawn from the study are listed in **Chapter 8** of **Volume 1**.

2 SPATIAL AND TEMPORAL DATABASES

In order to map areas optimally and sub-optimally suited to the growth of selected biofuel feedstocks as well as quantifying the water use impacts of feedstock production, various spatial and temporal databases were acquired or developed. In addition, spatial datasets required to run the selected yield model were also developed. This section describes where relevant spatial information was sourced from as well as how the data were used in the land suitability evaluation.

2.1 Introduction

In order to derive land suitability maps for biofuel feedstock production, five important spatial datasets were collected from different sources. These include monthly rainfall totals, monthly means of daily temperature and relative humidity as well as soil depth and slope. The updated South African Atlas of Climatology and Agrohydrology (Schulze, 2007) provided a valuable source of climatic, edaphic and topographic information. The gridded databases of monthly rainfall, temperature, and relative humidity were of particular importance to this study. Each of these datasets is described next in more detail.

2.2 Rainfall

2.2.1 Description

Gridded datasets showing the spatial variation in monthly rainfall totals were required to derive seasonal rainfall (i.e. monthly rainfall accumulated over the growing season). In South Africa, two projects funded by the Water Research Commission (WRC) have provided spatial estimates of monthly rainfall that were derived from rain gauge (i.e. point) measurements. These two projects are briefly described next. However, data developed by Lynch (2004) was used in this study.

The first project was titled "*Mapping of Mean Annual Precipitation and Other Rainfall Statistics over Southern Africa*" (Dent *et al*., 1989), which was superseded by the second project in 2004. The latter project was titled "*Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*" and the report was finalised in December 2004 (Lynch, 2004).

The Lynch (2004) study developed rainfall databases containing daily and monthly data collected from rainfall recording stations located in the SADC (South African Development Community) region. The SADC region includes South Africa, Namibia, Zimbabwe and Mozambique. Different in-filling algorithms were used to patch missing rainfall data and produce a continuous daily rainfall dataset. These included Inverse Distance Weighting, the Expectation Maximisation Algorithm, the Median Ratio Method and a Monthly Infilling Technique (Lynch, 2004). Spatial estimates of monthly and annual rainfall were derived from the points using a spatial interpolation technique (i.e. geographically weighted regression). Site factors including latitude, longitude, altitude and slope were used to interpolate monthly rainfall for each minute of a degree arc (Lynch, 2004).

2.2.2 Source

The gridded rainfall databases of mean monthly rainfall totals are freely available for download from SAEON's data portal (http://data.saeon.ac.za/). To assist with data downloads, it is recommended the user sets the "Custodian:" search field to the following:
BioEngineering and Environmental Hydrology, UKZN

2.3 Temperature

2.3.1 Description

Gridded datasets showing the spatial variation in monthly maximum, minimum and average temperatures were derived by Schulze and Maharaj (2007a) in a project also funded by the WRC. Schulze and Maharaj (2004) developed a database of 51 years (1950-2000) of observed daily minimum and maximum temperature for approximately 970 temperature recording stations in South Africa. The observed temperature data were quality controlled, with missing values in-filled to produce a continuous daily record. Missing temperature records were in-filled because modelling cannot be undertaken without a continuous dataset. For each minute of a degree arc, two recording stations were selected (from different quadrants). The selection was based on minimising the distance from, and the altitude between, the grid point and each temperature station. Point estimates of daily temperature were then derived by adjusting for the altitude difference between the grid point and the two recording stations, using regionally and seasonally determined lapse rates. This process was then repeated for each of the 437 039 grid points across southern Africa, to produce an extensive database (≈160 Gb in size) of 51 years of estimated daily minimum and maximum temperatures (Schulze and Maharaj, 2007a).

2.3.2 Source

The gridded rainfall databases of mean monthly rainfall totals are freely available for download from SAEON's data portal (http://data.saeon.ac.za/). To assist with data downloads, it is recommended the user sets the "Custodian:" search field to the following:
BioEngineering and Environmental Hydrology, UKZN

2.4 Relative Humidity

2.4.1 Description

According to Schulze *et al*. (2007a), uncorrected actual vapour pressure is predictable month-by-month in South Africa, using predominantly geographical factors and regression equations for each month. Saturated vapour pressure is a function of air temperature and thus varies daily and within the day. Hence, RH_{min} and RH_{max} can also vary from day to day (Schulze, 2007). Daily estimates of RH_{min}, RH_{max} and RH_{ave} (averaged) were derived for every minute of a degree arc, using the daily temperature dataset described above.

2.4.2 Source

The gridded rainfall databases of mean monthly rainfall totals are freely available for download from SAEON's data portal (http://data.saeon.ac.za/). To assist with data downloads, it is recommended the user sets the "Custodian:" search field to the following: BioEngineering and Environmental Hydrology, UKZN

2.5 Soil Depth

2.5.1 Description

The Land Type soils database at a 1:250,000 scale, developed by the former Soil and Irrigation Research Institute (SIRI, 1987 and updates), represents the most detailed soils information currently available for South Africa. For the purpose of mapping, the depth of the A- and B-horizons was extracted for all soil series in South Africa and the values were then summed to provide total soil depth (Schulze and Horan, 2007b). According to Schulze and Horan (2007b), the B-horizon is the "moisture storage" horizon and largely determines plant water availability. This reflects the underlying geology and shows a greater range of depth than the topsoil (Schulze and Horan, 2007b).

2.5.2 Source

This dataset is available on DVD as part of the 2007 version of the South African Atlas of Climatology and Agrohydrology (Schulze, 2007). The reader is requested to contact the WRC (orders@wrc.org.za) for a copy of this DVD.

2.6 Saturated Hydraulic Conductivity

2.6.1 Description

The soil's hydraulic conductivity determines the rate of water delivery to the evaporation zone (typically the top 10 cm of the soil profile), which limits the evaporation rate of soil water. The *AQUACROP* model requires the saturated hydraulic conductivity (K_{SAT} in mm d^{-1}), which is not available in the quinary sub-catchment soils database and hence was estimated for this project using a pedotransfer function developed by Saxton and Rawls (2006). The reader is referred to **Section 6.5.2.1** of **Volume 2** for more information on the derivation of this parameter.

2.6.2 Source

This dataset was generated specifically for this study.

2.7 Slope

2.7.1 Description

According to Schulze and Horan (2007a), altitude for South Africa was initially mapped at a spatial resolution of one-minute arc. The gridded altitude values were derived from various sources, with altitudes initially collated from 1:250 000 topographic sheets during the Dent *et* *al*. (1989) study of spatial rainfall. These initial values were then modified and corrected with the 200 m Digital Elevation Model (DEM) obtained from the Surveyor General's office (Schulze and Horan, 2007a). Since then, the 200 m DEM was superseded by the SRTM 90-m DEM.

2.7.2 Source

For more information, regarding the 90-m DEM for South Africa, the reader is referred to http://dds.cr.usgs.gov/srtm/. The slope dataset was derived as part of a WRC-funded project by Weepener *et al*. (2011). The reader is requested to contact the WRC (orders@wrc.org.za) for this dataset.

2.8 Land Use/Cover

2.8.1 Description

The National Land Cover (NLC) project of 2000 (NLC2000) was published in 2005 and superseded the first national land cover dataset of 1994 (NLC1994) published in 1996. Due to the rather outdated information on land use, there is high demand for improved information at the national scale. Since 2000, some Provinces (e.g. KwaZulu-Natal, North West, Gauteng, Mpumalanga & Northern Cape) and certain municipalities (nine in the Western Cape) have already produced finer scale land cover and/or land use data products.

SANBI undertook a project in 2009 to join the best available land cover datasets together and produce an updated layer called NLC2009. If no updated land cover information is available for a region, the project made use of NLC2000 as the base layer. This was the case for the Limpopo, Free State and Eastern Cape Provinces. The merging of spatial information from different sources (or custodians) is complex. The goal was to ensure spatial compatibility and thematic comparability amongst the different land cover datasets. Updated information was also obtained from other custodians and included:

- cultivated areas (ARC),
- informal settlements (ESKOM),
- commercial plantations (DWA),
- indigenous forests (DWA), and
- dams (DWA).

All updated raster and vector (i.e. polygon) datasets were re-projected to meters (Albers Conical Equal Area; datum & spheroid as WGS1984). Raster datasets were resampled (using a majority filtering) to a spatial resolution of 30 by 30 m where needed. Resampling was performed. Vector data were converted to raster (cell size of 30 x 30 m). All datasets were clipped using official provincial boundaries obtained from the Demarcation Board[1] to prevent problems from cross-boundary overlap.

Due to the different spatial scales of the datasets and mapping classes used, a standardised classification scheme was developed that was common to all datasets and applicable for the proposed utilisation of the final product. The final classification scheme was reduced to

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[1] http://www.demarcation.org.za/pages/default_new.html

seven classes in total as presented in **Figure 1**. Unfortunately, the boundaries of protected areas were not included in the NLC2009 database.

“Plantations” refers to commercial forestry areas. The “urban (built-up)” areas include cities, rural clusters, formal residential, informal residential, commercial, industrial and smallholdings. “Water bodies” include lakes, dams and wetlands of South Africa. “Natural” areas include indigenous forest, woodland, bushland, shrubland, herbland, Fynbos as well as bare rock and soil. “Cultivation” includes commercial and subsistence farmland, whether dryland or irrigated, as well as sugarcane.

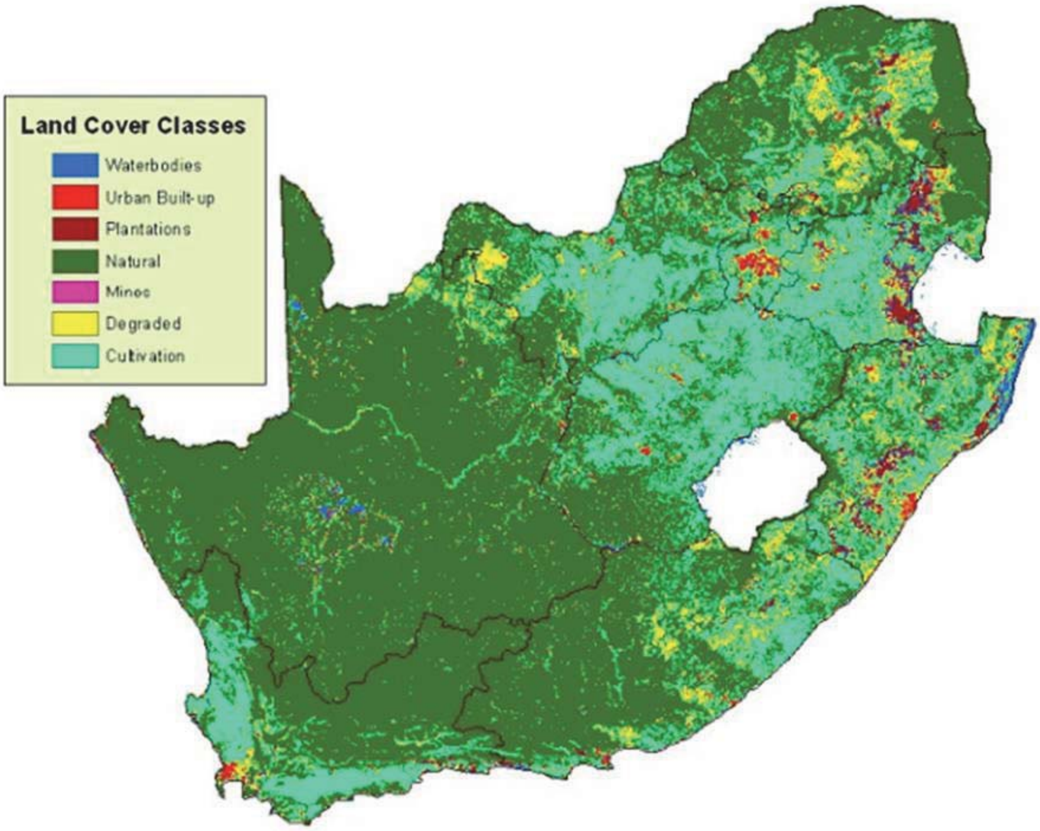


Figure 1 Updated national land cover of 2009 showing seven classes (Source: SANBI website[2])

2.8.2 Source

The South African National Biodiversity Institute (SANBI) distributes their biodiversity information to end-users via their Biodiversity-GIS website (http://bgis.sanbi.org/).

2.9 Protected Areas

2.9.1 Description

The formal protected areas (**Figure 2**) include land-based and marine protected areas that are recognised in terms of the Protected Areas Act. Protected areas are defined in the 2008

[2] http://bgis.sanbi.org/landcover/project.asp

National Protected Area Expansion Strategy (NPAES) as areas of land or sea that are formally protected by law and managed mainly for biodiversity conservation. These are:

- special nature reserves,
- national parks,
- nature reserves (including provincial nature reserves),
- protected environments,
- natural world heritage sites (not cultural world heritage sites),
- marine protected areas,
- specially protected forest areas,
- mountain catchment areas, and
- local authority protected areas.

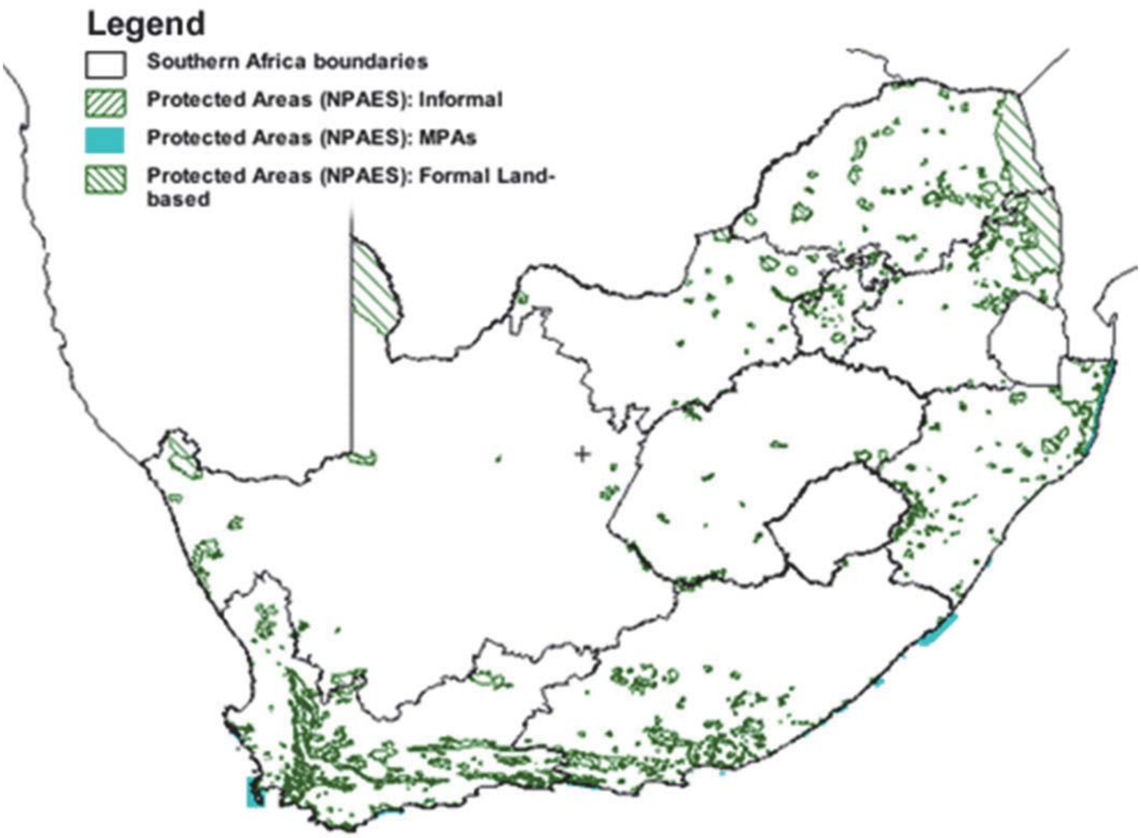


Figure 2 Formal protected areas as part of the National Protected Areas Expansion Strategy (Source: SANBI website[3])

It does not include informal conservation areas (e.g. conservancies) or non-natural areas within protected environments. Conservation areas are areas of land not formally protected by law but informally protected by the current owners and users and managed at least partly for biodiversity conservation. Because there is no long-term security associated with conservation areas, they are not considered a strong form of protection. Conservation areas are not a major focus of the NPAES and are therefore not included in the formal protected area layer.

[3] http://bgis.sanbi.org/protectedareas/protectedAreas.asp

2.9.2 Source

The South African National Biodiversity Institute (SANBI) distributes their biodiversity information to end-users via their Biodiversity-GIS website (http://bgis.sanbi.org/).

2.10 Quinary Sub-catchment Boundaries

2.10.1 Description

Quinary sub-catchments are topographically based sub-divisions of the national quaternary catchments, originally delineated by the former Department of Water Affairs. Each fourth level quaternary catchment was sub-delineated into three fifth level quinary 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 procedures (**Figure 3**), which is available within the ArcGIS software suite. This resulted in 5 838 quinary catchments deemed to be more homogeneous than the quaternaries in terms of their altitudinal range.

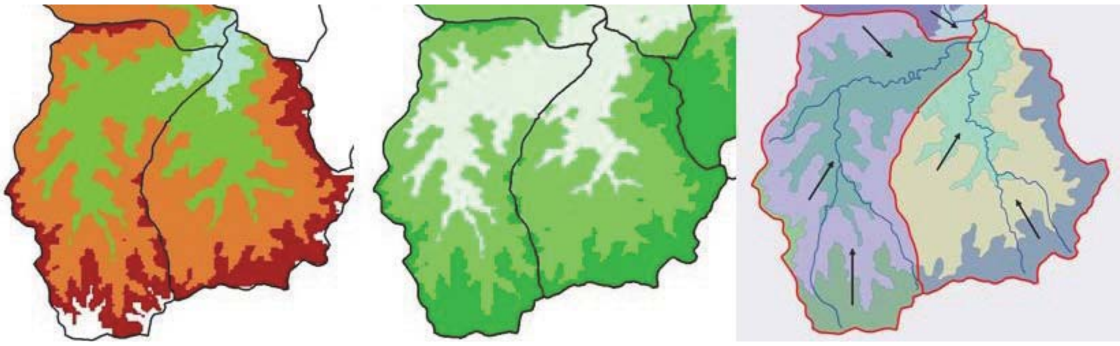


Figure 3 Sub-delineation of quaternary catchments from altitude (left) into three quinaries by natural breaks (middle) with flow paths of water (right) (Schulze *et al*., 2011)

The rainfall station selected to represent the parent quaternary catchment was again selected to represent all three quinary catchments (located within the quaternary). Owing to a lack of reliable station data in certain areas, a particular rainfall station could "drive" the hydrology of more than one quaternary catchment (and hence multiple quinary catchments). A total of 1 240 rainfall "driver" stations were used to provide daily rainfall for each of the 5 838 quinaries.

For each quinary, monthly rainfall adjustment factors were applied to the driver station's record in order to generate daily rainfall data deemed more representative of that quinary. These monthly adjustment factors were determined by comparing the driver station's mean monthly rainfall totals to the spatial average of all mean monthly rainfall grid cells (derived by Lynch, 2004) located within each quinary.

A representative temperature "station" for each quinary was selected from the temperature database derived by Schulze and Maharaj (2004) as follows. The 200 m digital elevation model was used to calculate the spatially averaged altitude for each quinary. Grid cells with mean altitudes similar to those of the quinary means, and located as close as possible to the quinary centroid (and preferably located within the quinary boundary), were then selected to represent each of the 5 838 quinaries. An exponential decay function using the altitude difference (between the catchment mean and grid cell) and distance (between the quinary centroid and grid cell) was developed to automate the selection process.

2.10.2 Source

This dataset is available on request from UKZN (contact Mark Horan; horan@ukzn.ac.za).

2.11 Revised Quinary Sub-catchment Database

2.11.1 Description

The quinary sub-catchment climate database was revised, based on a number of improvements 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. The reader is referred to **Section 6.5.1** of **Volume 2** of a detailed description of this dataset.

2.11.2 Source

This dataset was specifically generated for this study and is not yet considered part of the public domain.

2.12 Summary

Table 1 summarises the various data sources used for land suitability mapping. For additional information pertaining to each data set, the reader is referred to the reference provided in the table. The sub-section that follows describes the methodology used in this study to evaluate the suitability of land to grow biofuel feedstocks.

Table 1 Sources of climatic (rainfall, temperature & relative humidity), edaphic (soil depth) and topographic (slope) data used in this study

Datasets	**Description**	**[1]Source**	**Reference**
Rainfall	Monthly rainfall totals	CWRR	Lynch (2004)
Temperature	Means of daily maximum, minimum & average temperature	CWRR	Schulze and Maharaj (2007a)
Relative humidity	Means of daily average & minimum relative humidity	CWRR	Schulze *et al*. (2007a)
Slope	Digital elevation model	ARC	Weepener *et al*. (2011)
Soil depth	Depth of topsoil and subsoil horizons	CWRR	Schulze (2007)
Land use	Land use in South Africa	SANBI	Bhengu *et al*. (2008)
Protected Areas	Formal and informal protected areas in South Africa	SANBI	Bradshaw (2010)

[1] Note: Centre for Water Resources Research (CWRR)
Agricultural Research Council (ARC)
South African National Biodiversity Institute (SANBI)

3 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.

3.1 Introduction

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. Thus, 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.

3.2 Hydrological Baseline

3.2.1 Background

"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). 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.

3.2.2 Methodology

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. The *ACRU* model (Schulze, 1995) was selected to assess the hydrological impacts of land use changes to feedstock production on downstream water availability. *ACRU* is primarily a catchment-scale, daily time-step rainfall-runoff model. The model operates as a process-based, multi-soil layer water budget which is sensitive to land management and land use changes. *ACRU* is a physical-conceptual model with various outputs which have been widely verified against observations in many countries and conditions.

The approach followed was similar to that used in previous studies and is as follows:

- The revised quinary sub-catchment database, together with the *ACRU* agrohydrological model (Schulze, 1995), was used to simulate the runoff response from a land cover of natural vegetation.

- The monthly rainfall adjustment factors developed for the original quinary sub-catchment database were used in this study.

- The monthly adjustments were applied to the observed daily rainfall record obtained from the rainfall driver station in order to improve the representativeness of rainfall at the sub-catchment scale.

- Solar radiation was estimated from temperature using the technique described by Chapman (2004) and Schulze and Chapman (2007).

- Daily estimates of reference evapotranspiration for each quinary were derived using the Penman-Monteith (FAO56) method. A new wind speed of 2.0 m s^{-1} was assumed.

- 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.

- New monthly adjustment factors 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.

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

- *ACRU* input parameters and variables for Acocks Veld Types were obtained from the COMPOVEG database maintained by the CWRR.

- Model parameters representing Acocks were characterised in accordance with guidelines from the National Botanical Institute.

- Further explanation on the derivation of these values for the 70 baseline land cover types was provided by Schulze (2004) and Schulze (2008). If the dominant land cover is grassland, the model parameterisation represents the average state of grassland in a particular quinary sub-catchment.

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

- 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 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.

3.2.3 Results and discussion

Figure 4 represents the mean annual runoff (MAR; based on the *ACRU* output variable *SIMSQ*) produced from a land cover of natural vegetation using the revised quinary sub-catchment climate database (i.e. MAR_{base}). The map highlights the low runoff response from the western parts of the country due to the low and erratic rainfall experienced in this region.

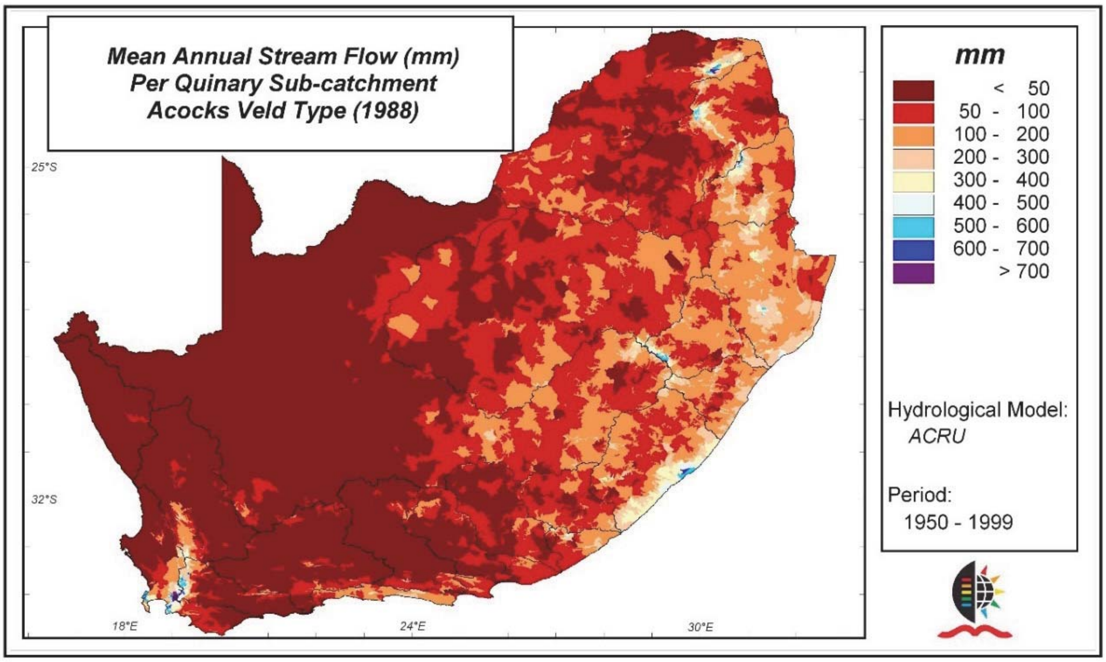


Figure 4 Mean annual stream flow simulated for each quinary sub-catchment for a land cover of natural vegetation using the revised quinary sub-catchment climate database

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 5** and shows that values range from 0.5 to 1.0 for the majority (89%) of quinary sub-catchments.

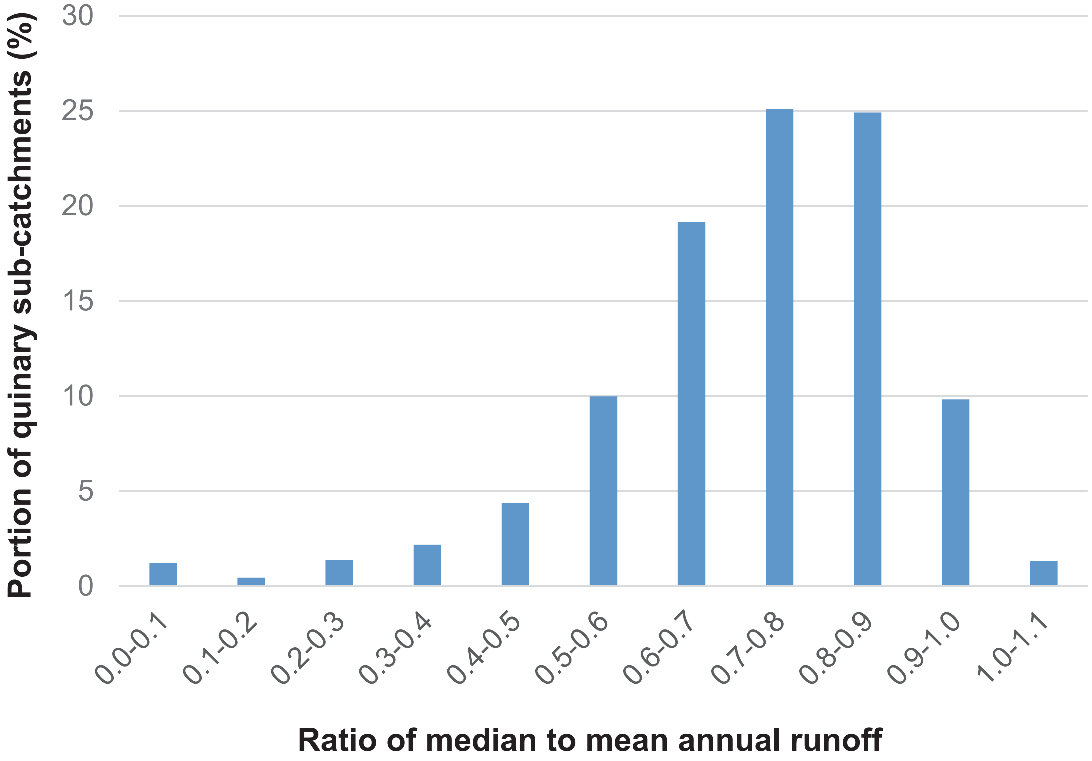


Figure 5 Histogram of the median annual runoff to mean annual runoff ratio across all 5 838 quinaries

The spatial distribution of the median to mean annul runoff ratio is shown in **Figure 6**. 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.

It is evident that, compared to the original quinary climate database (Schulze *et al.*, 2011), the revised A-pan equivalent evaporation estimates are higher, which results in less stream flow being simulated.

The "enhanced" A-pan evaporation resulted in a reduction in simulated MAR 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).

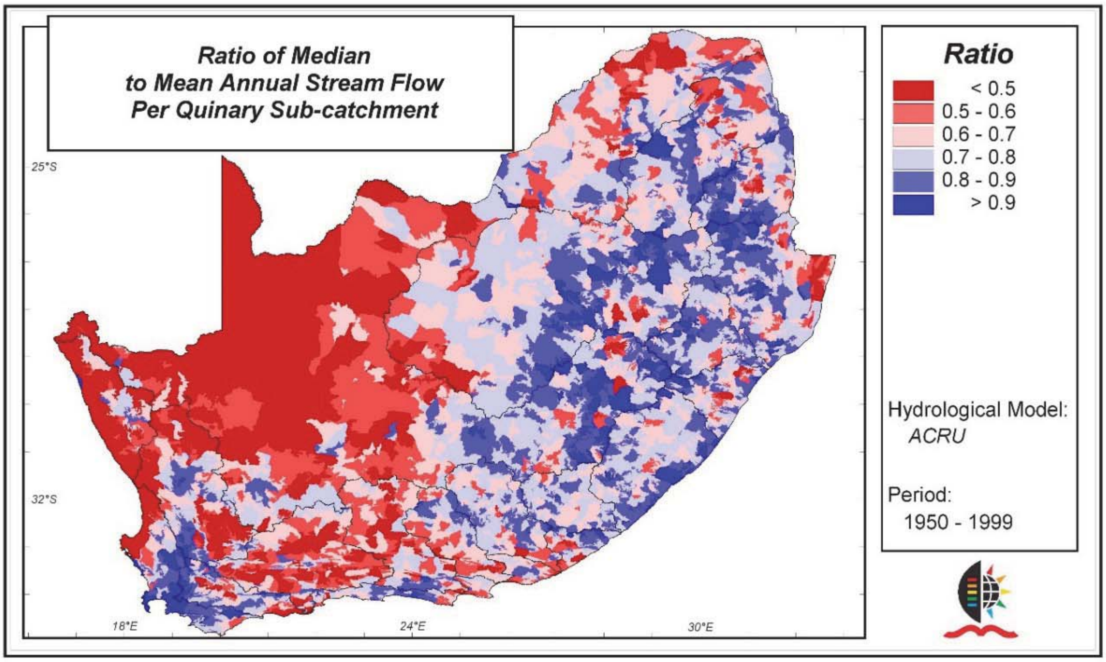


Figure 6 The ratio of median to mean annual runoff for the baseline

For the majority of quinaries, the highest and lowest monthly runoff is generated predominately in February and August respectively. This highlights the fact that most of the quinaries occur within the summer rainfall region of southern Africa. The same trends were observed for monthly stream flows generated using the original quinary climate database. Hence, the revised database of enhanced evaporation did not alter the monthly distribution of simulated runoff. 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.

3.3 Feedstock Water Use

3.3.1 Background

Land cover and land use affect hydrological responses through canopy and litter interception, infiltration of rainfall into the soil and the rates of soil water evaporation and transpiration from the vegetation layer. The sensitivity analysis undertaken by Angus (1989) showed that stream flow output is sensitive to changes in crop coefficients. For this reason, considerable effort was spent on deriving crop coefficient values for selected feedstocks from field-based observations. This addressed a recommendation from the biofuels scoping study (Jewitt *et al.*, 2009a) for better knowledge of crop water use, especially the emerging crops such as sugarbeet and sweet sorghum.

3.3.2 Methodology

The *ACRU* model was run at a national scale to estimate the runoff response from a land cover of biofuel feedstock. The model was run for three bioethanol feedstocks and two biodiesel feedstocks, some with two typical planting dates as shown in **Table 2**.

Table 2 Feedstock planting dates assumed for the simulation of runoff response using the *ACRU* model

Feedstock	Planting date
Sugarcane - averaged	ratoon
Sugarbeet - summer	1st September
Sugarbeet - winter	1st June
Sweet sorghum - inland	1st December
Sweet sorghum - interior	1st December
Grain sorghum	1st November
Soybean	1st November
Canola - winter	1st April

The approach followed for each feedstock was similar to that used for the simulation of baseline runoff, except for the following:

- Typical planting dates were selected for each feedstock that was modelled.

- 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.

- 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).

- 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 crop coefficients 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 a lower planting density.

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

- 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).

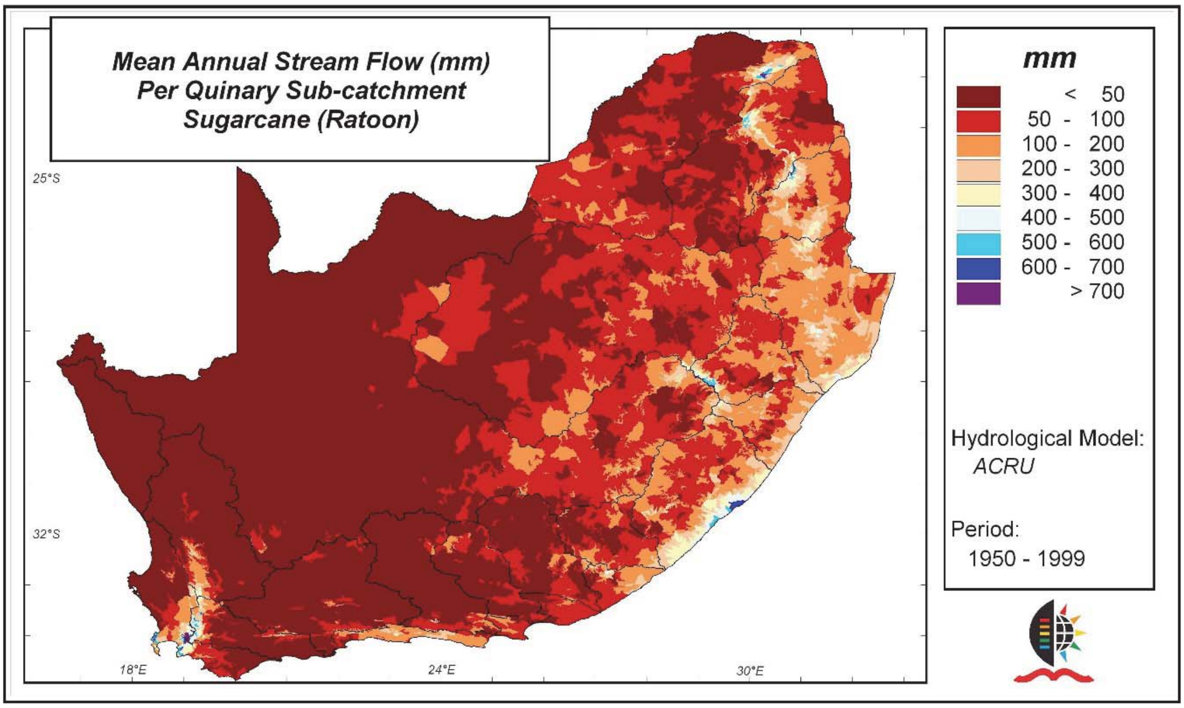
- Since all crop coefficients derived from field-based research used FAO56 as the evaporation, they were adjusted to APAN equivalent values using the pan coefficients calculated with the *PENPAN* equation.

- For annual crops, a monthly crop coefficient of 0.35 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.

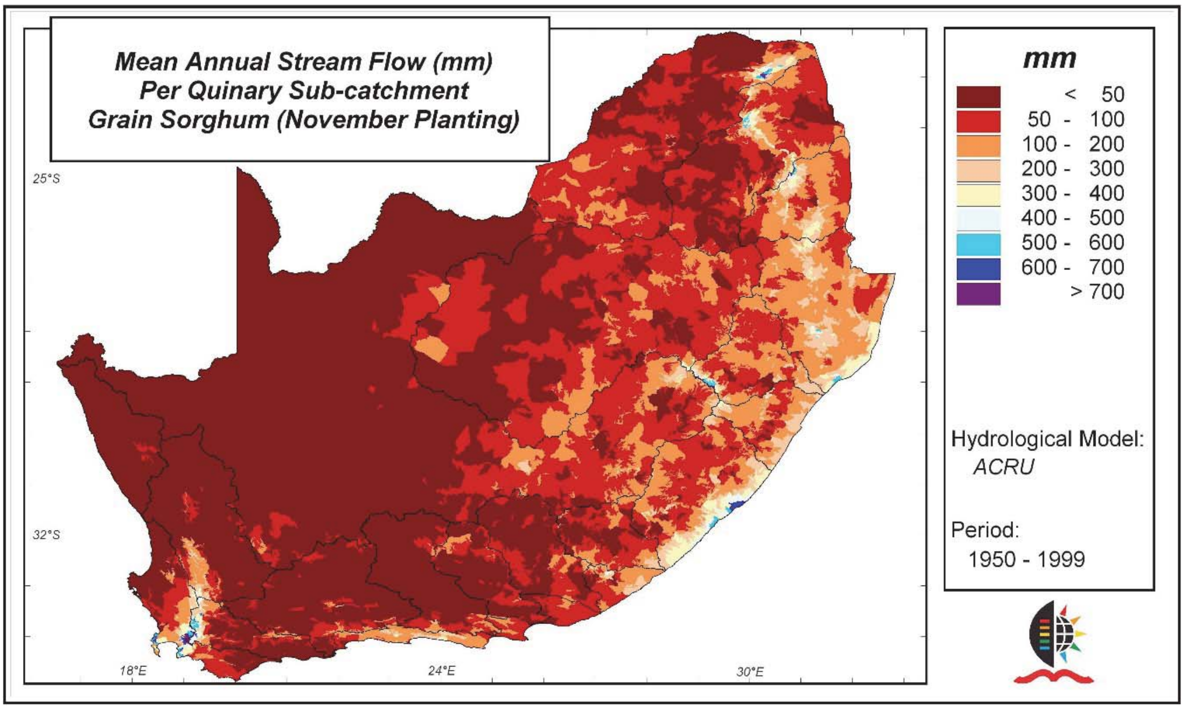
- The model was re-run for a 100% land cover change to a particular crop (i.e. biofuel feedstock), in order to simulate mean annual runoff from the crop surface (MAR_{crop}).

3.3.3 Results and discussion

Simulated mean annual stream flow (MAR_{crop}; in mm) is shown in **Figure 7** for selected bioethanol feedstocks (with similar data for biodiesel feedstocks given in **Figure 8**). These maps were then compared to the mean annual stream flow simulated for each quinary sub-catchment for a land cover of natural vegetation (MAR_{base}; **Figure 4**). All the maps of MAR show the same trend in that generated runoff is highly influenced by rainfall magnitude.

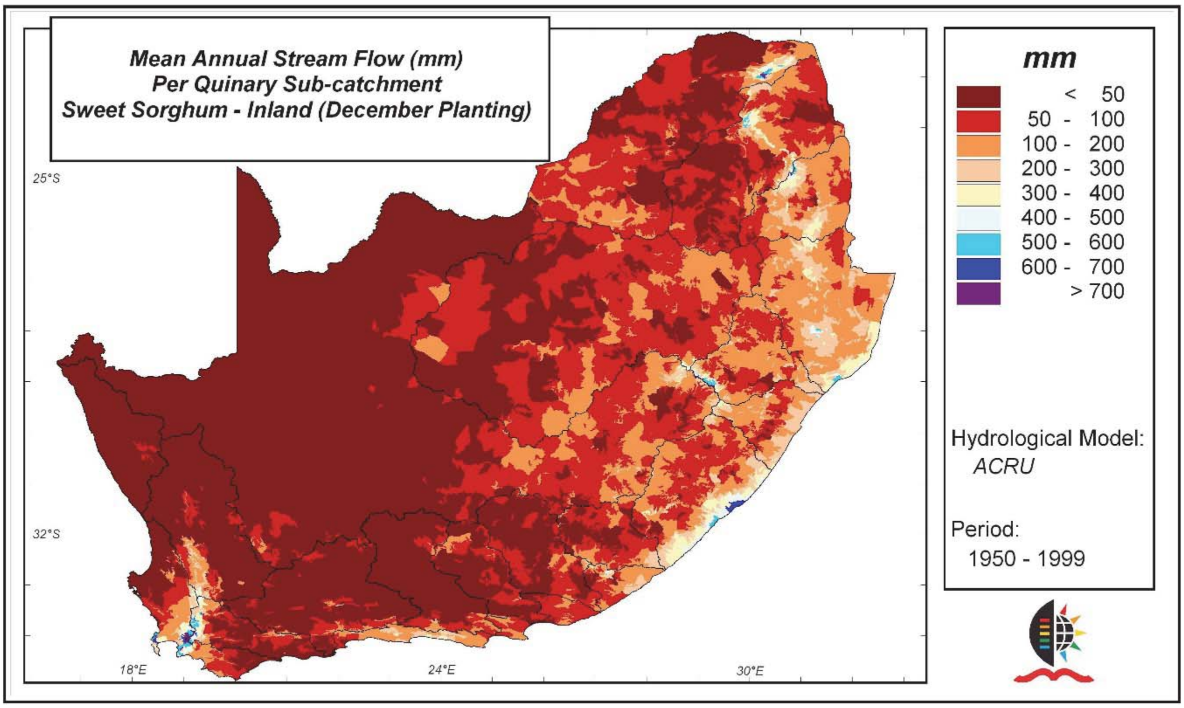


(a)



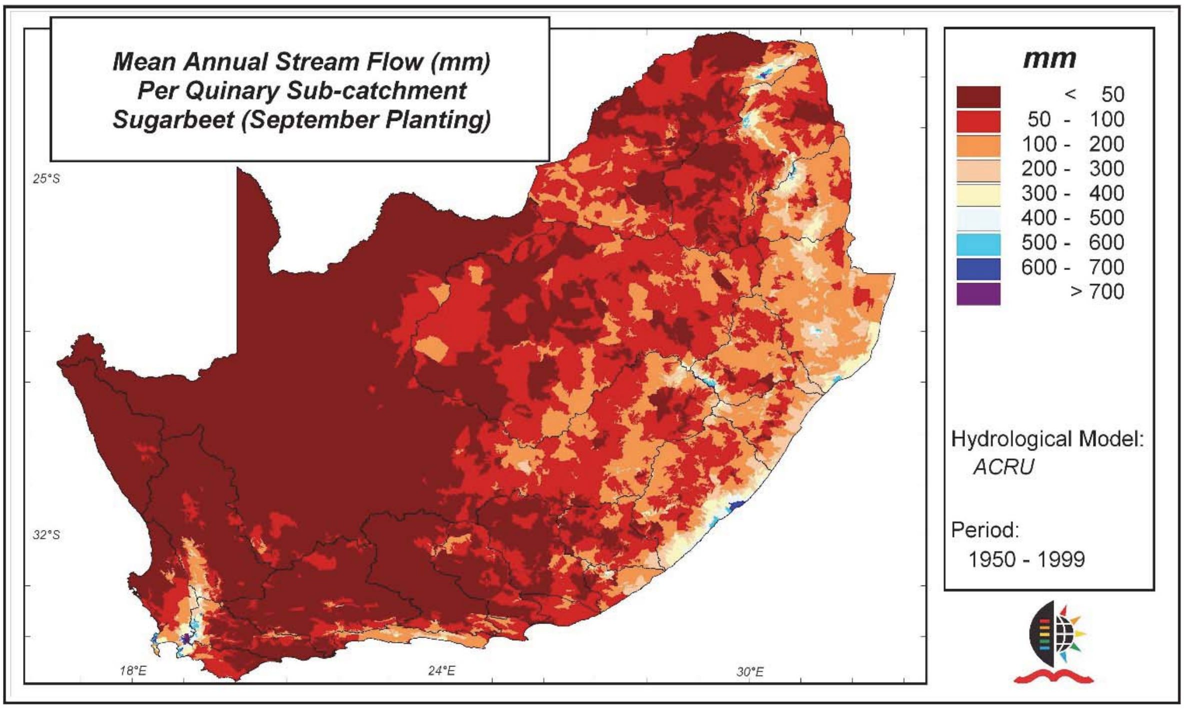
Mean Annual Stream Flow (mm)
Per Quinary Sub-catchment
Grain Sorghum (November Planting)
25°S
32°S
18°E
24°E
30°E
mm
< 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
> 700
Hydrological Model:
ACRU
Period:
1950 - 1999

(b)



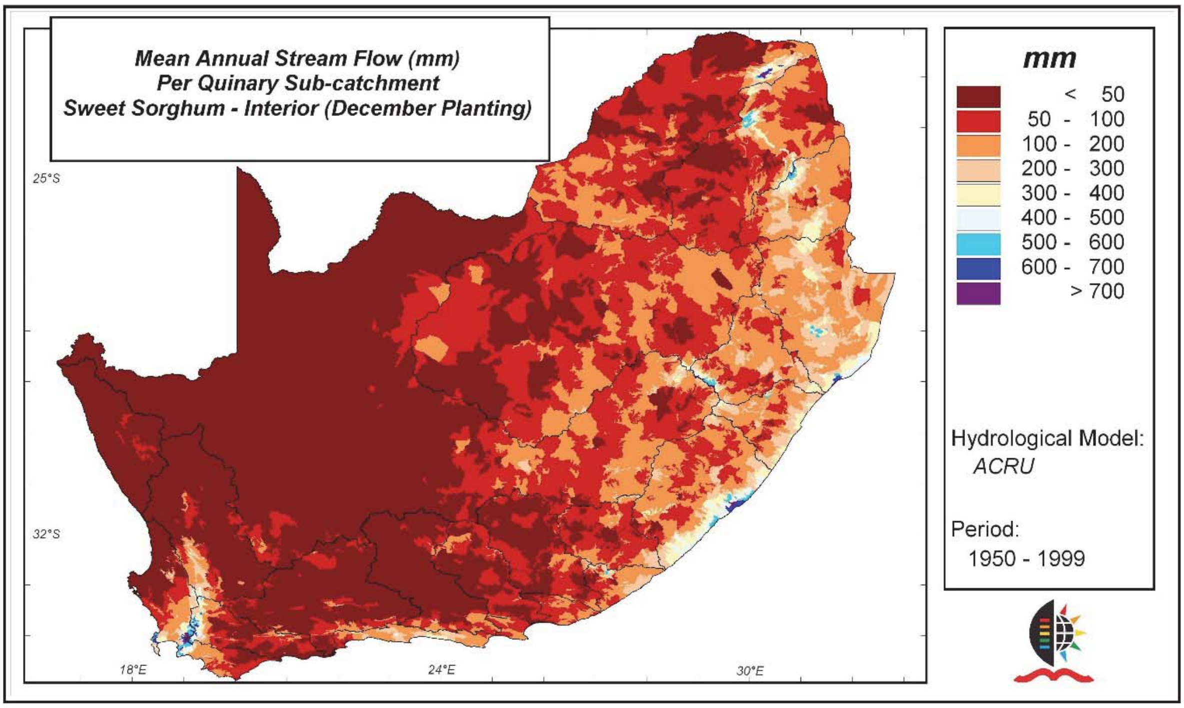
Mean Annual Stream Flow (mm)
Per Quinary Sub-catchment
Sweet Sorghum - Inland (December Planting)
25°S
32°S
18°E
24°E
30°E
mm
< 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
> 700
Hydrological Model:
ACRU
Period:
1950 - 1999

(c)



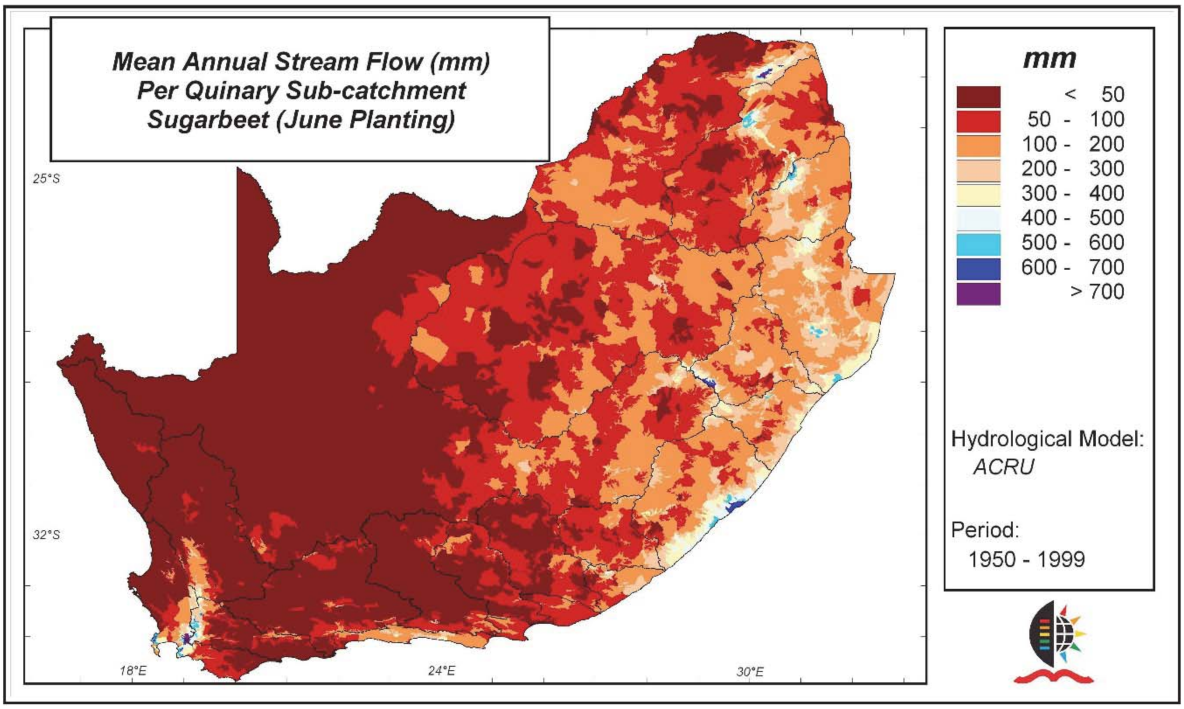
Mean Annual Stream Flow (mm)
Per Quinary Sub-catchment
Sugarbeet (September Planting)
25°S
32°S
18°E
24°E
30°E
mm
< 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
> 700
Hydrological Model:
ACRU
Period:
1950 - 1999

(d)



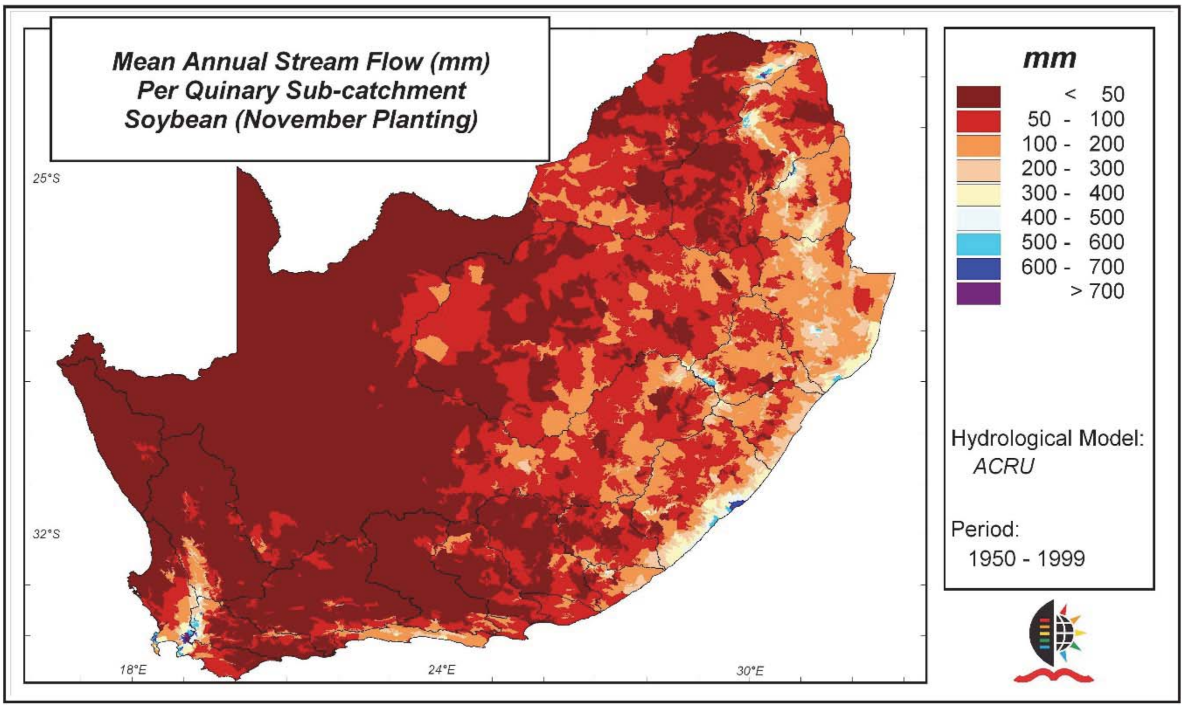
Mean Annual Stream Flow (mm)
Per Quinary Sub-catchment
Sweet Sorghum - Interior (December Planting)
25°S
32°S
18°E
24°E
30°E
mm
< 50
50 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600
600 - 700
> 700
Hydrological Model:
ACRU
Period:
1950 - 1999

(e)

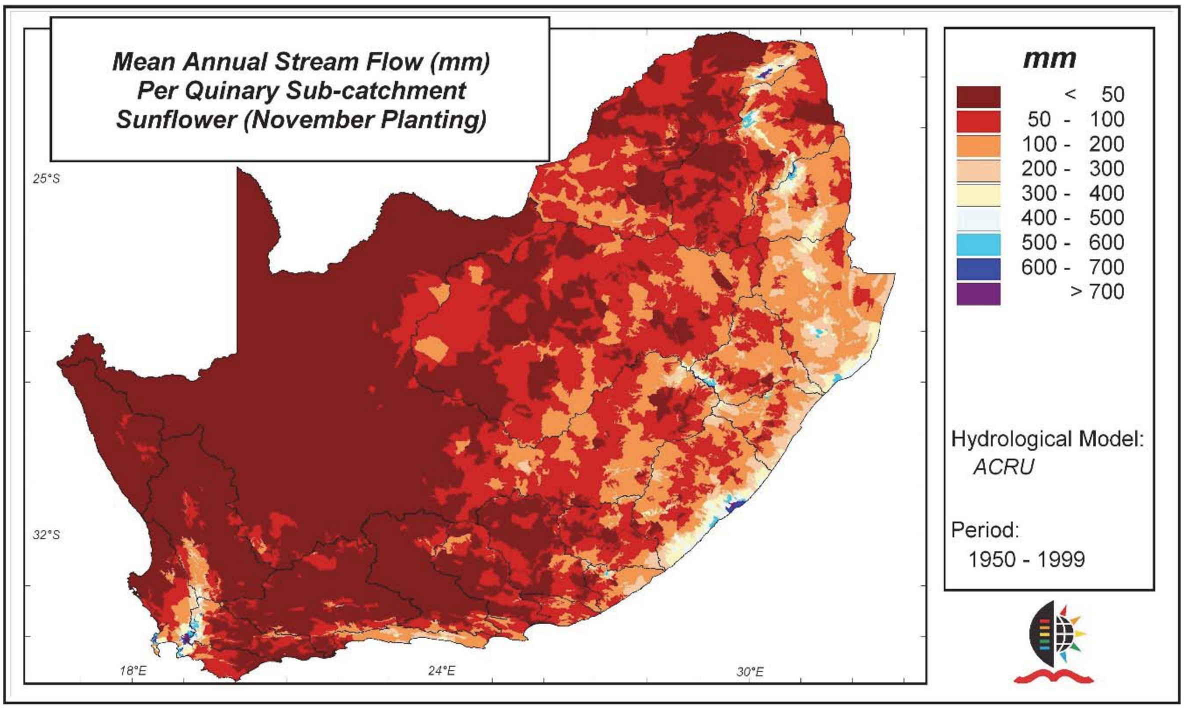


(f)

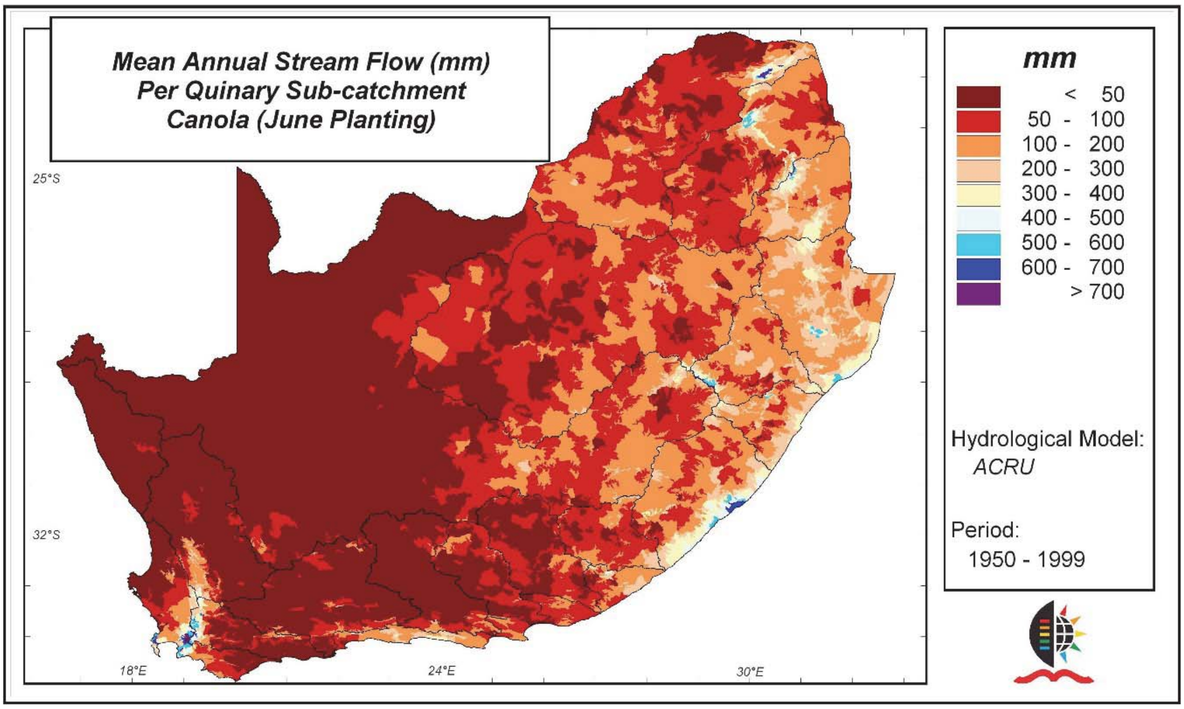
Figure 7 Mean annual stream flow (in mm) simulated using the *ACRU* model for each bioethanol feedstock (a-f)



(a)



(b)



(c)

Figure 8 Mean annual stream flow (in mm) simulated using the *ACRU* model for each biodiesel feedstock (a-c)

3.4 Stream Flow Reduction

3.4.1 Background

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 (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).

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. 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 ≥ 25% for low flows.

3.4.2 Methodology

The approach followed was similar to that used in previous studies:

- 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.

- This difference in annual runoff (*MARbase* - *MARcrop*) was then expressed as a percentage of the baseline stream flow (*MARbase*).

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

3.4.3 Results and discussion

3.4.3.1 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 $100 \cdot (MAR_{base} - MAR_{crop})/MAR_{\text{base}}$. Similarly, water use calculated from median annual runoff (MdAR) is given by 100·

($MdAR_{base}$ - $MdAR_{crop}$)/$MdAR_{base}$. 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 3** 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 3 Number of quinary sub-catchments in which the reduction in annual runoff (relative to the baseline) is 10% or larger

Feedstock	No. 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. However, calculating the difference between two median values is not mathematically sound (Morris, 2015). 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 4** 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 above in **Table 3**).

Table 4 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 this volume are based on an analysis of mean annual and mean monthly flows.

3.4.3.2 Original *vs*. revised quinary climate database

Using the original quinary sub-catchment climate database derived by Schulze *et al*. (2011), the mean annual runoff was determined using *ACRU* variables for each sugarcane growing region (i.e. Inland, South Coast & North Coast). The results showed that 23.1% of the 134 quinaries exhibited a reduction in runoff (relative to the baseline) of 10% or more (**Table 5**).

Table 5 Analysis of simulated runoff based on preliminary *ACRU* runs (i.e. original quinary climate database), for sub-catchments which contain 10% or more of the sugarcane mill supply areas

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**

A very similar result (26.1%) was obtained using the mean annual runoff derived from the averaged crop-related variables. **Table 5** 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. The similarity in results indicates that the decision to use averaged variables for sugarcane is well justified.

The above exercise was repeated using the revised quinary sub-catchment database. As noted earlier, the revised A-pan equivalent evaporation estimates are much higher than the original values, which means that less runoff is generated. The results presented in **Table 6** show the same trends as those derived using the original quinary climate database (**Table 5**). 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 6 Analysis of simulated runoff based on finalised *ACRU* runs (i.e. revised quinary climate database), for sub-catchments which contain 10% or more of the sugarcane mill supply areas

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**

3.4.3.3 Threshold to assess SFRAs

It must be noted that the 10% reduction in MAR threshold, which is used to flag a potential SFRA, was suggested by Jewitt *et al*. (2009b) and based on the original (1972) Afforestation Permit System (APS). For the impact on low flows, a threshold of 25% was suggested by Jewitt *et al*. (2009b). The APS considered up to a 10% reduction in mean annual runoff from whole or part of primary catchments where afforestation was being considered. However, this threshold is not stated in the Water Act (Act No. 36 of 1998). It is also important to note that a 10% (or larger) relative reduction in annual runoff is assumed to be "significant". The problem with this assumption is that it probably lies within the confidence limits of the modelling approach and perhaps, needs to be reviewed.

For South Africa, MAR estimated using *ACRU* for the baseline ranges from 0 (quinary 2544) to 1 822 mm (quinary 2911). Hence, a 10% reduction in MAR is equivalent a range of 0 to 182.2 mm, which highlights a shortcoming of this approach. In other words, a difference of just 1 mm in mean annual runoff (MAR_{base} - MAR_{crop}) is equivalent to reductions ranging from 100 to 0.05% for MAR_{base} of 1 to 1 822 mm respectively. Thus, the 10% threshold is very sensitive to low baseline MARs. This is highlighted in quinary 2589 where the MAR may be reduced from 0.02 to 0.00 mm (i.e. 100% reduction) when the land cover is changed to sugarcane. Thus, a high relative reduction can occur in sub-catchments with little to no runoff response, which can be misleading. Furthermore, a 10% (or larger) stream flow reduction in areas with a high runoff ratio (i.e. MAR/MAP) exhibits a greater impact than a similar reduction in drier areas (i.e. low runoff ratio). On average, only 9% of the country's rainfall is converted into stream flow (DWA, 1986).

3.4.3.4 Reduction in mean annual runoff

Simulated mean annual stream flow (MAR_{crop}) for each feedstock was then compared to the MAR simulated for each quinary sub-catchment for a land cover of natural vegetation (MAR_{base}). The absolute difference (i.e. MAR_{base} - MAR_{crop}) in mm is given for bioethanol and biodiesel crops in **Figure 72** and **Figure 73** (in **APPENDIX A**) respectively.

This difference in MAR between the baseline (base) and each feedstock (crop) was then expressed as a percentage relative to the baseline for each quinary, i.e. $100 \cdot (MAR_{base} - MAR_{crop})/MAR_{\mathrm{base}}$. Thus, **Figure 10** highlights the relative reduction in runoff that may result from a land cover change from natural vegetation to selected bioethanol crops (with **Figure 11** showing the relative reduction in runoff for selected biodiesel crops).

Figure 9 shows for each feedstock, the portion of quinary sub-catchments in which no reduction in MAR (i.e. MAR ≤ 0%) as well as a positive reduction in MAR (i.e. MAR > 0%) was simulated using the *ACRU* model. To re-cap, the MAR for each feedstock is compared to that generated for the baseline (i.e. land cover of natural vegetation).

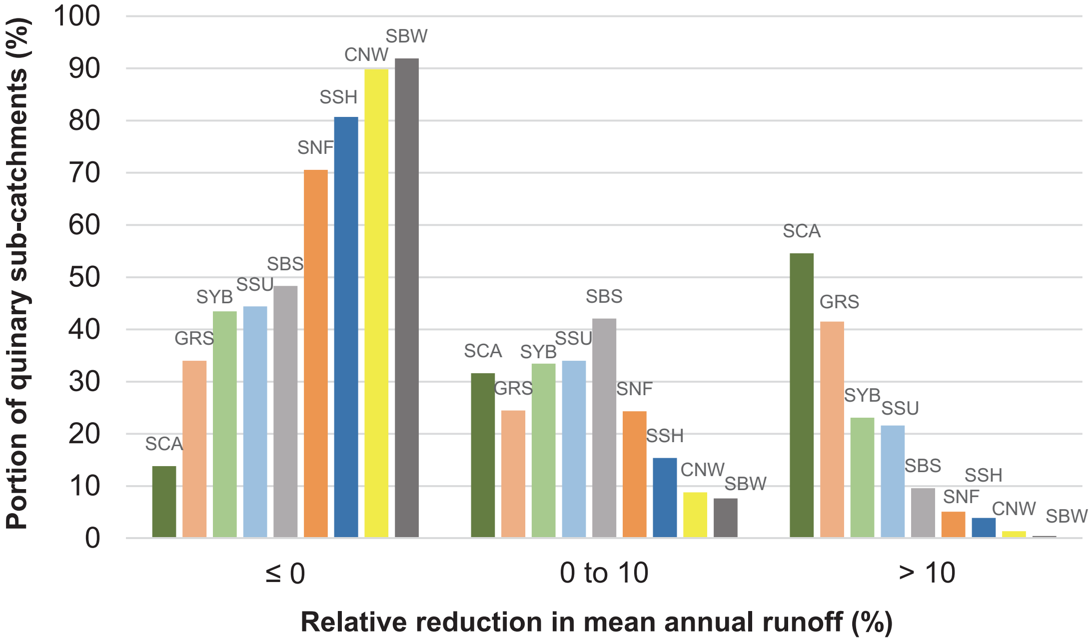
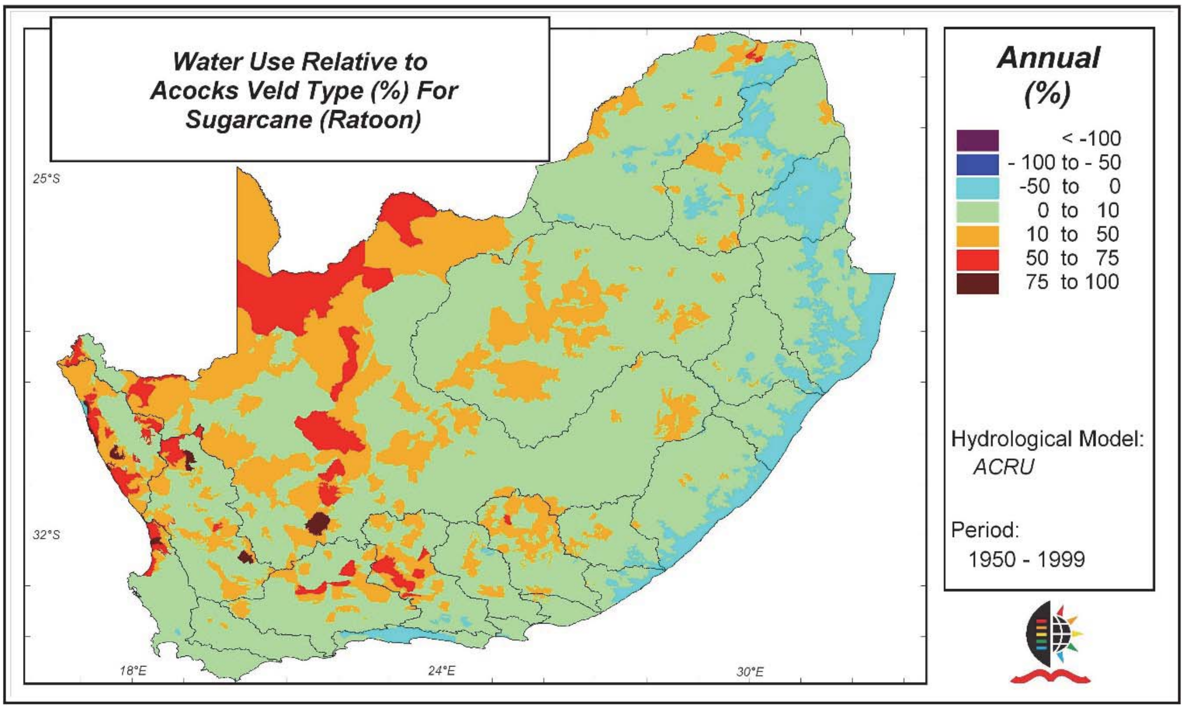


Figure 9 Reduction in mean annual runoff relative to the baseline (expressed as a percentage) for selected biofuel feedstocks

Using the 10% threshold considered as a significant reduction in MAR, the feedstocks can be ranked in terms of their potential to reduce water availability to downstream users as follows:

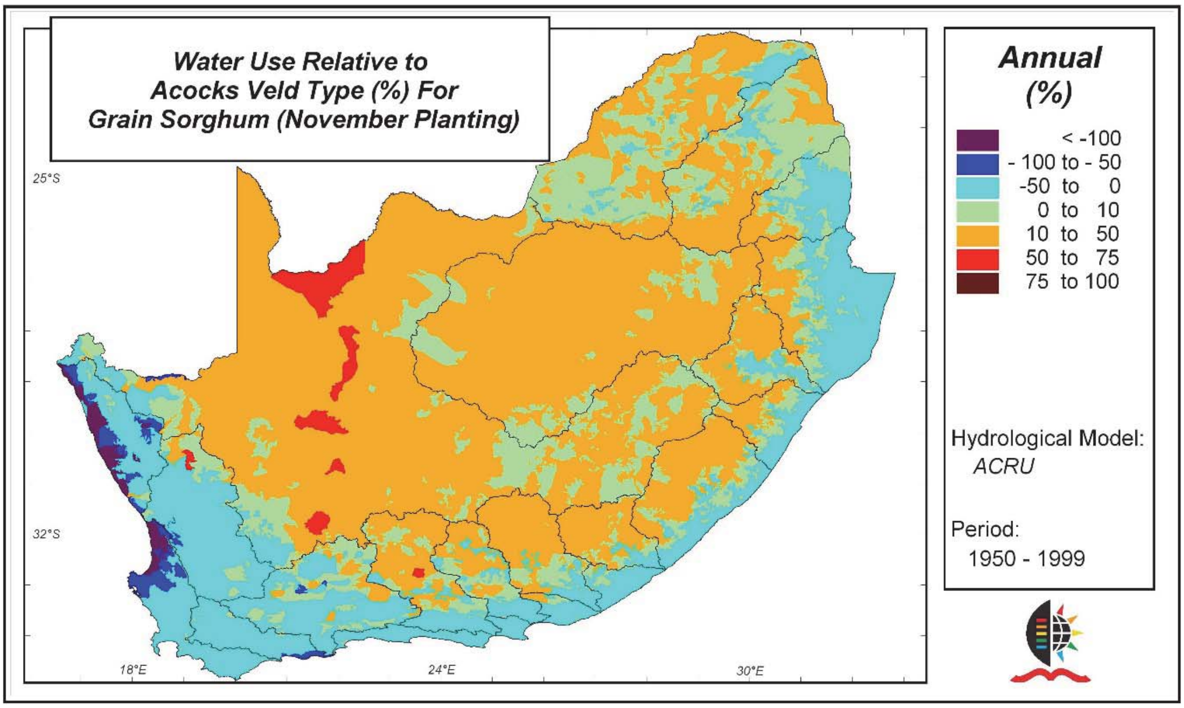
1. Sugarcane (SCA; highest potential)
2. Grain sorghum (GRS)
3. Soybean (SYB)
4. Sweet sorghum - inland (SSU)
5. Sugarbeet - summer (SBS)
6. Sunflower (SNF)
7. Sweet sorghum - interior (SSH)
8. Canola (CNW)
9. Sugarbeet - winter (SBW; least potential)

These results concur with the findings of the scoping study (Jewitt *et al*., 2009a) which concluded that sugarcane exhibits the most potential to utilise more water than the dominant Acocks Veld Type it replaces, based on a comparison of mean annual runoff. The scoping study also highlighted sweet sorghum production as a potential SFRA. However, the results presented in this study show that grain sorghum's potential to reduce runoff production is similar to that of sugarcane.



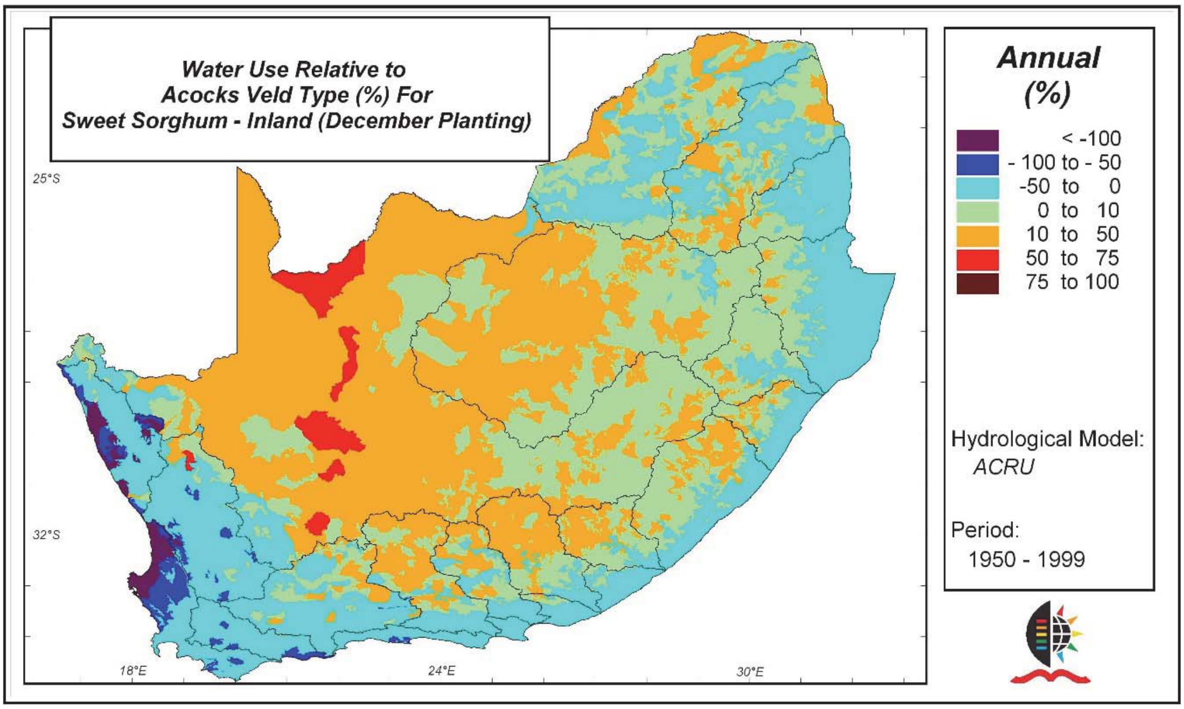
Water Use Relative to
Acocks Veld Type (%) For
Sugarcane (Ratoon)
25°S
32°S
18°E
24°E
30°E
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999

(a)

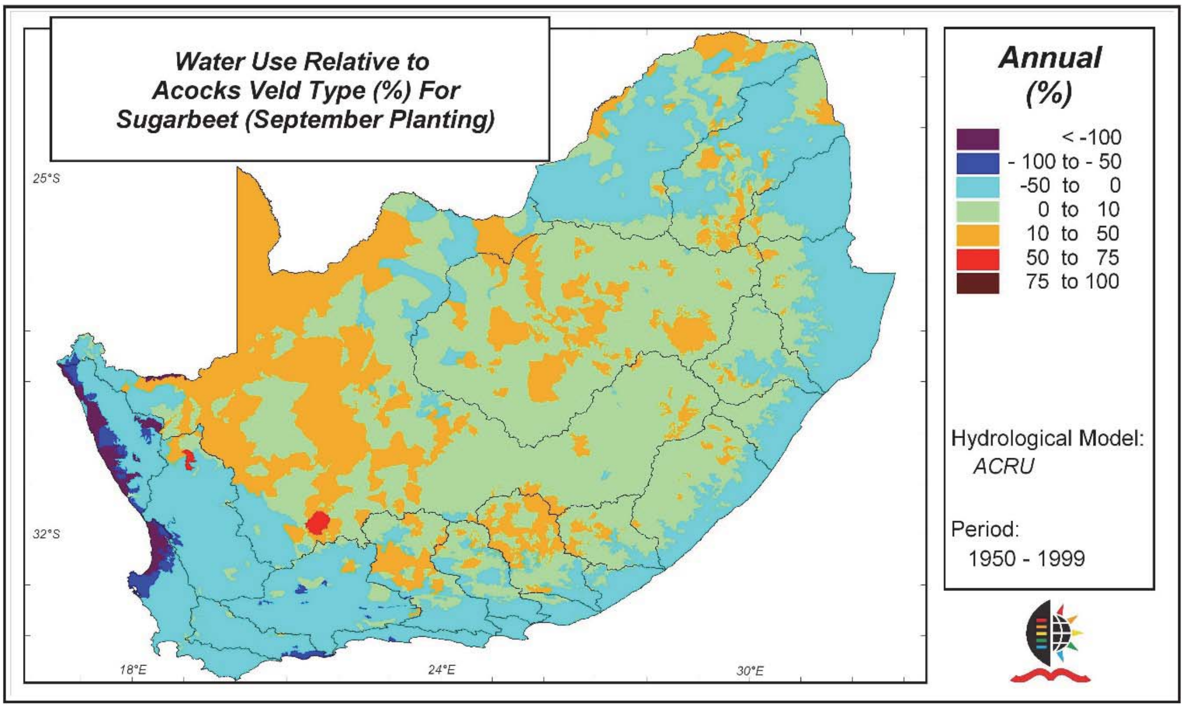


Water Use Relative to
Acocks Veld Type (%) For
Grain Sorghum (November Planting)
25°S
32°S
18°E
24°E
30°E
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999

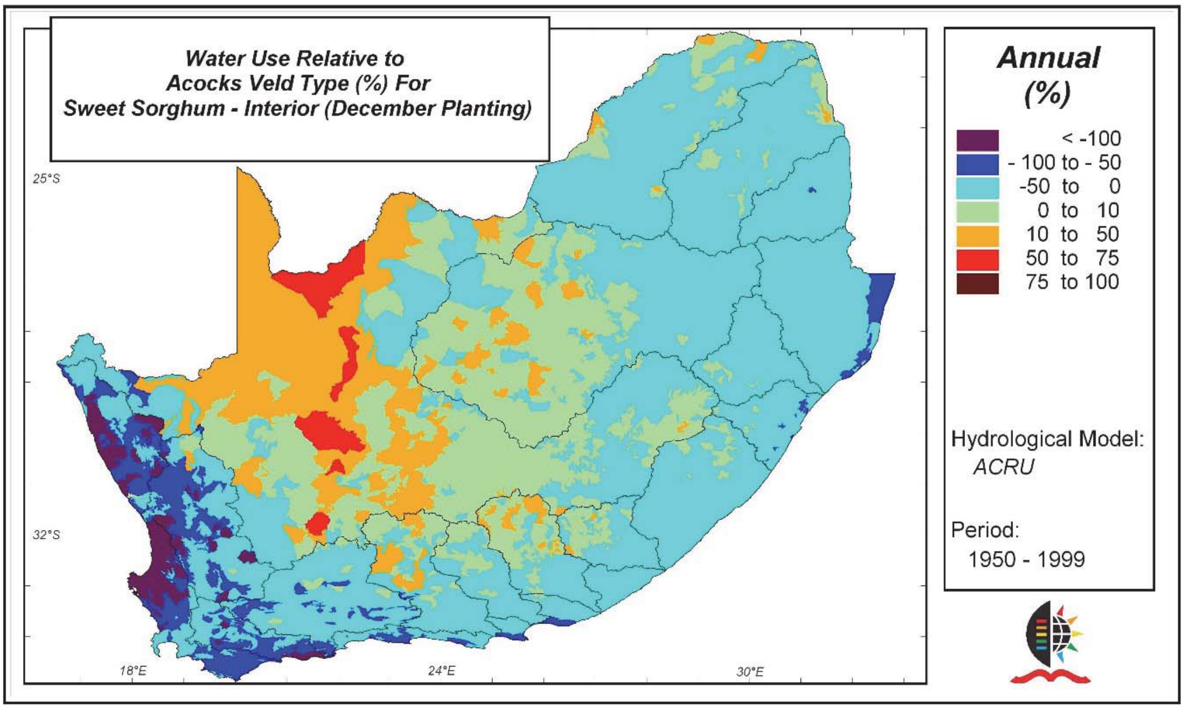
(b)


Water Use Relative to
Acocks Veld Type (%) For
Sweet Sorghum - Inland (December Planting)
25°S
32°S
18°E
24°E
30°E
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999

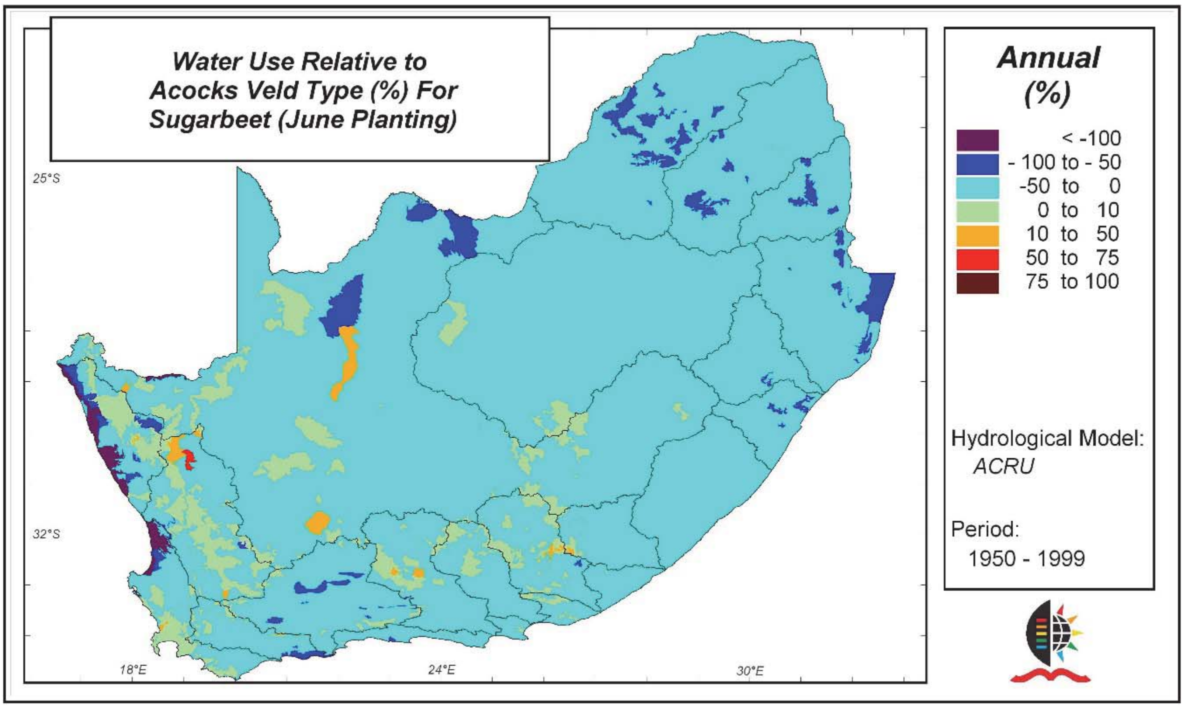
(c)


Water Use Relative to
Acocks Veld Type (%) For
Sugarbeet (September Planting)
25°S
32°S
18°E
24°E
30°E
Annual
(%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model:
ACRU
Period:
1950 - 1999

(d)

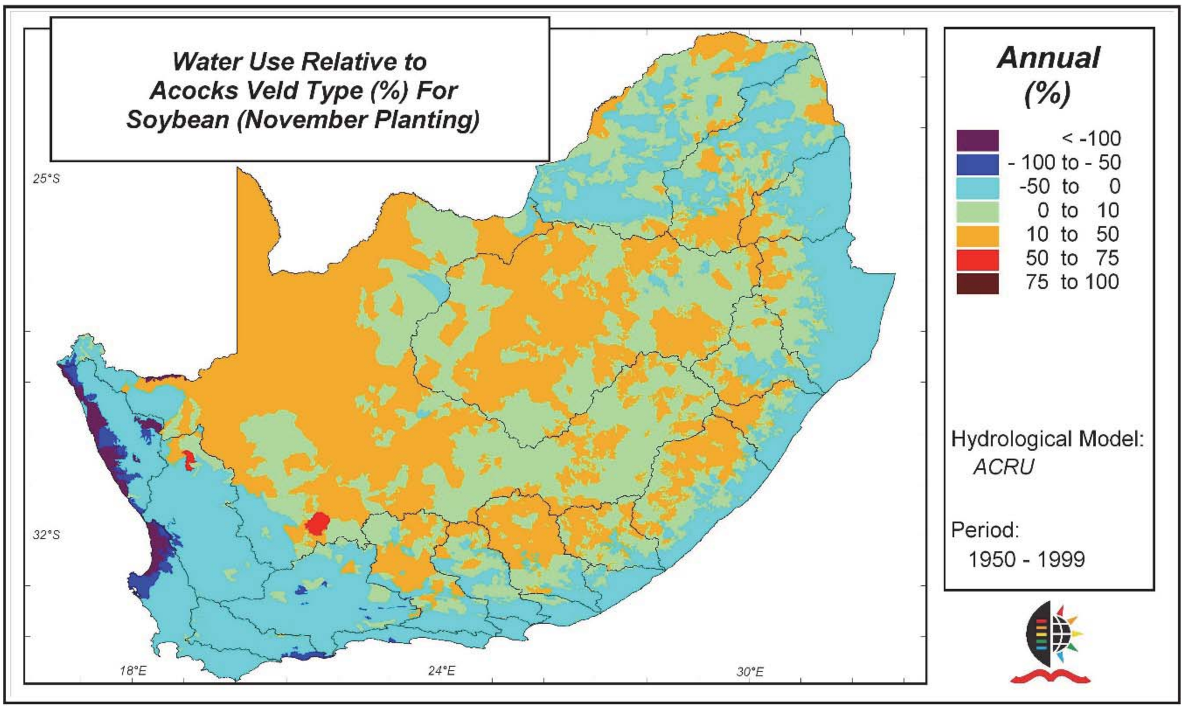


(e)

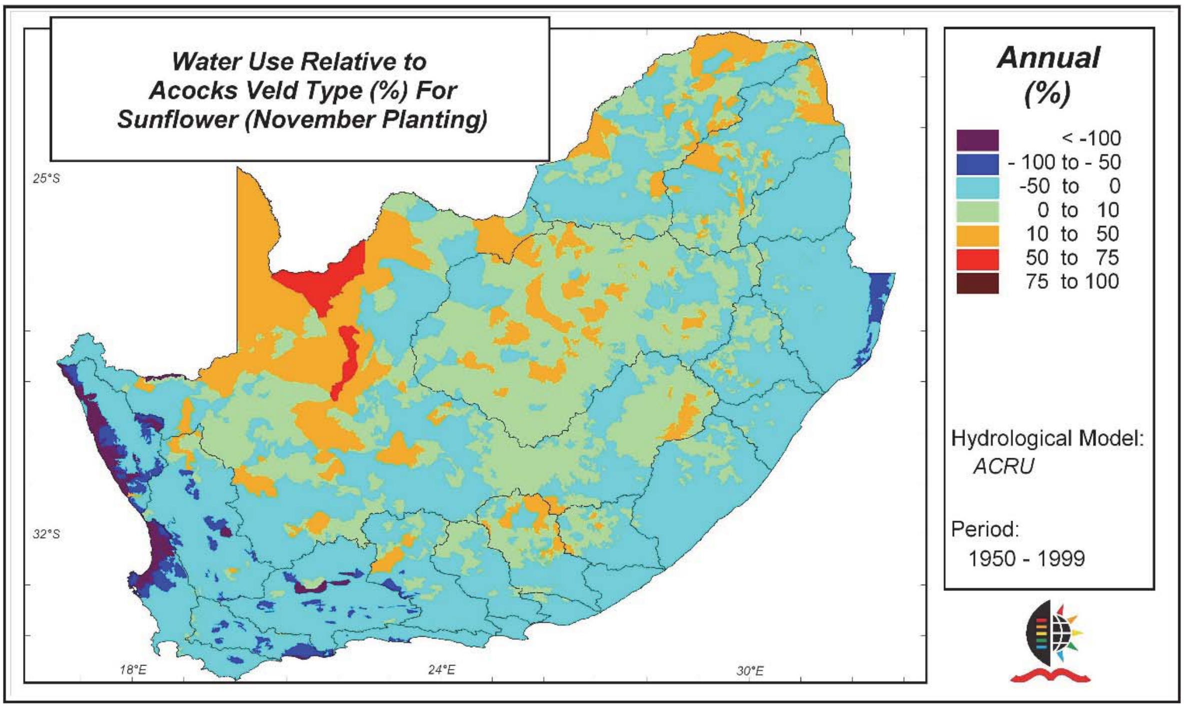


(f)

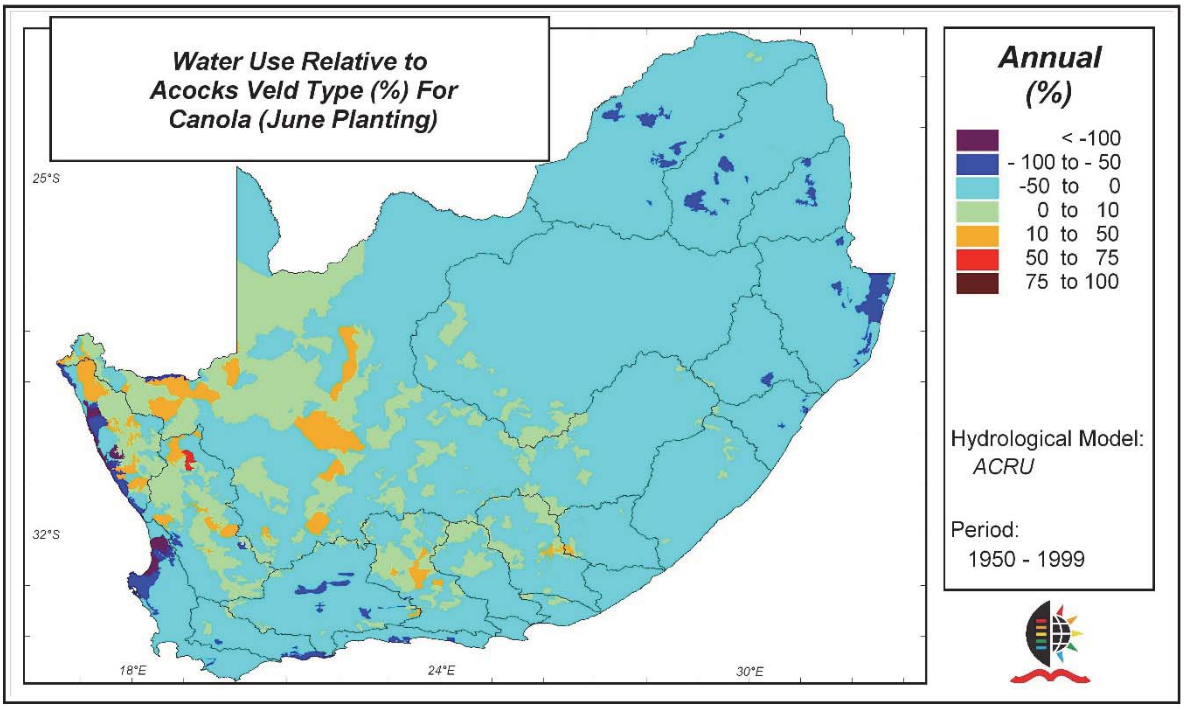
Figure 10 Water use of selected bioethanol feedstocks (a-f) expressed as a relative percentage of the baseline


Water Use Relative to Acocks Veld Type (%) For Soybean (November Planting)
Annual (%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model: ACRU
Period: 1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)


Water Use Relative to Acocks Veld Type (%) For Sunflower (November Planting)
Annual (%)
< -100
- 100 to - 50
-50 to 0
0 to 10
10 to 50
50 to 75
75 to 100
Hydrological Model: ACRU
Period: 1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



(c)

Figure 11 Water use of selected biodiesel feedstocks (a-c) expressed as a relative percentage of the baseline

3.4.3.5 Hydrological impact on low flows

Mean monthly flows were accumulated over the driest quartile (i.e. 3 months with the lowest runoff response) for the baseline as well as for each feedstock. The percentage difference (relative to the baseline) was then calculated. The reduction in low flow runoff (LFR) is considered "significant" if 25% or larger, as recommended by Jewitt *et al*. (2009b; Figure 4.1). **Figure 12** shows for each feedstock, the portion of quinary sub-catchments in which no reduction in LFR (i.e. LFR ≤ 0 %) was simulated using the *ACRU* model, as well as a positive reduction in LFR (i.e. > 0%).

Compared to **Figure 9**, the above chart shows that based on an analysis of low flows, the impact of feedstock cultivation is much less. The feedstocks were also ranked in terms of their potential to significantly reduce stream flow during the low flow period as:

1. Sugarcane (SCA; highest potential)
2. Grain sorghum (GRS)
3. Canola (CNW)
4. Soybean (SYB)
5. Sweet sorghum - inland (SSU)
6. Sugarbeet - summer (SBS)
7. Sugarbeet - winter (SBW)
8. Sunflower (SNF)
9. Sweet sorghum - interior (SSH; least potential)

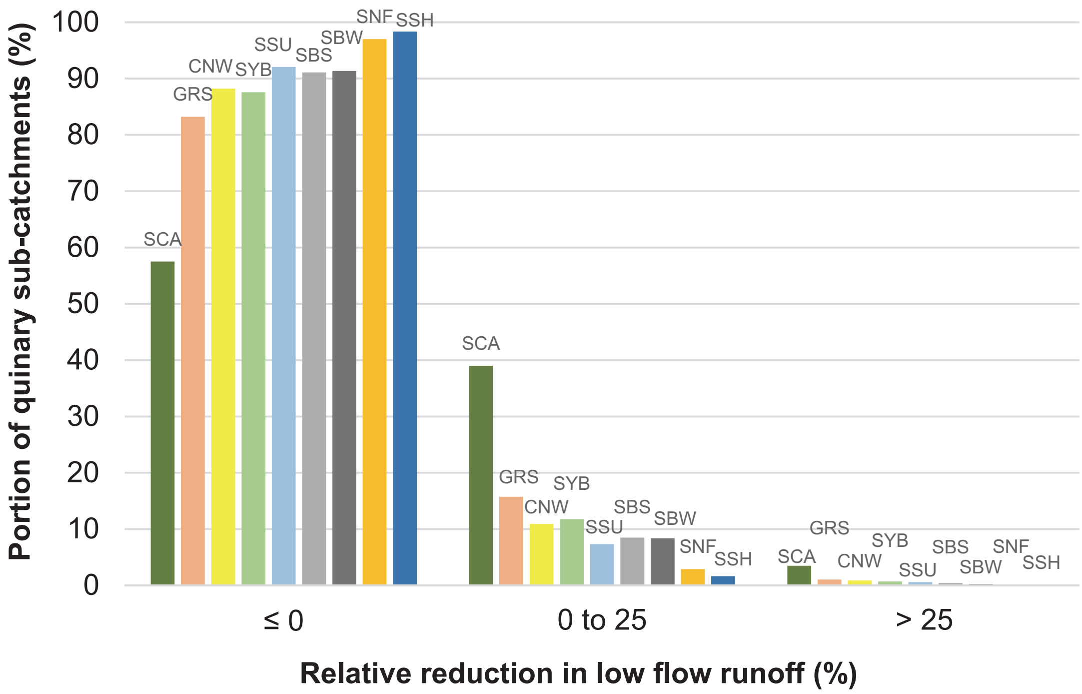
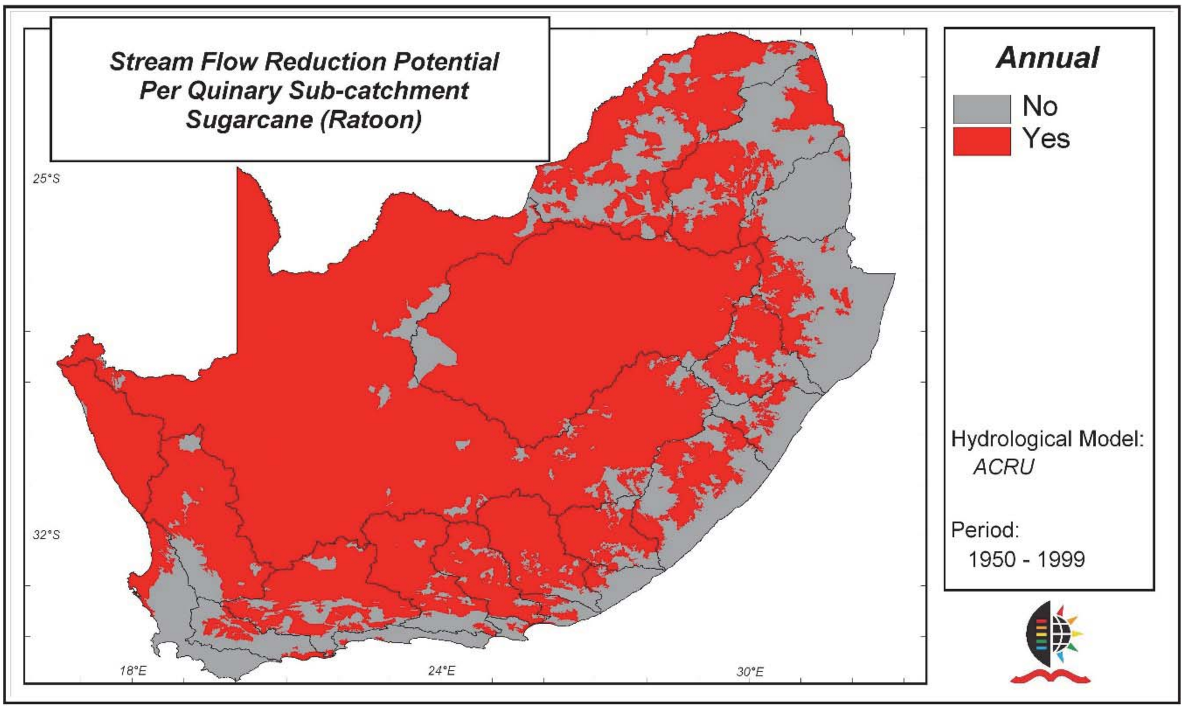


Figure 12 Reduction in low flow runoff relative to the baseline (expressed as a percentage) for selected biofuel feedstocks

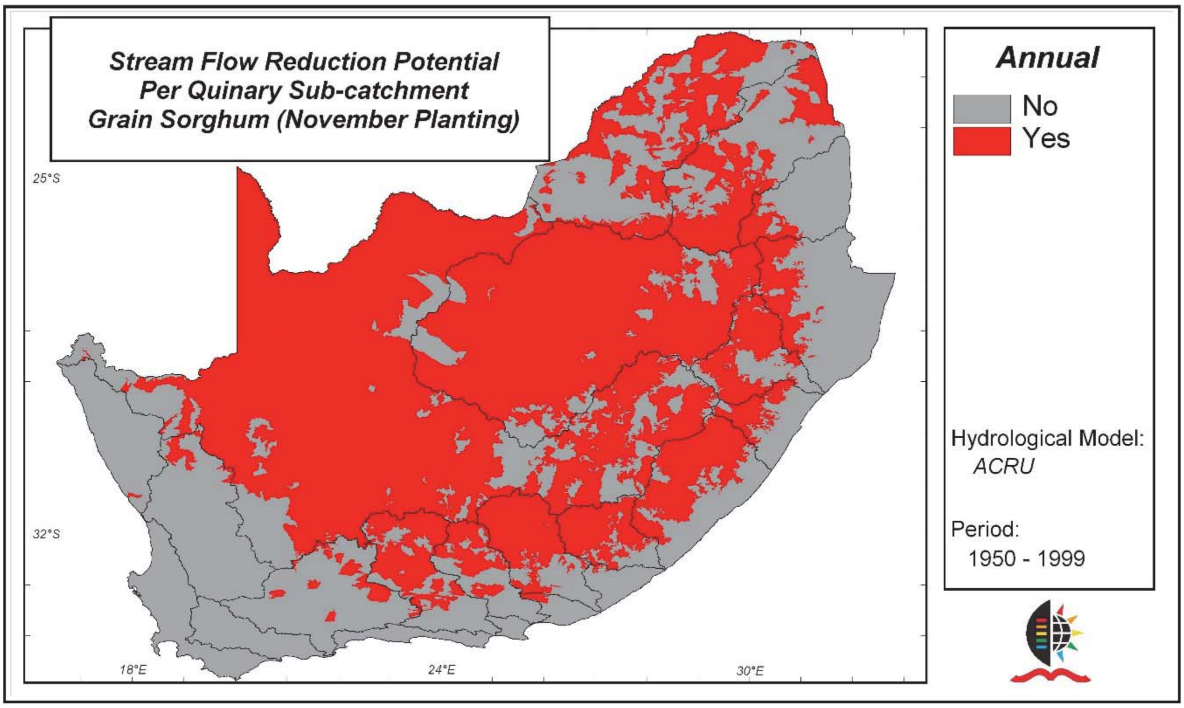
3.4.3.6 Potential SFRAs (annual runoff)

Of particular interest are quinary sub-catchments in **Figure 10** and **Figure 11** where the reduction in runoff is 10% or greater (relative to the baseline) were highlighted for bioethanol and biodiesel crops respectively. These areas are shown in **Figure 13** and **Figure 14** for bioethanol and biodiesel feedstocks respectively. The feedstocks are presented in order of most to least ability to reduce stream flow. The maps highlight the fact that all feedstocks have the potential to significantly reduce annual stream flow production. However, of all the bioethanol feedstocks considered, sugarcane exhibits the highest potential to reduce runoff in a particular quinary. Similarly, a change in land use to soybean cultivation has the highest potential of causing a significant reduction in stream flow generation, compared to the other two biodiesel feedstocks (i.e. sunflower and canola).

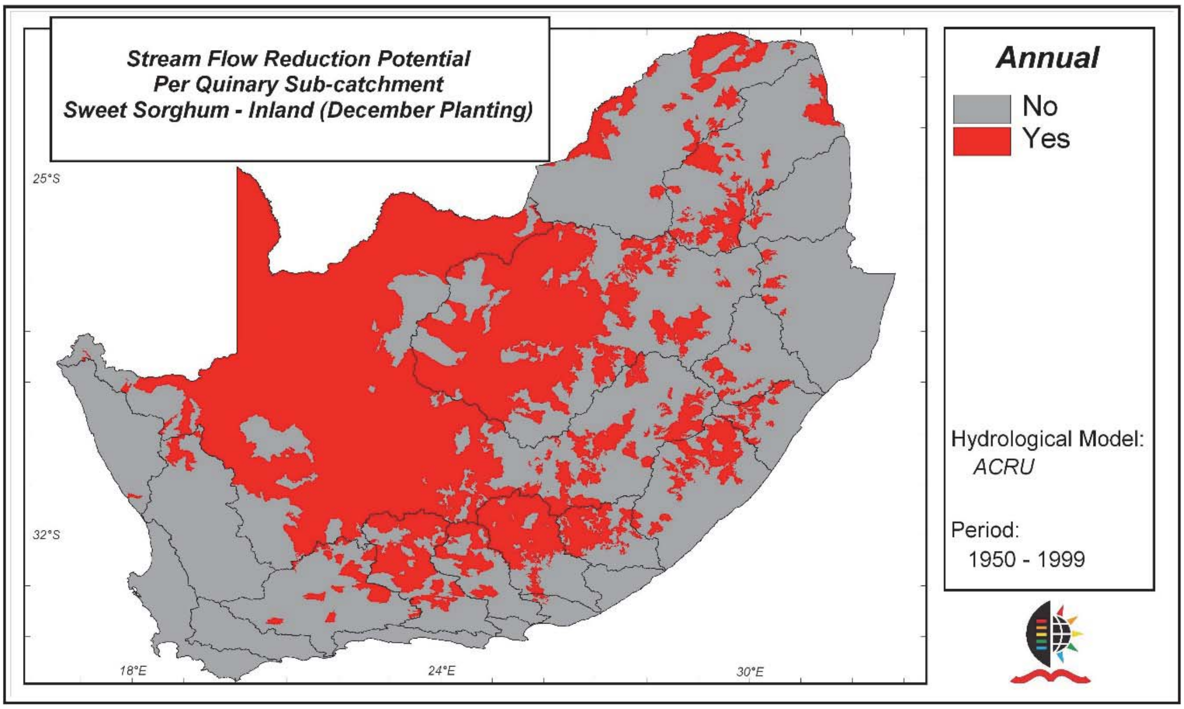
Few quinaries along the eastern and southern coastline (or just inland of the coast) are flagged as potential stream flow reduction zones. As highlighted in the SFRA project (Jewitt *et al*. 2009b), the impact on available water resources resulting from a land use change to feedstock production is negligible along the North and South Coasts (even for sugarcane). The reason for this is the dominant Acocks Veld Type along the coastline of KwaZulu-Natal is “Coastal Tropical Forest”, which is considered a tall evergreen land cover with a deep root system. Replacing this vegetation type with an annual (or perennial) crop exhibiting a shallower rooting system, will likely result in higher runoff production from the new land cover.


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sugarcane (Ratoon)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

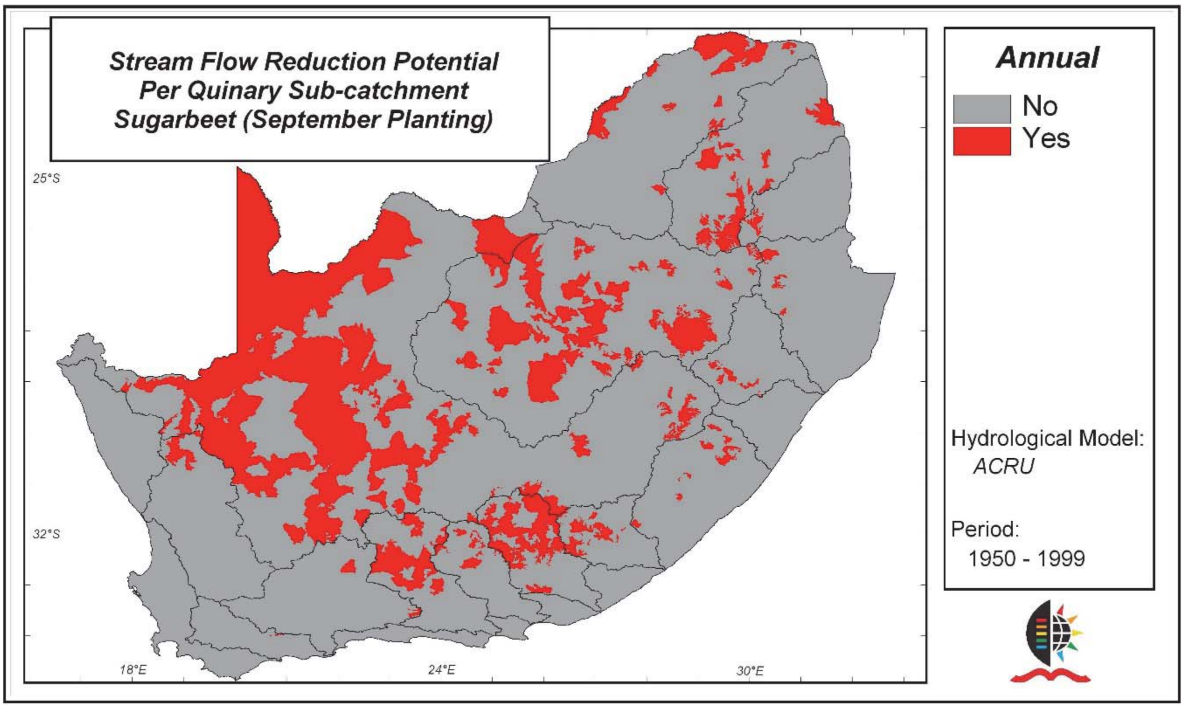
(a)


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Grain Sorghum (November Planting)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

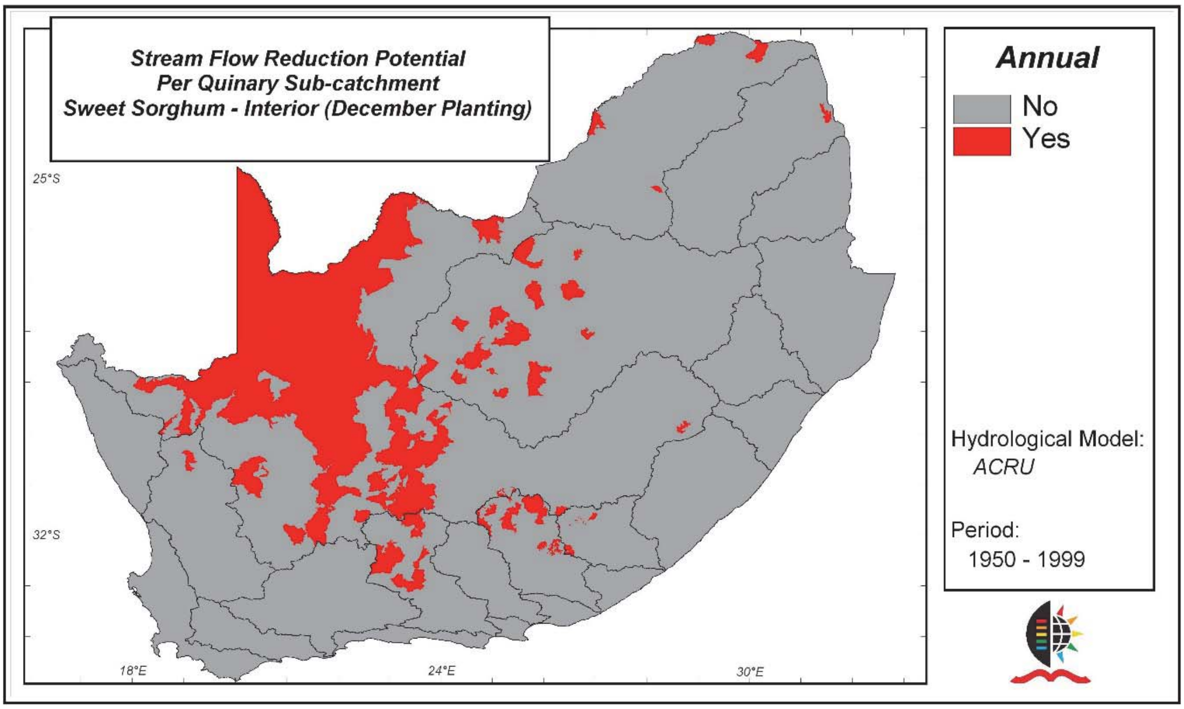
(b)


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sweet Sorghum - Inland (December Planting)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

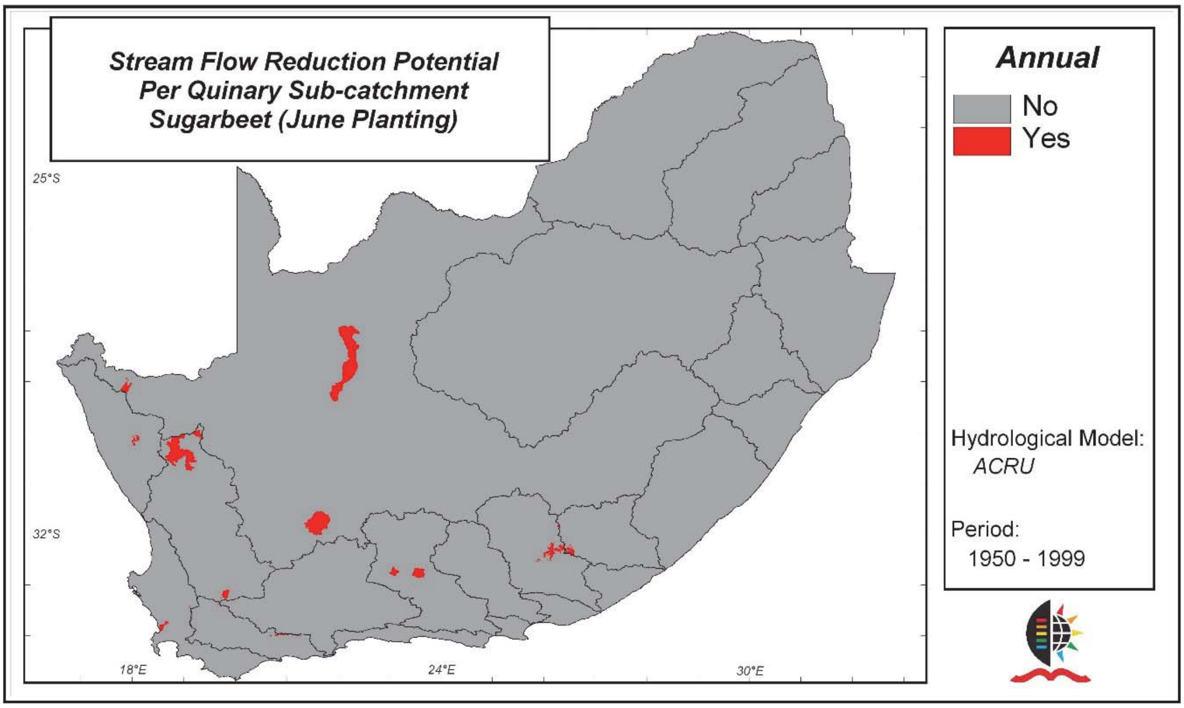
(c)


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sugarbeet (September Planting)
Annual
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

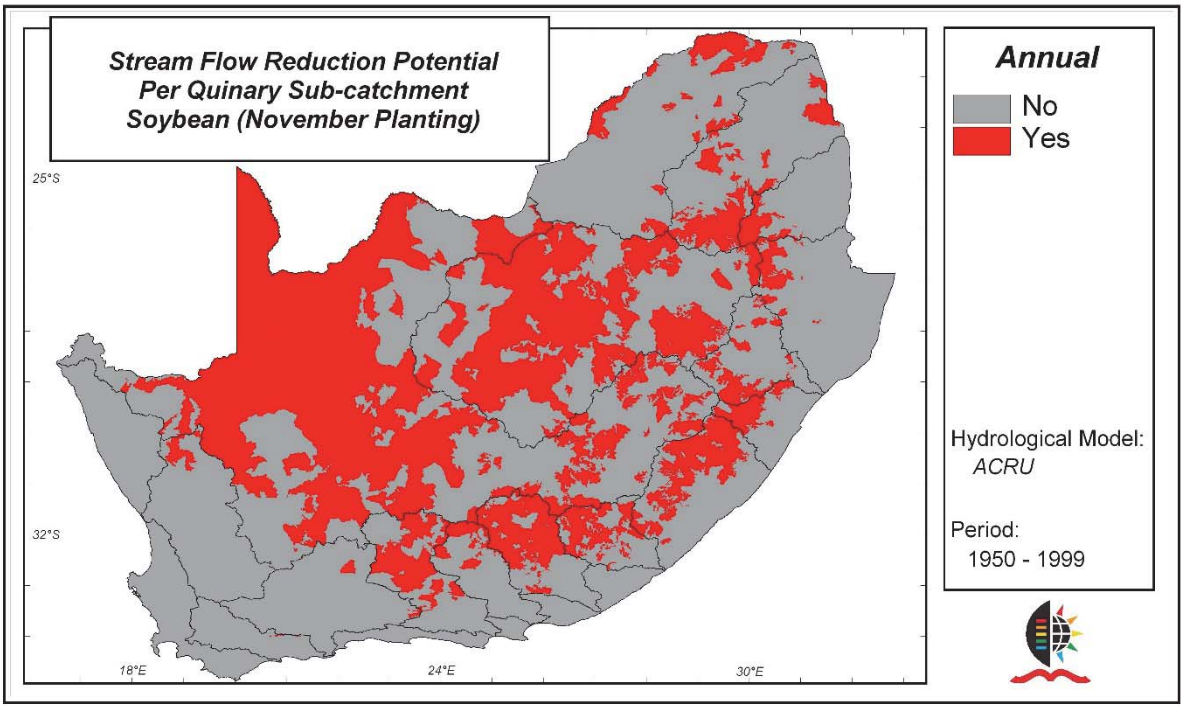


(e)



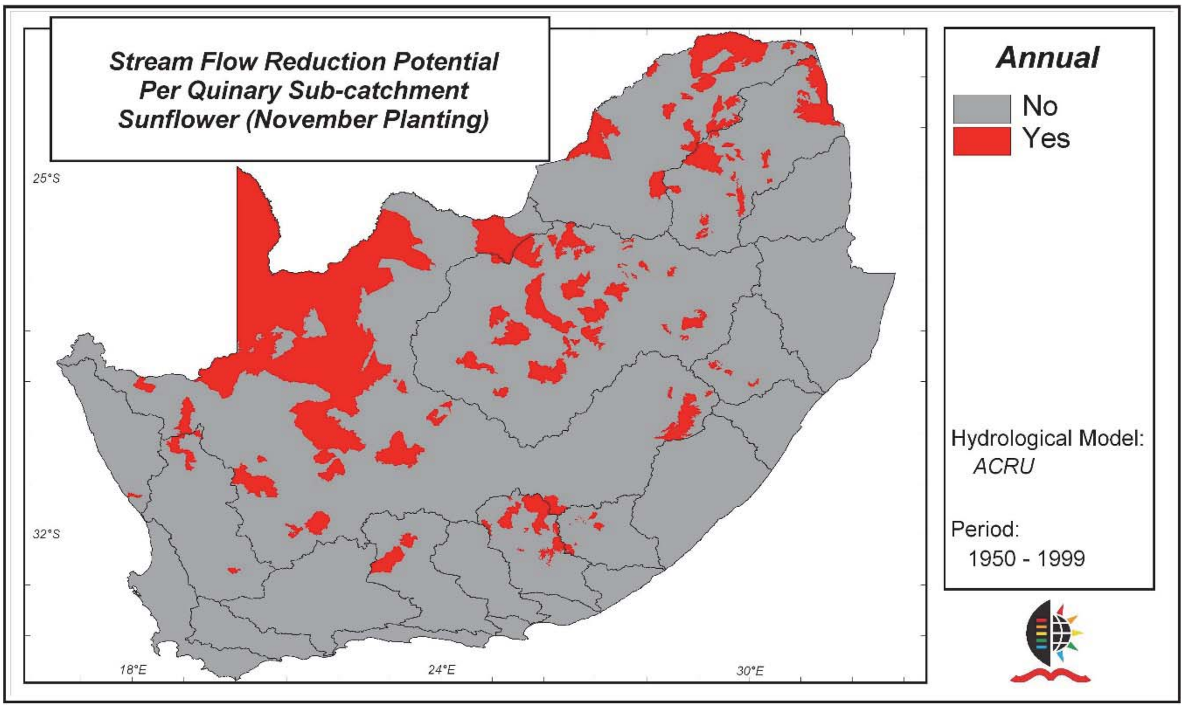
(f)

Figure 13 Sub-catchments in which the reduction in mean annual runoff resulting from a land use change from natural vegetation to a bioethanol feedstock is ≥ 10%



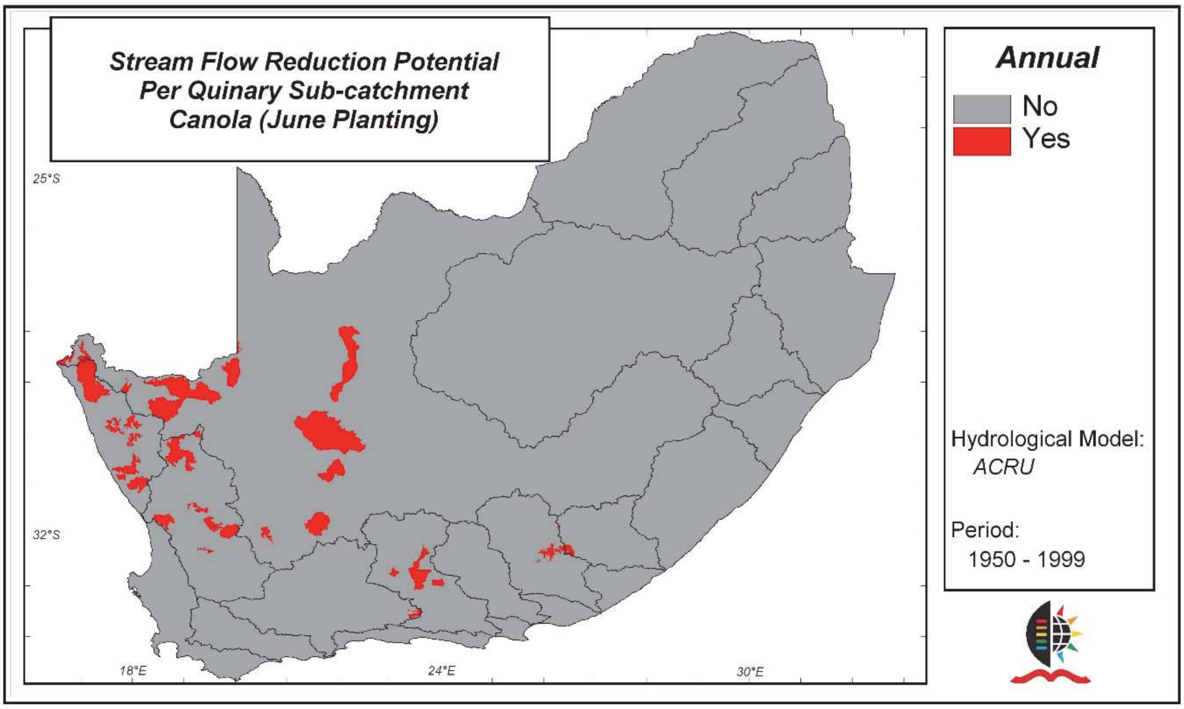
Stream Flow Reduction Potential
Per Quinary Sub-catchment
Soybean (November Planting)
Annual
No
Yes
25°S
32°S
18°E
24°E
30°E
Hydrological Model:
ACRU
Period:
1950 - 1999

(a)



Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sunflower (November Planting)
Annual
No
Yes
25°S
32°S
18°E
24°E
30°E
Hydrological Model:
ACRU
Period:
1950 - 1999

(b)



(c)

Figure 14 Sub-catchments in which the reduction in mean annual runoff resulting from a land use change from natural vegetation to a biodiesel feedstock is ≥ 10%

The difference between the sweet sorghum maps labelled "inland" and "interior" highlight the sensitivity of the *ACRU* model to crop coefficient inputs as well as the influence of management practice (in particular planting density) on derived crop coefficients. The "inland" and "interior" maps are based on crop coefficients derived at the Ukulinga and Hatfield research farms respectively. Instead of averaging the crop coefficients obtained at these two locations, separate national runs were done to illustrate this point. The difference also highlights the fact that crop coefficients are site-specific and need to be adapted to local growing conditions before being used in impact assessment studies. Thus, there is less confidence in the maps for canola and sunflower, which are based on international (i.e. FAO-based) crop coefficients, since no information is available locally for these two feedstocks. Finally, the importance and value of the field work component of the biofuels project needs to be emphasised.

Feedstocks planted in winter (e.g. sugarbeet and canola) are least likely to negatively impact stream flow generation. The reason for this is stream flow generation typically occurs in the summer months when rainfall is highest. However, this result can be misleading as it does not account for the supplemental irrigation that is required to establish a winter crop, especially for sugarbeet grown in the Cradock area. Similarly, canola requires at least 25 mm of rainfall/irrigation during the germination phase to ensure successful establishment. Although the maps shown in **Figure 13** and **Figure 14** highlight quinaries where feedstock production may cause a reduction in stream flow generation, they do not indicate whether or not cultivation is economically viable in that sub-catchment.

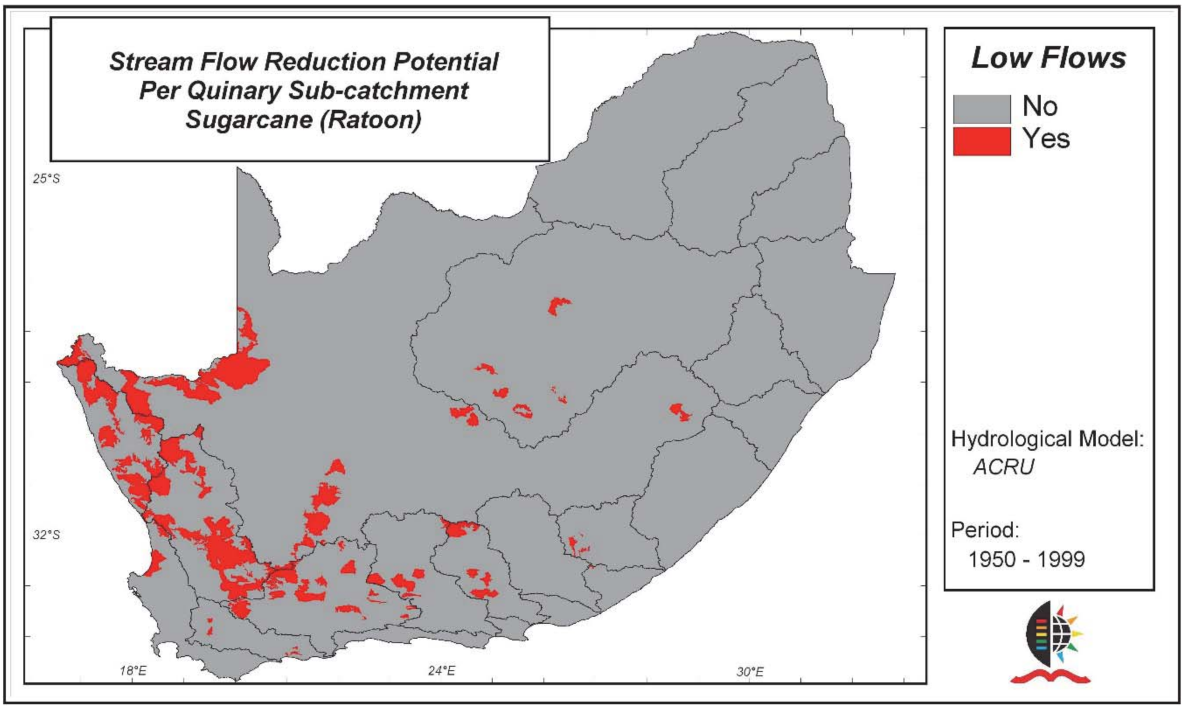
Finally, areas where dryland cultivation is deemed unfeasible (i.e. MAP < 250 mm) were not eliminated. It is not recommended that the land suitability maps (as shown in **Section 5.4.3**) are used to "filter out" quinary sub-catchments deemed unsuitable for feedstock cultivation. The reason is that the land suitability maps are not applicable at the farm level, due to the coarse spatial scale of some of the input data sets (e.g. soils data). Hence, it is likely that feedstock cultivation is possible within the majority of quinaries, except for those sub-catchments located in extremely arid areas of the country (i.e. MAP < 250 mm). In other words, crop growth is possible if the micro-climate is suitable, or irrigation is used, or a drought/heat tolerant cultivar is planted.

3.4.3.7 Potential SFRAs (low flow runoff)

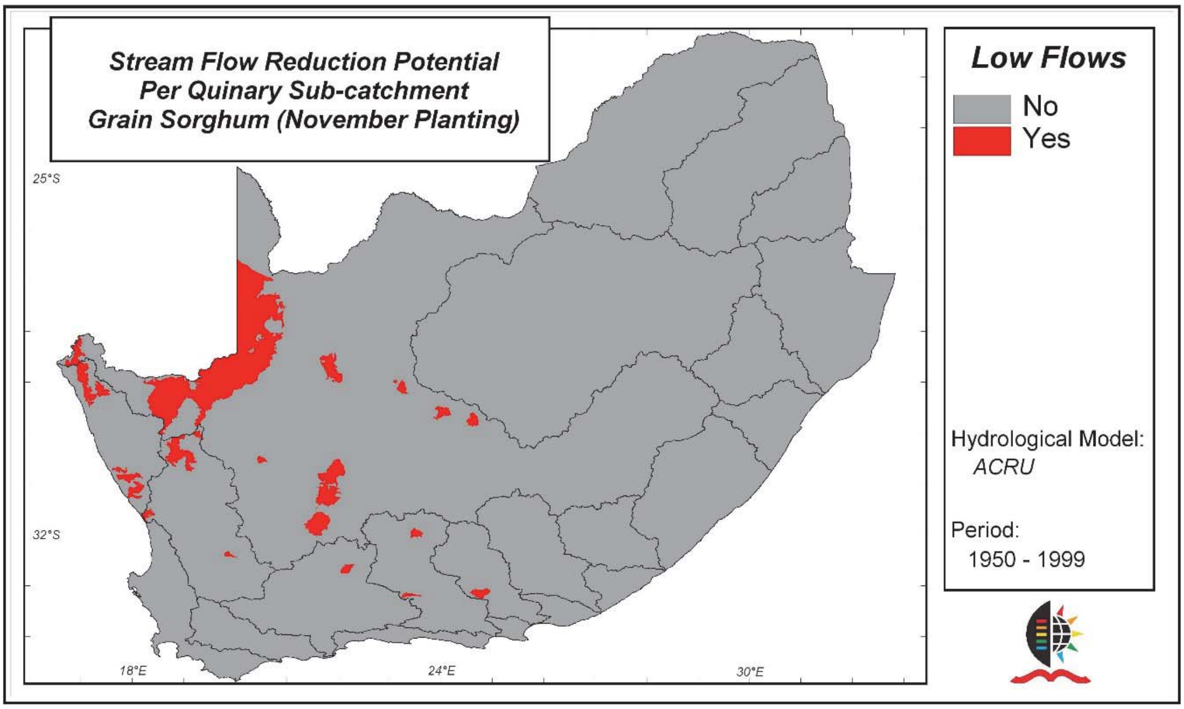
The maps presented in the previous section (c.f. **Section 3.4.3.6**) only consider the annual (and not a shorter) time scale. Hence, the impact on stream flow during an individual month in summer may be much higher for certain feedstocks.

In **Figure 15**, sub-catchments in which the reduction in mean monthly low flows is 25% or larger for bioethanol feedstocks are shown (with similar areas given in **Figure 16** for the biodiesel crops). The results indicate that, for the majority of the summer rainfall region, no feedstock should reduce the stream flow by 25% or more during the driest three months of the year (i.e. during the low flow period). The only exception is sub-catchments situated in the very late summer, winter and all-year rainfall regions (i.e. western parts of the country).

However, according to the land suitability maps given in **Section 5.4.3**, this region of the country is not suited to the growth of the key feedstocks. Finally, further investigation may be warranted to determine if the 25% threshold is too high. This recommendation is similar to that regarding the 10% threshold assumed for annual flows (c.f. **Section 3.4.3.3**).

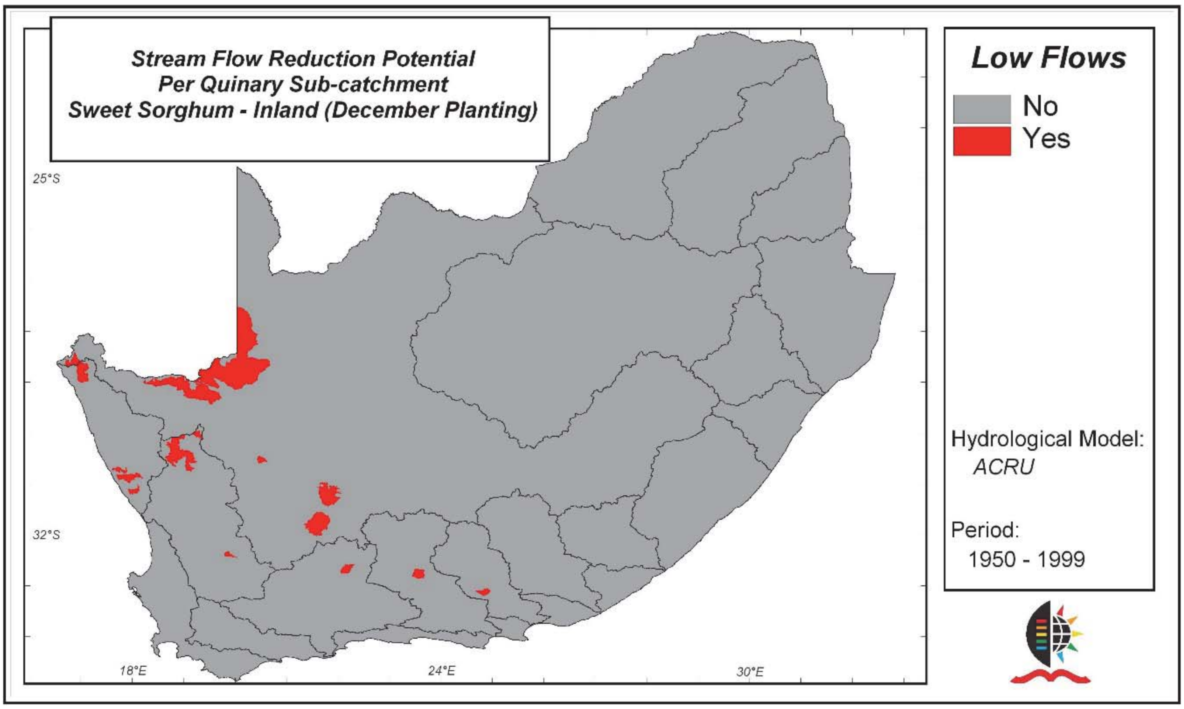


(a)



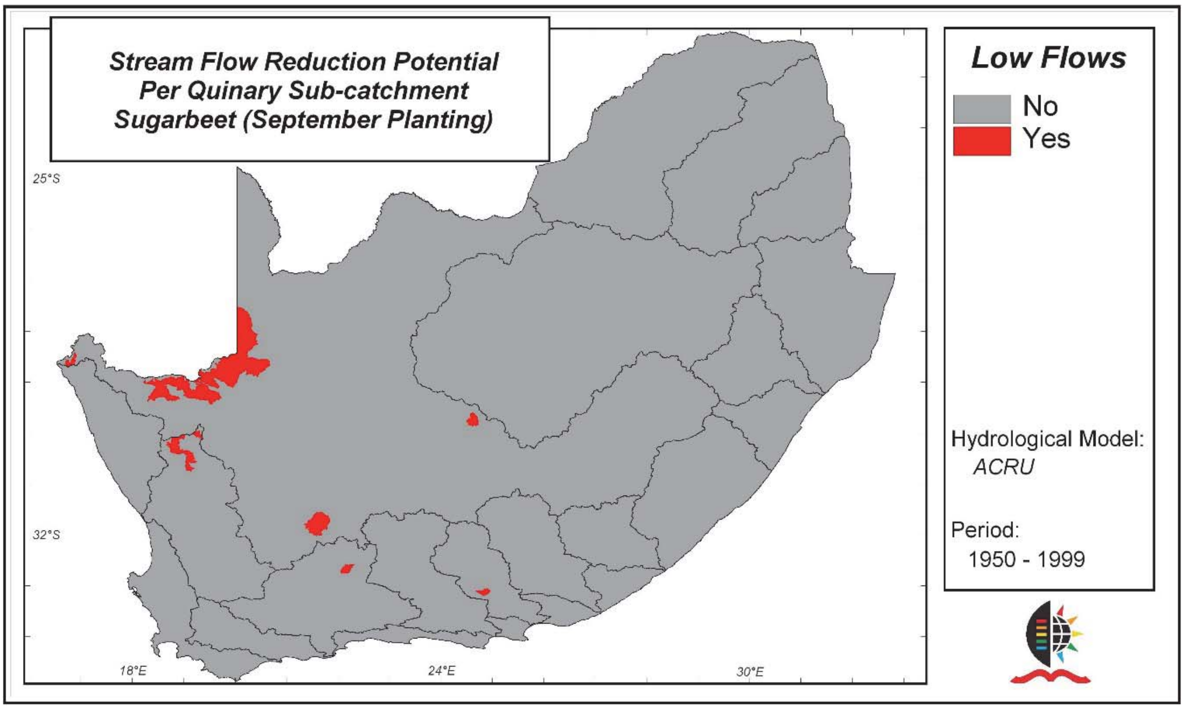
Stream Flow Reduction Potential
Per Quinary Sub-catchment
Grain Sorghum (November Planting)
Low Flows
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)

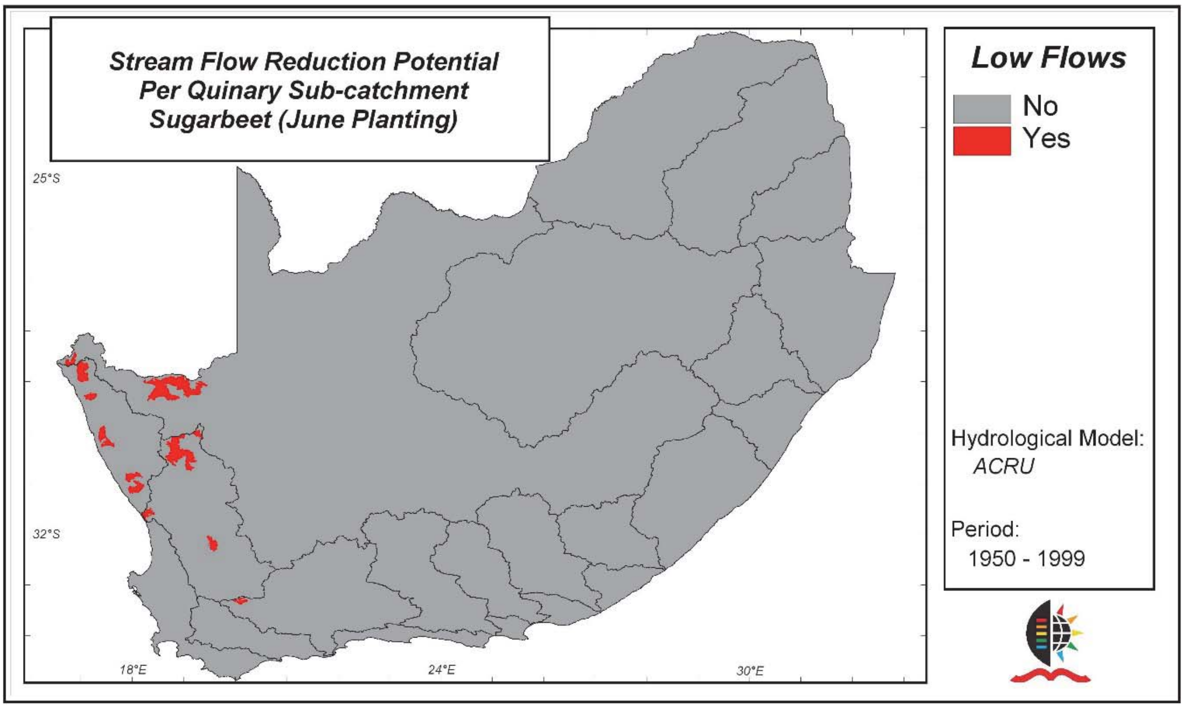


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sweet Sorghum - Inland (December Planting)
Low Flows
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

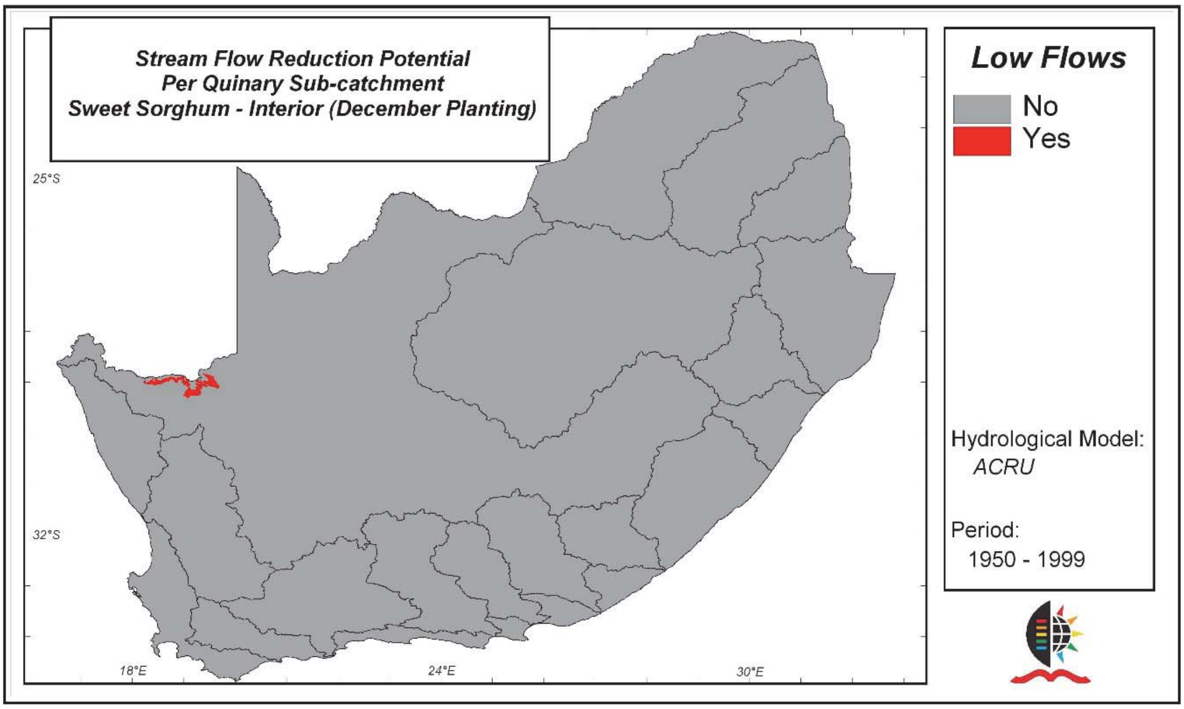
(c)


Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sugarbeet (September Planting)
Low Flows
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

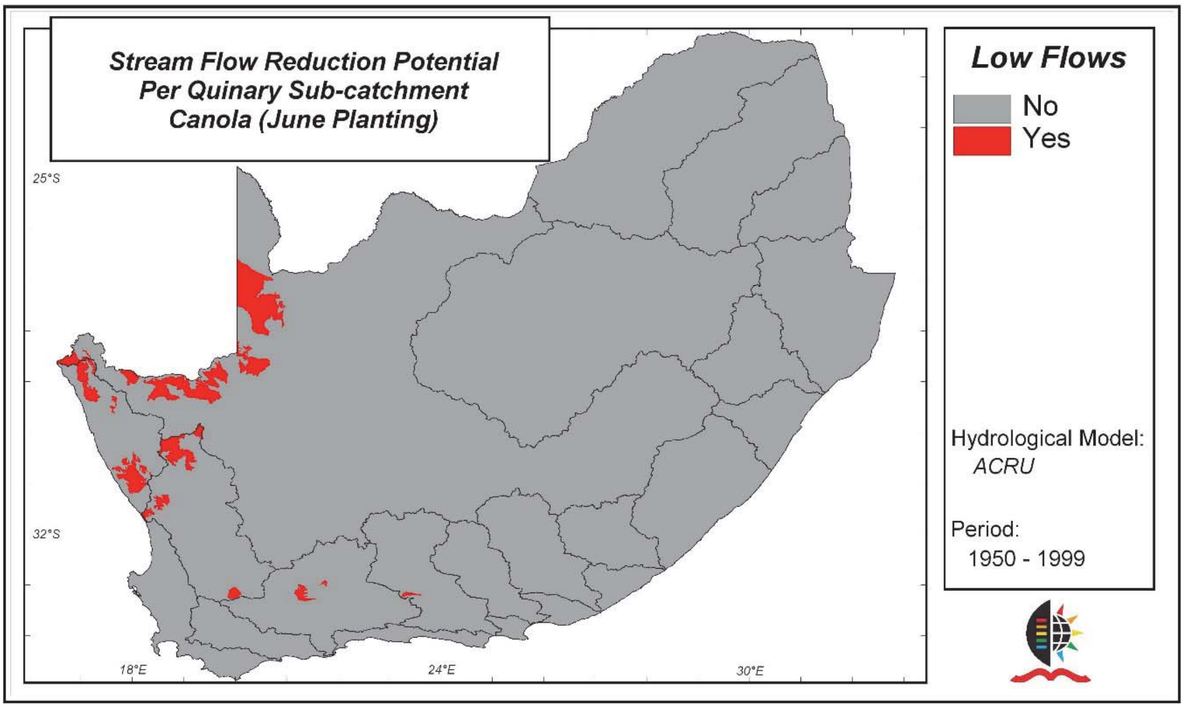

Stream Flow Reduction Potential
Per Quinary Sub-catchment
Sugarbeet (June Planting)
Low Flows
No
Yes
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(e)

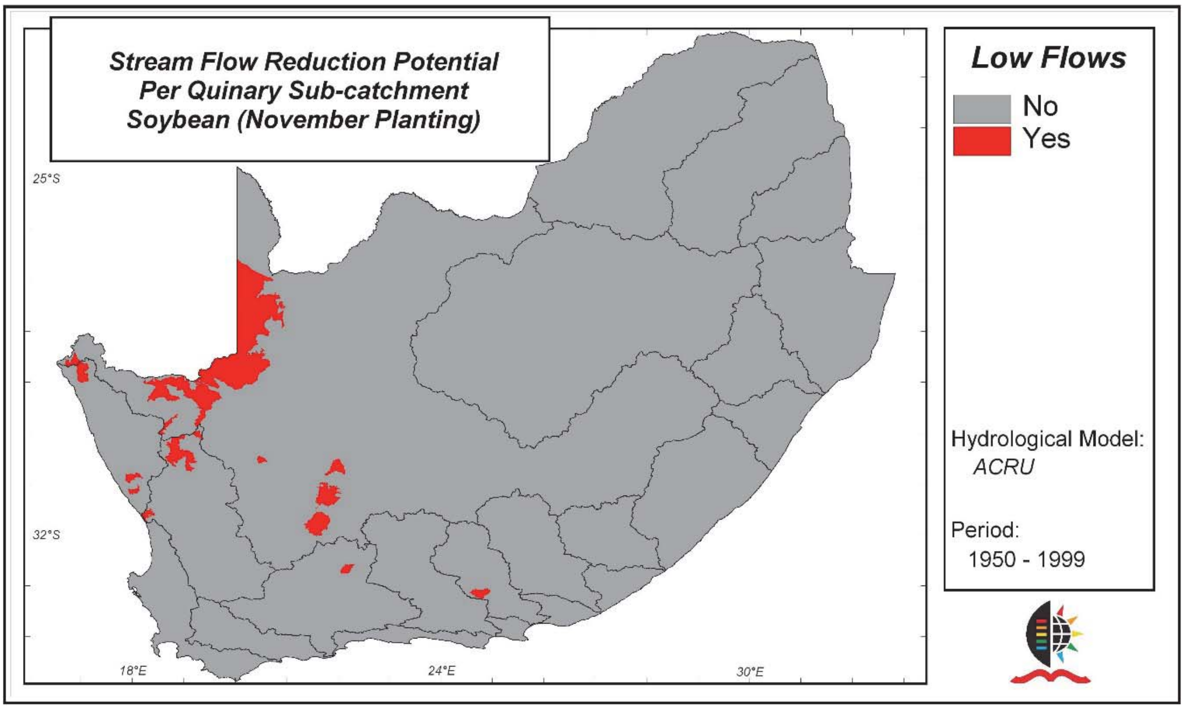


(f)

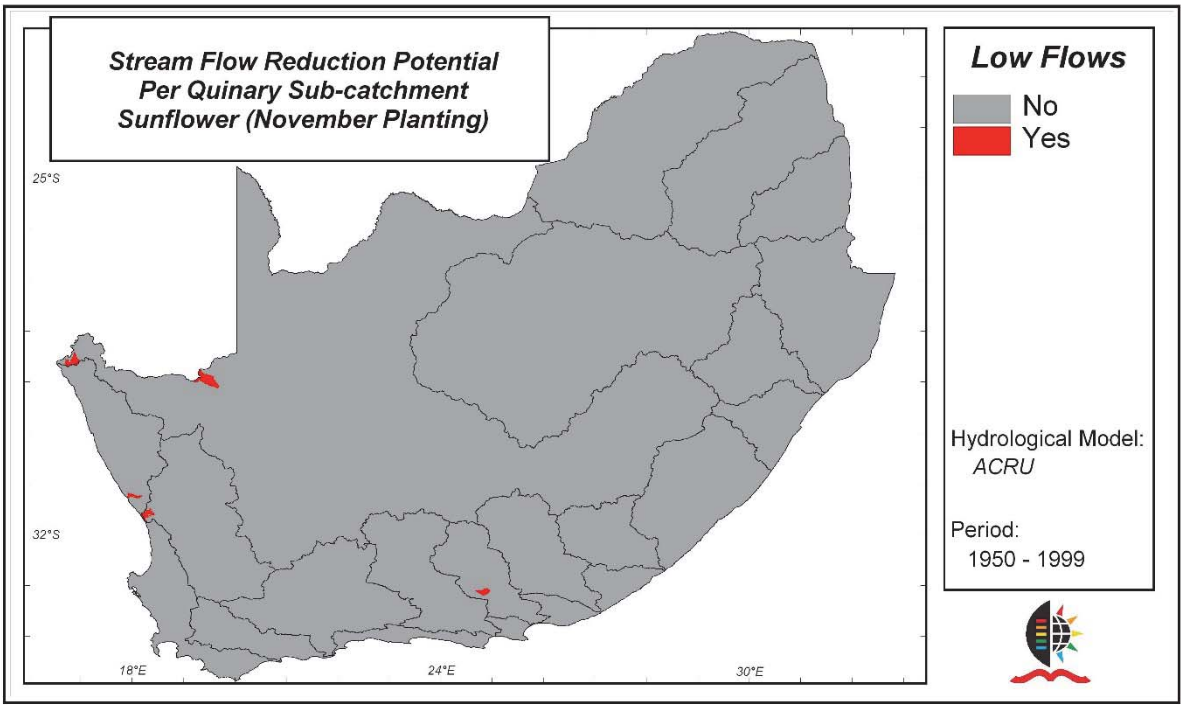
Figure 15 Sub-catchments in which the reduction in mean monthly low flows that results from a land use change from natural vegetation to a bioethanol feedstock is 25% or larger



(a)



(b)



(c)

Figure 16 Sub-catchments in which the reduction in mean monthly low flows that results from a land use change from natural vegetation to a biodiesel feedstock is 25% or larger

3.4.3.8 Shift in low flow period

In order to accumulate monthly runoff over the driest three months of the year, the start of the low flow quartile first needs to be determined. This was done using simulated mean (not median) monthly stream flows for the baseline land cover. The start month of the low flow period (i.e. driest quartile) is depicted in **Figure 17**.

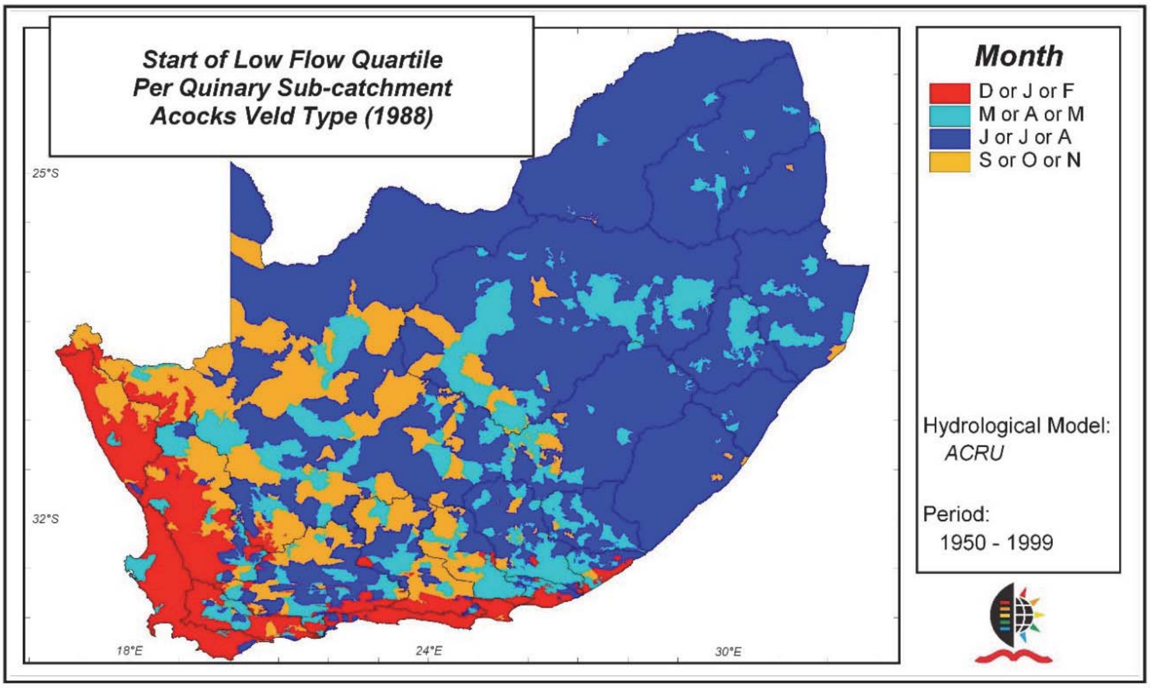


Figure 17 The first month of the low flow period, based on mean monthly stream flow simulated using the *ACRU* model for each quinary sub-catchment

For the early and mid-summer summer rainfall region (red and orange areas shown in **Figure 18**), the driest quartile typically starts in June or July or August (dark blue areas in **Figure 17**). Moving westwards across the country, the driest period starts in September or October or November. This roughly coincides with the late to very late summer rainfall region in **Figure 18**. Finally, the winter and all-year rainfall regions along the respective western and southern parts of the country largely overlap with the red areas in **Figure 17** (i.e. driest quartile starting in December or January or February).

Maps showing the first month of the low flow period for the selected bioethanol and biodiesel feedstocks are shown in **Figure 19** and **Figure 20** respectively. These maps were compared against **Figure 17** to determine if the start of the low flow quartile for the baseline, corresponded to that for each feedstock.

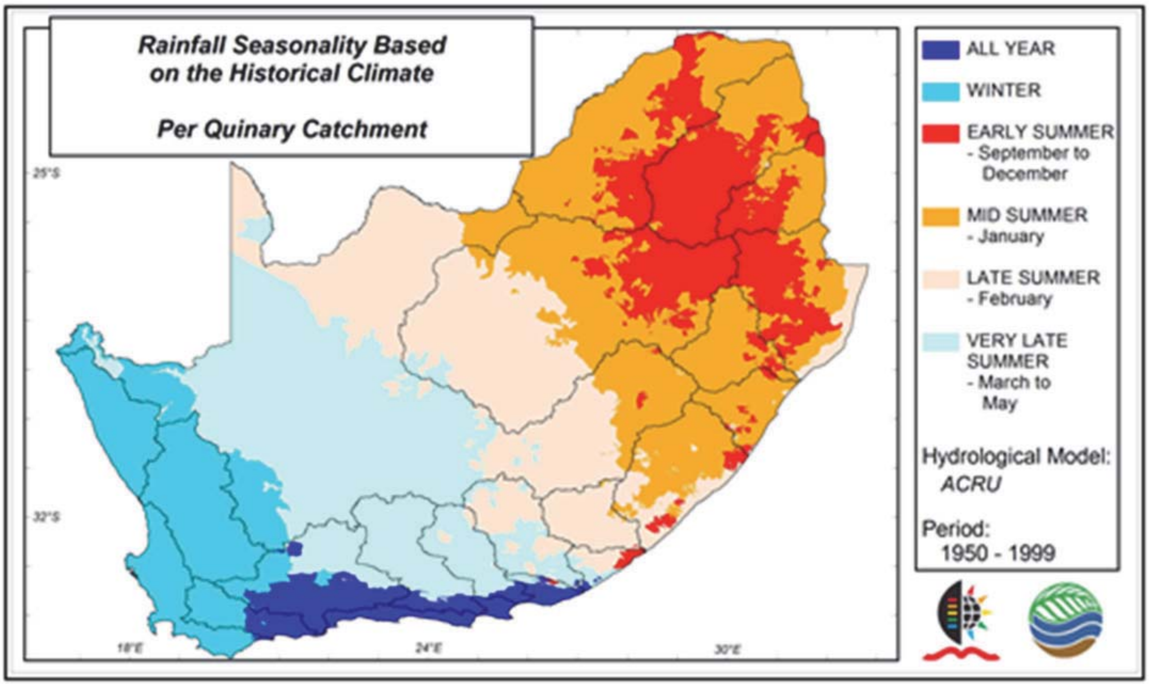
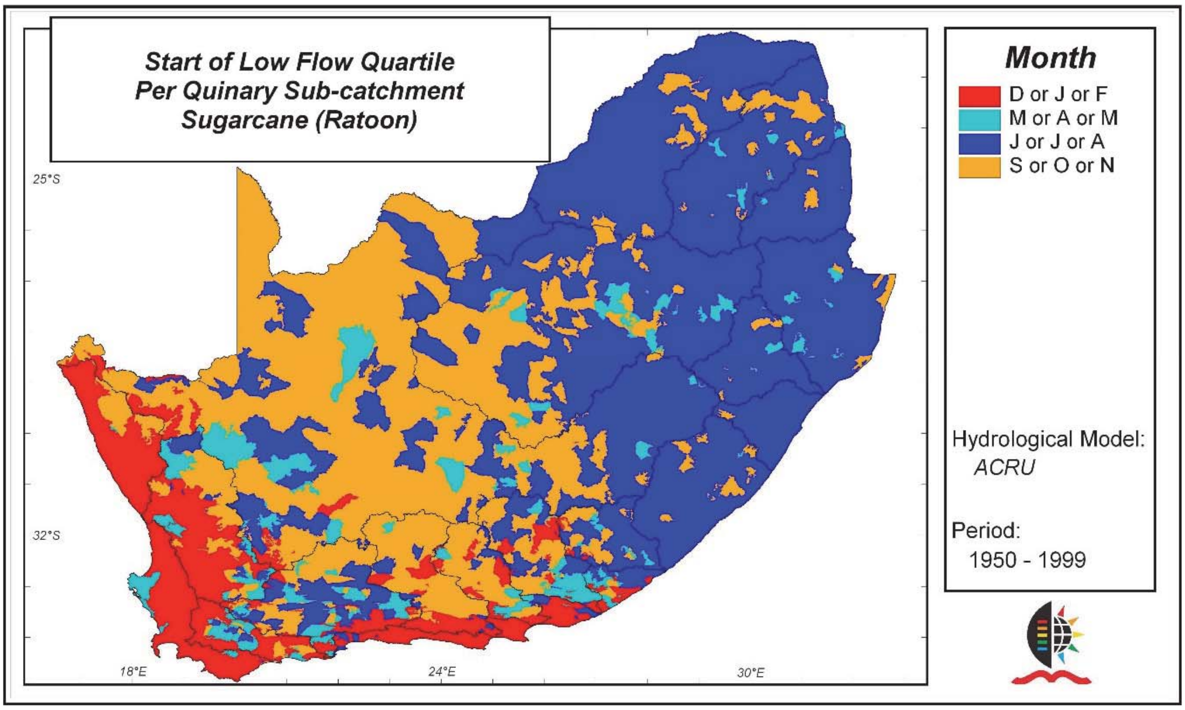
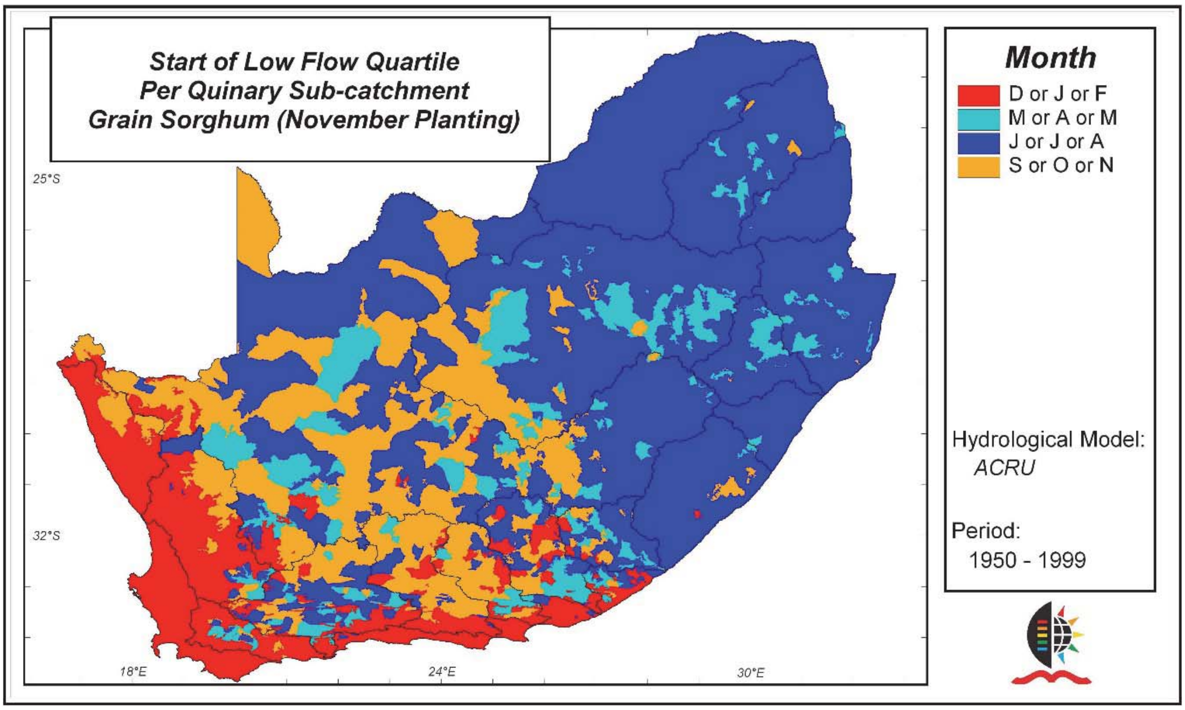


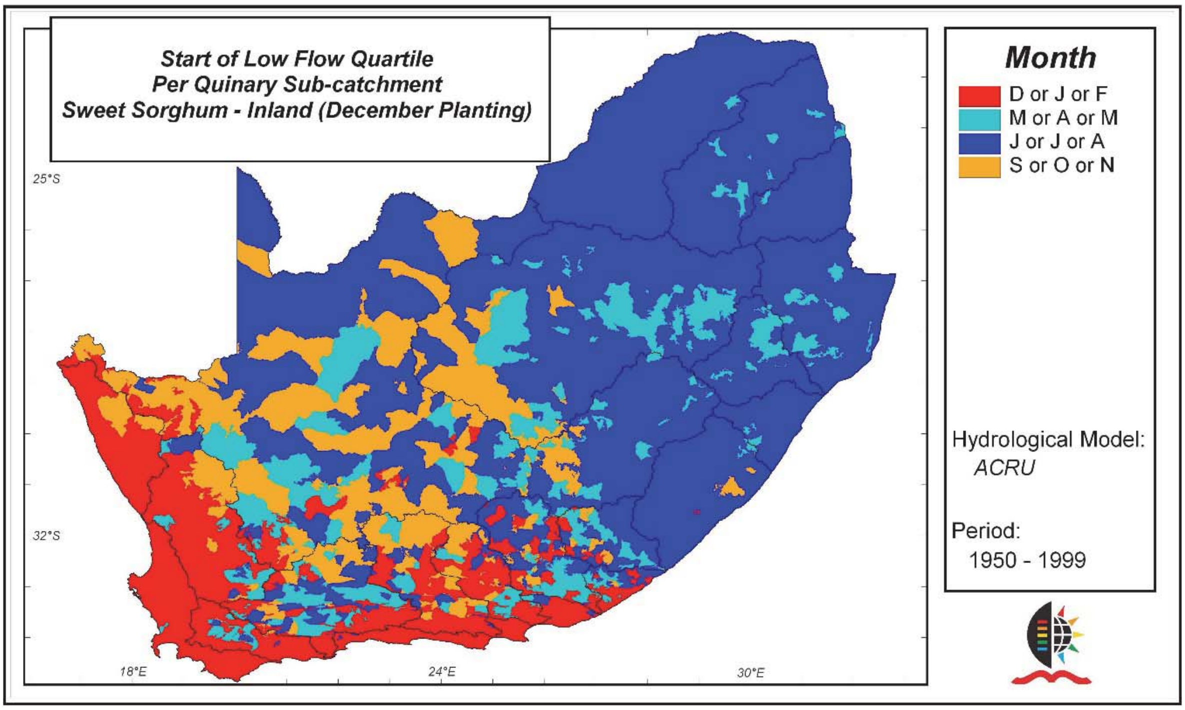
Figure 18 Rainfall seasonality classes over South Africa for the baseline (i.e. historical) climate (Schulze and Kunz, 2010a)



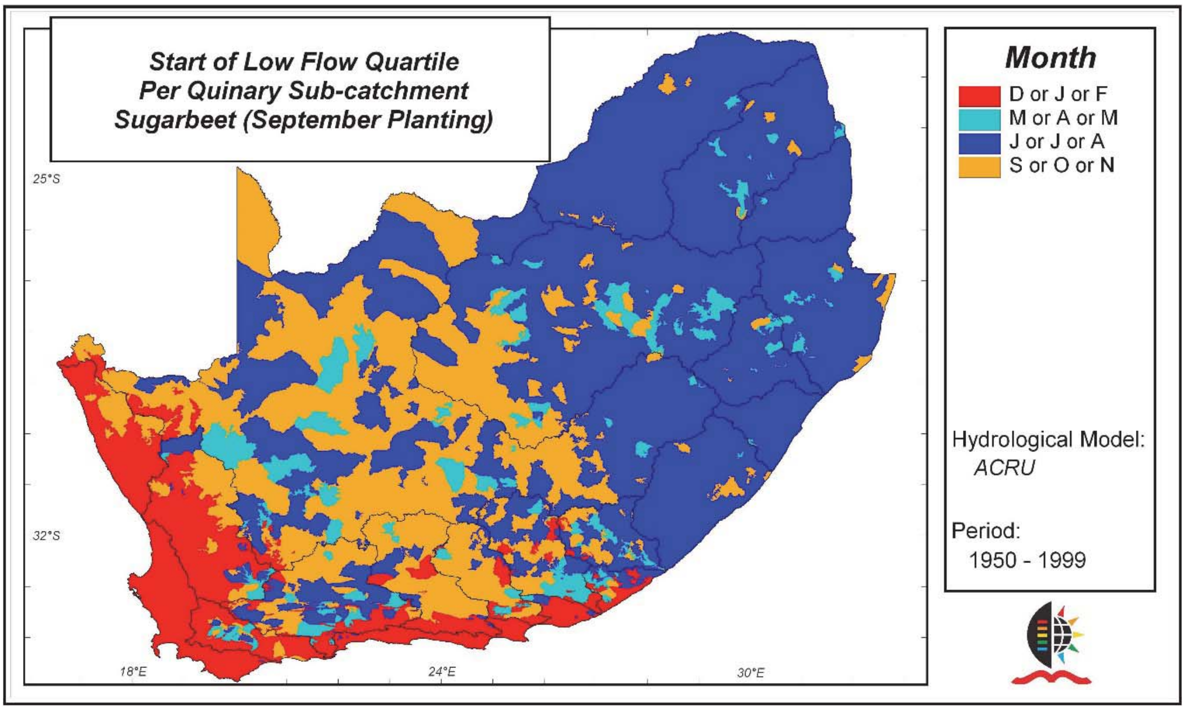
(a)


Start of Low Flow Quartile
Per Quinary Sub-catchment
Grain Sorghum (November Planting)
Month
D or J or F
M or A or M
J or J or A
S or O or N
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

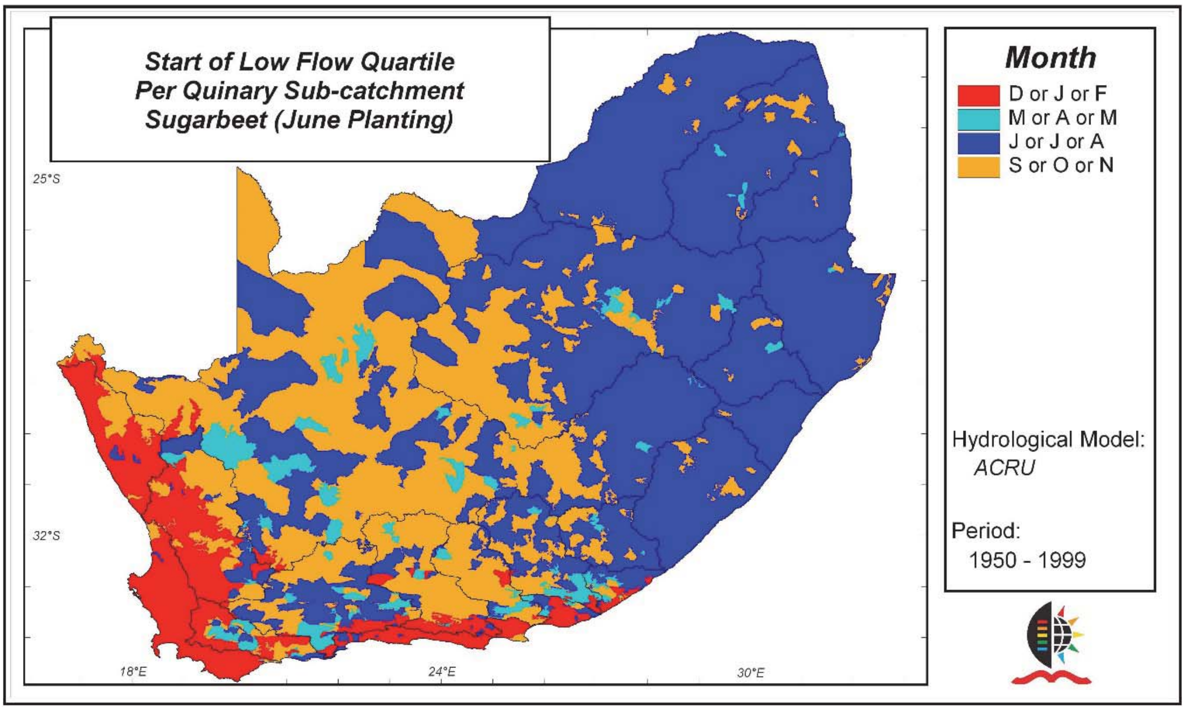
(b)


Start of Low Flow Quartile
Per Quinary Sub-catchment
Sweet Sorghum - Inland (December Planting)
Month
D or J or F
M or A or M
J or J or A
S or O or N
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

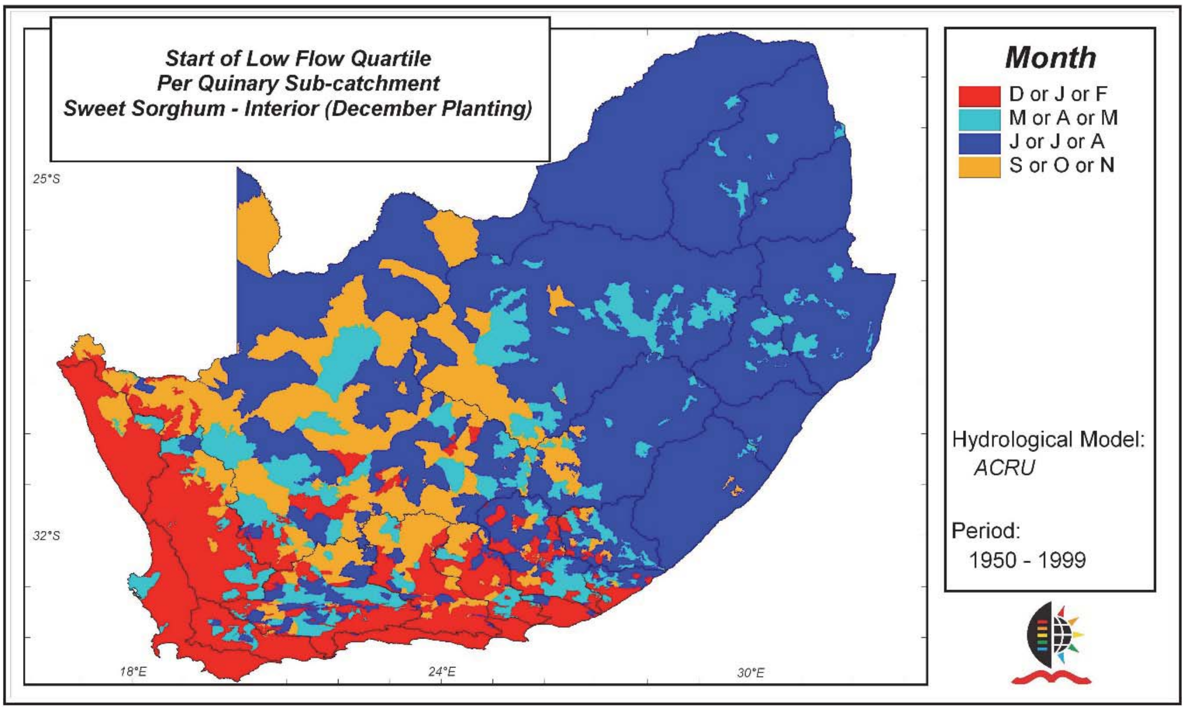
(c)


Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarbeet (September Planting)
Month
D or J or F
M or A or M
J or J or A
S or O or N
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

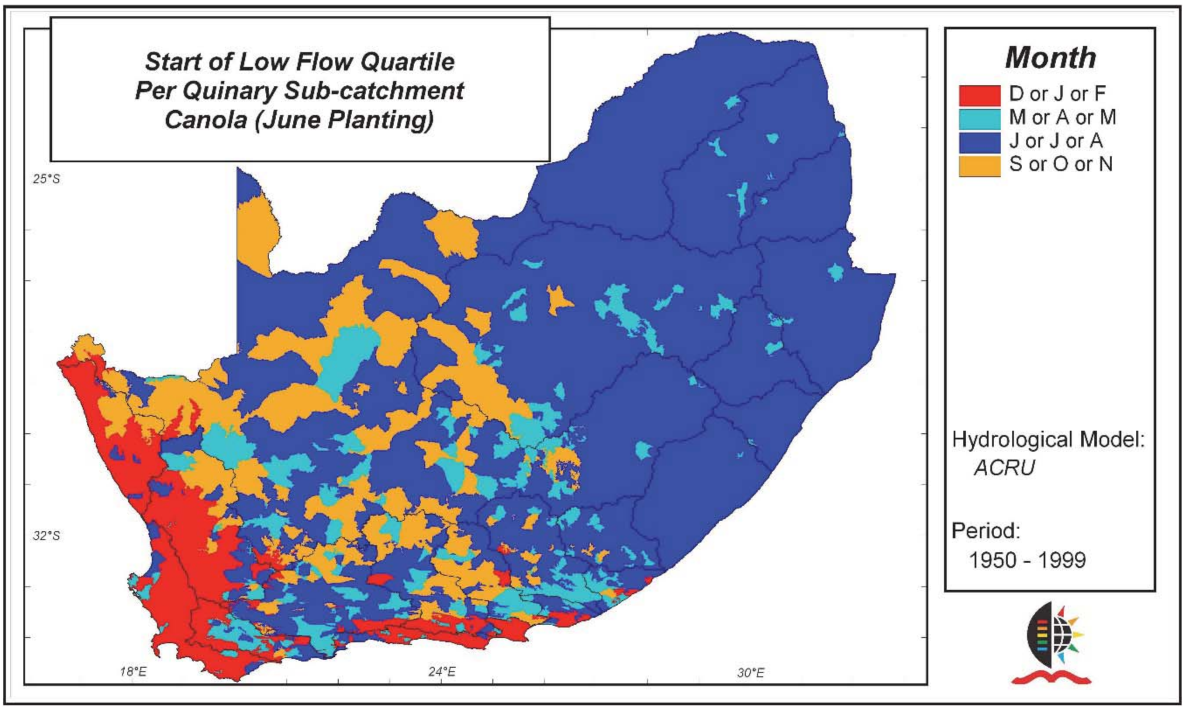

Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarbeet (June Planting)
Month
D or J or F
M or A or M
J or J or A
S or O or N
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(e)

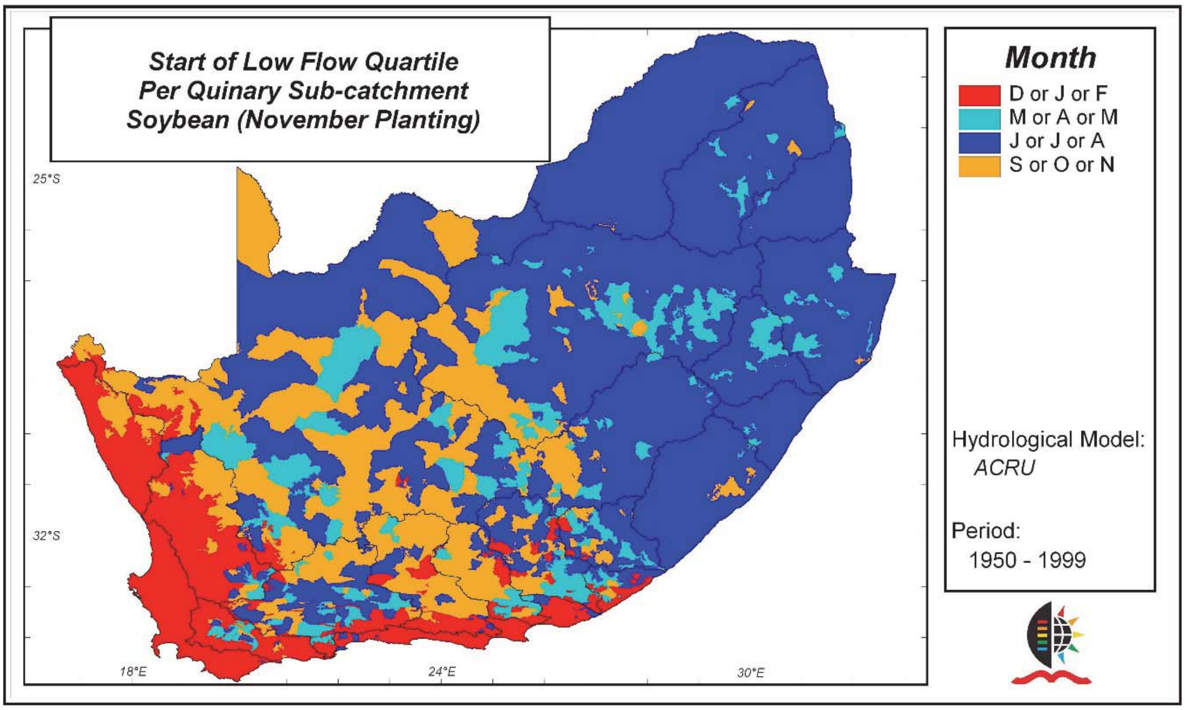


(f)

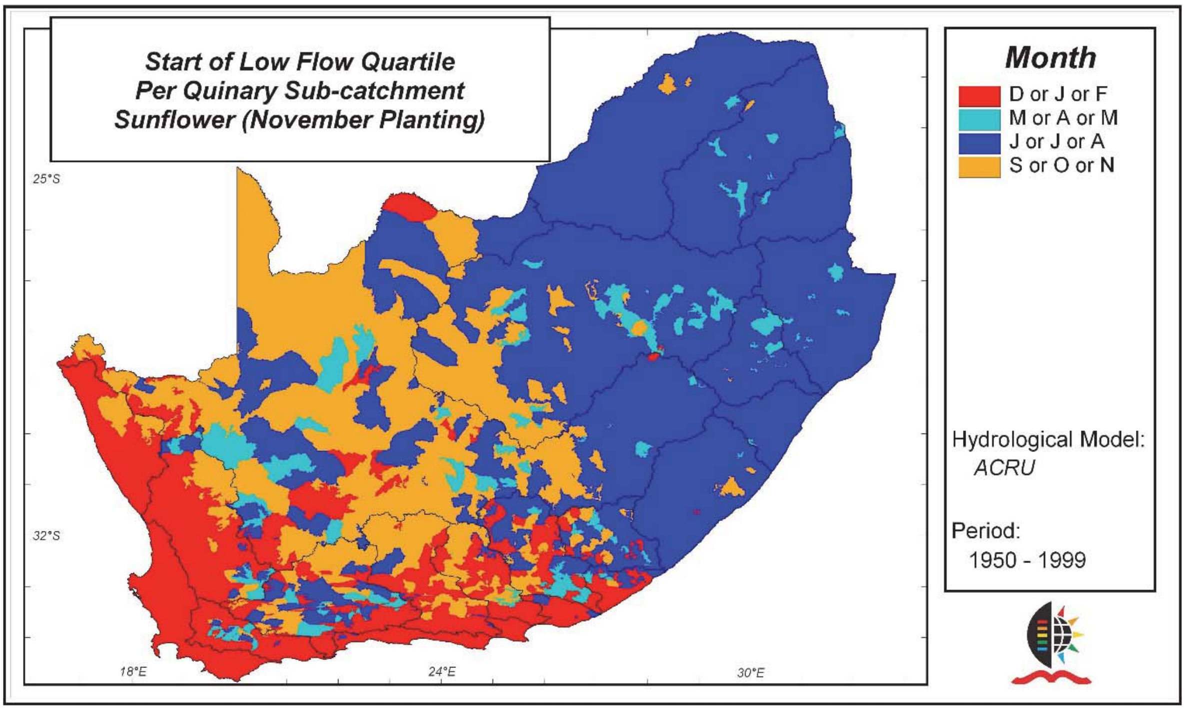
Figure 19 The first month of the low flow period for each bioethanol feedstock, based on mean monthly stream flow simulated using the *ACRU* model for each quinary sub-catchment



(a)



(b)



(c)

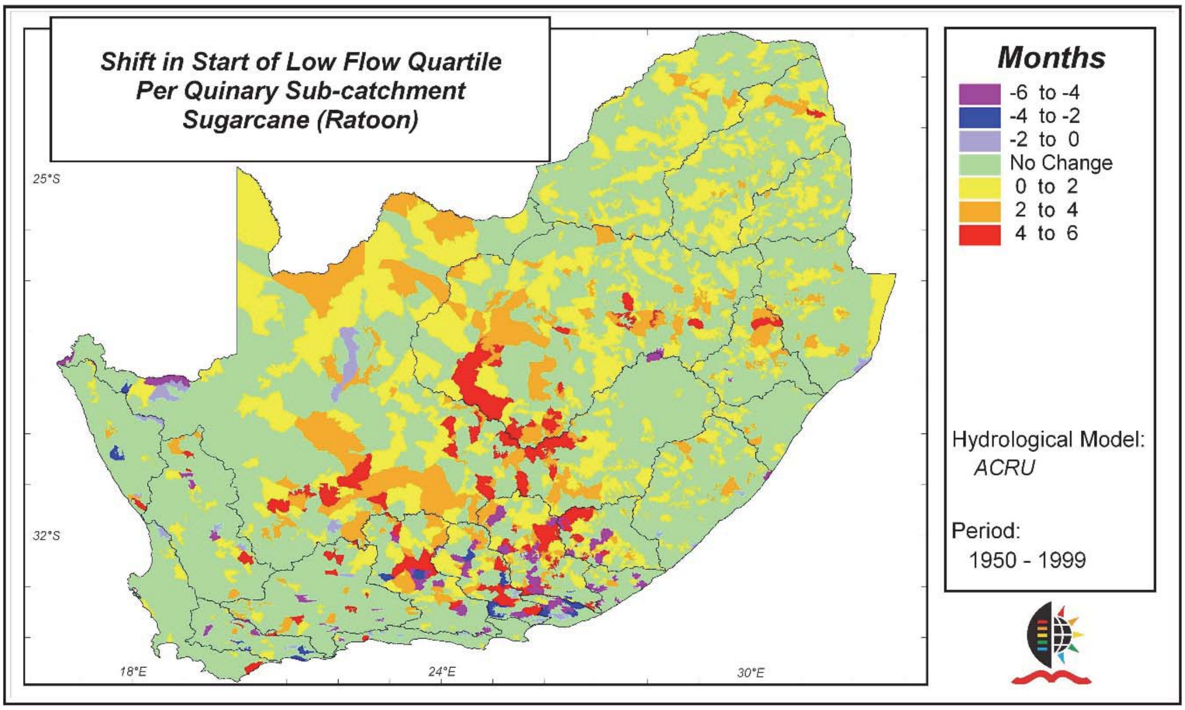
Figure 20 The first month of the low flow period for each biodiesel feedstock, based on mean monthly stream flow simulated using the *ACRU* model for each quinary sub-catchment

The results showed that for the majority of quinary catchments, a land use change to feedstock production should not cause a shift in the low flow period (green bars in **Figure 21**). However, it is interesting to note that, in some quinary sub-catchments and for all feedstocks considered, the start of the low flow periods does not coincide. For example, sugarcane (SCA) and winter sugarbeet (SBW) exhibit the highest potential of shifting the low flow quartile to later in the season (by up to 6 months). On the other hand, grain sorghum (GRS) and soybean (SYB) may cause the low flow period to occur earlier (i.e. sooner) in the season (by as much as 5 months).

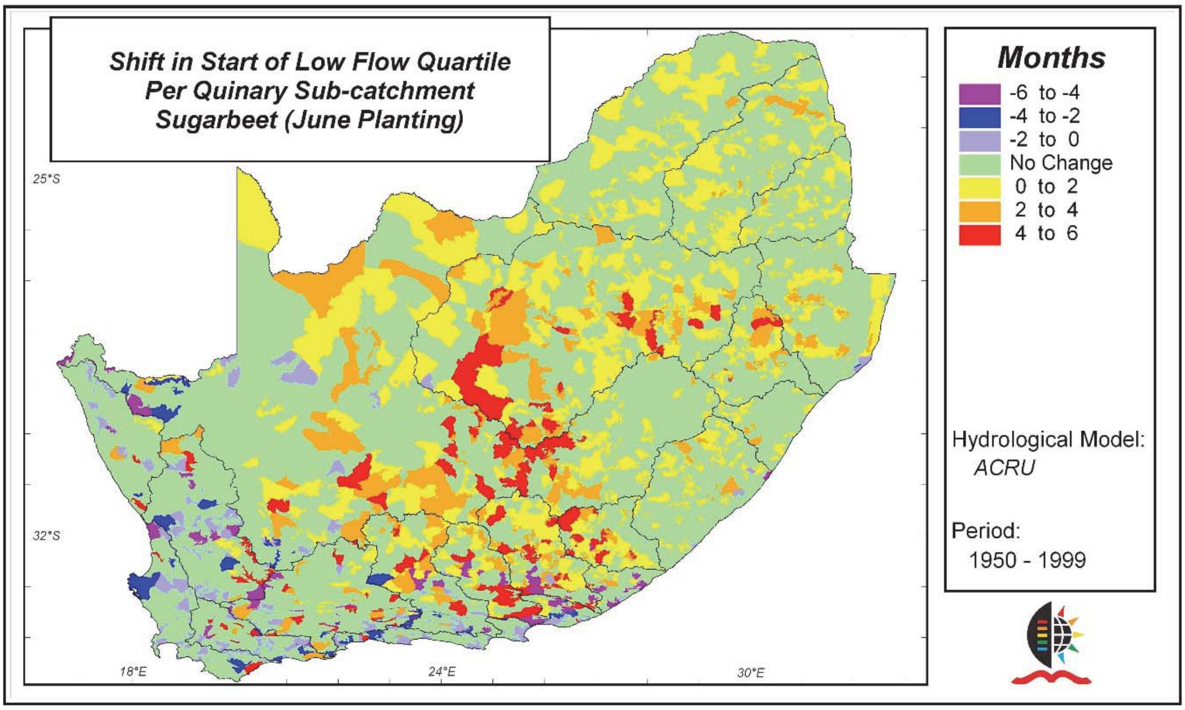
Figure 21 Possible shift in the low flow period that may result from a land use change to feedstock cultivation (SCA = sugarcane; SBW = winter sugarbeet; refer to **Table 8** for a list of all abbreviations)

Maps showing the shift in the start of the low flow period for each feedstock (relative to the baseline) are given in **Figure 22** and **Figure 23**. The maps are presented in order of the feedstock's ability to cause a delayed shift in the start of the low flow period (as indicated in **Figure 21**). For sugarcane, a delay of up to two months was simulated for most of the early- to mid-summer rainfall region (as shown in **Figure 18**). For the majority of feedstocks, the low flow period may start up to 6 months later for sub-catchments located in the late- to very-late summer rainfall region.

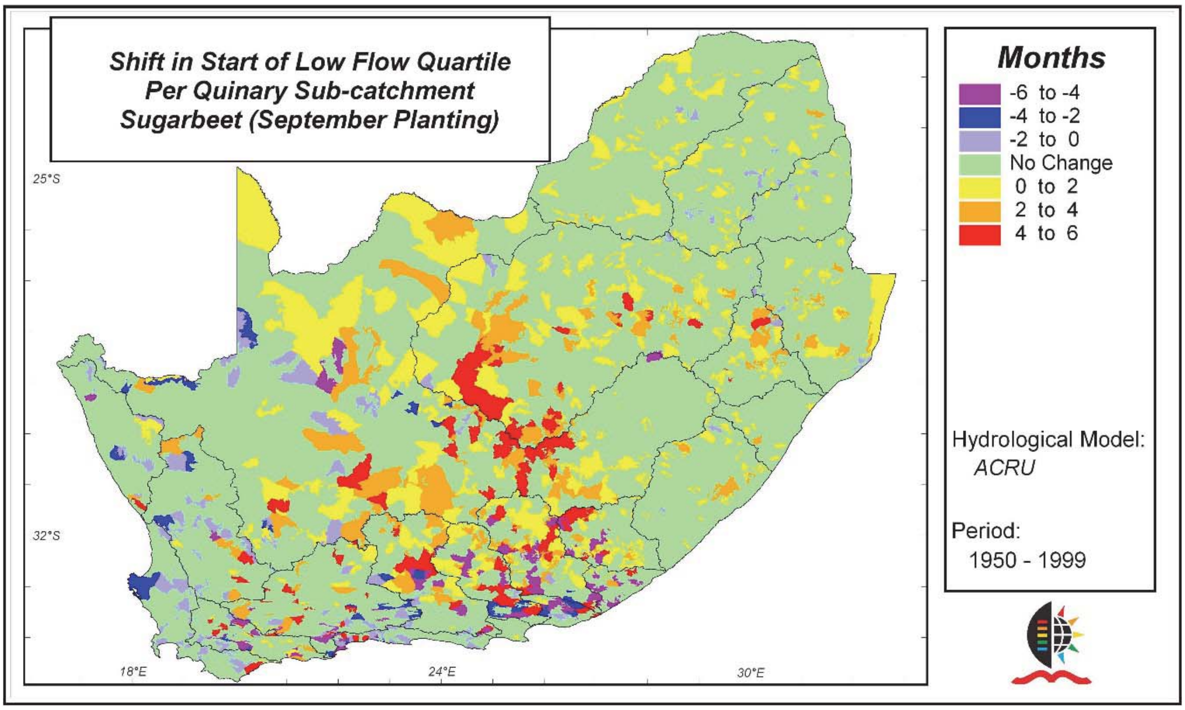
The above analysis raises a question as to what constitutes the correct method of determining the 3-month low flow period. In other words, should the monthly stream flows for the baseline be used to determine the start month (i.e. **Figure 17**) or the monthly stream flows for the proposed land use (i.e. **Figure 19** or **Figure 20**)? This decision will impact the outcome of whether or not the feedstock should be declared a SFRA based on the impact on low flows.


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarcane (Ratoon)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

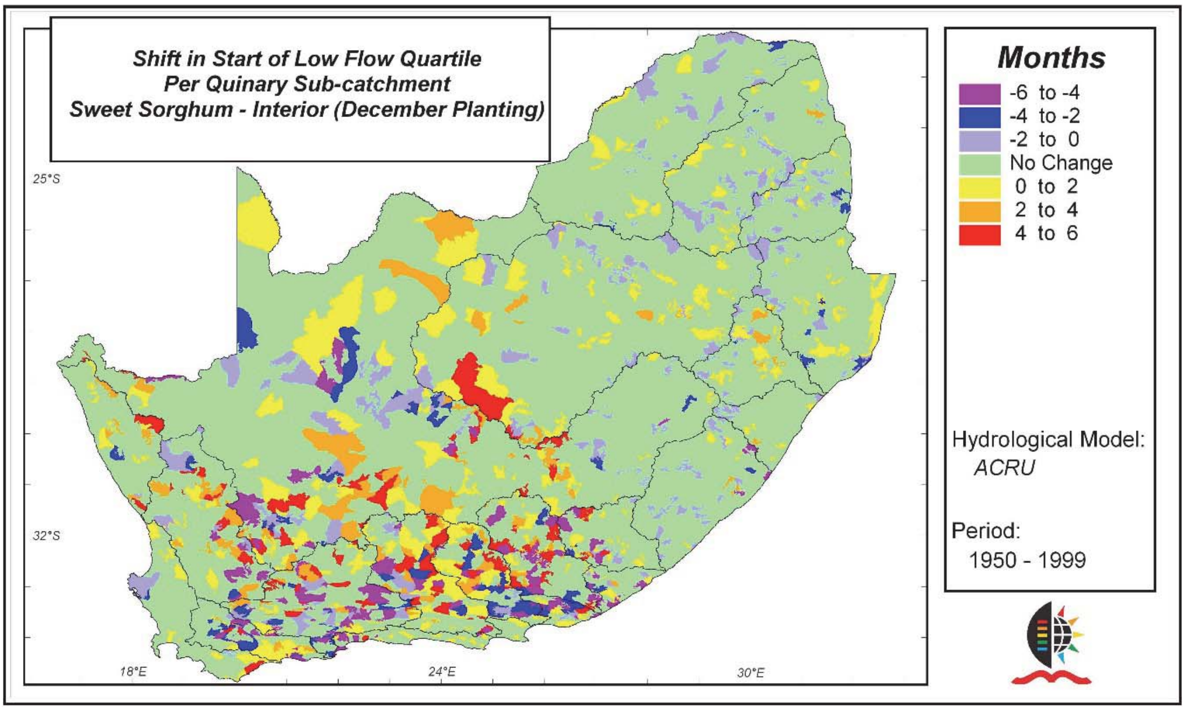
(a)


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarbeet (June Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

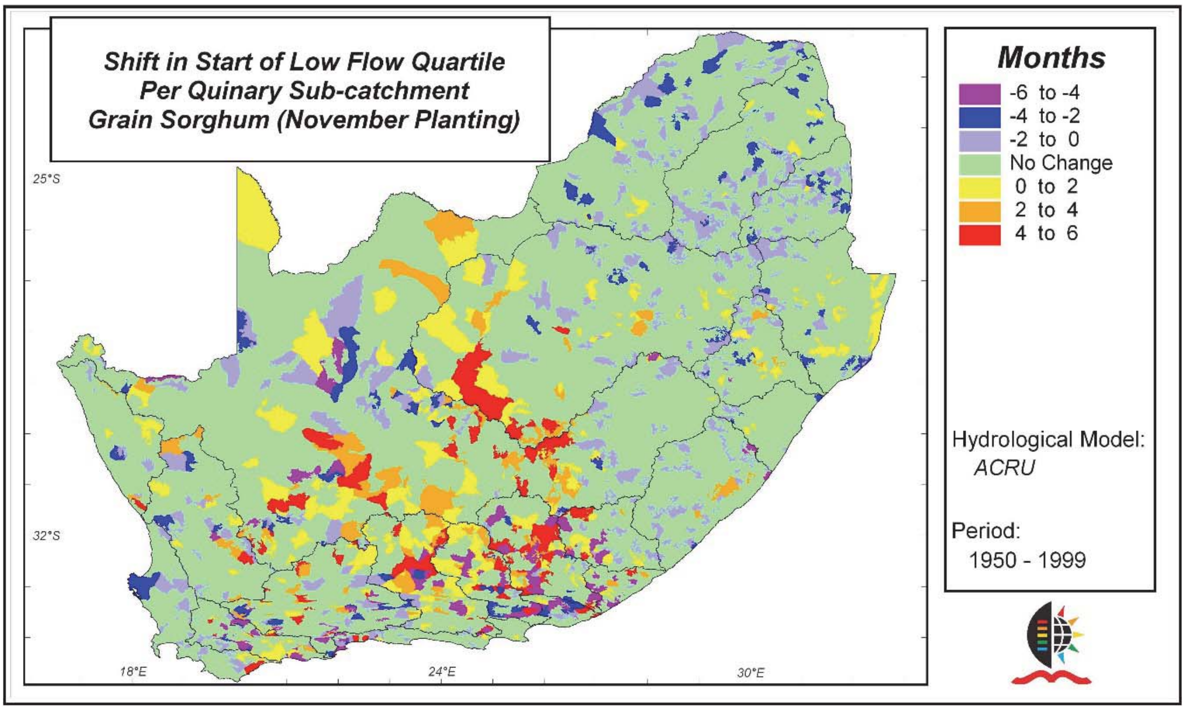
(b)


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sugarbeet (September Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

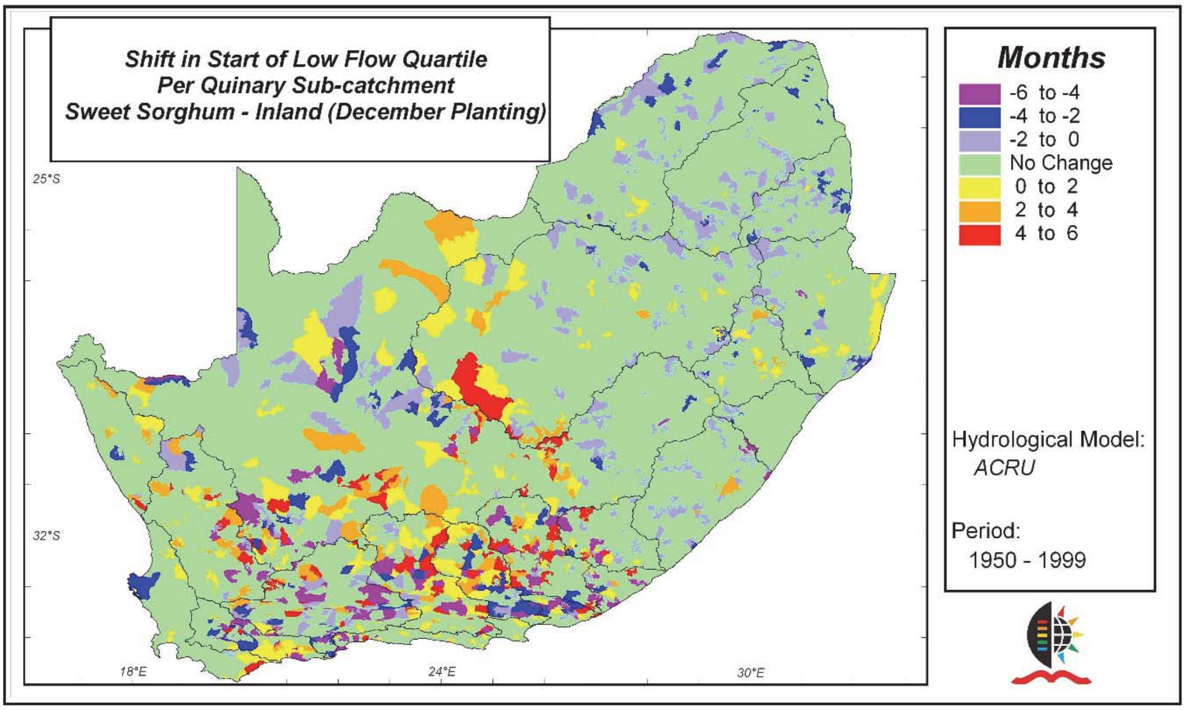
(c)


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sweet Sorghum - Interior (December Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

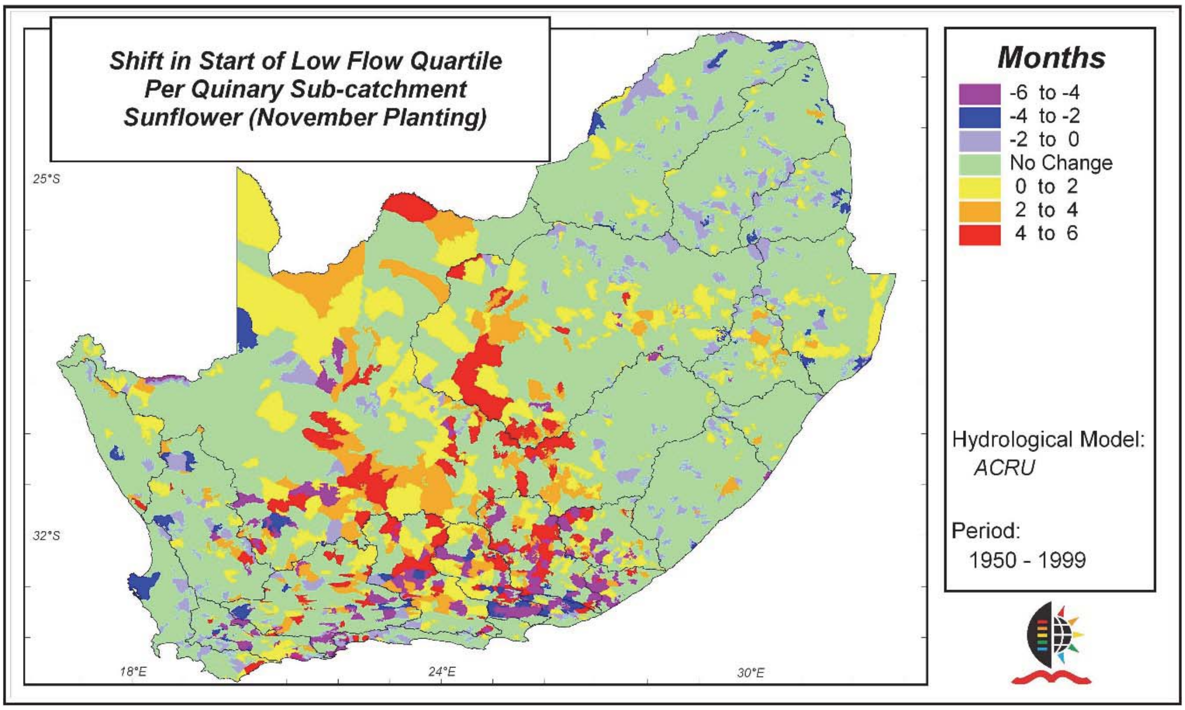


(e)

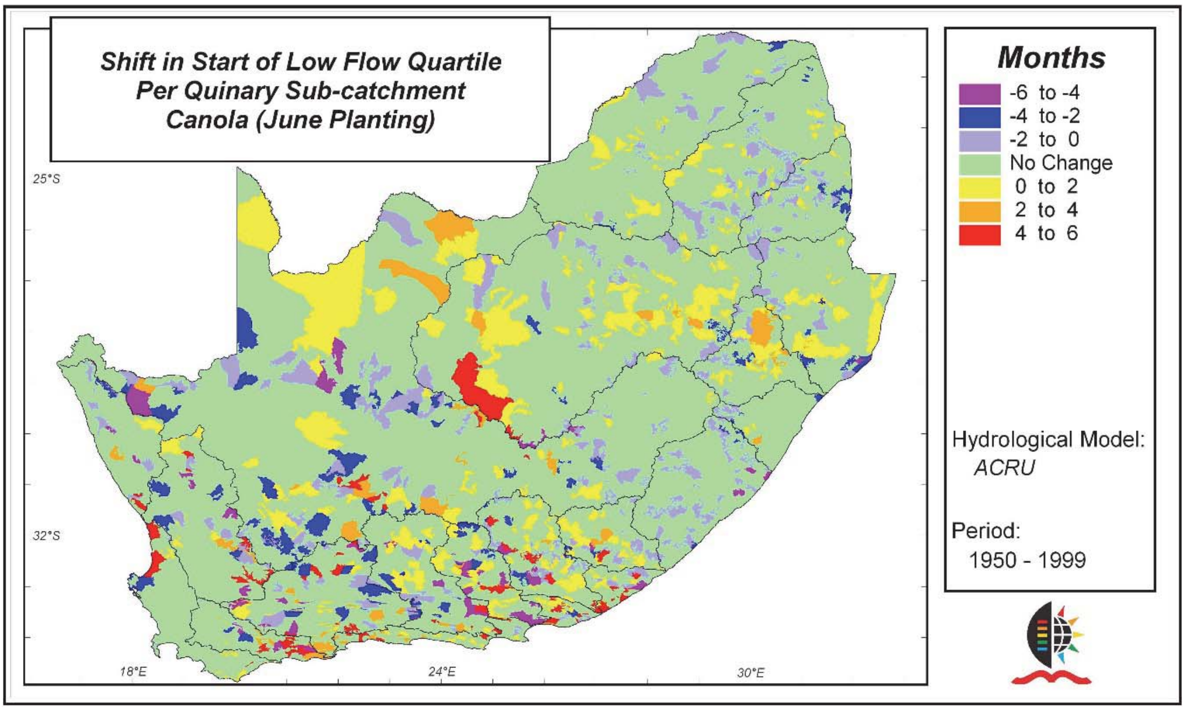


(f)

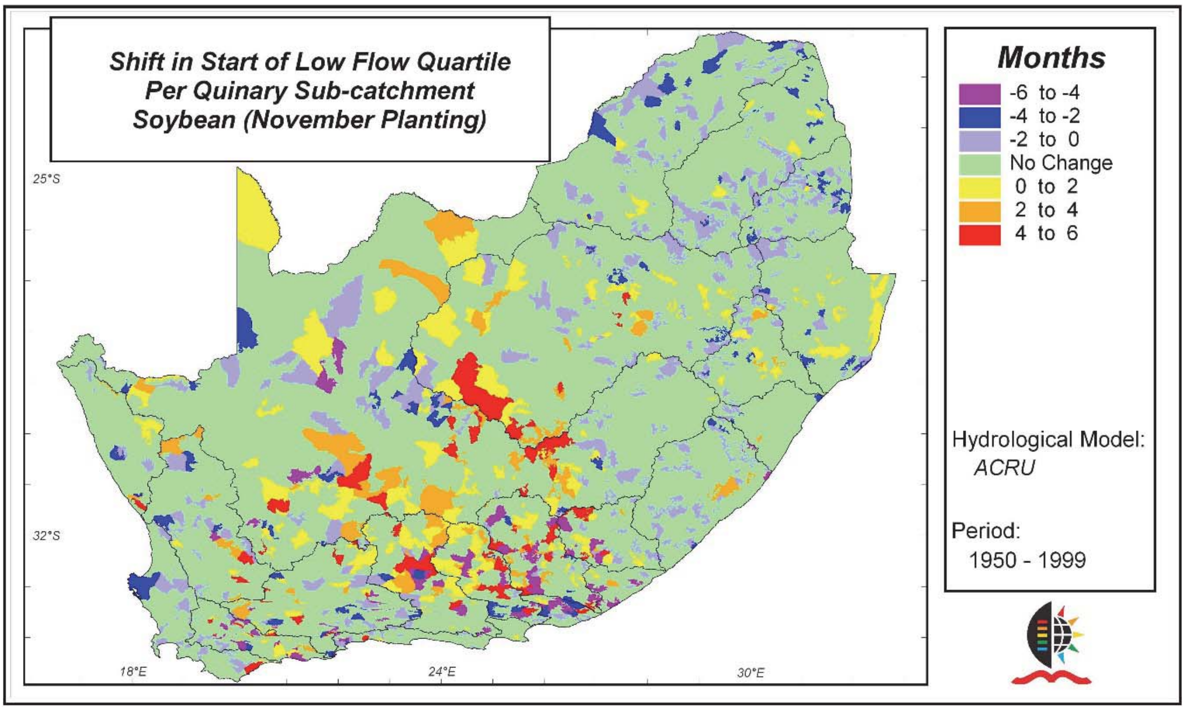
Figure 22 Possible shift in the start of the low flow period (i.e. driest three months of the year) relative to the baseline, for selected bioethanol feedstocks


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Sunflower (November Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)


Shift in Start of Low Flow Quartile
Per Quinary Sub-catchment
Canola (June Planting)
Months
-6 to -4
-4 to -2
-2 to 0
No Change
0 to 2
2 to 4
4 to 6
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



(c)

Figure 23 Possible shift in the start of the low flow period (i.e. driest three months of the year) relative to the baseline, for selected biodiesel feedstocks

3.4.3.9 Declaration of SFRAs

The previous three sections (c.f. **Section 3.4.3.6** to **Section 3.4.3.8**) indicated that a change in land use from natural vegetation to feedstock cultivation may result in the following impacts:

- a reduction in annual runoff of 10% or more, and/or
- a reduction in low flow runoff of 25% or more, and/or
- a shift in the start of the low flow period.

It must be noted that far fewer quinaries are flagged as potential stream flow reduction areas when low flows are considered. For example, a land use change to sugarcane may reduce annual runoff production by more than 10% in a total of 3 187 quinary sub-catchments (**Table 7**). Of these, only 210 also exhibit a 25% reduction in low flow runoff (LFR; i.e. driest 3 months). Hence, 2 977 sub-catchments do not experience significantly less runoff in the three driest months (**Table 7**). This may indicate that the 25% threshold used for the low flow period is somewhat conservative.

Only DWS have the authority to declare a crop a SFRA. They should base this decision on the research output from this project. The figures in the table below (**Table 8**) correspond to quinaries in which a:

- "significant" (i.e. ≥ 25%) reduction in low flow (i.e. 3-month accumulated) stream flow may occur, and
- "significant" (i.e. ≥ 10%) reduction in MAR may also occur, together with a
- possible shift in the low flow quartile.

Table 7 Portion of quinary sub-catchments in which a significant reduction in only mean annual runoff (MAR) occurs, together with a significant reduction in low flow runoff (LFR)

Feedstock	MAR ≥ 10% only		MAR ≥ 10% and LFR ≥ 25%		LFR ≥ 25% only		Total	
	No.	%	No.	%	No.	%	No.	%
Sugarcane	2 977	93.4	210	6.6	0	0.0	3 187	100.0
Grain sorghum	2 376	98.1	47	1.9	17	0.7	2 440	100.0
Soybean	1 314	97.5	34	2.5	9	0.7	1 357	100.0
Sweet sorghum - inland	1 233	97.6	30	2.4	7	0.6	1 270	100.0
Sugarbeet - summer	537	95.7	24	4.2	4	0.7	565	100.0
Sunflower	295	99.0	3	1.0	4	1.3	302	100.0
Sweet sorghum - interior	225	98.7	3	1.3	0	0.0	228	100.0
Canola	56	70.0	24	22.4	27	25.2	107	100.0
Sugarbeet - winter	23	85.2	4	9.5	15	35.7	42	100.0

Thus, the cultivation of feedstock in these quinaries should be considered carefully because there is both a reduction in generated runoff as well as a shift in the start of the low flow period. The table also highlights another issue in that a 25% (or more) runoff reduction in the low flow period does not necessarily mean that the mean annual runoff is reduced by ≥ 10%. For example, 27 (i.e. 51 - 24) quinaries show a significant reduction in the low flow period, but not in the annual runoff for winter canola. This “anomaly” can occur when the monthly runoff totals are very low, which results in a high relative difference. Thus, the 25% threshold for the low flow period should not be considered on its own to identify potential SFRAs (i.e. the MAR ≥ 10% “filter” should also be applied).

Table 8 For each feedstock, the number of quinaries where the relative reduction in low flow runoff is significant (≥ 25% only) and the mean annual runoff is reduced by more than 10%, together with a shift in the start month of the low flow period

Abbreviation	Feedstock	No. of quinaries		
		LFR ≥ 25% only	and MAR ≥ 10%	and shift
SSH	Sweet sorghum - interior	3	3	0
SNF	Sunflower	7	3	1
SBW	Sugarbeet - winter	19	4	3
CNW	Canola - winter	51	24	6
SBS	Sugarbeet - summer	28	24	9
SSU	Sweet sorghum - inland	37	30	12
SYB	Soybean	43	34	12
GRS	Grain sorghum	64	47	15
SCA	Sugarcane	210	210	46

4 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 1**. 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.

4.1 Introduction

It is virtually impossible to measure crop yield for all possible combinations of climate, soils and management conditions in South Africa, it is necessary to either develop a new model, or use an existing crop model. The model should accurately simulate the attainable yield of biofuel feedstocks across a wide range of growing conditions and management practices.

According to Teixeira (2008), the most common methods for estimating crop production include calculations range from simple empirical methods, to complex mechanistic crop growth models. A crop model should be complex enough to comprehensively represent the system, yet simple enough to be applied and used. To date, a single universal crop model does not exist. Instead, numerous crop yield models have been developed that simulate, *inter alia*, different crops, processes and environmental conditions (Steduto, 2006).

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 (Steduto *et al*., 2012). From the list of available crop models, the *AQUACROP* model developed by the FAO (Rome, Italy) was selected to simulate crop yield for selected biofuel feedstocks.

4.2 Attainable Crop Yield

4.2.1 Background

The *AQUACROP* model was used in this study to attainable yield for a number of prioritised biofuel feedstocks at the national level. Attainable yield is defined as the utilisable portion of the plant biomass that contains sugar, starch or vegetable oil which can be converted into biofuel. This yield was obtained under dryland farming conditions which may be water stressed and thus, is referred to as a water-limited yield potential. Although the crop may be water stressed, it is assumed that soil fertility is not limiting to plant growth and that no competition from weeds exists.

Version 4.0 of the model is packaged with a set of conservative crop parameters for a number of crops:

- barley (*Hordeum vulgare* L.),
- cotton (*Gossypium hirsutum* L.),
- maize (*Zea mays* L.),
- potato (*Solanum tuberosum*),
- quinoa (*Chenopodium quinoa* Willd.),
- rice (*Oryza sativa* L.),

- **soybean** (*Glycine max* (L.) Merr.),
- **sugarbeet** (*Beta vulgaris* L.),
- **sugarcane** (*Saccharum officinarum*),
- **sorghum** (*Sorghum bicolor* (L.) Moench),
- **sunflower** (*Helianthus annuus* L.),
- tef (*Eragrostis tef* (Zucc.) Trotter),
- tomato (*Solanum lycopersicum* L.), and
- wheat (*Triticum aestivum* L.; *Triticum turgidum* durum).

Conservative crop parameters are available for a number of potential biofuel feedstocks (highlighted in **bold** above), which are considered general and widely applicable and thus, don't require local calibration. However, Steduto *et al*. (2012) provided a list of parameters likely to require adjustment in order to account for different cultivars, local conditions and management practices. The process of calibrating and running the crop model as the national scale is described next.

4.2.2 Methodology

4.2.2.1 Model calibration

Although *AQUACROP* is already parameterised for sugarcane and sugarbeet, Mokonoto (2015) calibrated the 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 grain sorghum, *AQUACROP*'s default parameter file was used, which was initially calibrated using growth data from Texas (USA). For canola, a parameter file was obtained from Canada where the model was calibrated using data from two different growing regions in Alberta (Pincher Creek & Swift Current). Slight "tweaks" were made to the latter two crop parameter files. Hence, the source of the crop parameter files used in this study is summarised in **Table 9**. However, maize yields were not simulated since maize is still currently banned as a potential feedstock owing to food security concerns.

Table 9 Source of crop parameter files used in study

Crop	Location	Country	Year	Source
Sugarcane	La Mercy KwaZulu-Natal	South Africa	06/1989-12/1990	Mokonoto (2015)
Sugarbeet	Ukulinga KwaZulu-Natal	South Africa	05/2013-12/2013	Mokonoto (2015)
Grain sorghum	Bushland Texas	USA	05/1993	*AQUACROP*
Maize	Baynesfield KwaZulu-Natal	South Africa	11/2012-04/2013	Moyo and Savage (2014)
Soybean	Baynesfield KwaZulu-Natal	South Africa	10/2012-04/2013	Moyo and Savage (2014)
Canola	Pincher Creek Alberta	Canada	Unknown	Kienzle (2015)
Canola	Swift Current Saskatchewan	Canada	Unknown	Kienzle (2015)

4.2.2.2 Soils input

A utility was developed 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. A pedotransfer function was developed to estimate K_{SAT} from the soil water retention parameters using equations developed by Saxton and Rawls (2006).

4.2.2.3 Climate input

A utility was developed to extract daily rainfall, temperature (T_{max} & T_{min}) and reference crop evaporation (ET_o) from the revised quinary sub-catchment climate database. A total of 46 704 input files (climate and soils) were generated to run *AQUACROP* for each of the 5 838 quinary sub-catchments.

4.2.2.4 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 developed to create an *AQUACROP* project file for multiple simulations. For each feedstock, a representative planting date was chosen and the harvest date was determined for each sub-catchment based on the GDD method. The length of each season varied, depending on the time required to accumulate sufficient growing degree days to reach maturity. However, the maximum season length was limited to 730 days. For certain feedstocks, two planting dates were modelled as shown in **Table 10**.

Table 10 Feedstock planting dates assumed for the simulation of crop yield using the *AQUACROP* model

Feedstock	Planting date
Sugarcane - summer	1st February
Sugarcane - winter	1st April
Sugarbeet - summer	1st September
Sugarbeet - winter	1st June
Grain sorghum	1st November
Soybean	1st November
Canola - winter	1st April
Canola - summer	1st June

4.2.2.5 Standalone version

Owing to the large number of model runs (i.e. 5 838 at the national scale for each feedstock), the plug-in[4] version of the *AQUACROP* model was used. 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.

4.2.2.6 GDD *vs*. calendar mode

The *AQUACROP* model was run 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.

[4] http://www.fao.org/nr/water/docs/AquaCropPlugInV40.doc

4.2.2.7 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.

4.2.3 Results and discussion

As noted previously, the *AQUACROP* model can be run in two different modes, where the length of the crop cycle is 1): fixed for each simulation (i.e. calendar days from planting date), or 2) varies according to accumulated GDD from planting date to crop maturity, i.e. thermal time. In **Section 4.2.3.1**, output from the *AQUACROP* model based on thermal time is compared to that derived from calendar time. This section also helps the reader to better understand the series of maps that were produced.

In **Section 4.2.3.2**, a comparison is made of yield and WUE output from *AQUACROP* with that simulated using *SWB*. Both models were run for 113 quinary sub-catchments situated in the Western Cape. From **Section 4.2.3.3** onwards, maps for each feedstock are presented for a number of variables calculated from *AQUACROP* model output.

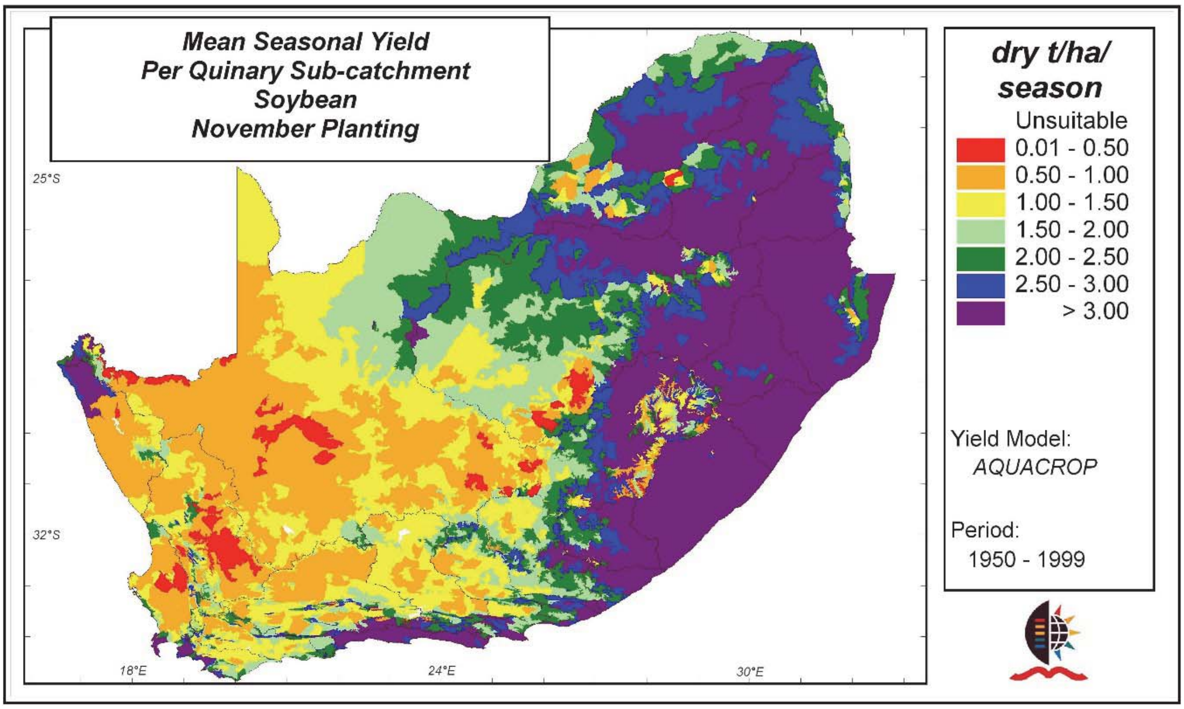
4.2.3.1 Calendar *vs*. thermal time

The comparison is undertaken for soybean only. In essence, the findings show that where possible, simulations should rather be based on thermal time.

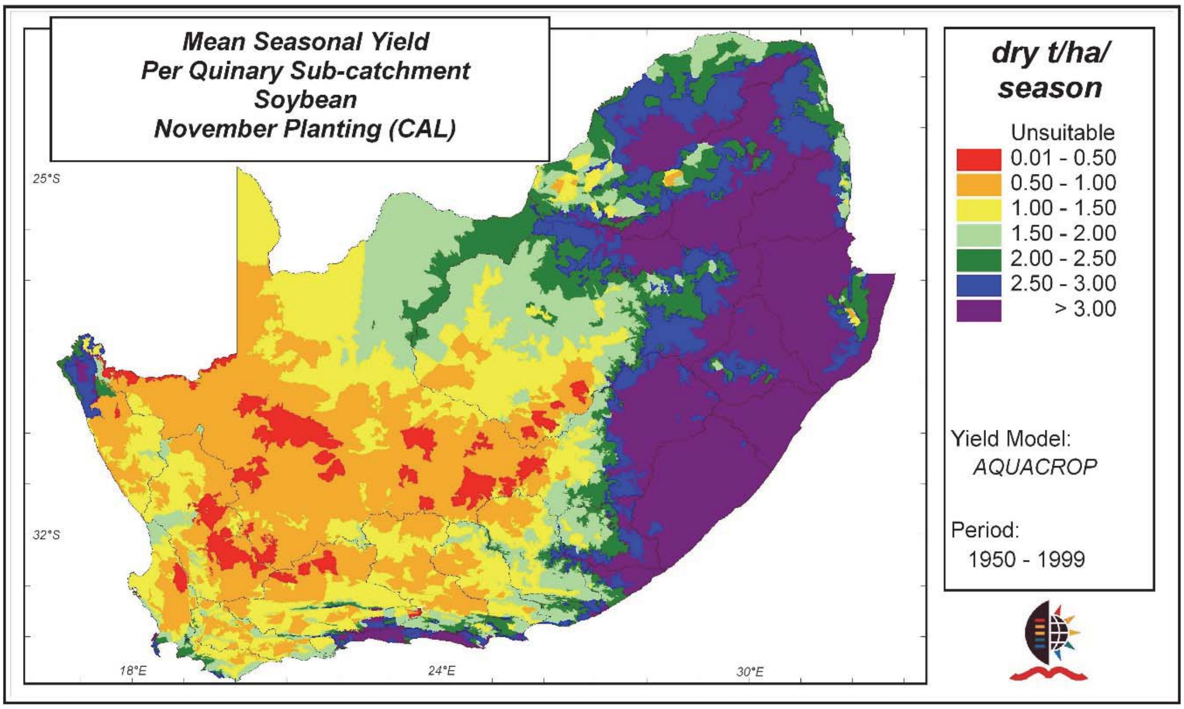
<u>Seasonal yield</u>

Figure 24 illustrates differences in seasonal yield derived from crop cycles based on thermal and calendar time for both the mean and median statistic. Steduto *et al*. (2012) noted that for crop cycles based on GDD, much of the temperature effects on crops, such as on phenology and canopy expansion rate, are accounted for. In addition, soybean flowering is determined by thermal regime (and the photoperiod). Steduto *et al*. (2012) also 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 (cutoff) temperatures in the crop parameter file is critical.

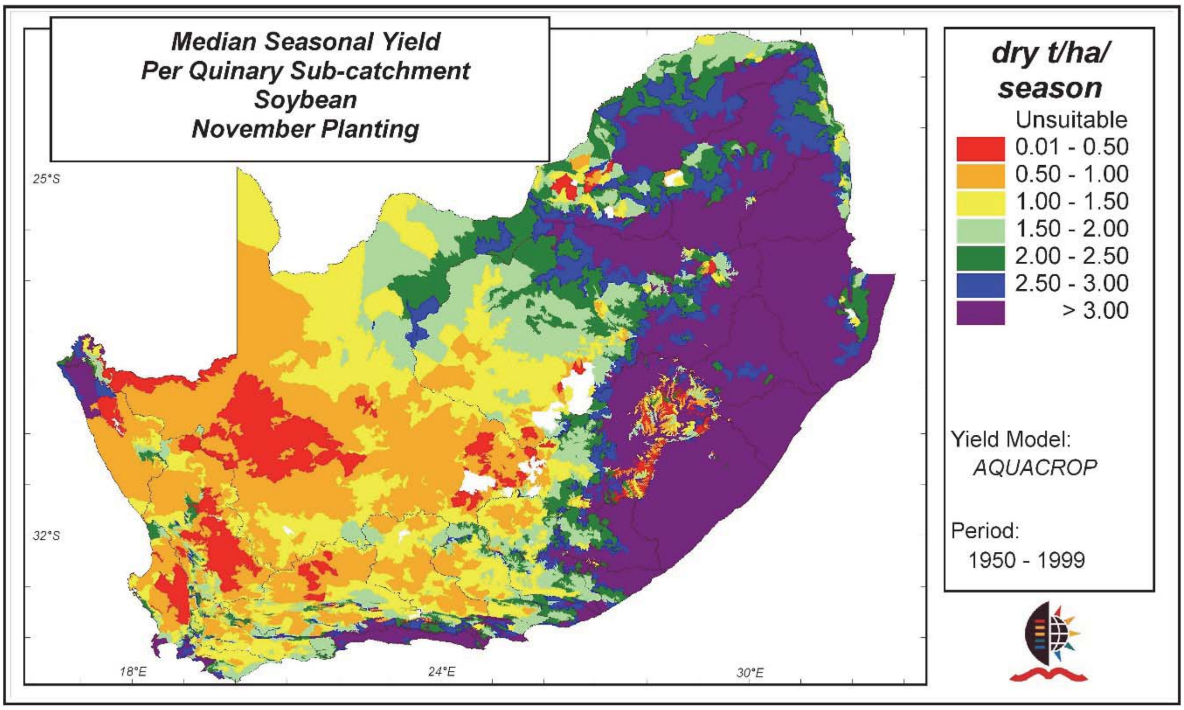
More importantly, the model inhibits the conversion of transpiration into biomass at low temperatures when using thermal time. The white areas marked as unsuitable in Figure 24**c** indicate that the median yield is zero dry tons per hectare. These areas are too cold for soybean growth, whereas the calendar-based run produced yield (> 3 dry t ha^{-1}) even for the Lesotho highland areas. Steduto *et al*. (2012) added that for simulation of production and water use under different yearly climate 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 fixe crop cycle (i.e. calendar days).


Mean Seasonal Yield
Per Quinary Sub-catchment
Soybean
November Planting
dry t/ha/ season
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

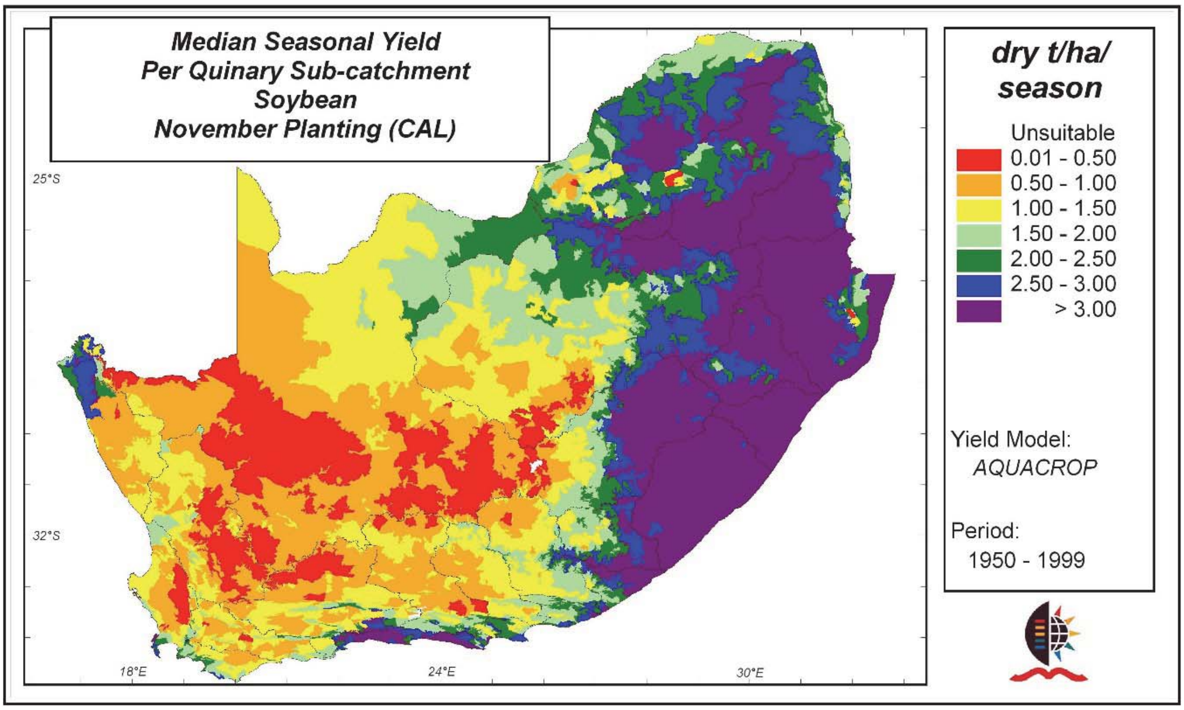
(a)


Mean Seasonal Yield
Per Quinary Sub-catchment
Soybean
November Planting (CAL)
dry t/ha/ season
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



(c)

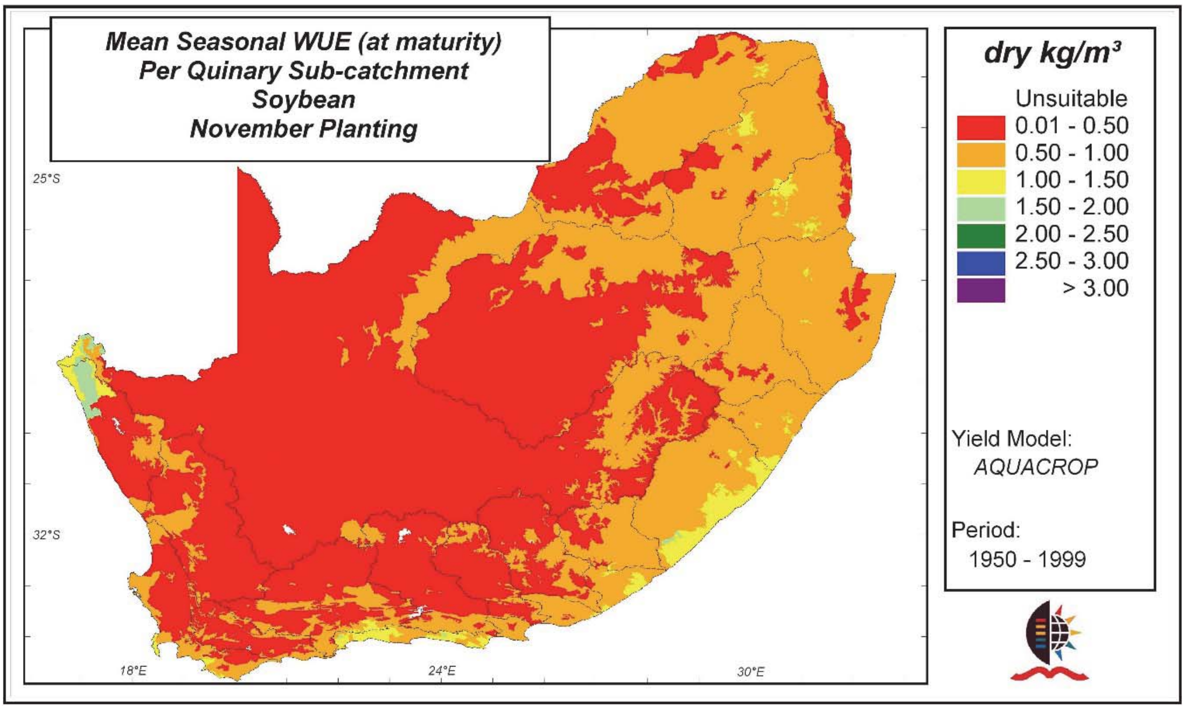


(d)

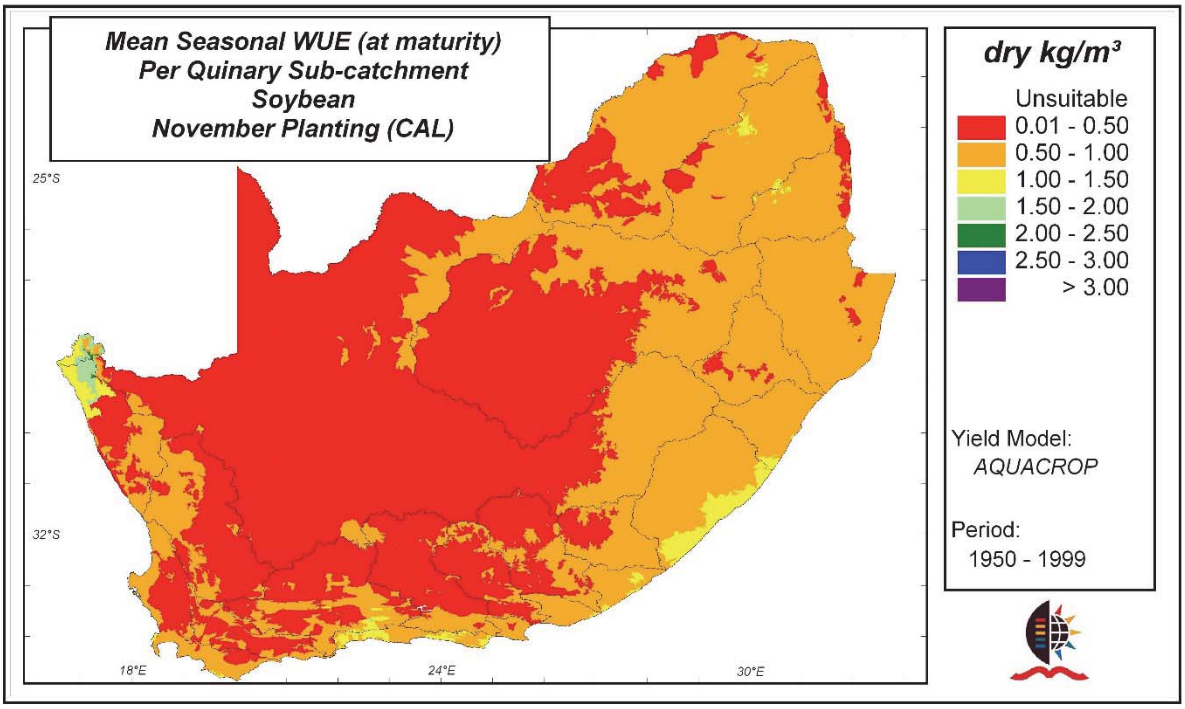
Figure 24 Differences in seasonal yield derived from crop cycles based on thermal (a & c) and calendar (b & d) time for both the mean (a & b) and median (c & d) statistic

Seasonal WUE

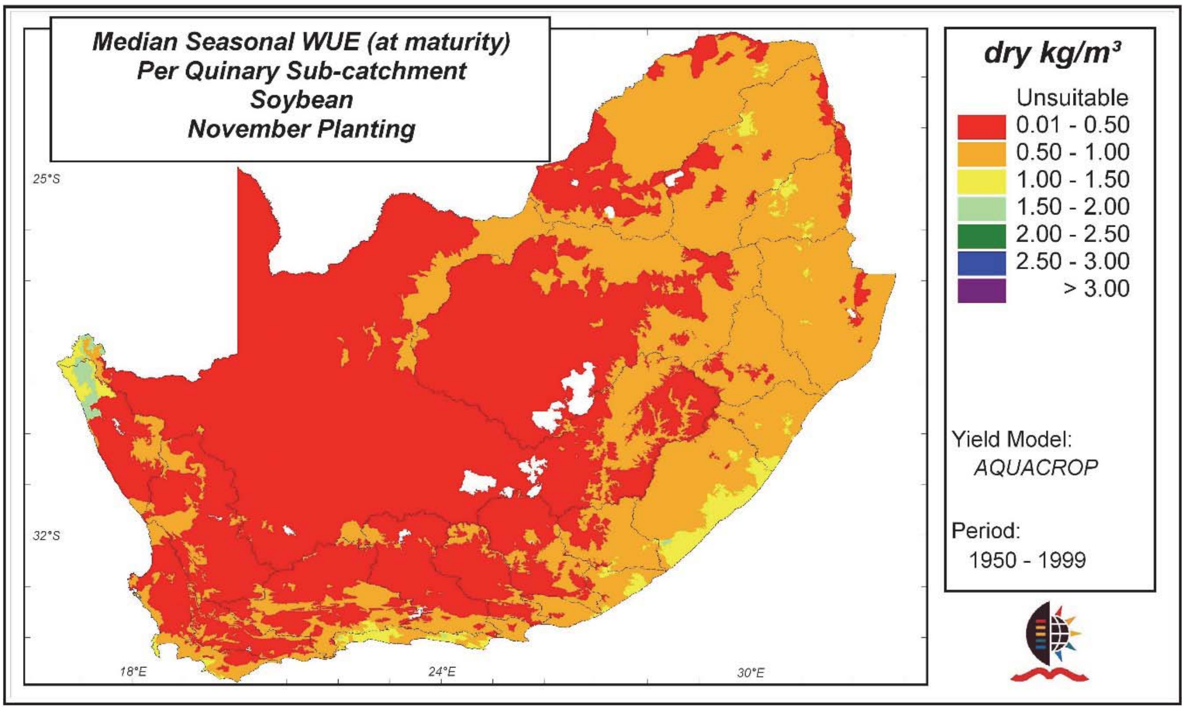
In terms of WUE, the differences between GDD- and calendar-based output is less noticeable as shown in **Figure 25**. The main exception is the lower WUE in colder areas (e.g. Lesotho highland areas). In addition, there is little difference between the WUE calculated at maturity compared to that based on when the maximum yield was obtained (maps not shown here).



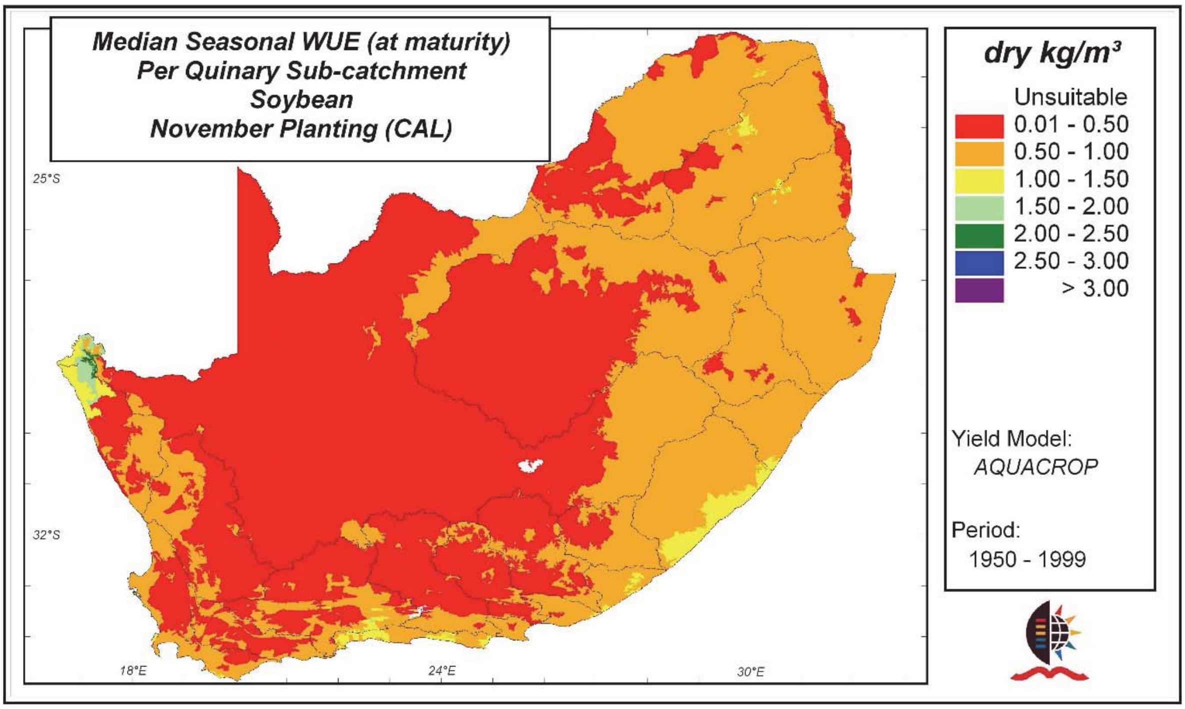
(a)



(b)



(c)

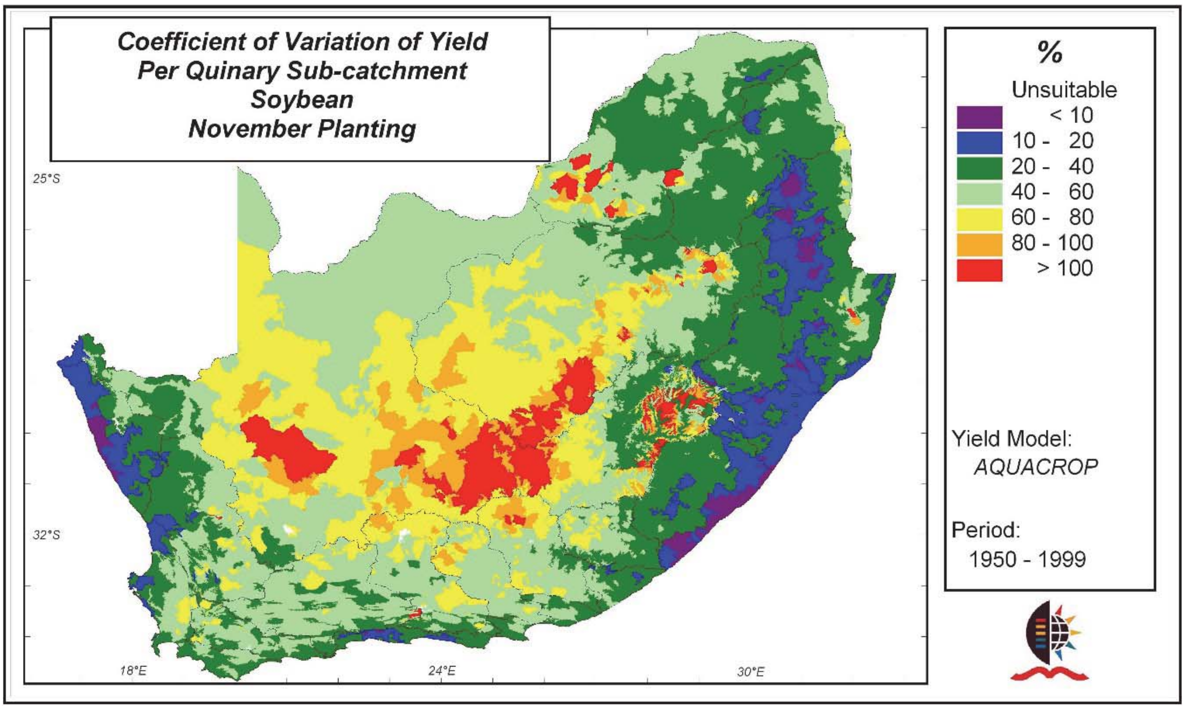


(d)

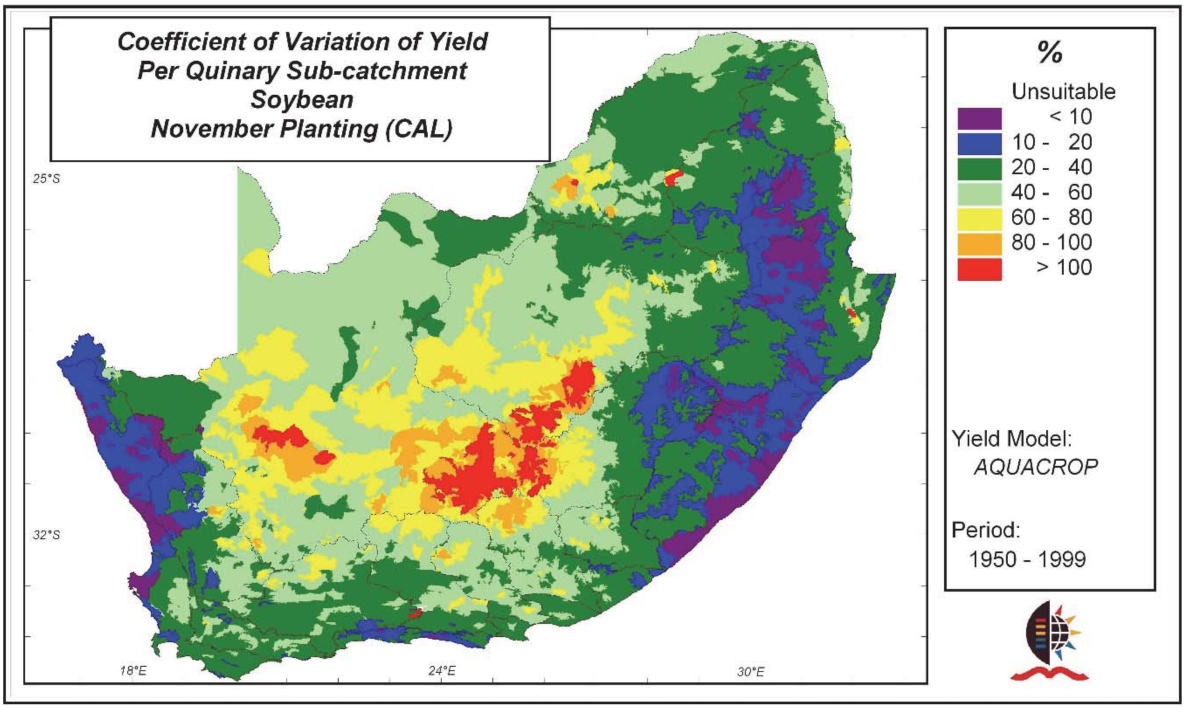
Figure 25 Differences in seasonal WUE derived from crop cycles based on thermal (a & c) and calendar (b & d) time for both the mean (a & b) and median (c & d) statistic

Inter-seasonal variability

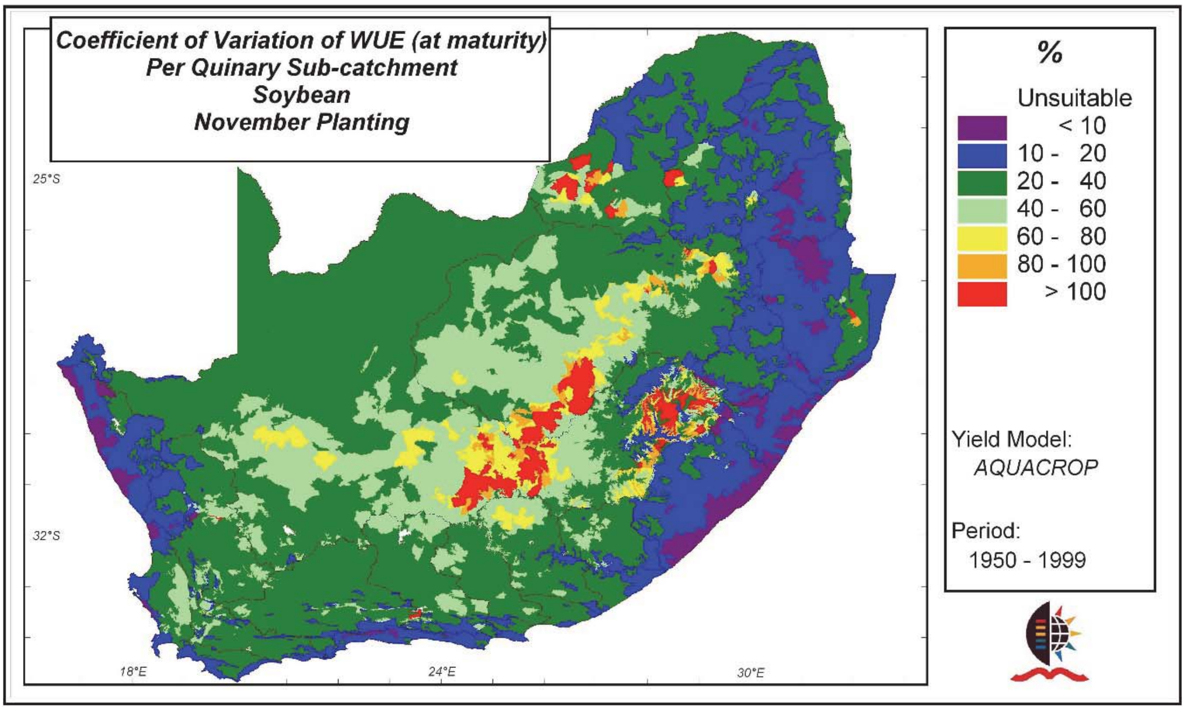
The variability in inter-seasonal yield and WUE is higher for the GDD simulation than compared to the fixed crop cycle (Figure 26). In addition, the variation in yield is higher than that for WUE, particularly for the interior regions of the country. Areas with high variation in yield and/or WUE are not deemed suitable for soybean production.



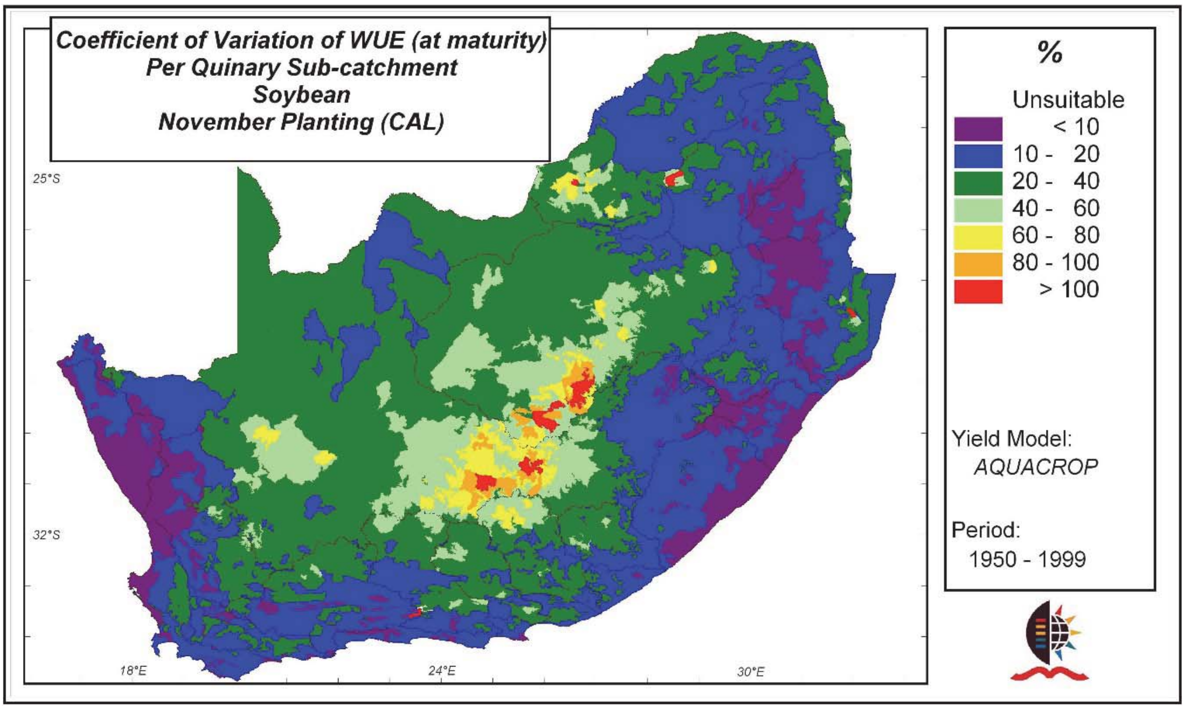
(a)



(b)



(c)

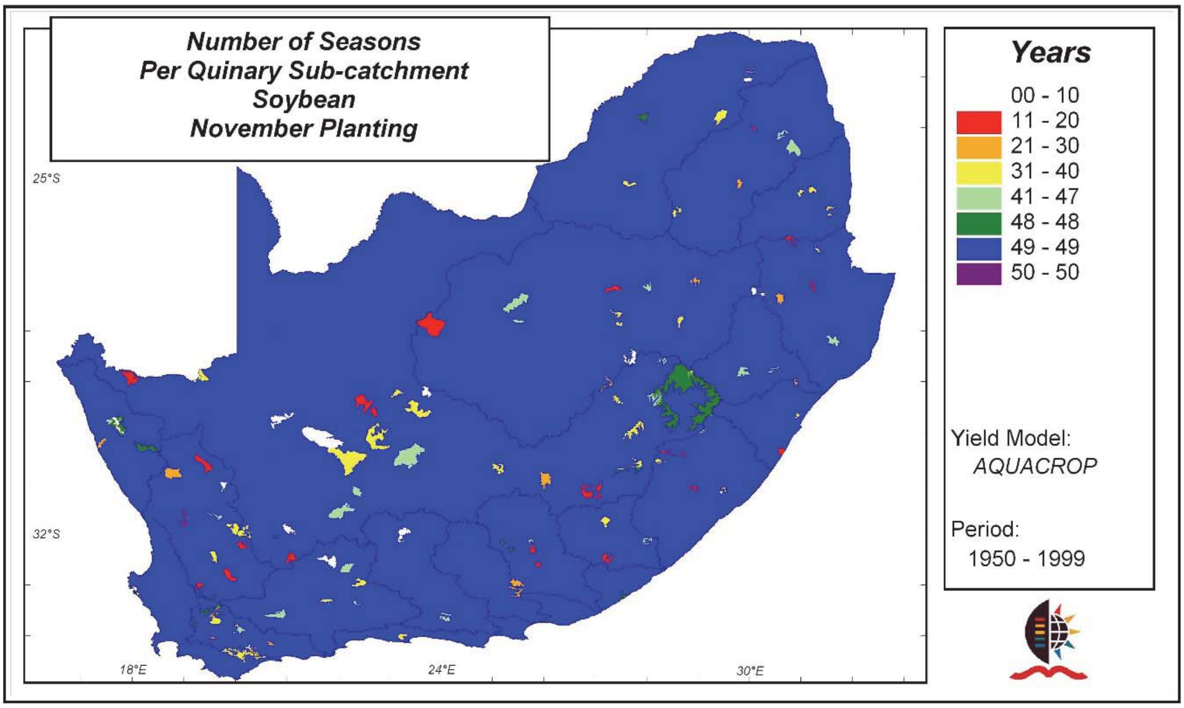


(d)

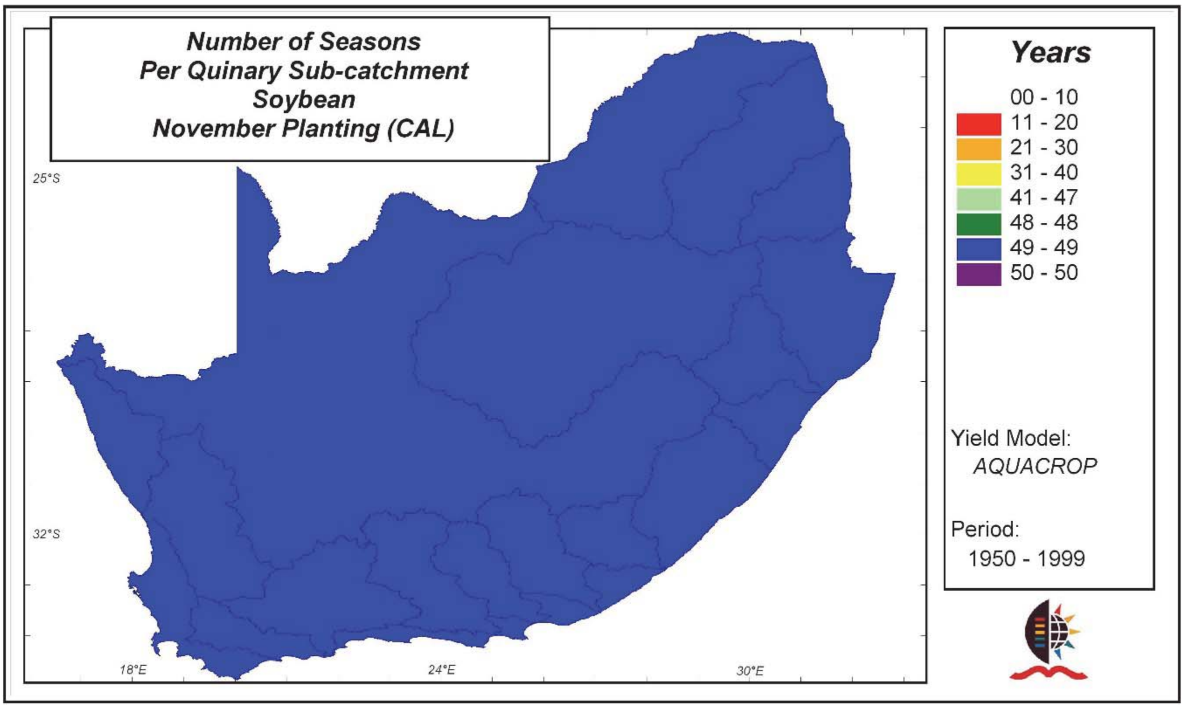
Figure 26 Differences in variability of yield (a & b) and WUE (c & d) derived from crop cycles based on thermal (a & c) and calendar (b & d) time

Number of seasons

The number of seasons that was used to calculate the long-term yield and WUE is shown in **Figure 27**. Since soybean is planted on 1st November for each quinary sub-catchment, the maximum number of seasons in 49, since the last season (1999/11/01 - 2000/03/10) is not simulated because the climate data ends on 31st December 1999.



(a)



(b)

Figure 27 Differences in the number of seasons derived from crop cycles based on thermal (a) and calendar (b) time

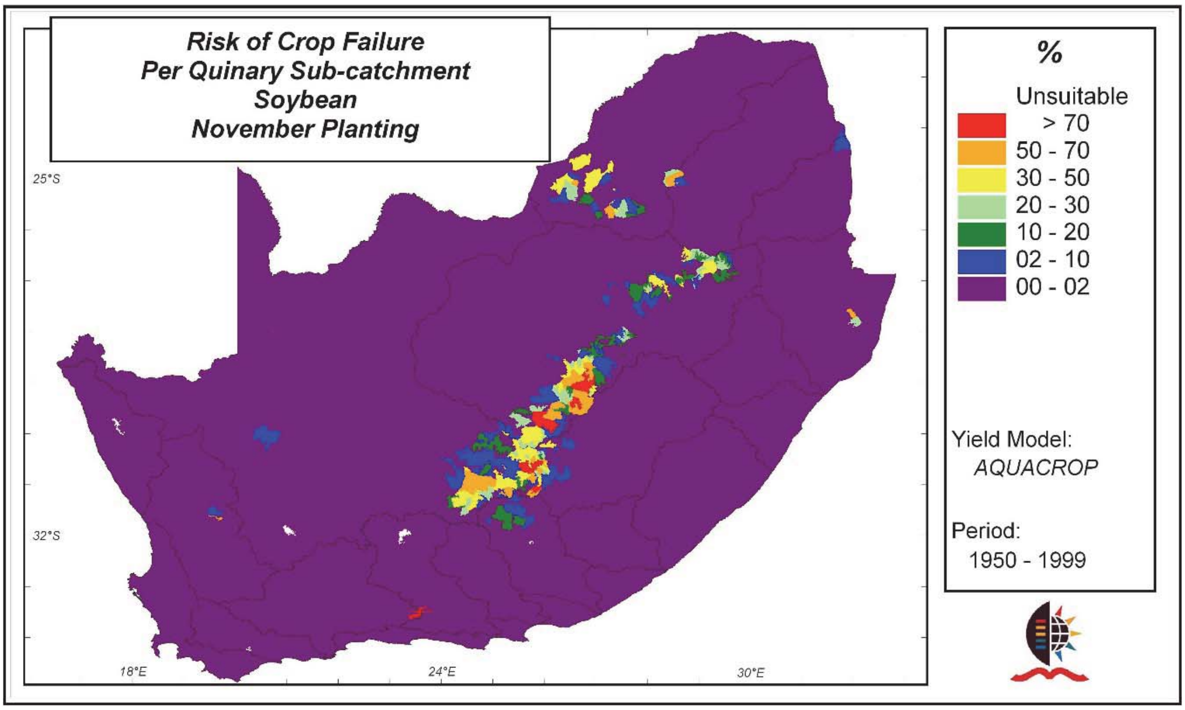
However, for the GDD mode, the model produces division by zero errors in certain sub-catchments. This causes the model to “crash” and the remainder of the 49-year season is not simulated. This is illustrated in **Figure 27a** where in certain quinaries, less than 10 of the 50 seasons were simulated (shown in white).

According to Steduto *et al*. (2012), in order to determine the long-term attainable yield at a location, at least 20 years of daily climate data should be used for simulations. However, 30 years of data is considered the *de facto* standard. Hence, statistics (e.g. mean, median & coefficient of variation) derived for sub-catchments with less than 20 years of simulated data should be considered unreliable (and discarded). Thus, soybean should not be grown in these areas.

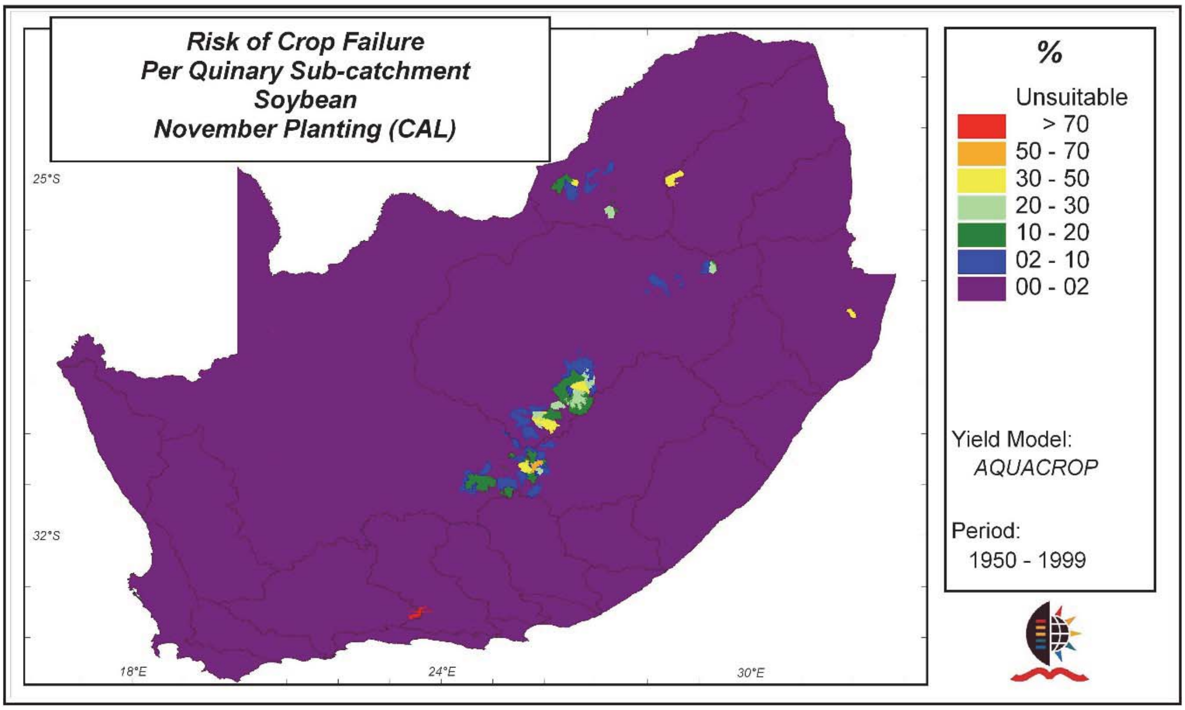
<u>Risk of crop failure</u>

The risk crop failure is shown in **Figure 28** for both the GDD and calendar modes. It represents the number of zero yields that were simulated over the maximum 50-year period, which is then doubled and expressed as a percentage. Hence, areas shown in red indicate that at 0.00 t ha^{-1} was simulated for at least 35 years. This represents a very high risk of crop failure and thus, soybean should not be grown in such areas.

The risk of crop failure deemed acceptable by a grower is dependent on the intended use of the crop. For example, a subsistence farmer who solely relies on a successful crop for household food (or animal feed) would prefer a very low risk of crop failure. For biofuel production, crop failure would result in a loss of income and possibly a breach of contract with a biofuel manufacturer. The GDD mode produced a higher risk of crop failure and for a larger area than compared to the calendar mode, which is explained in the section that follows.



(a)



(b)

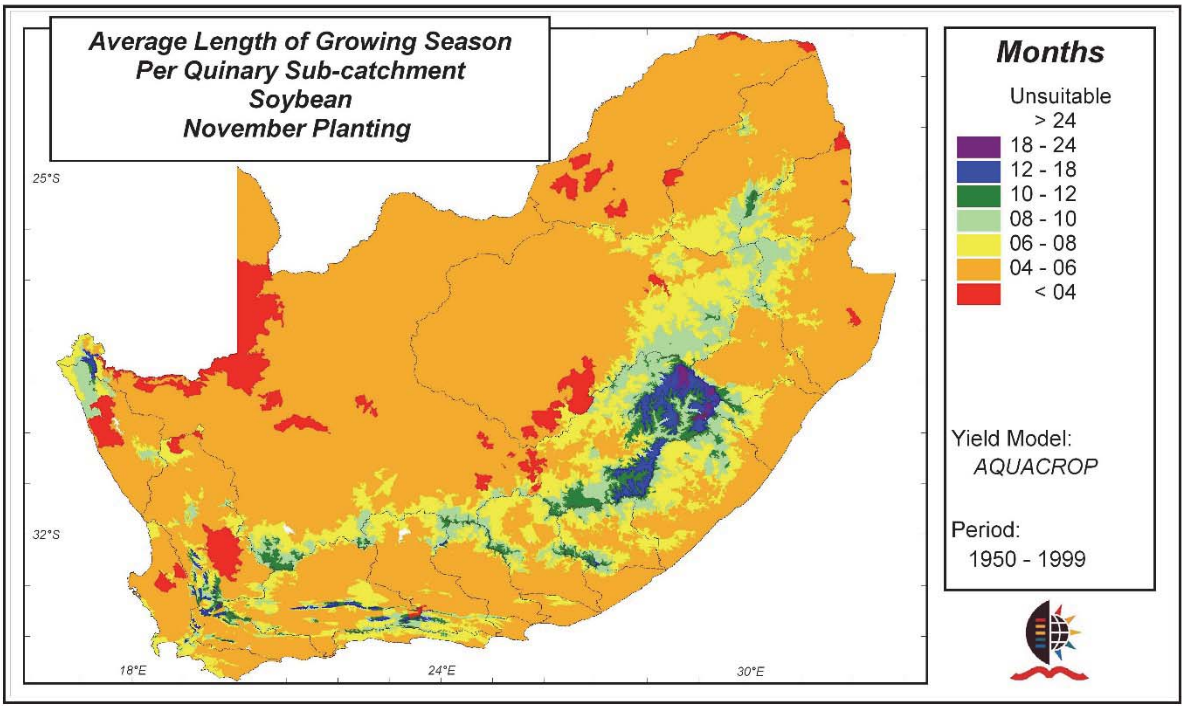
Figure 28 Differences in the number of crop failures derived from crop cycles based on thermal (a) and calendar (b) time

<u>Crop season length (*GRO*)</u>

The computational time required to complete a national run using the GDD mode far exceeds that based on calendar mode. In **Figure 29b** and **Figure 29d**, the fixed season length of 130 days (i.e. 4.32 months) for each quinary sub-catchment is clearly shown. However, the two maps indicate the crop season is less than four months (i.e. ≤ 121 days). It is important to note that the *AQUACROP* model calculates the crop cycle length from the germination date (not the planting date) to the time the peak yield is attained. Hence, *AQUACROP*'s crop cycle is always less than the crop season length based on GDD. This point is discussed further in the next section.

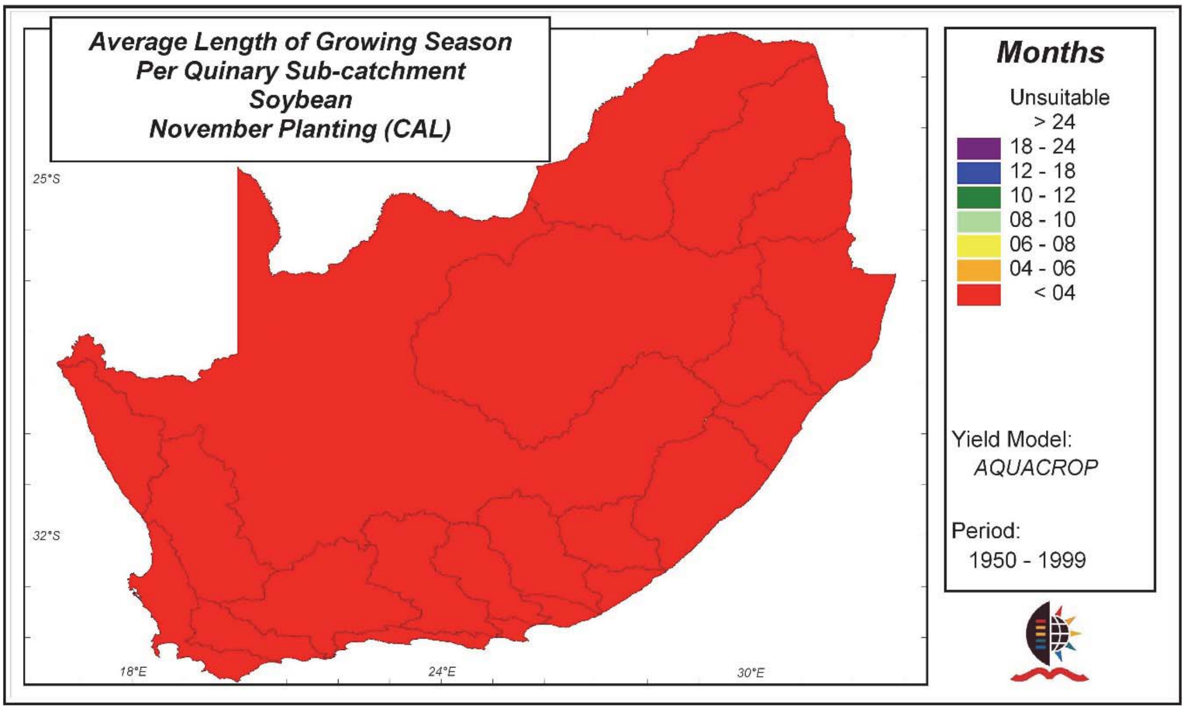
With the model run in GDD mode, the crop cycle varies according to the temperature regime of the sub-catchment. Thus, the time taken for soybean to mature in cold areas is much longer than that for hotter areas. **Figure 29a** and **Figure 29c** highlight the unrealistically long season lengths (> 18 months) associated with the high altitude areas of the Drakensberg and Lesotho highlands. Hence, the length of the growing season based on thermal time can be used to eliminate areas deemed unfeasible for soybean cultivation, with a lower threshold set for commercial farmers than for subsistence farmers.

Differences between the average (**Figure 29a**) and median (**Figure 29c**) crop season length highlights areas where the temperature regime is more variable. This results in extreme (i.e. very short or very long) season lengths, which affect the mean statistic but not the median statistic.



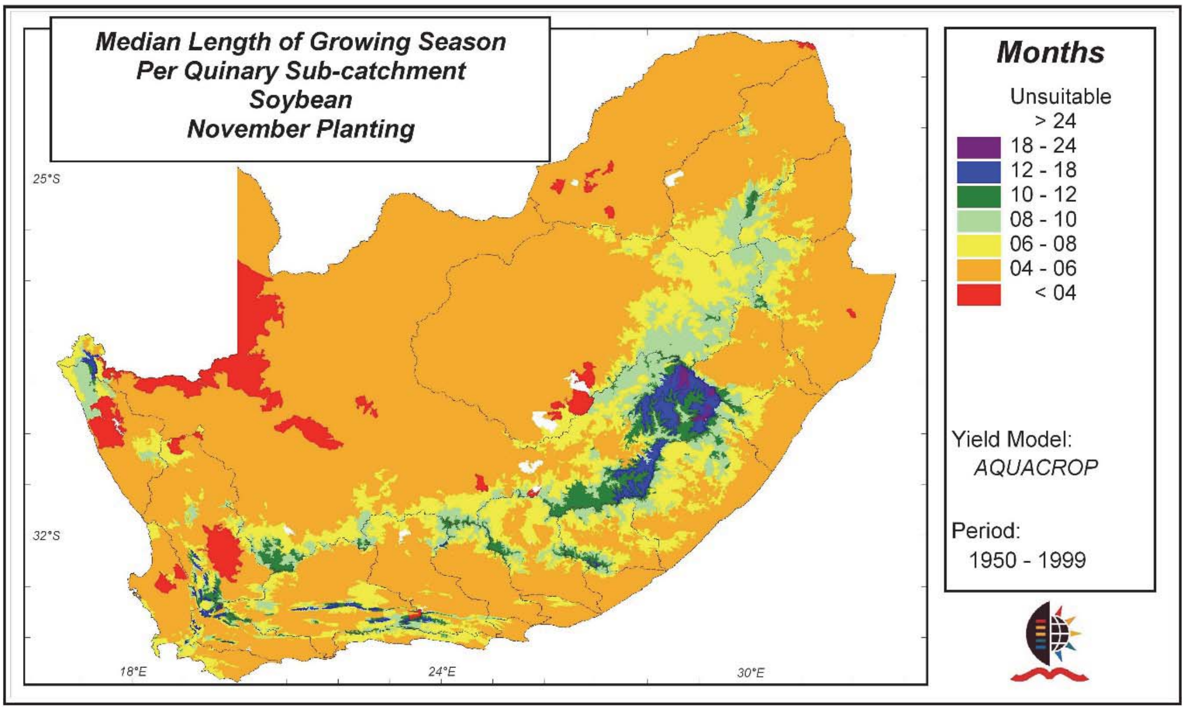
Average Length of Growing Season
Per Quinary Sub-catchment
Soybean
November Planting
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)

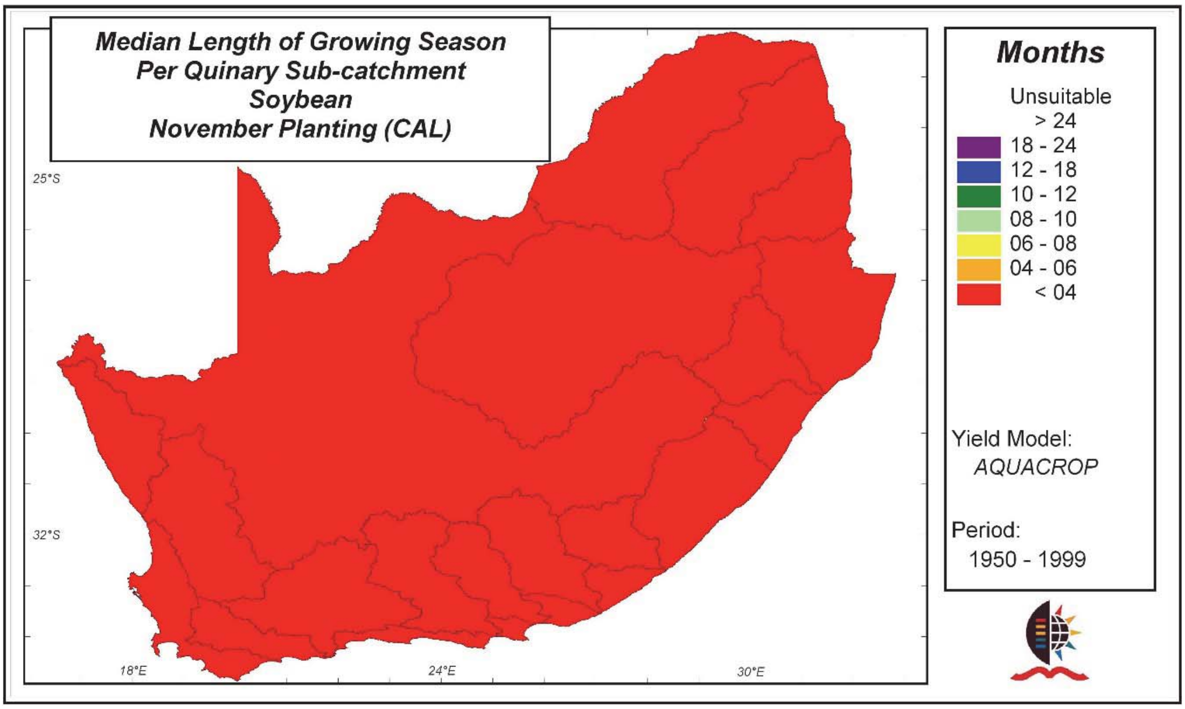


Average Length of Growing Season
Per Quinary Sub-catchment
Soybean
November Planting (CAL)
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



(c)

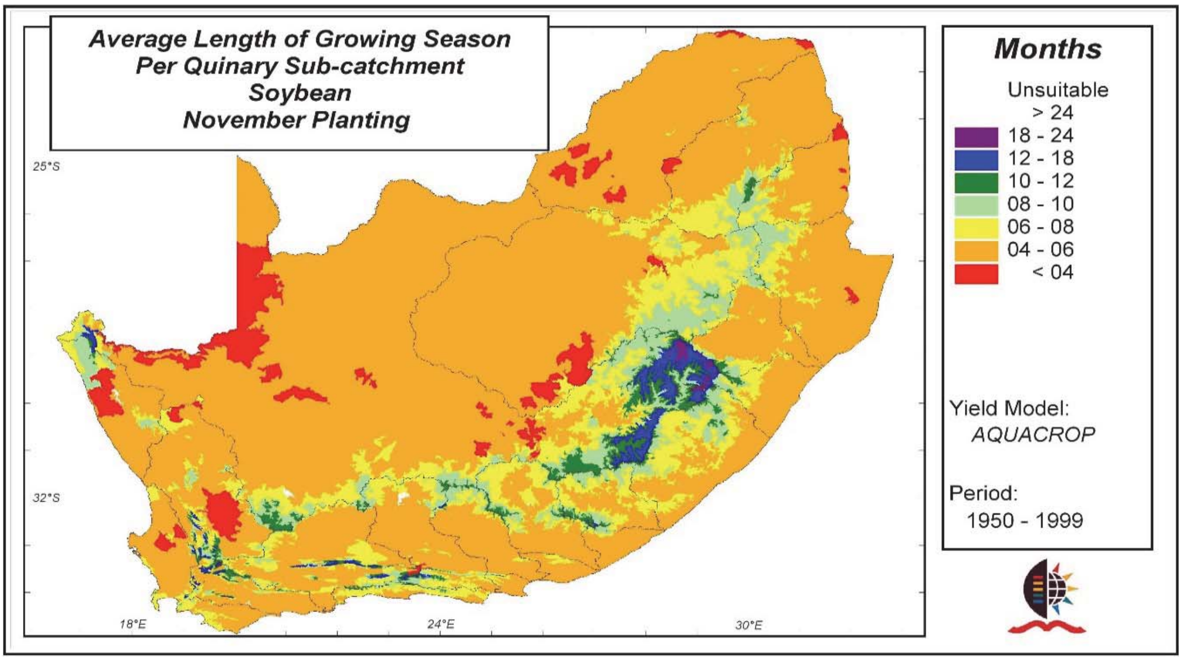


(d)

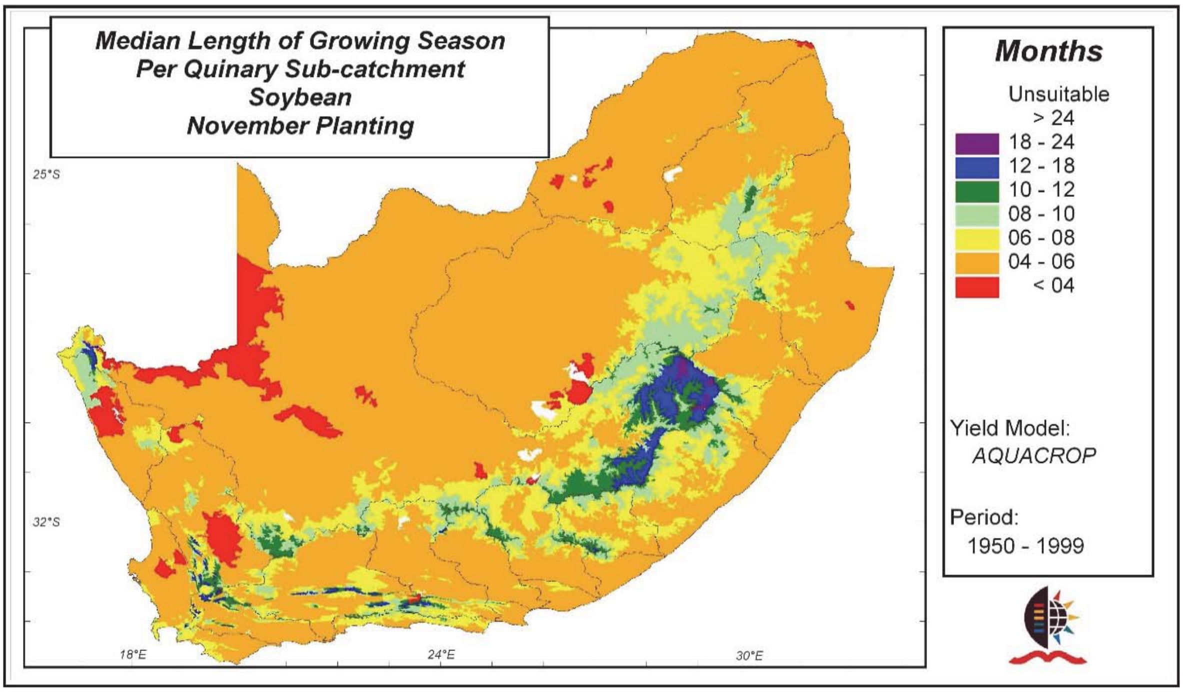
Figure 29 Differences in the length of the growing season derived using thermal (a & c) and calendar (b & d) time for both the mean (a & b) and median (c & d) statistic (as calculated by *AQUACROP*)

Crop season length (*CYC vs. GRO*)

AQUACROP defines the length of the crop cycle from the number of days after emergence to the date the peak yield is attained. It outputs this variable which is called *CYC* in this document, from which the mean (**Figure 30a**) and median statistic ((**Figure 30b**) were calculated.



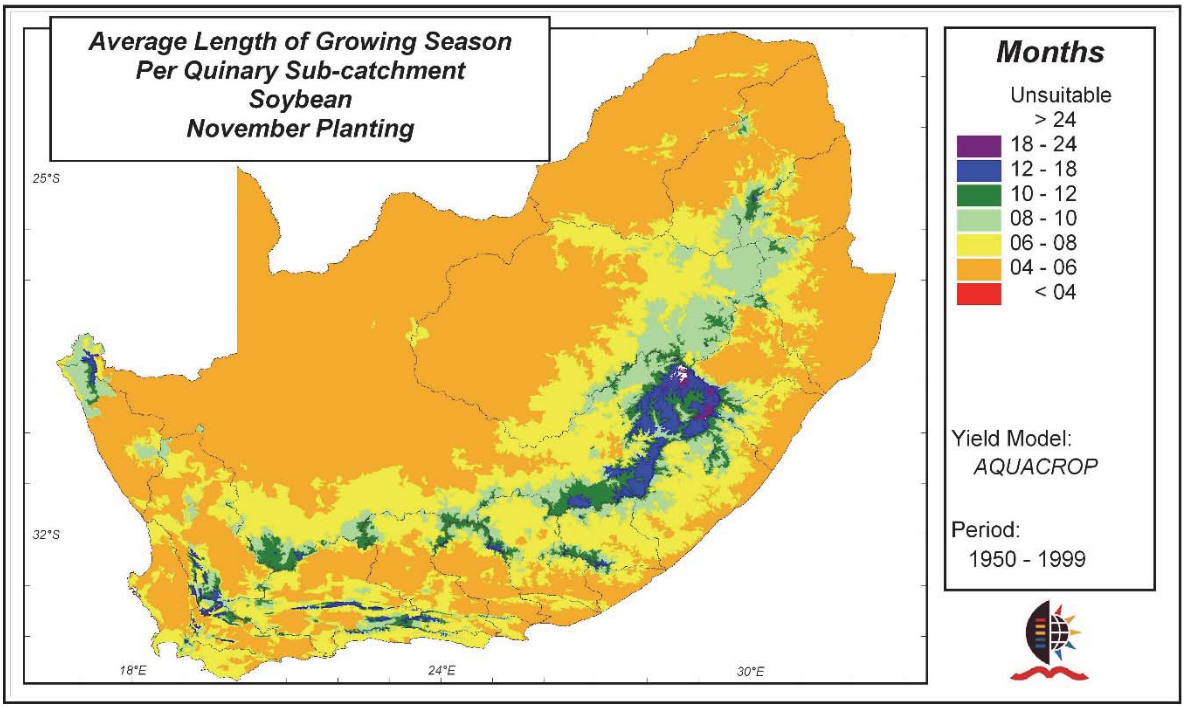
(a)



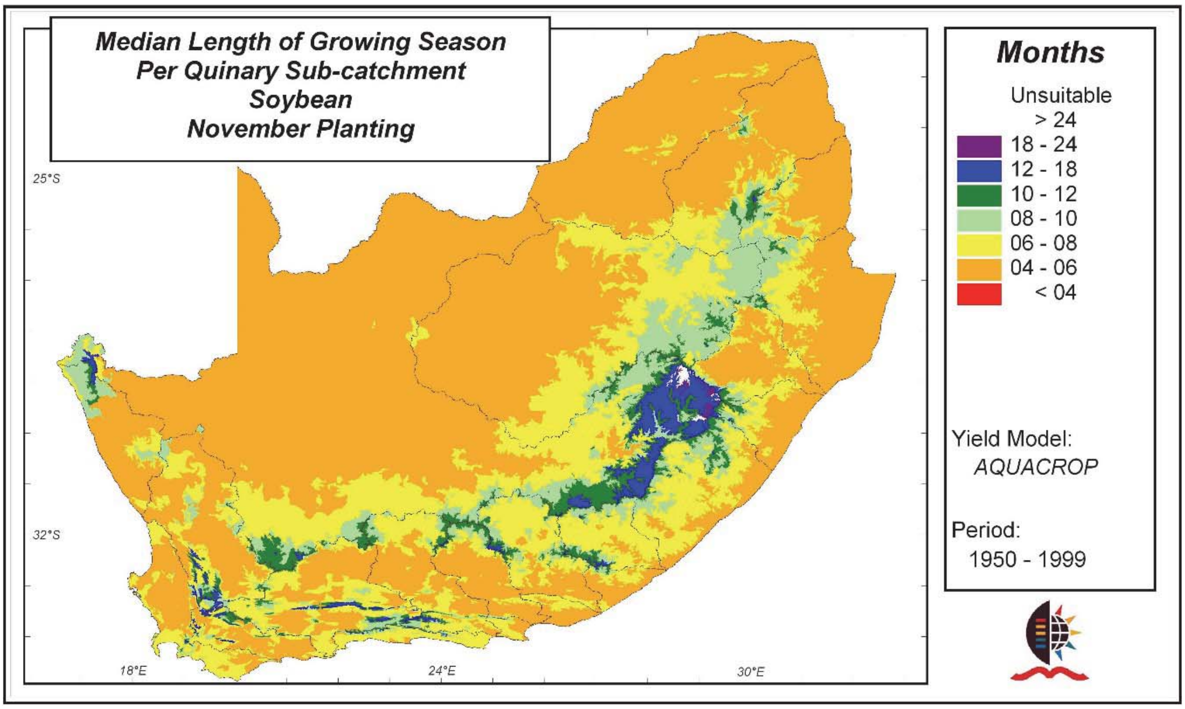
(b)

Figure 30 Length of the growing season derived using thermal time for both the mean (a) and median (b) statistic, as calculated by *AQUACROP* (called *CYC*)

As noted earlier, the length of the growing season length was also calculated as the number of days from planting to the crop maturity date. The mean (**Figure 31a**) and median statistic (**Figure 31b**) were calculated for this variable, which is referred to as *GRO* in this document.



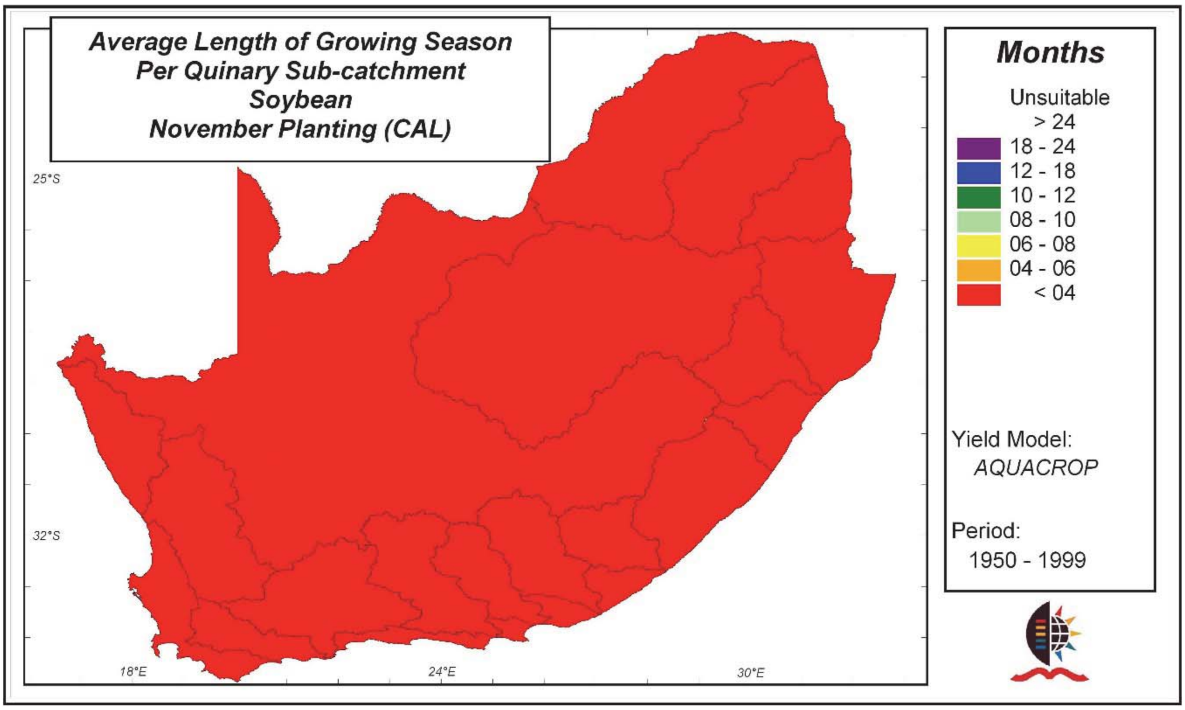
(a)



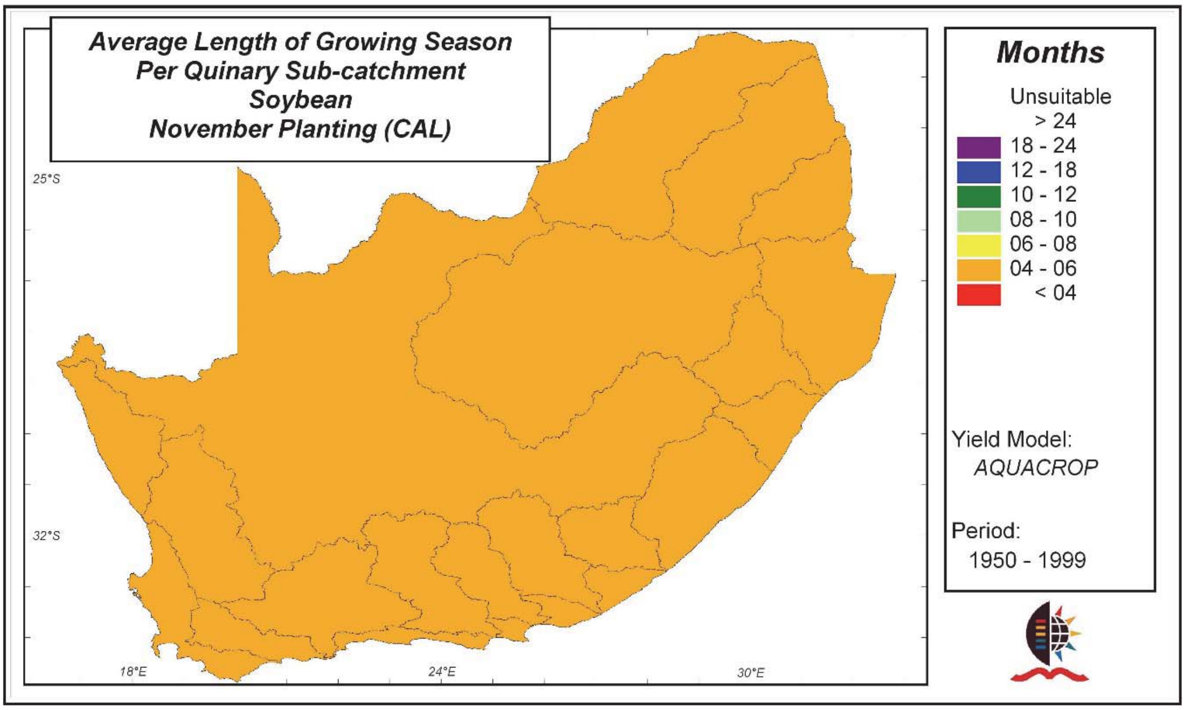
(b)

Figure 31 Length of the growing season derived using thermal time for both the mean (a) and median (b) statistic, as calculated via the crop maturity date (called *GRO*)

It must be noted that *CYC* is always shorter than *GRO*. This is clearly illustrated in **Figure 32** where the length of the growing season is based on calendar days. For soybean, *CYC* ranges from is 11 to 121 days (< 4 months) as shown in **Figure 32a** (red areas), with only 69 quinaries exhibiting average values below 100 days.



(a)



(b)

Figure 32 Differences in the mean length of the growing season derived using calendar time, as calculated by a) *AQUACROP* and b) via the crop maturity date

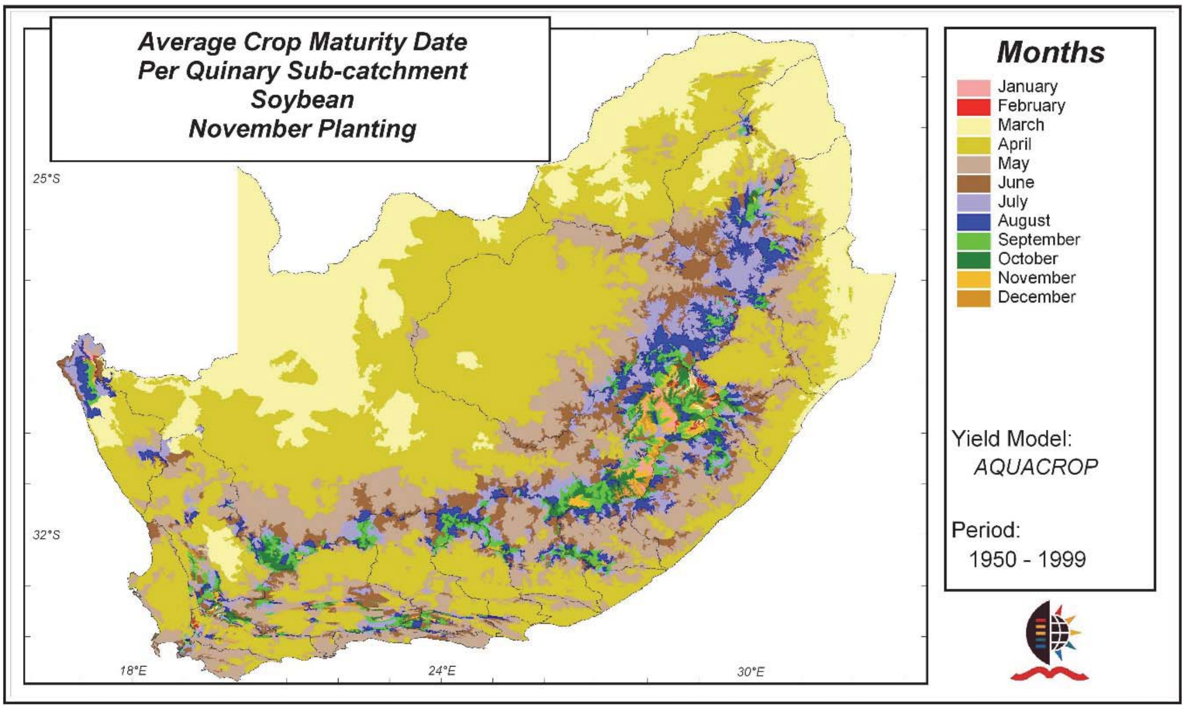
On the other hand, *GRO* averages 130 days or 4.32 months as shown in **Figure 32b** (orange areas). Based on these differences, the decision was made to map both *CYC* and *GRO* to represent the length of the growing season. **However, *GRO* is preferred over *CYC* to represent the length of the crop growing season**.

GRO is determined by accumulating GDD from planting to a defined threshold value called "*Total length of crop cycle in growing degree-days*". This threshold is also called "*GDDays: from transplanting to maturity*" or "*GDDays: from sowing to maturity*" in the crop parameter file. These two thresholds are specified in the crop parameter file and is thus specific for each crop.

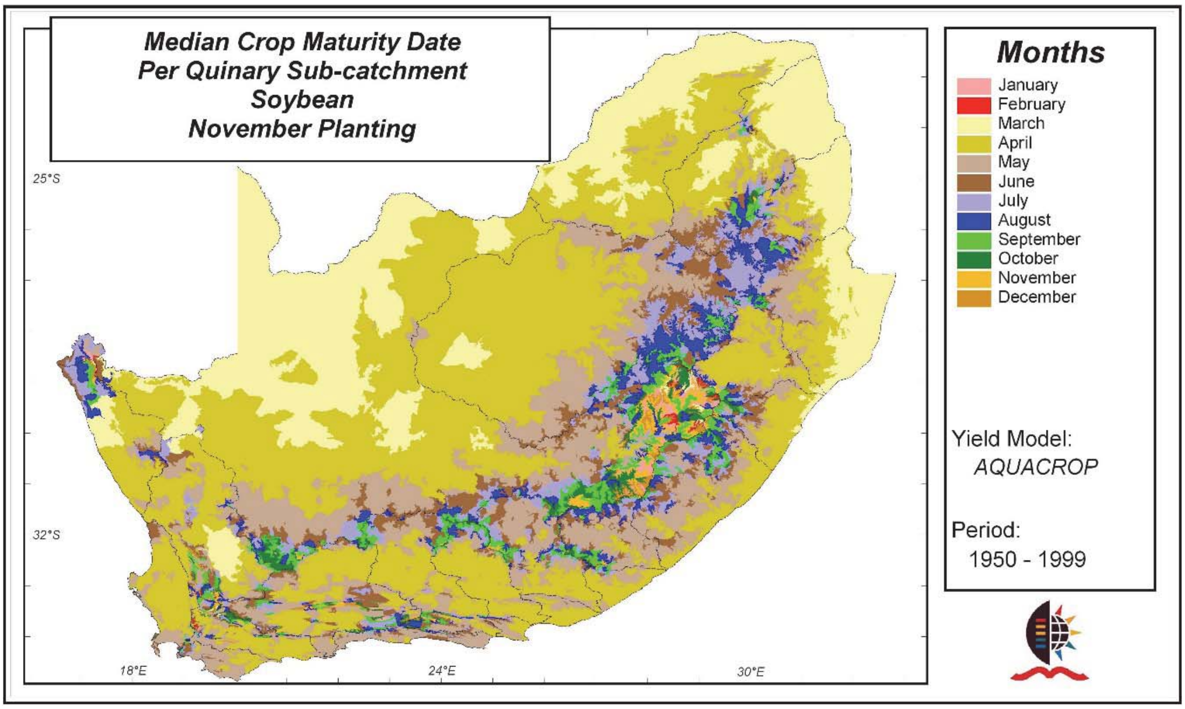
Crop maturity month

The month in which the crop matures was extracted for the GDD mode. This output represents the month in which the crop is ready for harvesting. The harvest month varies spatially when derived using the GDD mode, with differences between the mean and median shown in **Figure 33a** and **Figure 33b** respectively. In KwaZulu-Natal, the harvest month is typically March for the hotter areas along the coast, which is delayed until April or May for the cooler inland areas. By comparison, the harvest month is always March (the 10th) for a calendar-based (CAL) crop season of 130 days for soybean.

The harvest month is particularly useful for sugarcane, since only two ratoon dates were considered (i.e. 1st February and 1st April). These two dates may not be presentative or applicable to all areas. In reality, sugarcane is typically harvested from April to October, when the sugarcane mills are operating. The mills close in late December until March for maintenance. Since the growing season for sugarcane varies from 12 to 24 months, the harvest month may not fall in the desired "window" (i.e. April to October). This implies that an alternative planting date is more applicable to these areas.



(a)



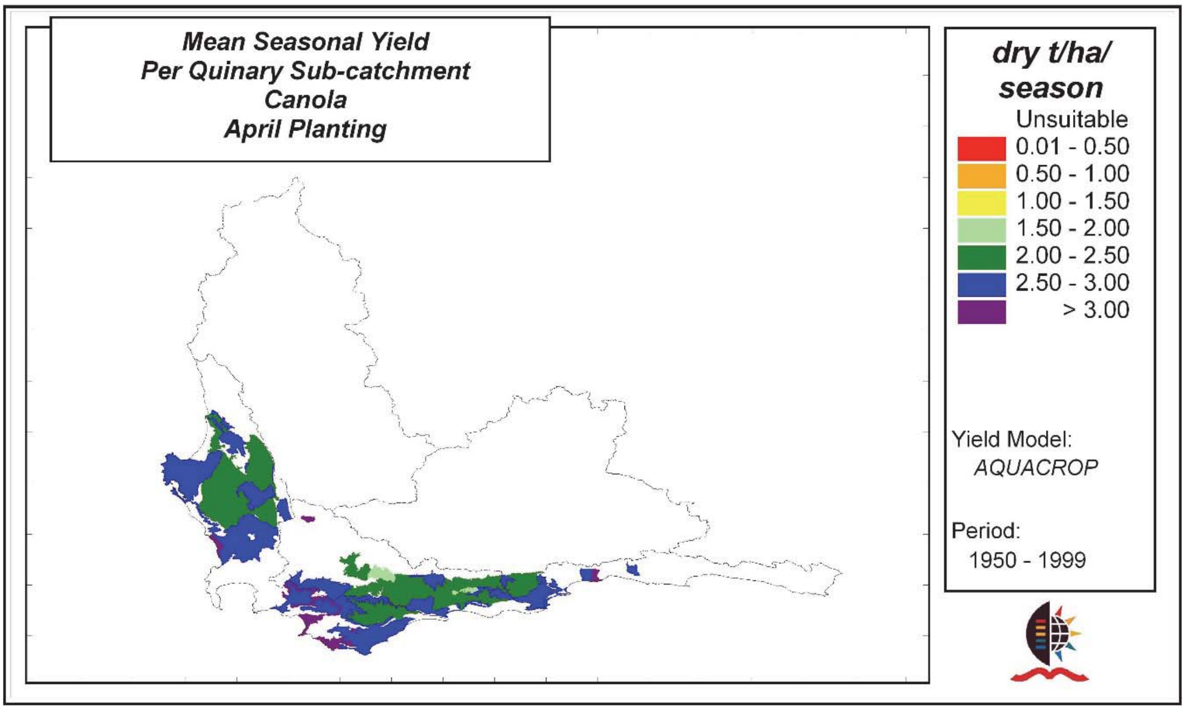
(b)

Figure 33 Harvest month derived from crop cycles based on thermal time for both the mean (a) and median (b) statistic

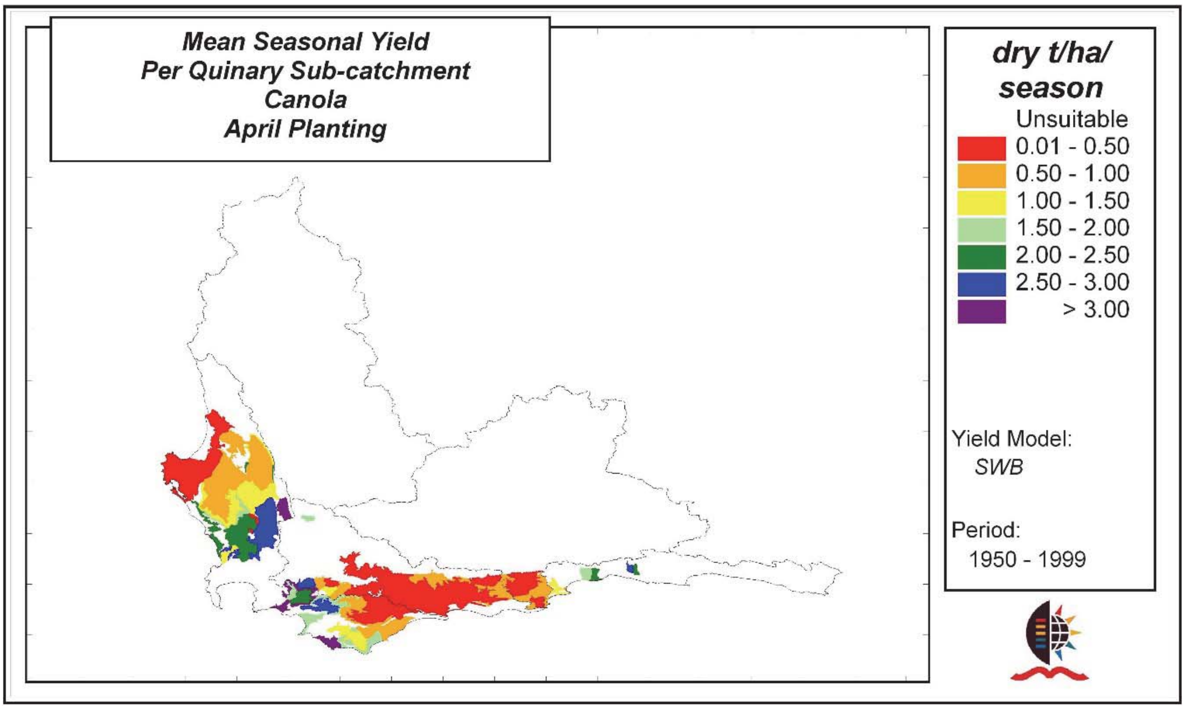
4.2.3.2 *AQUACROP* vs. *SWB*

In order to verify the output from *AQUACROP* for canola, it was compared to yield and WUE data calculated using the *SWB* model for 113 quinary sub-catchments located in the Western Cape. The *AQUACROP* model predicted higher yield (**Figure 34a**) and WUE (**Figure 36a**) for canola grown in the Western Cape, than did the *SWB* model (**Figure 34b** & **Figure 36b**). The variability in yield (**Figure 35b**) and WUE (**Figure 37b**) simulated by *SWB* is also much higher than similar output from the *AQUACROP* model (**Figure 35a** & **Figure 37a**). Ideally, the two models should have produced similar trends. It is unknown why the two models produced contrasting output.

Yield data obtained from Fouché (2015) for canola grown in the Western Cape from 2001 to 2011 ranged from 1.5 t ha^{-1} (Malmesbury) to 3.3 t ha^{-1} (Riviersonderend). Similarly, yields ranged from 2.4 to 3.2 t ha^{-1} for the period 1990-1992. The yield obtained at Malmesbury represented a dry year (2004), with 2.6 t ha^{-1} recorded in 2002. The average canola yield estimated by *AQUACROP* (from 1950 to 1999) for these quinaries ranged from 2.26 to 2.96 t ha^{-1}, which was higher than the range of 0.33 to 2.28 t ha^{-1} predicted by *SWB*. This suggests that *AQUACROP* yield estimates are higher than observed yields. Similarly, *SWB* yield estimates are lower than observations.

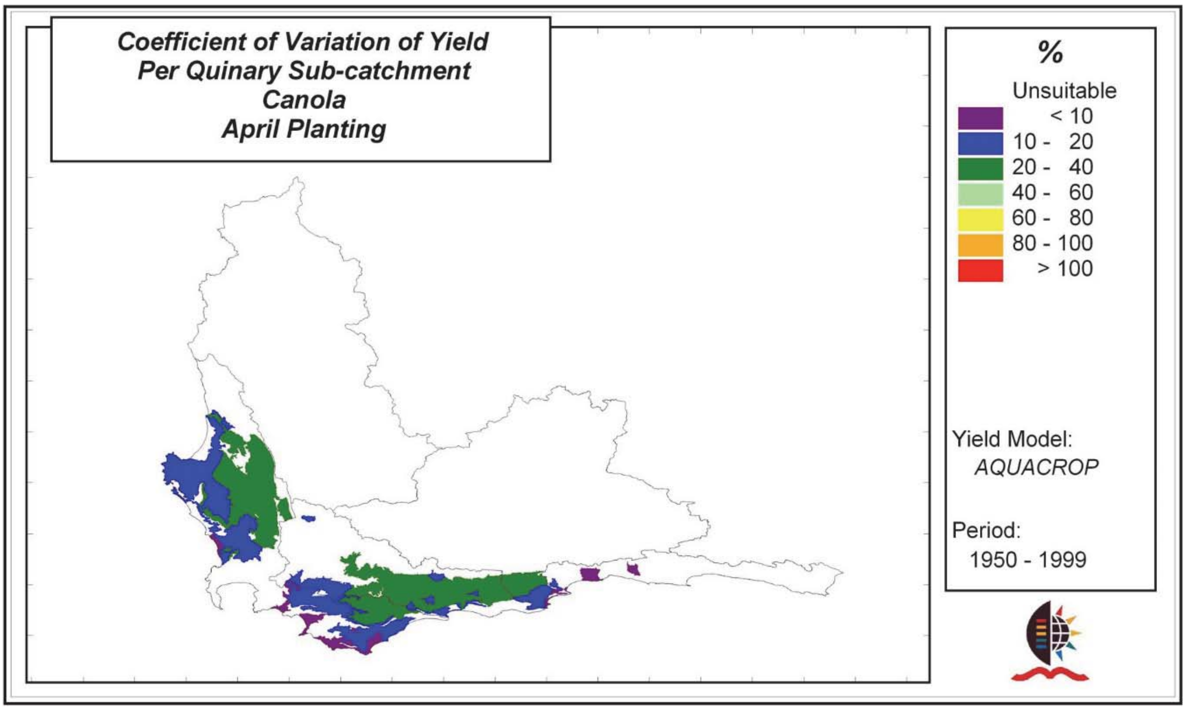


(a)

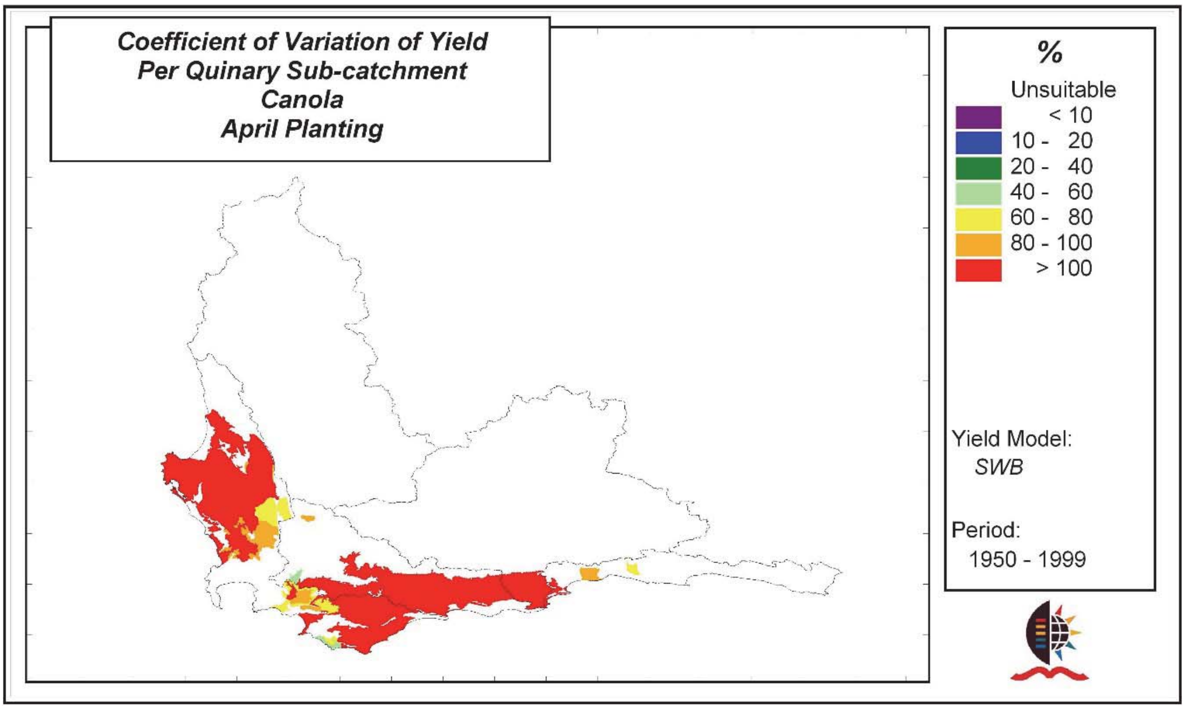


(b)

Figure 34 Differences in seasonal yield derived using the *AQUACROP* (a) and *SWB* (b) models for 113 quinaries in the Western Cape region

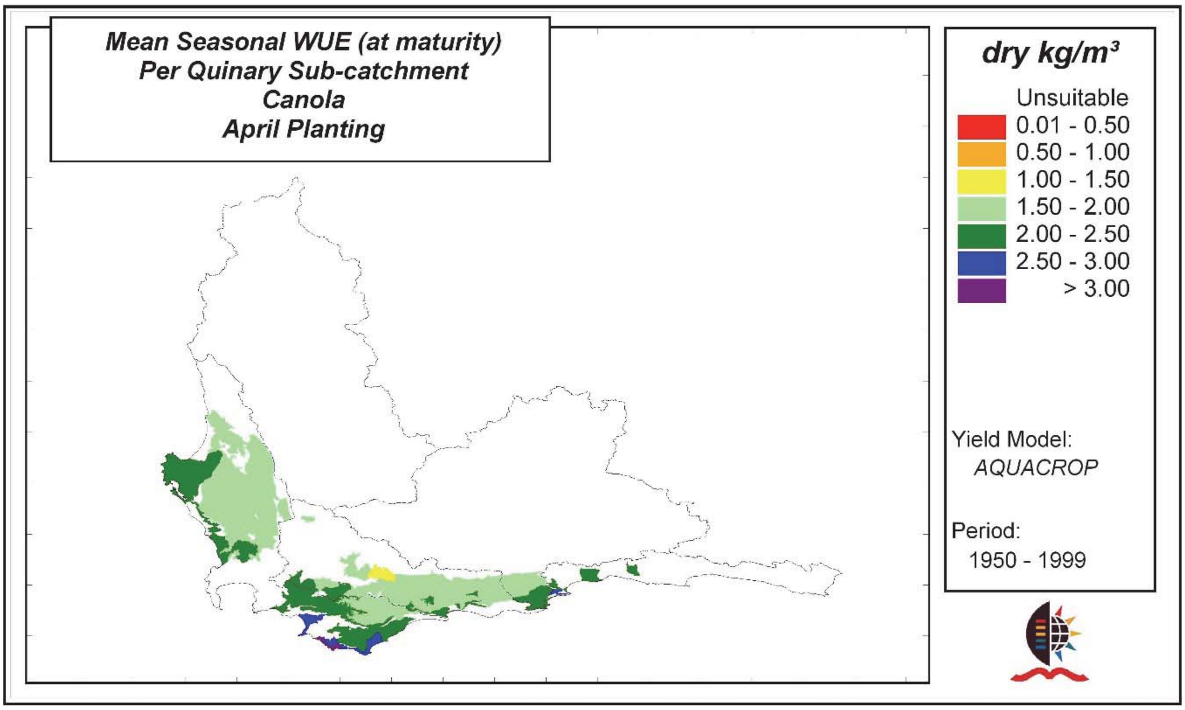


(a)

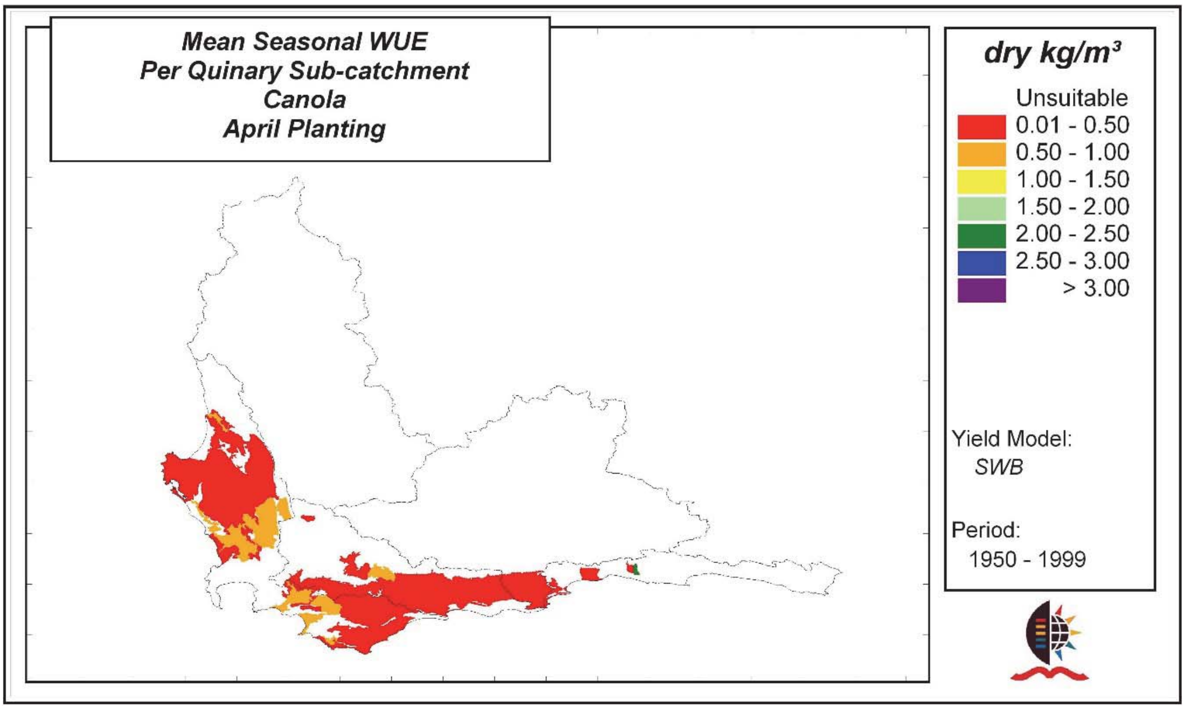


(b)

Figure 35 Differences in yield variability derived using the *AQUACROP* (a) and *SWB* (b) models for 113 quinaries in the Western Cape region

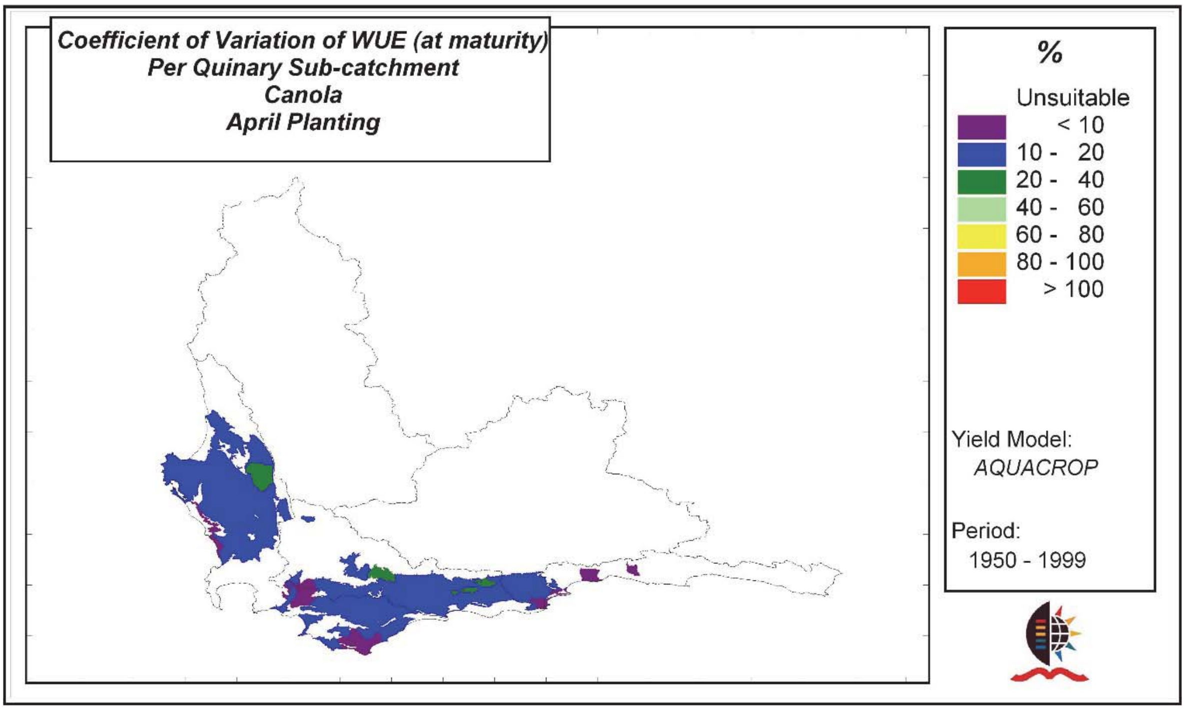


(a)

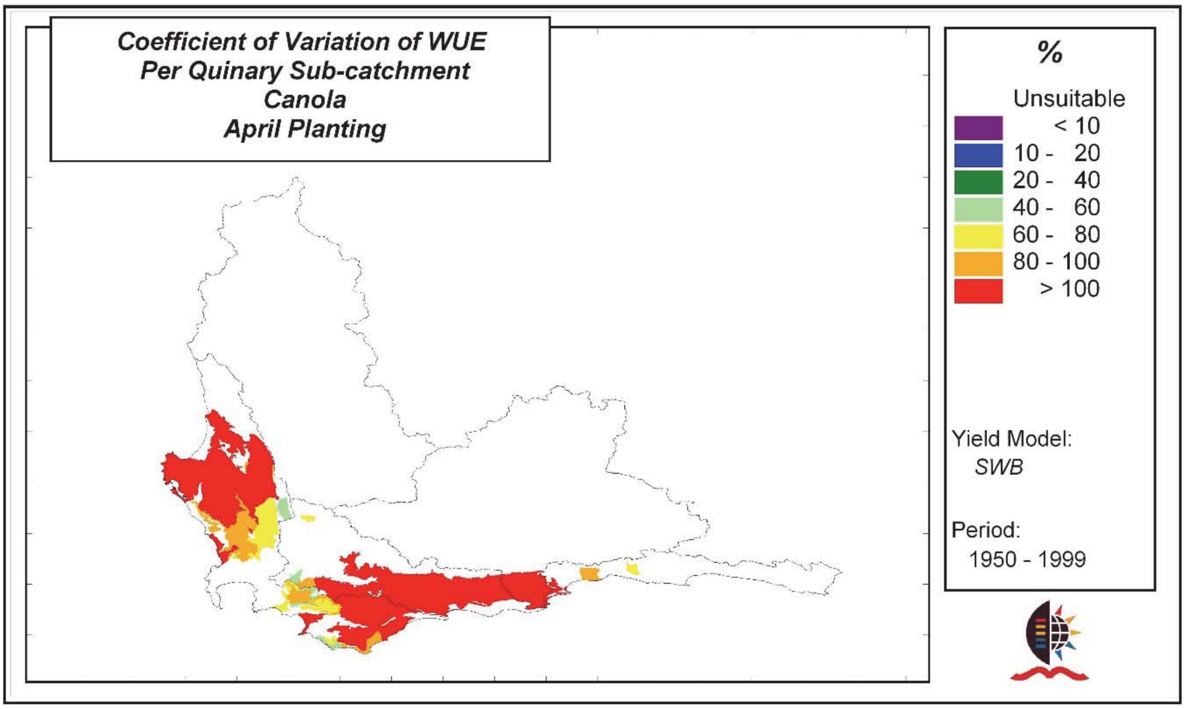


(b)

Figure 36 Differences in water use efficiency derived using the *AQUACROP* (a) and *SWB* (b) models for 113 quinaries in the Western Cape region



(a)



(b)

Figure 37 Differences in variability of water use efficiency derived using the *AQUACROP* (a) and *SWB* (b) models for 113 quinaries in the Western Cape region

A canola manual produced by the Protein Research Foundation published a map of canola yield potential as shown in **Figure 38** (Cumming *et al*., 2010). The very high yield areas correspond to 400 mm or more of seasonal rainfall accumulated from April to October. Seasonal rainfall totals of 200 to 300 mm should yield 1 to 2 t ha^{-1} respectively (Cumming *et al*., 2010). However, a yield of 4 t ha^{-1} was obtained at Riversdal in 2013 (Fouché, 2015), which is well above the low to average yield potential for that region as shown in **Figure 38**. As noted by Fouché (2015), canola yield is better determined by stored soil moisture, rather than seasonal rainfall. For example, a farmer in Heidelberg (Western Cape) obtained 1.8 t ha^{-1} in 2008 with a seasonal rainfall total of only 140 mm (Fouché, 2015).

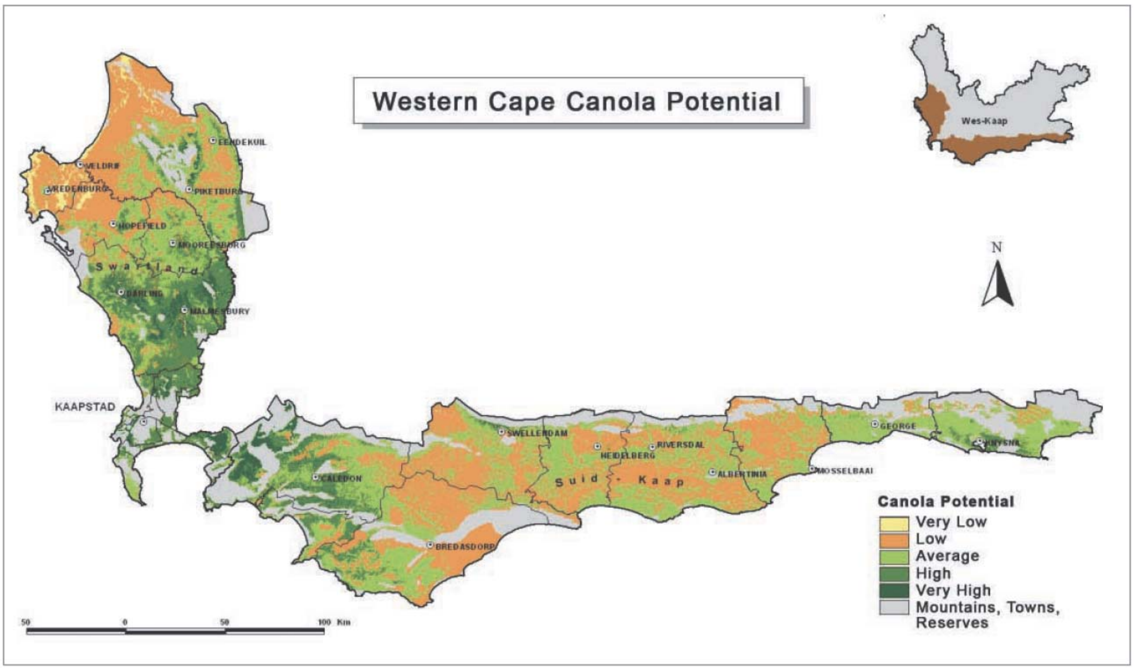
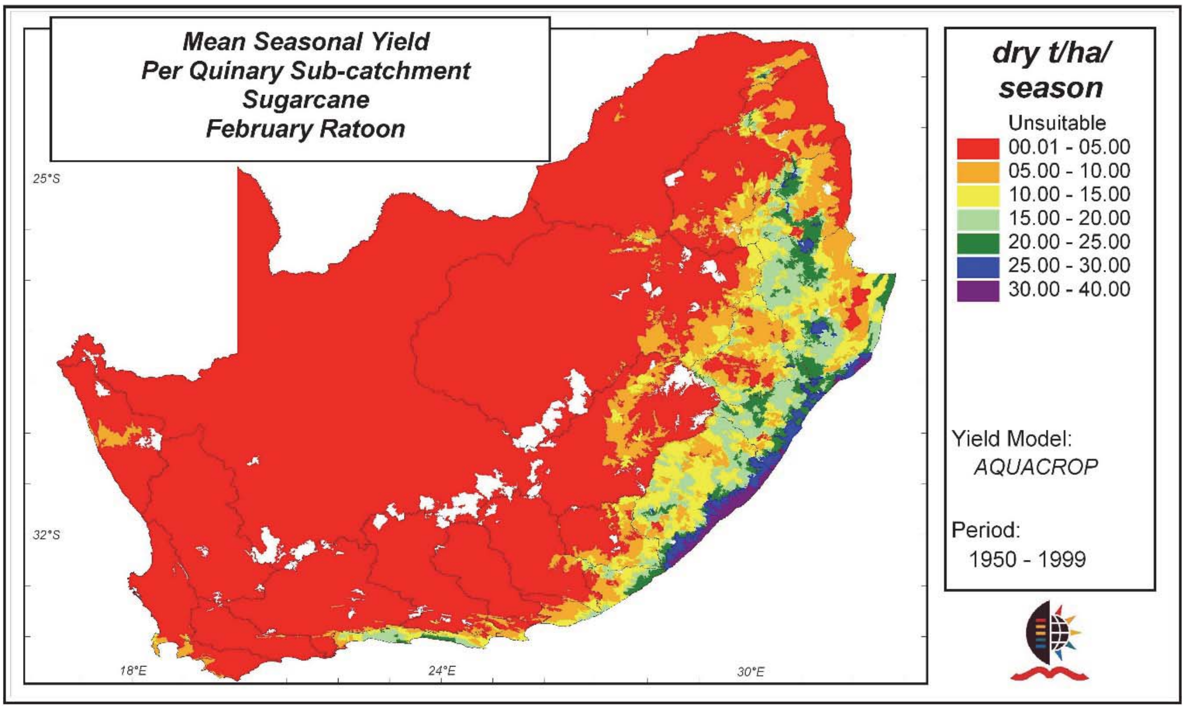


Figure 38 Yield potential of canola in the Western and Southern Cape in relation to soil and climatic conditions (Cumming *et al*., 2010)

The following sub-sections represent a comparison of, *inter alia*, simulated yield and WUE for the bioethanol and biodiesel feedstocks considered for modelling. Results based on the mean and median statistics as well as the coefficient of variation are presented.

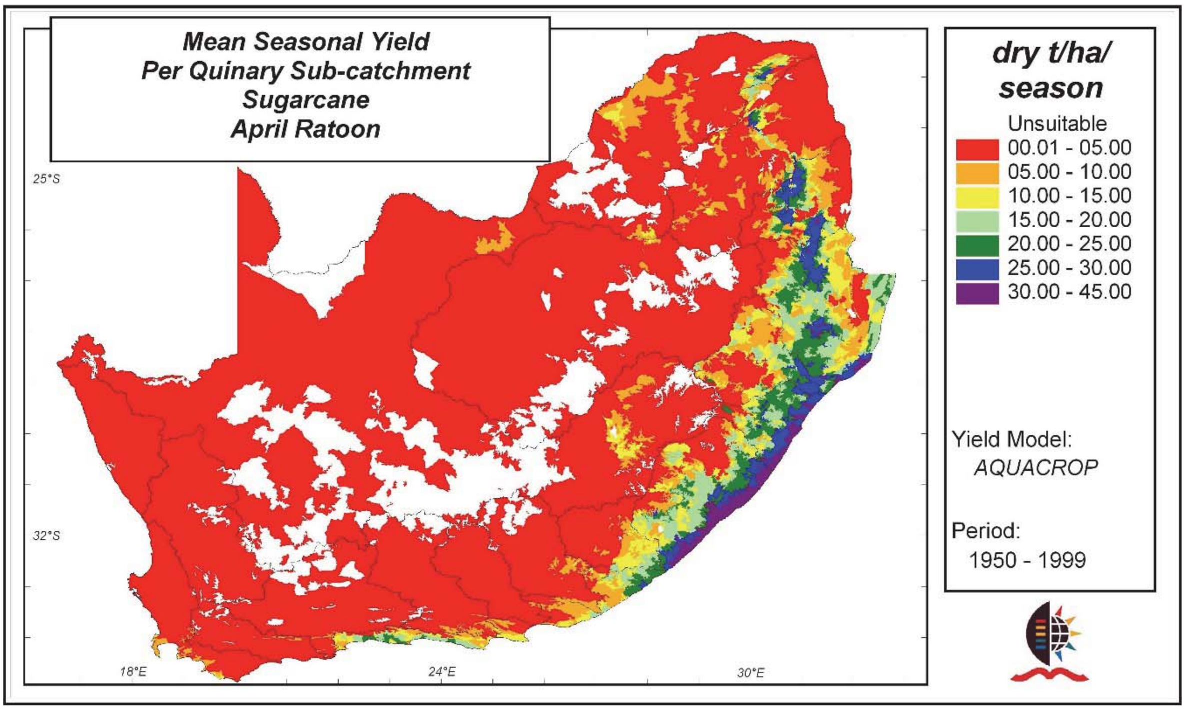
4.2.3.3 Mean seasonal yield

The mean seasonal yield for selected bioethanol feedstocks planted on different dates is shown in **Figure 39**. Yield estimates in dry tons per hectare (dry t ha^{-1}) were derived using the *AQUACROP* model (run in GDD mode) for each of the 5 838 quinary sub-catchments. The mean yield was calculated from up to 50 seasonal estimates for dryland (i.e. rainfed) growing conditions. The maps show that for most crops, the highest yields are attainable along the eastern (and southern) seaboard due to the distribution of summer rainfall. Large parts of the country's interior region, especially towards the western areas, are too dry for rainfed feedstock cultivation.



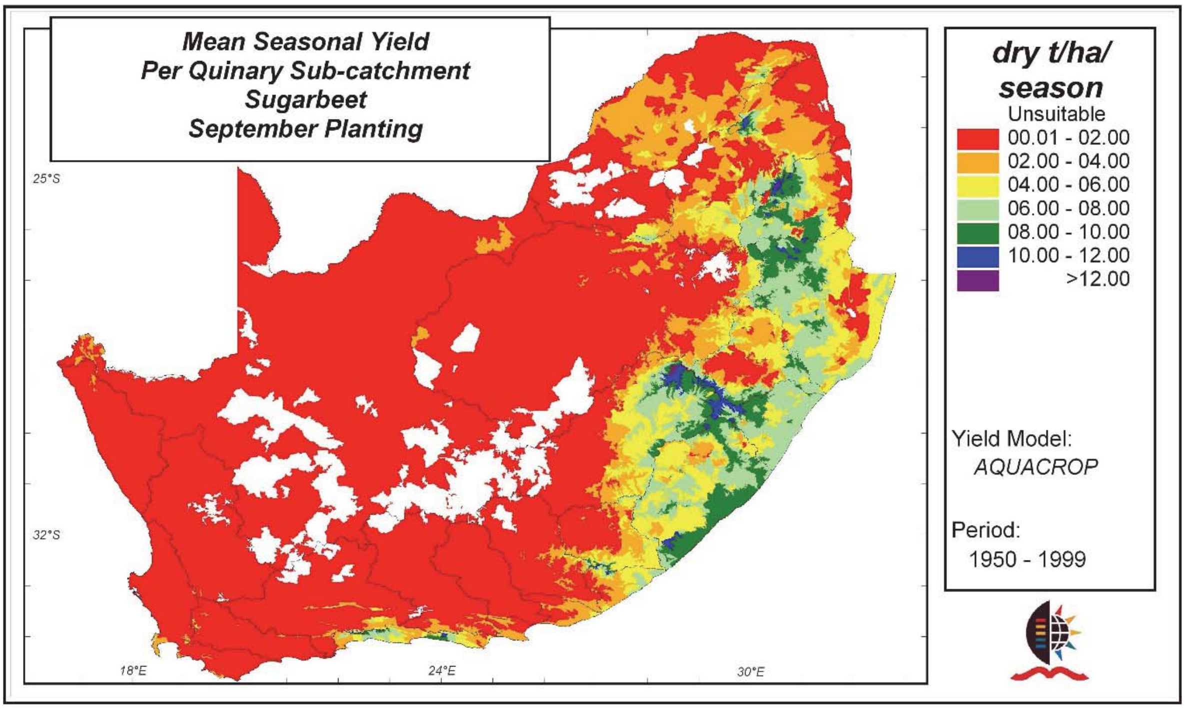
Mean Seasonal Yield
Per Quinary Sub-catchment
Sugarcane
February Ratoon
dry t/ha/
season
Unsuitable
00.01 - 05.00
05.00 - 10.00
10.00 - 15.00
15.00 - 20.00
20.00 - 25.00
25.00 - 30.00
30.00 - 40.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)

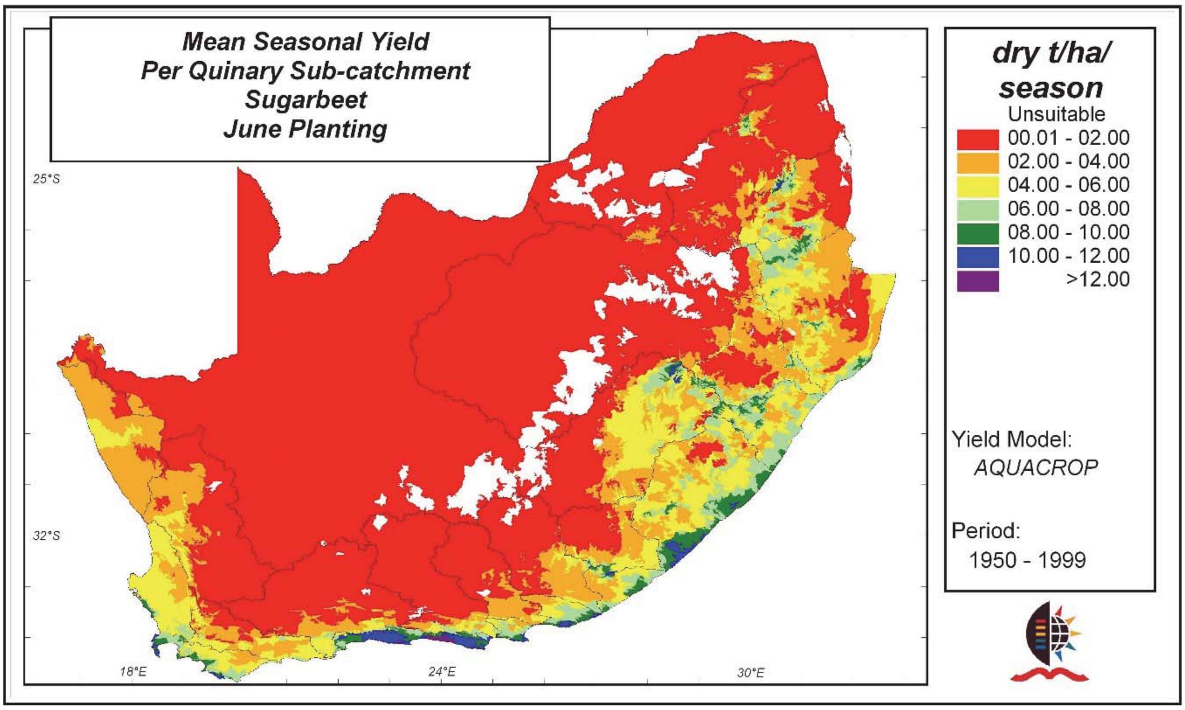


Mean Seasonal Yield
Per Quinary Sub-catchment
Sugarcane
April Ratoon
dry t/ha/
season
Unsuitable
00.01 - 05.00
05.00 - 10.00
10.00 - 15.00
15.00 - 20.00
20.00 - 25.00
25.00 - 30.00
30.00 - 45.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

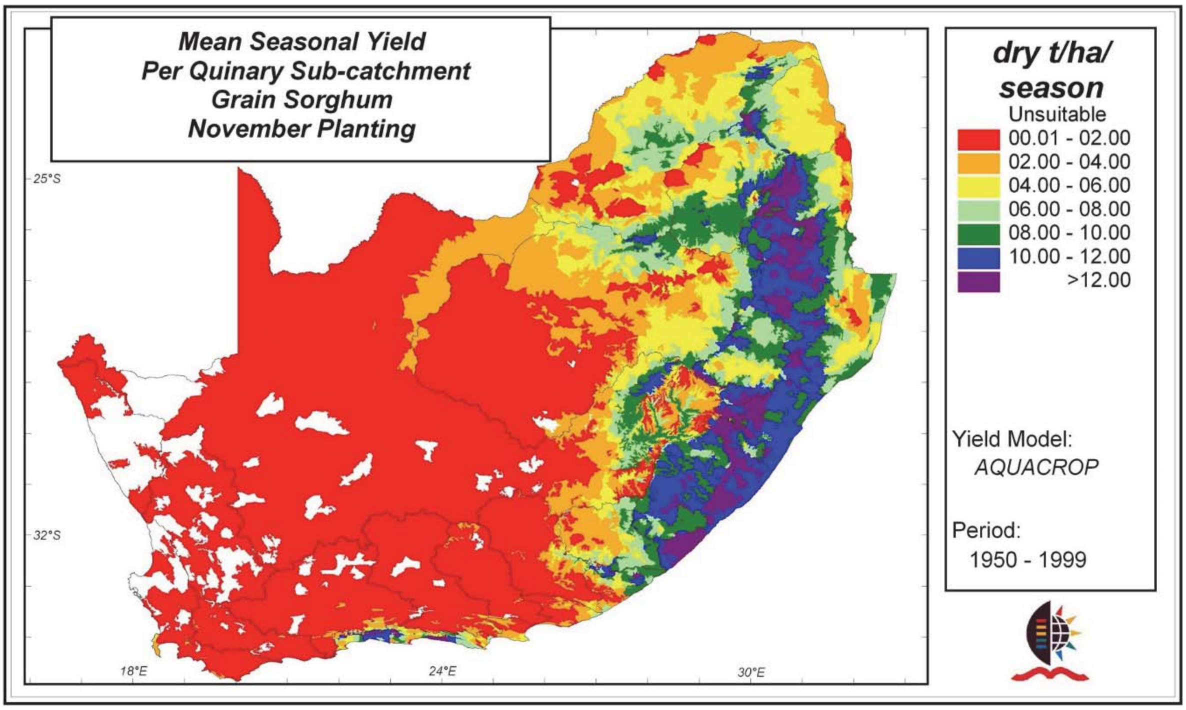
(b)


Mean Seasonal Yield
Per Quinary Sub-catchment
Sugarbeet
September Planting
25°S
32°S
18°E
24°E
30°E
dry t/ha/
season
Unsuitable
00.01 - 02.00
02.00 - 04.00
04.00 - 06.00
06.00 - 08.00
08.00 - 10.00
10.00 - 12.00
>12.00
Yield Model:
AQUACROP
Period:
1950 - 1999

(c)


Mean Seasonal Yield
Per Quinary Sub-catchment
Sugarbeet
June Planting
25°S
32°S
18°E
24°E
30°E
dry t/ha/
season
Unsuitable
00.01 - 02.00
02.00 - 04.00
04.00 - 06.00
06.00 - 08.00
08.00 - 10.00
10.00 - 12.00
>12.00
Yield Model:
AQUACROP
Period:
1950 - 1999

(d)



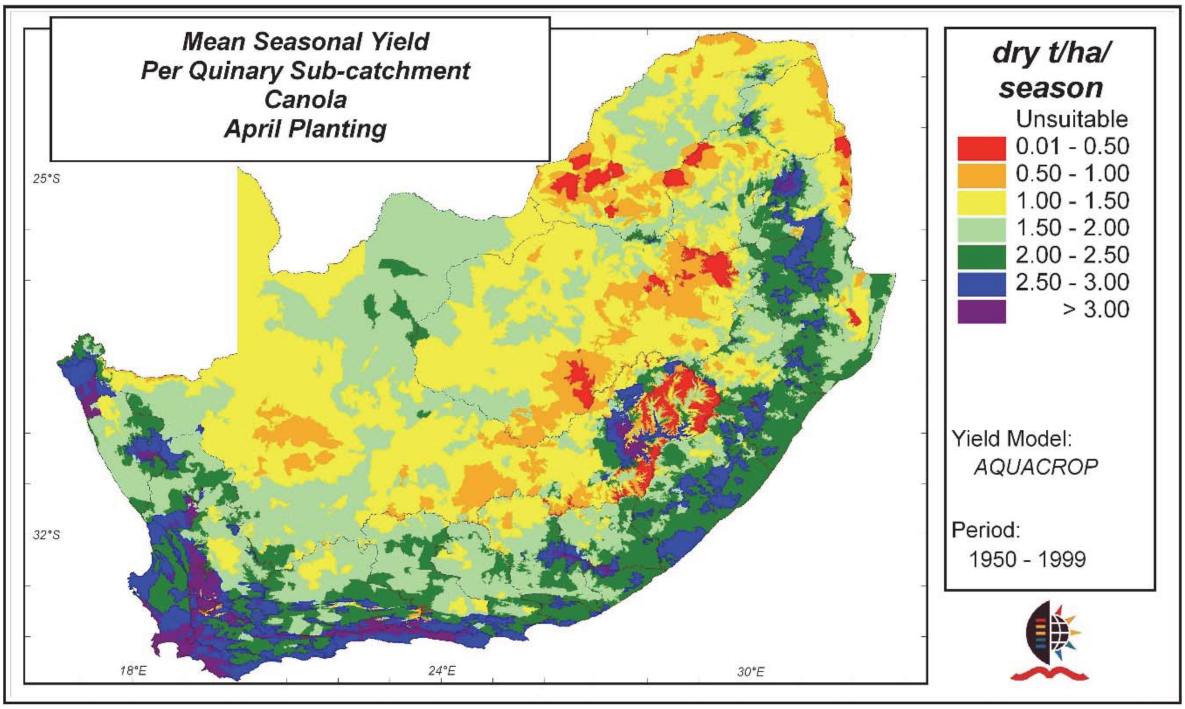
(e)

Figure 39 Mean seasonal yield (dry t ha^{-1}) estimated using *AQUACROP* for selected bioethanol feedstocks (a-e) planted on different dates

The coastal areas in KwaZulu-Natal and the Eastern Cape are most favourable for sugarcane production. A winter (i.e. June) planting of sugarbeet is likely to require supplemental irrigation to establish the crop. This is particularly the case for the Cradock region in the Eastern Cape. Grain sorghum exhibits the most potential as a bioethanol feedstock due to the large expanse of land area suited to its growth.

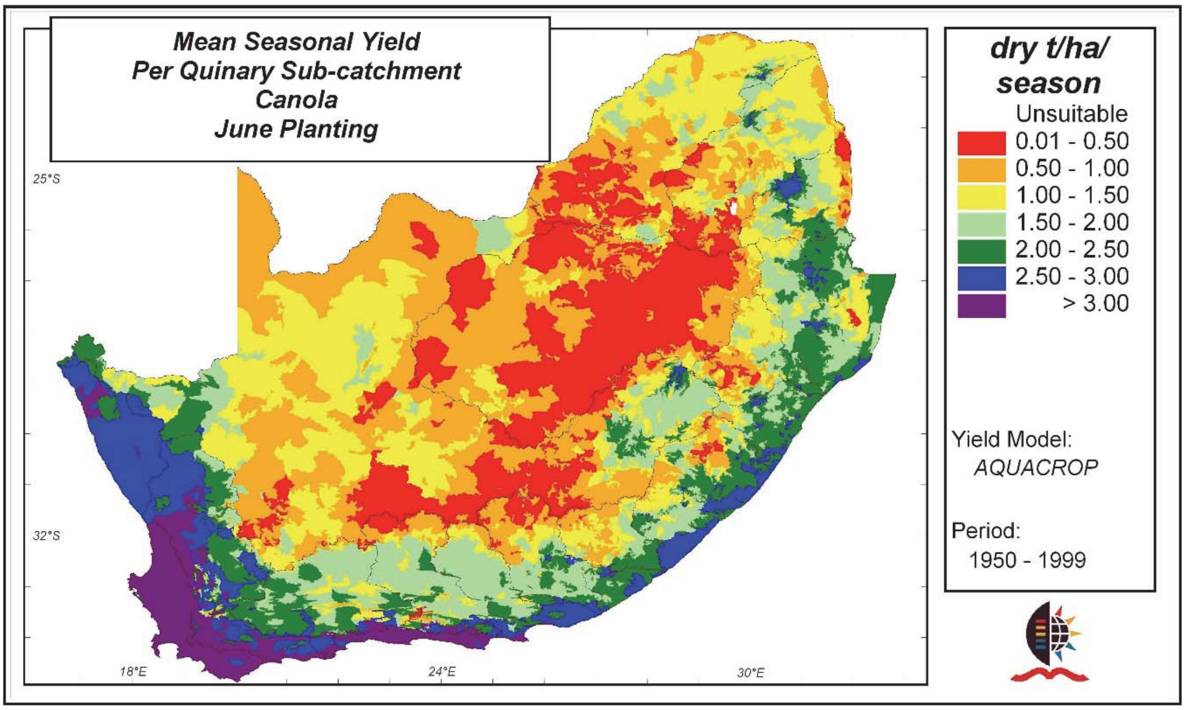
As noted, *AQUACROP* outputs yield in dry tons per unit land area (i.e. hectare). If information is not available, a general conversion factor, in terms of kg of dry matter per kg fresh weight, of 0.20 to 0.25 may be used (Raes *et al*., 2012c). According to Olivier (2014), sugarbeet from Komatipoort were separated into tubers and leaves before drying. The dry matter content (%) of the tubers varied from 16.09 to 16.30% for the well-watered and water-stressed treatments respectively. Similarly, the dry matter content of the leaves varied from 6.55% (well-watered) to 7.53% (water stressed). For sugarcane, the conversion of dry to fresh yield ranges by a factor of 2.86 to 3.33. This is based on cane stalks containing approximately 30 to 35% dry matter.

The mean seasonal yield for selected biodiesel feedstocks planted on different dates is shown in **Figure 40**. The western and southern Cape regions are most favourable for canola production, where the majority (≈99%) of canola is cultivated. Canola planted in April exhibits the most potential as a biodiesel feedstock due to the large expanse of land area suited to its growth. Large parts of the eastern seaboard are too cold for viable soybean production.



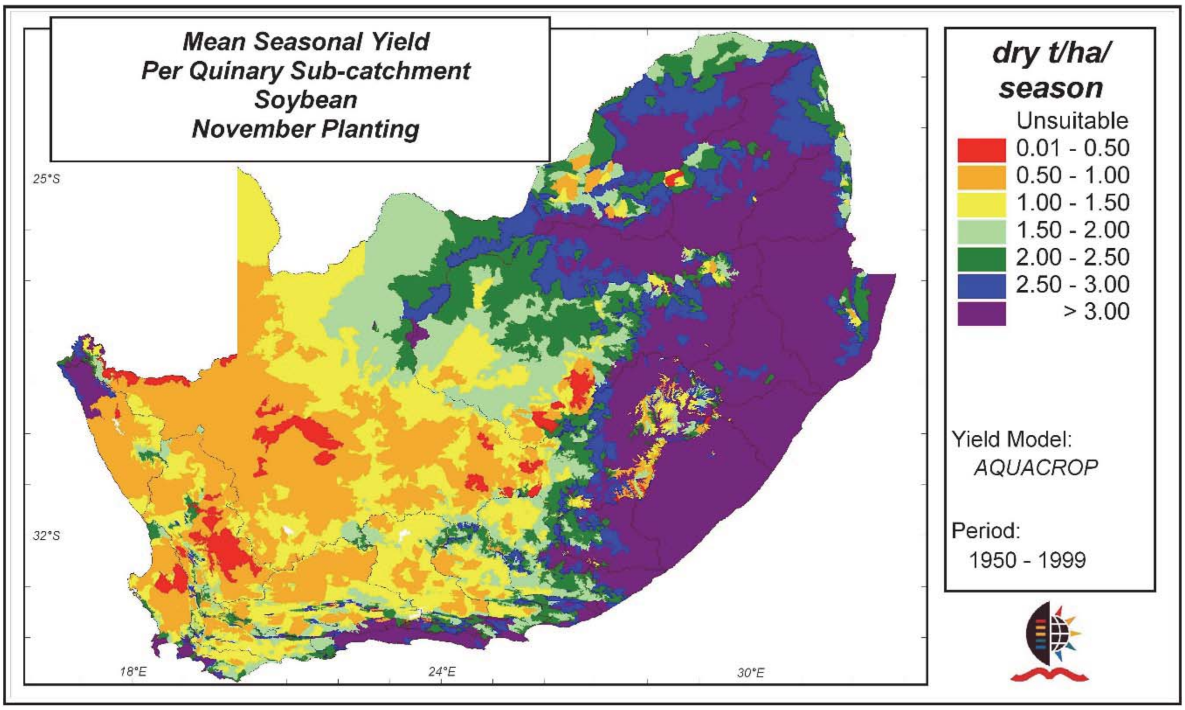
Mean Seasonal Yield
Per Quinary Sub-catchment
Canola
April Planting
dry t/ha/
season
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)



Mean Seasonal Yield
Per Quinary Sub-catchment
Canola
June Planting
dry t/ha/
season
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



(c)

Figure 40 Mean seasonal yield (dry t ha^{-1}) estimated using *AQUACROP* for selected biodiesel feedstocks (a-c) planted on different dates

4.2.3.4 Median seasonal yield

The median seasonal yield maps for bioethanol and biodiesel feedstocks are presented in **Figure 74** and **Figure 75** respectively (c.f. **APPENDIX B**). The difference between the mean and median is explained by considering the time series of seasonal yields given in **Table 11**. The average of the seven yields is 0.05 dry t ha^{-1}, which would appear red in the yield map. The median, however, represents the value that is midway in the time series, which is zero in this case and thus, would appear white in the yield map. The example highlights the fact that the median statistic is less influenced by very low or very high values.

Table 11 Time series of seven seasonal yield estimates, ranked from lowest to highest, with a median of 0.00 dry t ha^{-1} and a mean of 0.05 dry t ha^{-1}

Minimum			Median	Mean		Maximum
0.00	0.00	0.00	0.00	0.05	0.10	0.20

The maps in **APPENDIX B** show an expansion of area deemed unsuitable for feedstock cultivation. To re-cap, the areas in white represent a median yield of zero dry tons per hectare and are not considered suitable for feedstock cultivation. The median statistic therefore assists in identifying areas deemed suitable for feedstock cultivation, by eliminating areas with very low mean yields. For this reason, both the mean and median statistic are reported in this study, although it is acknowledged that the mean is the most commonly reported statistic in crop science literature.

4.2.3.5 Mean annual yield

Owing to the variability in season length for sugarcane in South Africa (typically 11 to 24 months), annualised yield maps for sugarcane transplanted in February and April are given in **Figure 76a** and **Figure 76b** respectively (c.f. **APPENDIX C**). These maps allow for the comparison of attainable yield between regions. The annualised yield (YLD_A in dry t ha^{-1}) was calculated using the formula:

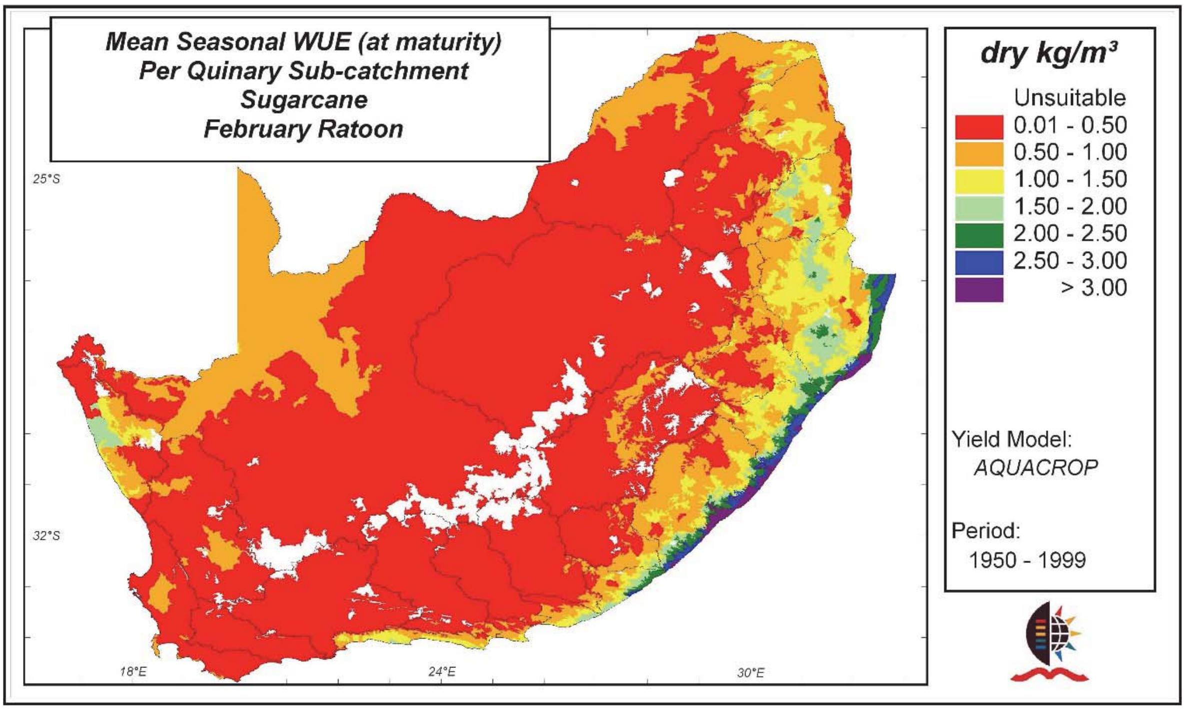
$$YLD_A = 365 \cdot YLD / GRO \quad \textbf{Equation 1}$$

where *YLD* is the seasonal sugarcane yield (dry t ha^{-1}) and *GRO* is the growing season length (days). As noted in **Section 4.2.3.1**, *GRO* is preferred over *CYC* to represent the length of the crop growing season.

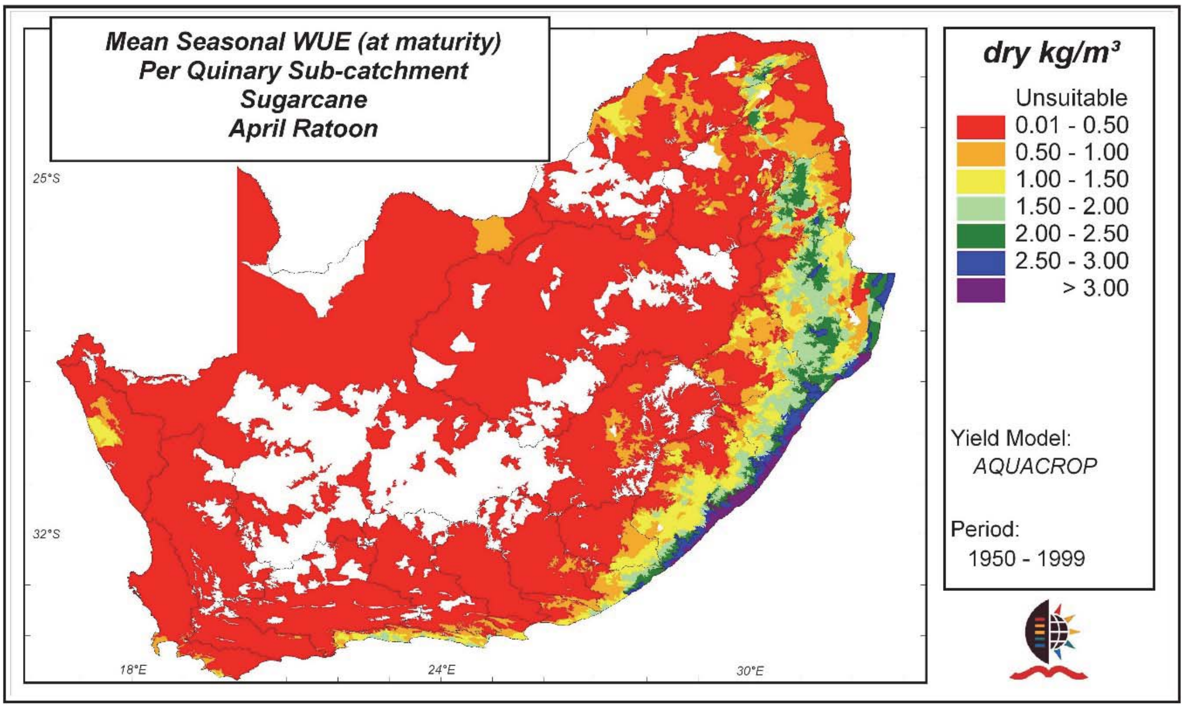
According to Schulze *et al*. (2007c), annualised dryland yields of sugarcane in KwaZulu-Natal are generally in the range of 45 to 65 fresh t ha^{-1} (equivalent to 15 to 22 dry t ha^{-1} per annum), decreasing to below 40 fresh t ha^{-1} over most of Mpumalanga and Limpopo. Singels (2015) recommended that 45 fresh t ha^{-1} can be used as the economically viable threshold for commercial production. The maps shown in **APPENDIX C** highlight the coastal areas of KwaZulu-Natal and Eastern Cape as being most suitable for sugarcane production.

4.2.3.6 Mean WUE (maturity)

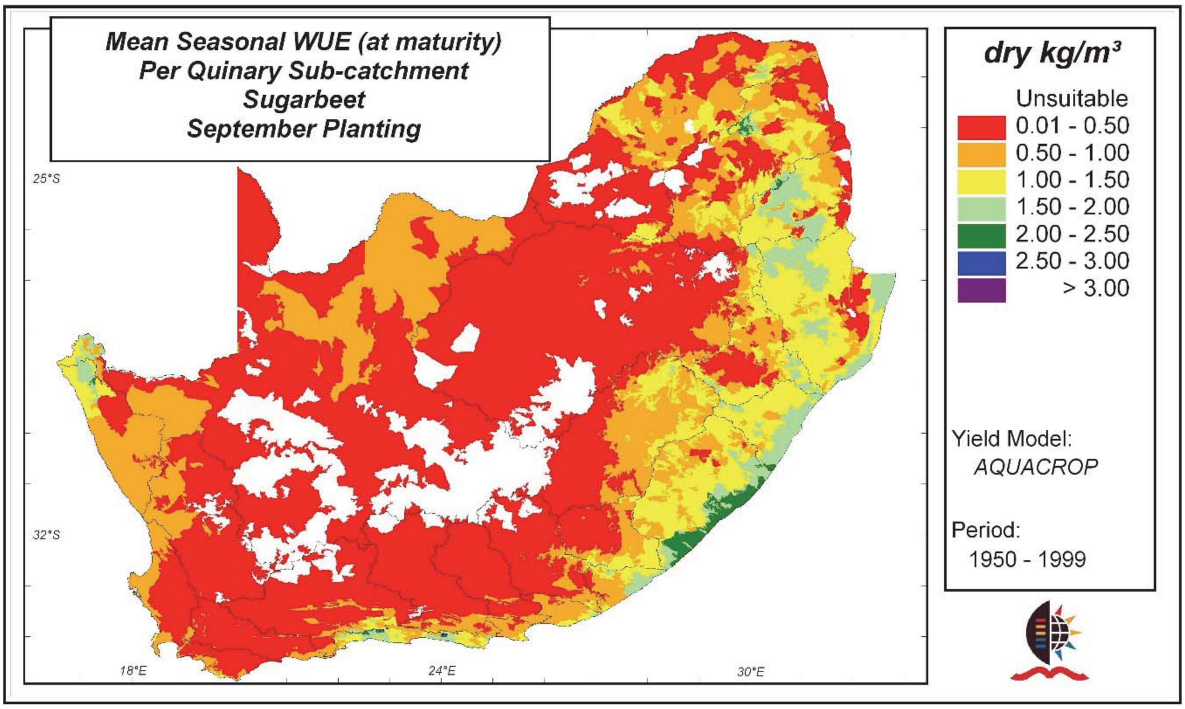
Maps of mean seasonal WUE for bioethanol feedstocks are presented in **Figure 41**, with selected biodiesel crops shown in **Figure 42**. The same legend was used for all maps to allow a comparison for crops. Unsuitable areas (shown as white in the figures below) indicate a mean WUE of zero dry kg m^{-3}. This is due to the model simulating a yield of zero dry t ha^{-1} for the majority of the consecutive seasons. Such areas are therefore too cold and/or too dry for crop production.



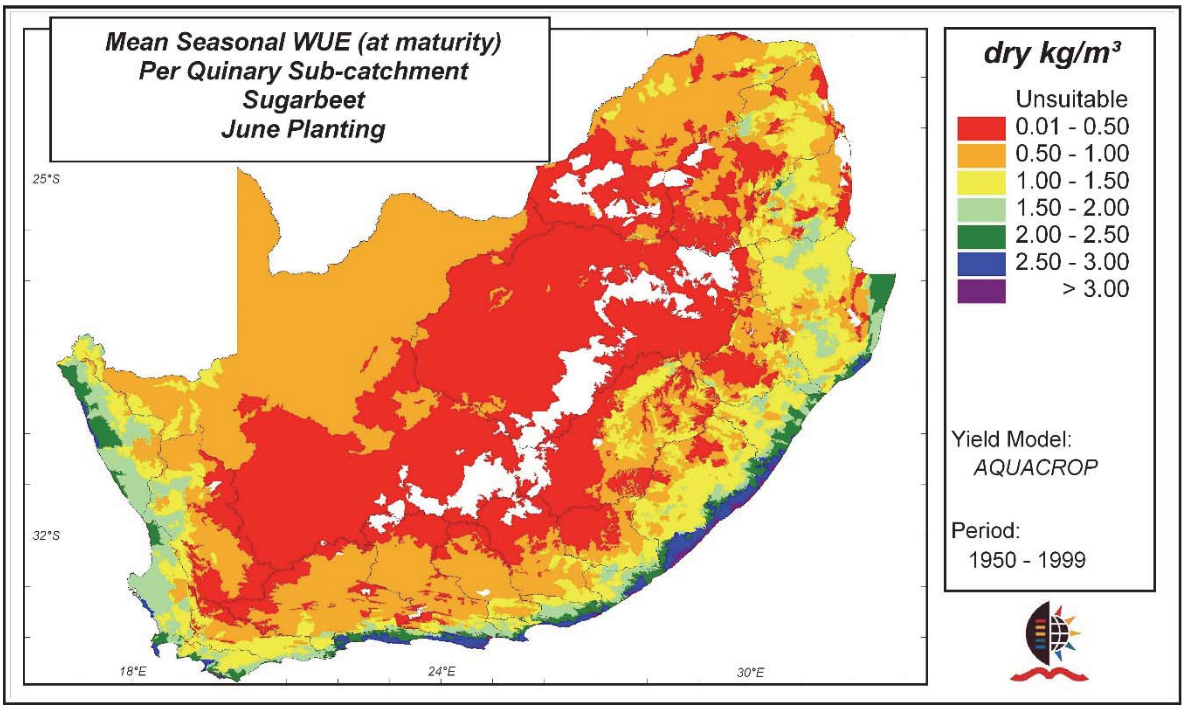
(a)


Mean Seasonal WUE (at maturity)
Per Quinary Sub-catchment
Sugarcane
April Ratoon
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

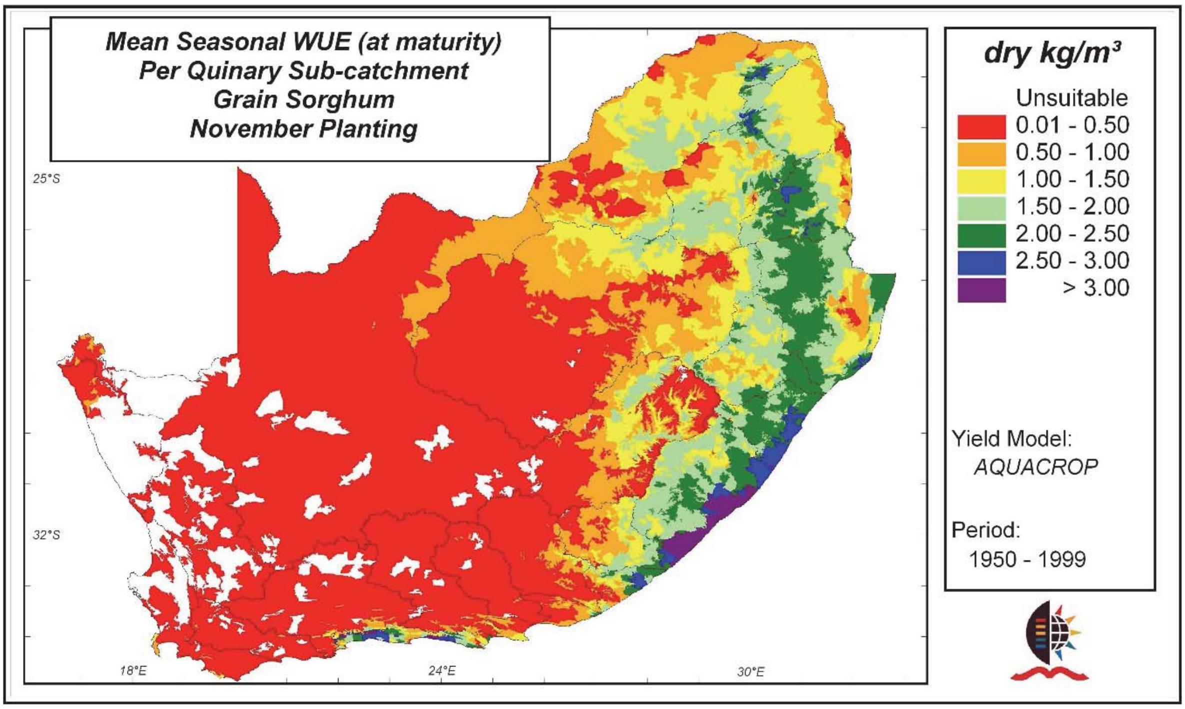
(b)


Mean Seasonal WUE (at maturity)
Per Quinary Sub-catchment
Sugarbeet
September Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)

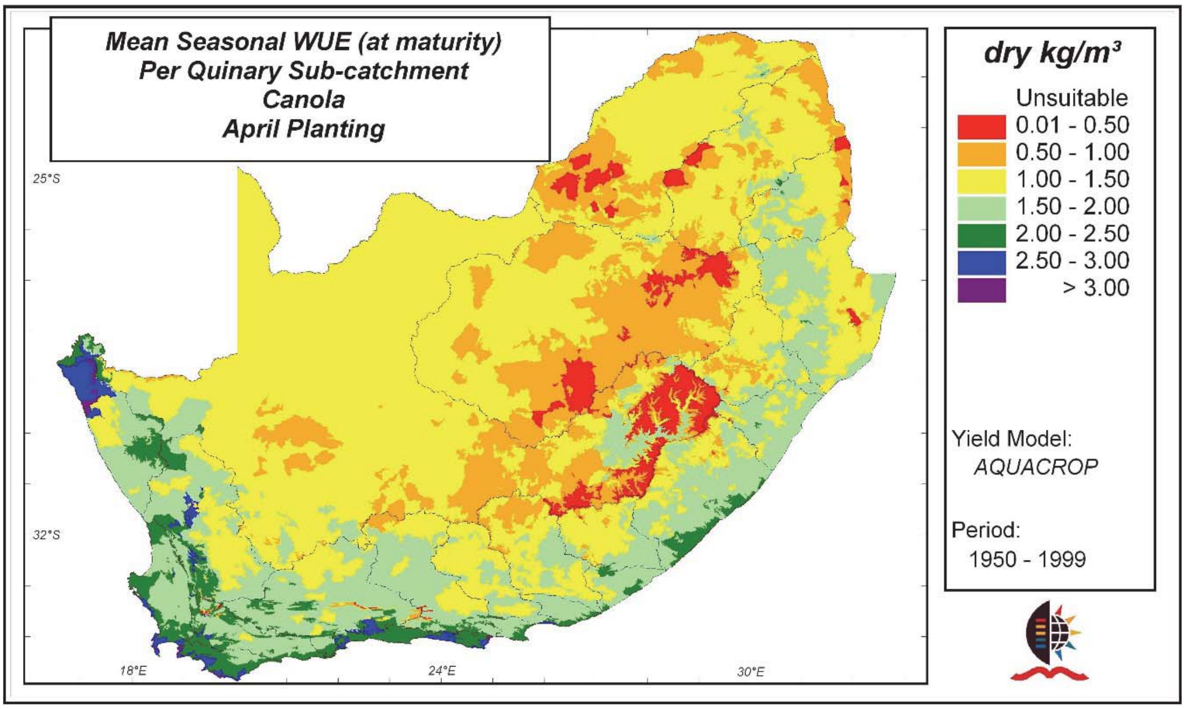


(d)

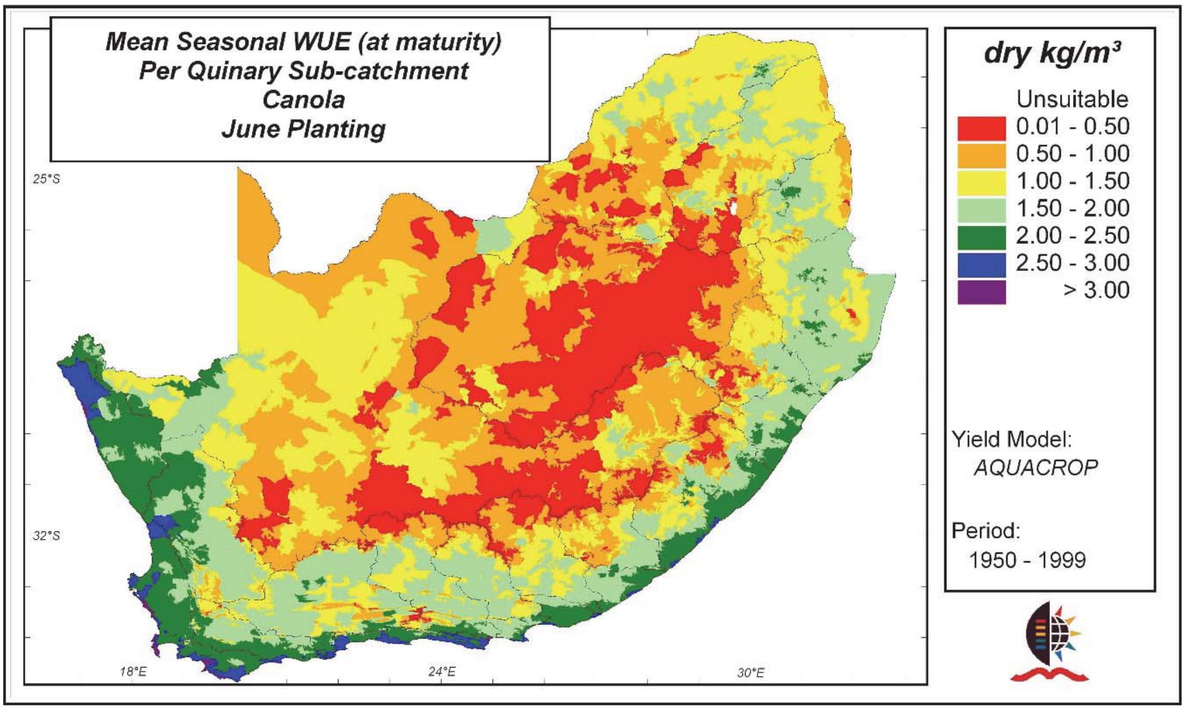


(e)

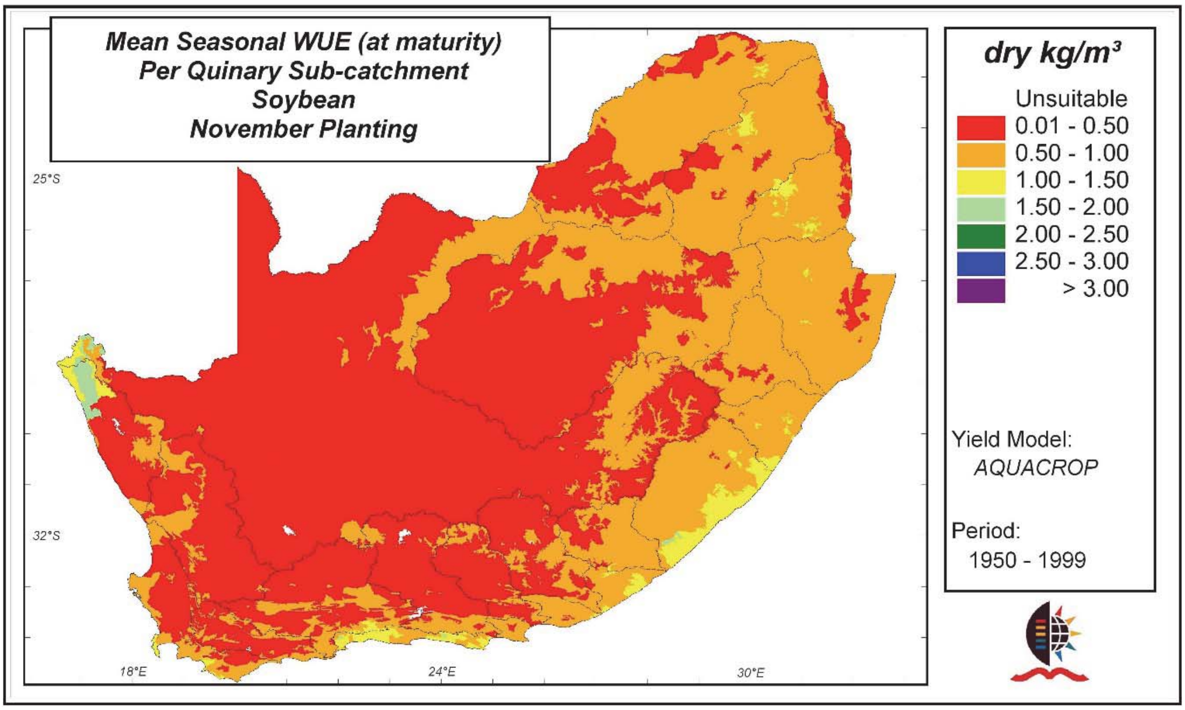
Figure 41 Mean seasonal WUE (dry kg m^{-3}) calculated at maturity for selected bioethanol feedstocks (a-e) planted on different dates


Mean Seasonal WUE (at maturity)
Per Quinary Sub-catchment
Canola
April Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)


Mean Seasonal WUE (at maturity)
Per Quinary Sub-catchment
Canola
June Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



(c)

Figure 42 Mean seasonal WUE (dry kg m^{-3}) calculated at maturity for selected biodiesel feedstocks (a-c) planted on different dates

To re-cap, the WUE at maturity is the attainable yield (in dry kg ha^{-1}), relative to crop water use (i.e. actual evapotranspiration in m^{-3}) accumulated from planting date to crop maturity (i.e. harvest) date. The maps show that sugarcane is most water use efficient when cultivated along the coastal areas of KwaZulu-Natal and the Eastern Cape, with the April transplanting producing more "crop per drop" than the February planting. Along the eastern seaboard, grain sorghum (November planting) and sugarcane (April transplanting) exhibit the highest WUE of all the bioethanol feedstocks considered. Maps of median seasonal WUE for bioethanol feedstocks are presented in **Figure 77** in **APPENDIX D**. As explained earlier, the median maps shown a large expansion in areas deemed unsuitable for bioethanol feedstock production.

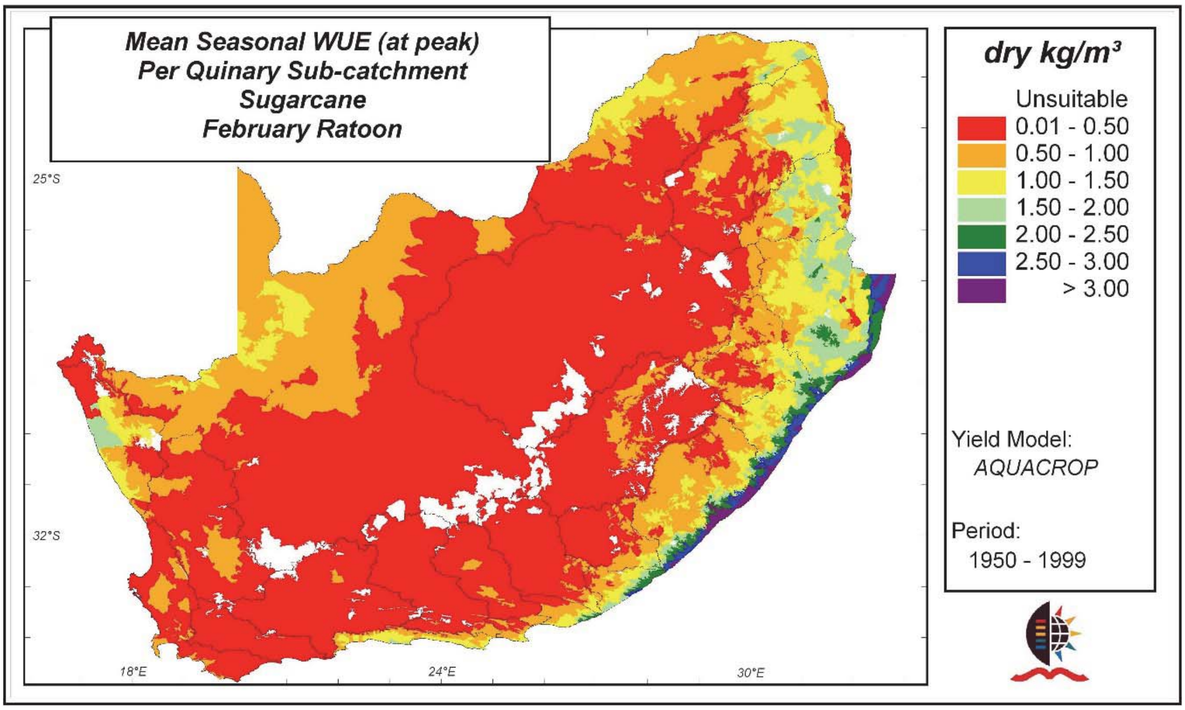
Canola represents the feedstock that can be grown on (almost) all arable farmland, in particular the medium-season cultivar planted in April. On the other hand, soybean is the least water use efficient feedstock. Maps of median seasonal WUE for biodiesel feedstocks are presented in **Figure 78** in **APPENDIX D** and are similar to the mean WUE maps.

It is important to note that the WUE maps can be misinterpreted. A relatively high WUE may be calculated for a crop in a particular area, which may result from very low crop evapotranspiration (and thus a low simulated yield). For example, sugarbeet planted in June exhibited relatively high WUE (i.e. 2.0-2.5 dry kg m^{-3}) along the north-western coastal areas of South Africa., yet the simulated yields are low (2-4 dry t ha^{-1}). It is therefore recommended that the water use efficiency maps are interpreted in conjunction with the yield maps.

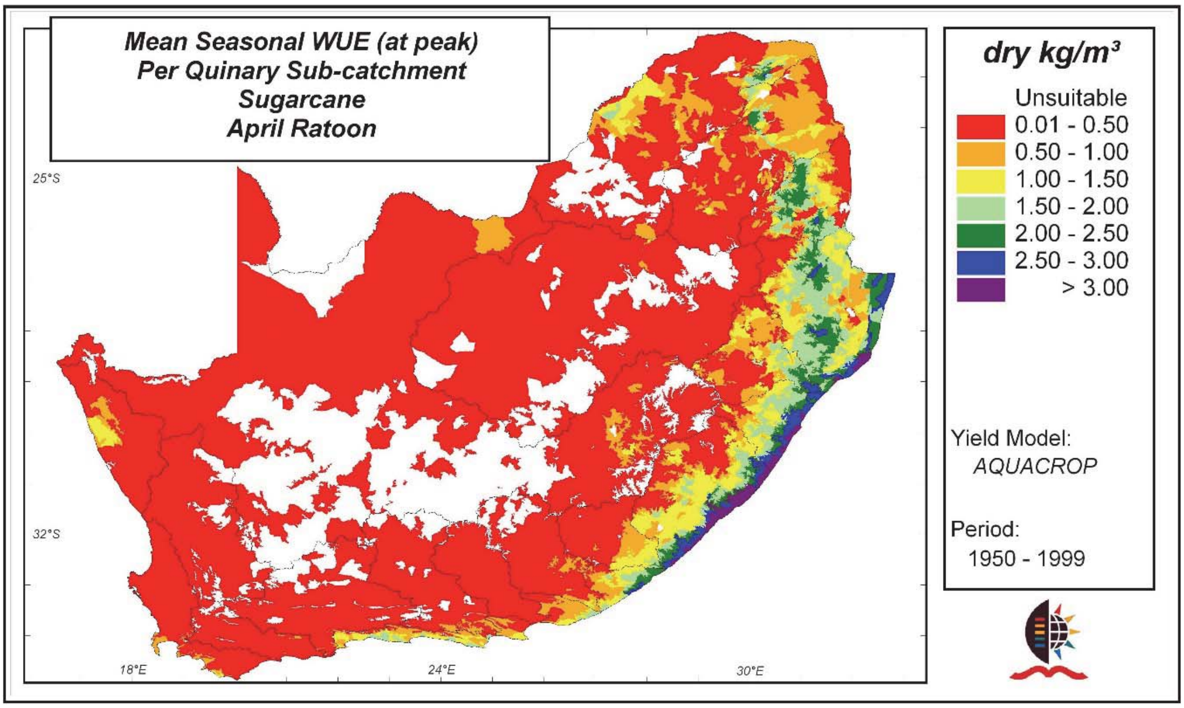
4.2.3.7 Mean WUE (peak)

The WUE calculated by *AQUACROP* (i.e. *WPY*) represents the attainable yield (in dry kg ha^{-1}), relative to the actual evapotranspiration (in m^{-3}) accumulated from planting date to the date the yield peaks. Hence, WUE (at peak) is always higher than WUE (at maturity). Of the bioethanol crops shown in **Figure 43**, WUE (at maturity) deviates from WUE (at peak) mostly in marginal areas (where crop yield is low), especially for sugarcane (February) and sugarbeet (June). Thus, if the two WUE values differ substantially, it indicates the crop yield is peaking early in the growing season and thus, the location should be considered less favourable for crop production. Similar trends were noticed when the two median WUEs were compared (i.e. comparison of **Figure 77** in **APPENDIX D** with **Figure 79** in **APPENDIX E**).

For the biodiesel crops, the spatial variation in WUE (at peak) shown in **Figure 44** is very similar to the WUE (at maturity) in **Figure 42**. The same trend is noticed when the median WUE maps are compared (i.e. comparison of **Figure 78** in **APPENDIX D** with **Figure 80** in **APPENDIX E**).

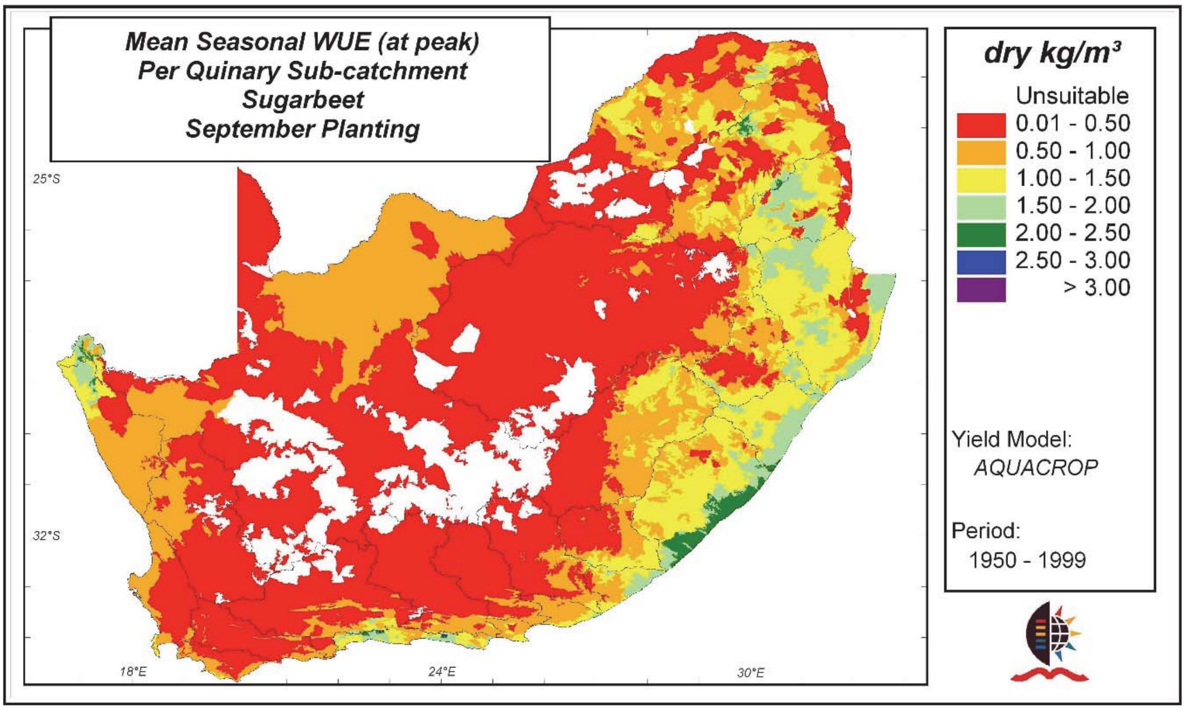


(a)



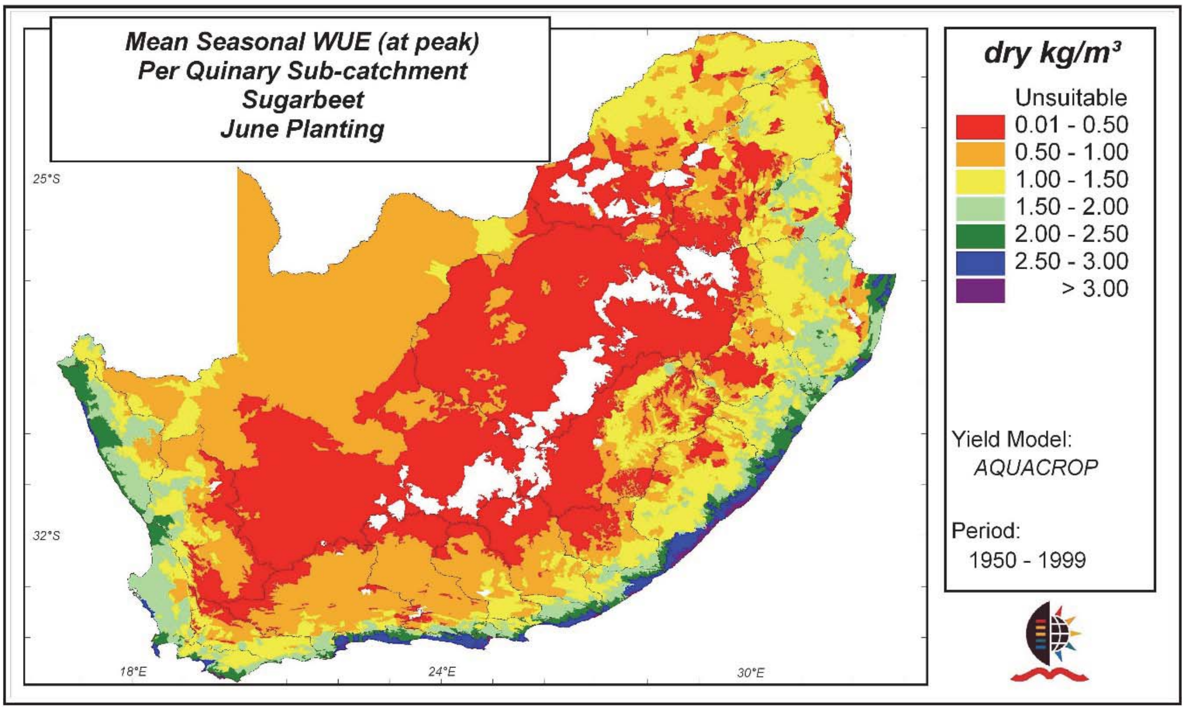
Mean Seasonal WUE (at peak)
Per Quinary Sub-catchment
Sugarcane
April Ratoon
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)

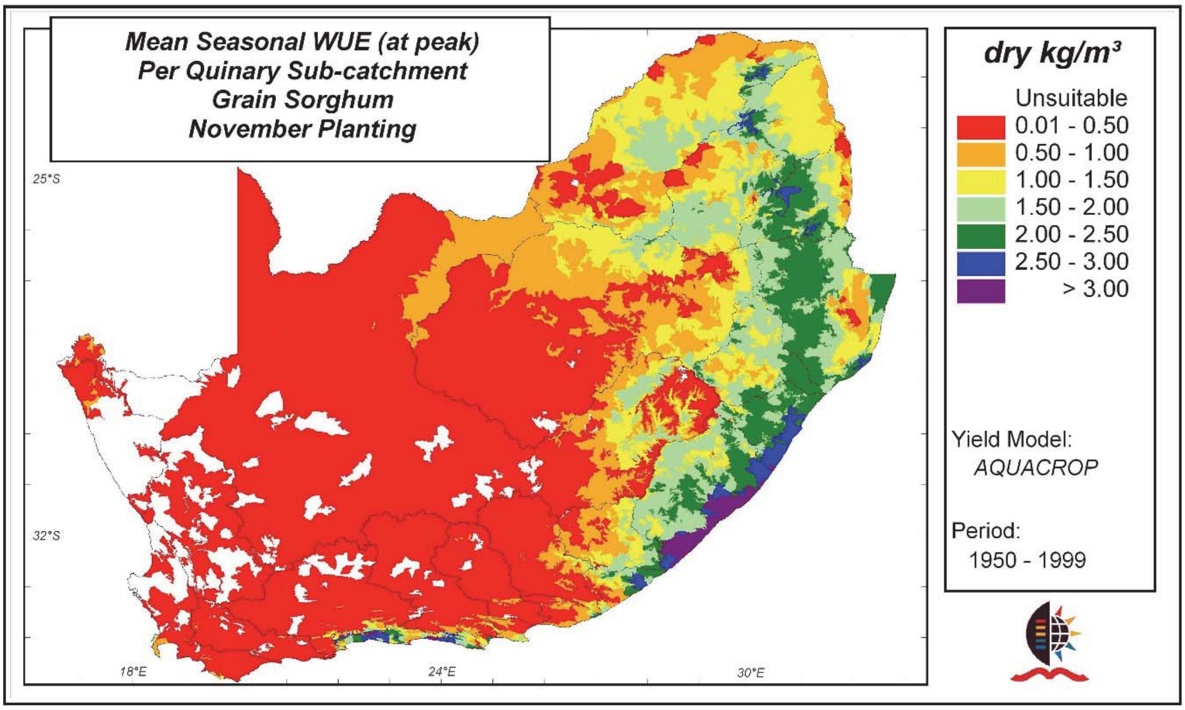


Mean Seasonal WUE (at peak)
Per Quinary Sub-catchment
Sugarbeet
September Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)

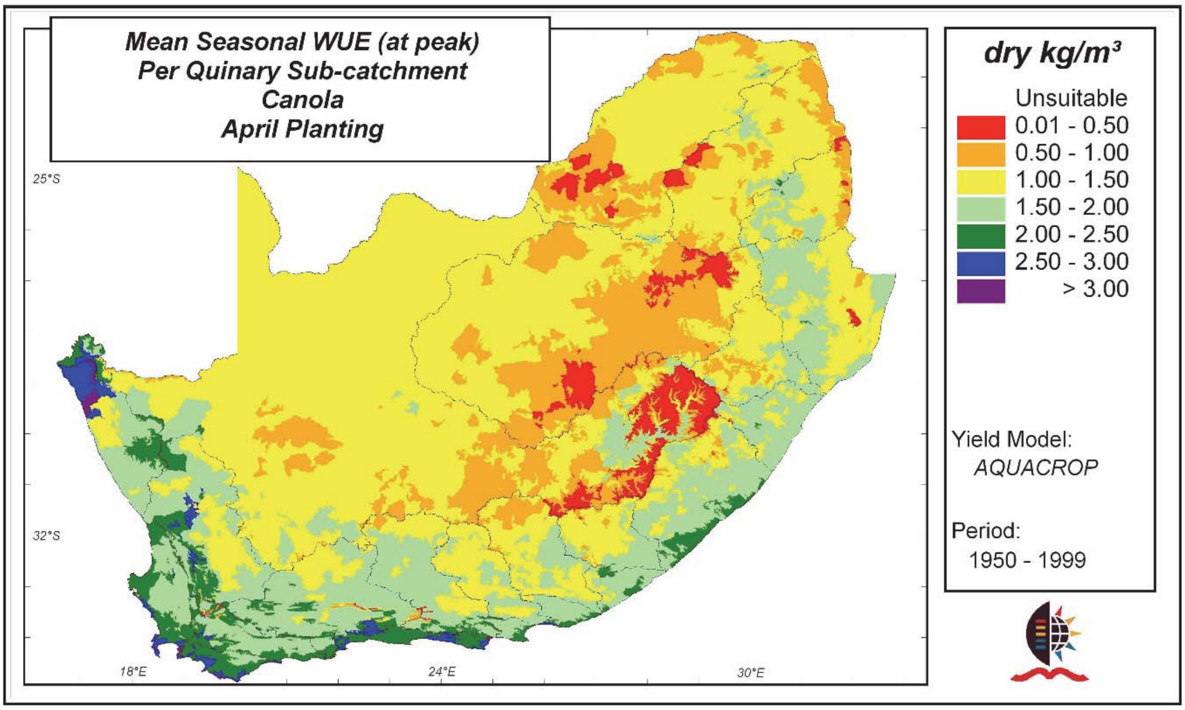


(d)

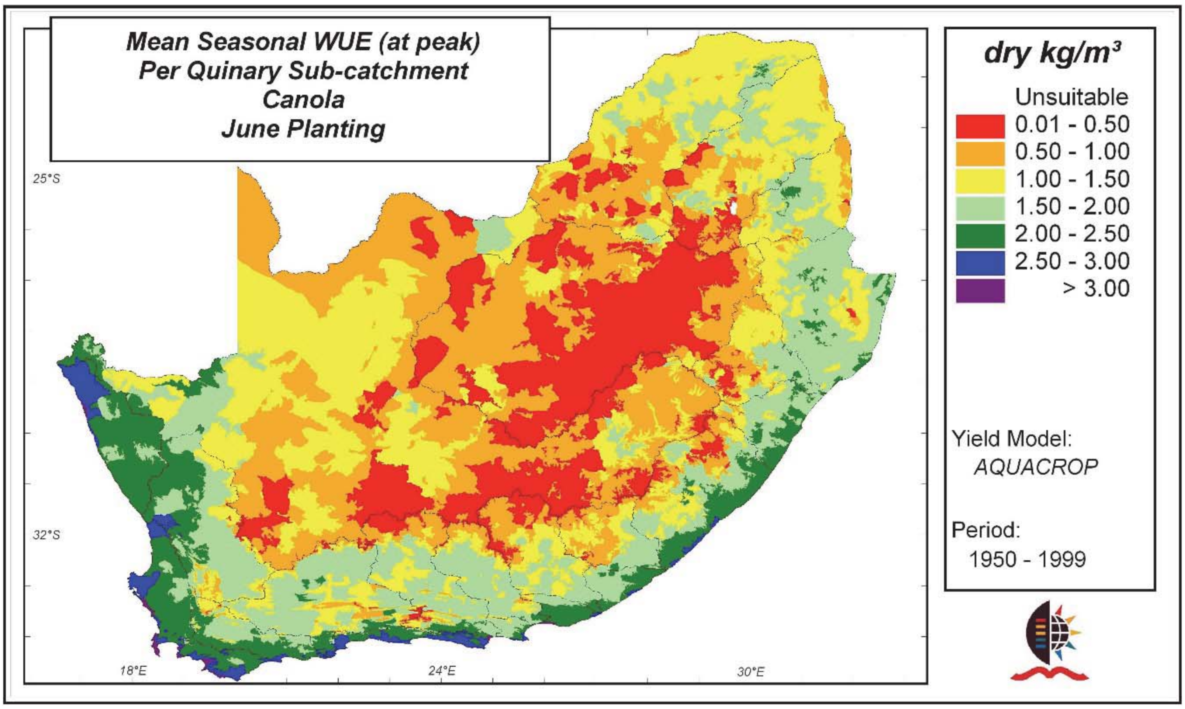


(e)

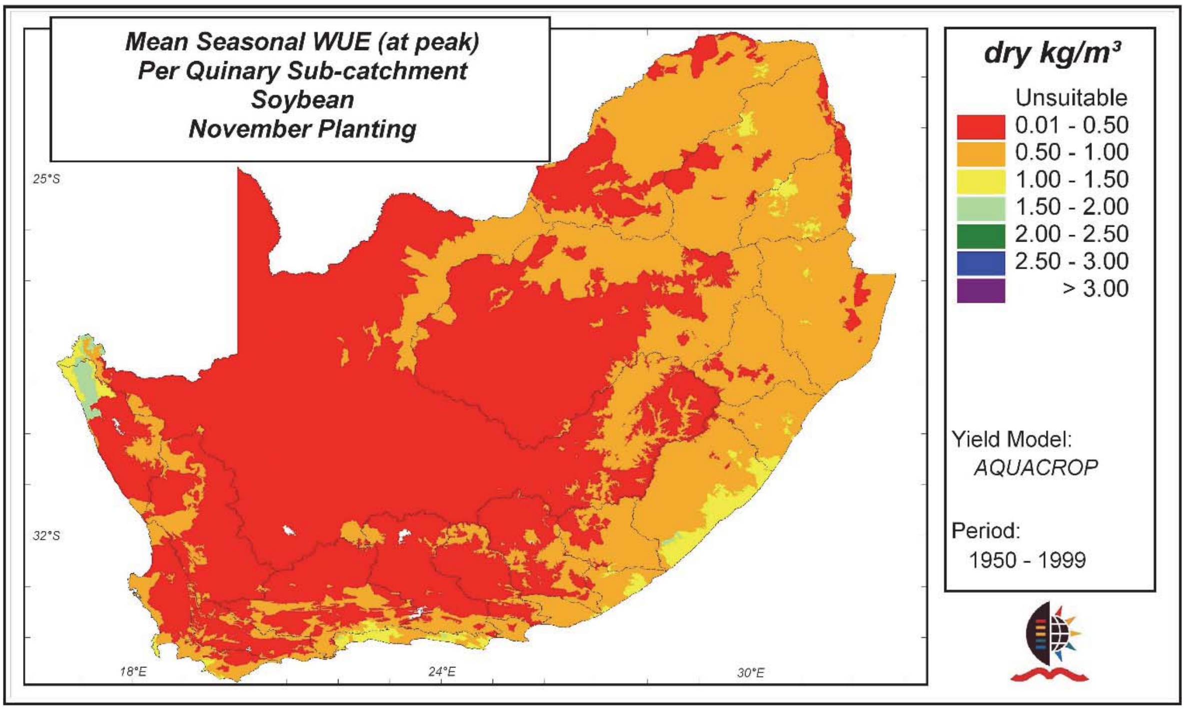
Figure 43 Mean seasonal WUE (dry kg m^{-3}) calculated by *AQUACROP* (peak) for selected bioethanol feedstocks (a-e) planted on different dates


Mean Seasonal WUE (at peak)
Per Quinary Sub-catchment
Canola
April Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)


Mean Seasonal WUE (at peak)
Per Quinary Sub-catchment
Canola
June Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



(c)

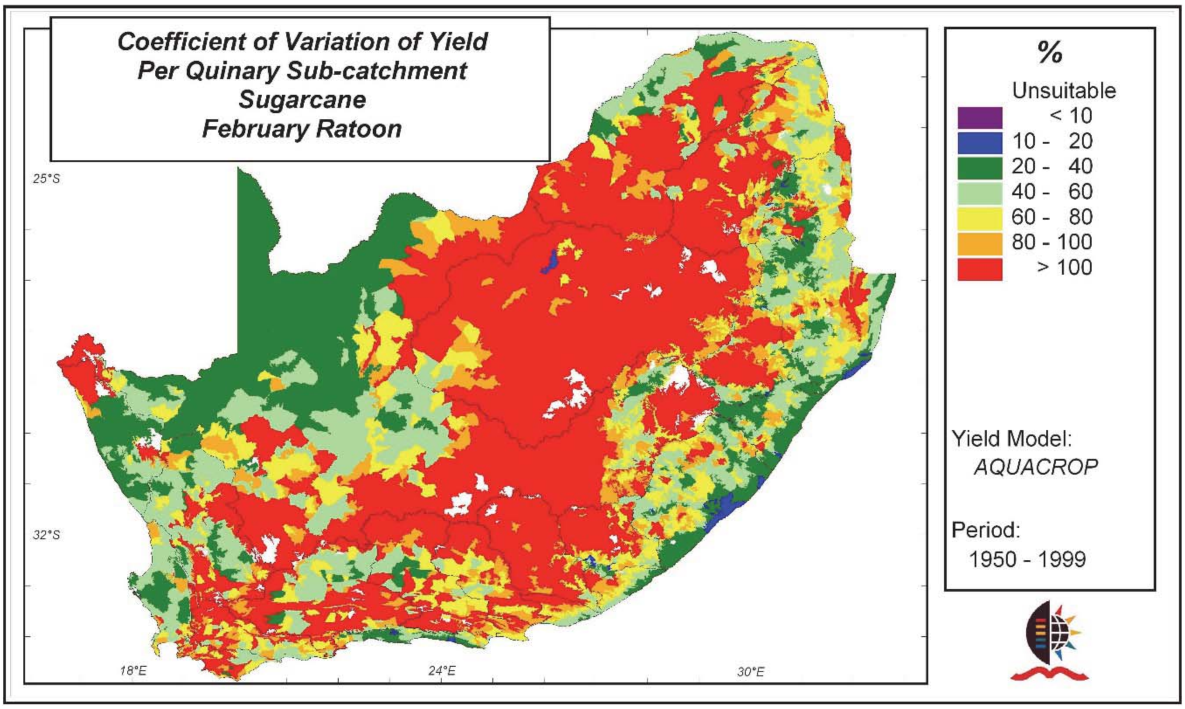
Figure 44 Mean seasonal WUE (dry kg m^{-3}) calculated by *AQUACROP* (peak) for selected biodiesel feedstocks (a-c) planted on different dates

4.2.3.8 Yield variability

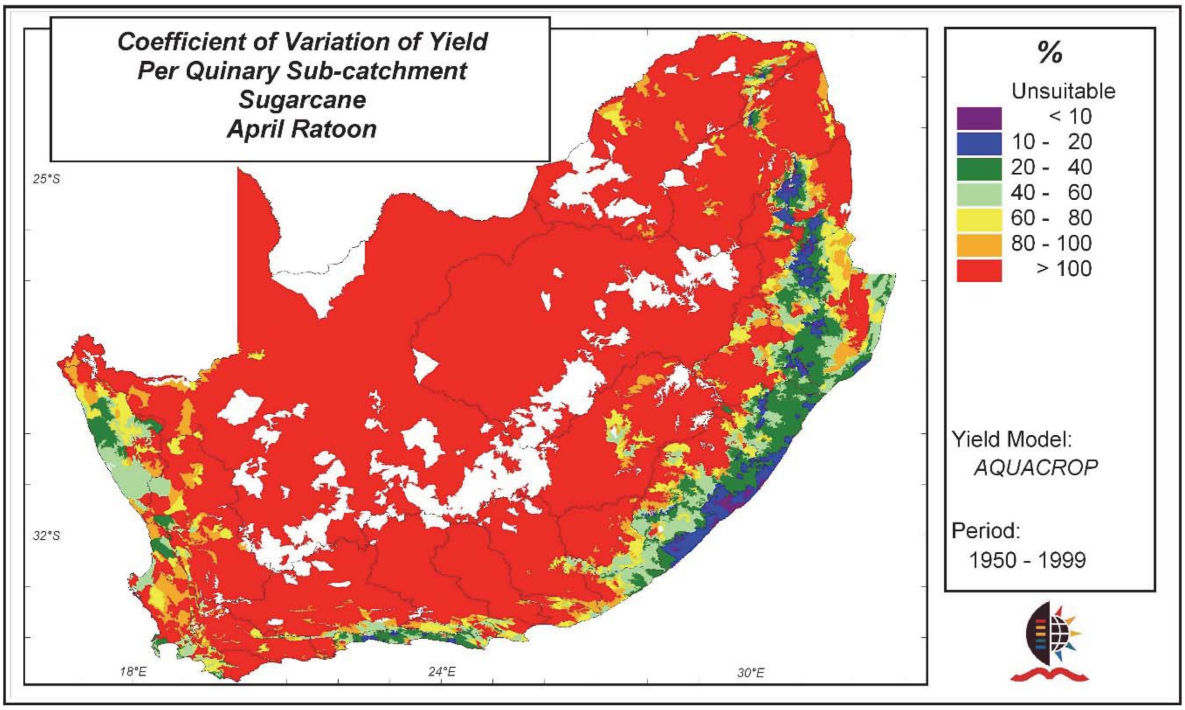
The inter-seasonal variation in yield for the selected bioethanol and biodiesel crops in shown in **Figure 45** and **Figure 46** respectively. The maps highlight areas where yield variability from season-to-season is high and thus, these areas should not be considered for feedstock production. For the majority of bioethanol crops, the coefficient of variation (expressed as a percentage) is lowest along the eastern seaboard.

For sugarcane and in particular the April transplanting, yield variability is lowest along the coastlines of KwaZulu-Natal and the Eastern Cape Provinces. Similarly, large portions of Mpumalanga exhibit consistent year-to-year yield predictions for Sugarbeet (September) and grain sorghum (November). However, the variability maps show relatively low yield variation in the Northern Cape Province for sugarcane (February) and Sugarbeet (June). This occurs because the *AQUACROP* model is consistently simulating low yields for each season in these areas. Thus, the variability maps should also not be interpreted on their own, but in conjunction with the yield maps.

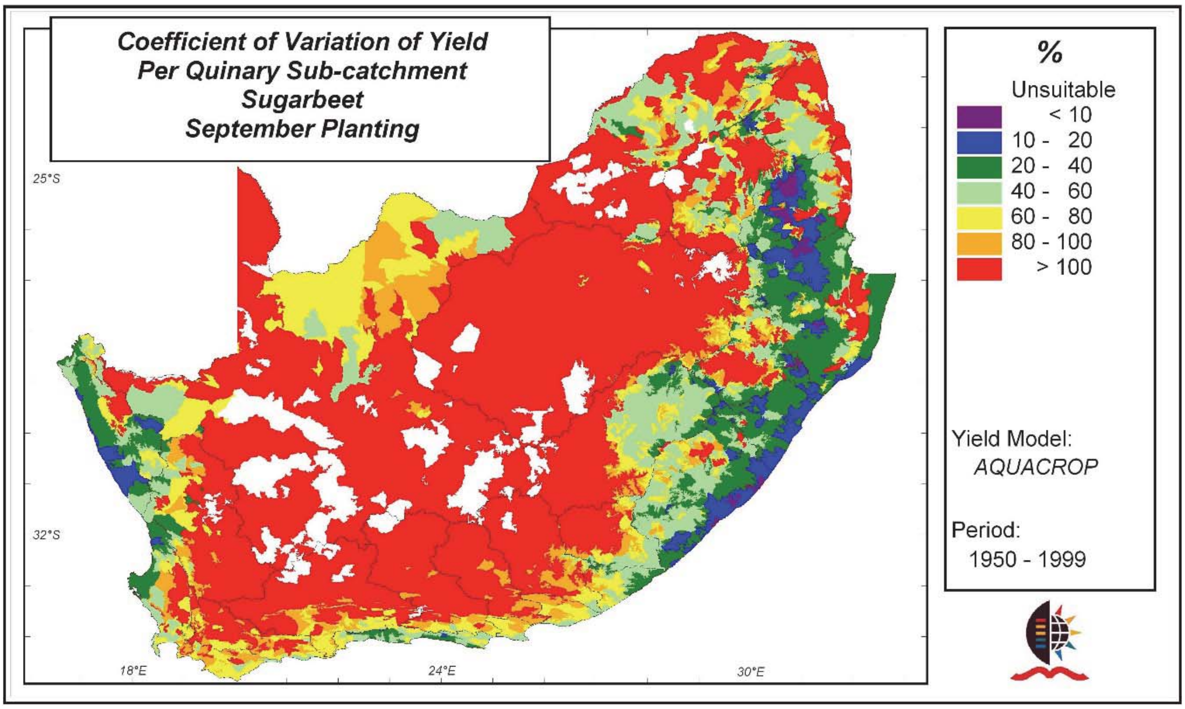
Variability in biodiesel yield is highest for the drier interior regions of the country (**Figure 46**). On the other hand, canola yields variation is lowest along the coastline of South Africa, including the west coast region. This once again highlights the need to overlay this yield variability map with the mean (or median) yield map when deciding if an area is suitable for feedstock cultivation.


Coefficient of Variation of Yield
Per Quinary Sub-catchment
Sugarcane
February Ratoon
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

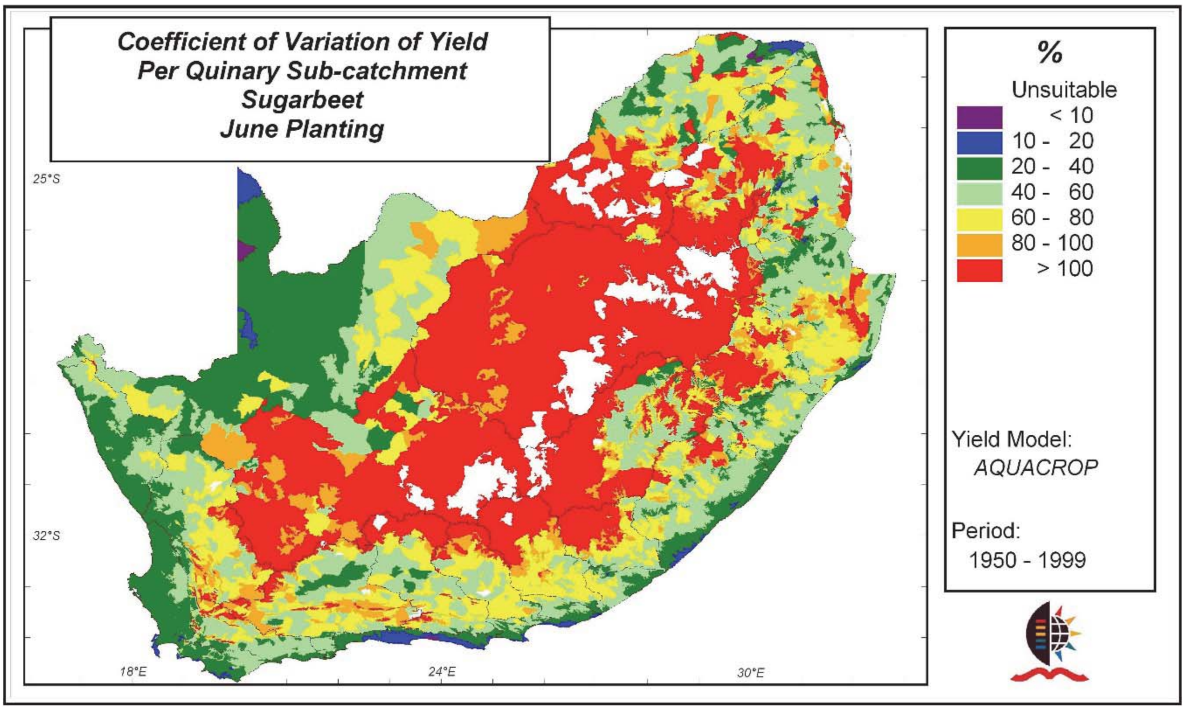
(a)


Coefficient of Variation of Yield
Per Quinary Sub-catchment
Sugarcane
April Ratoon
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

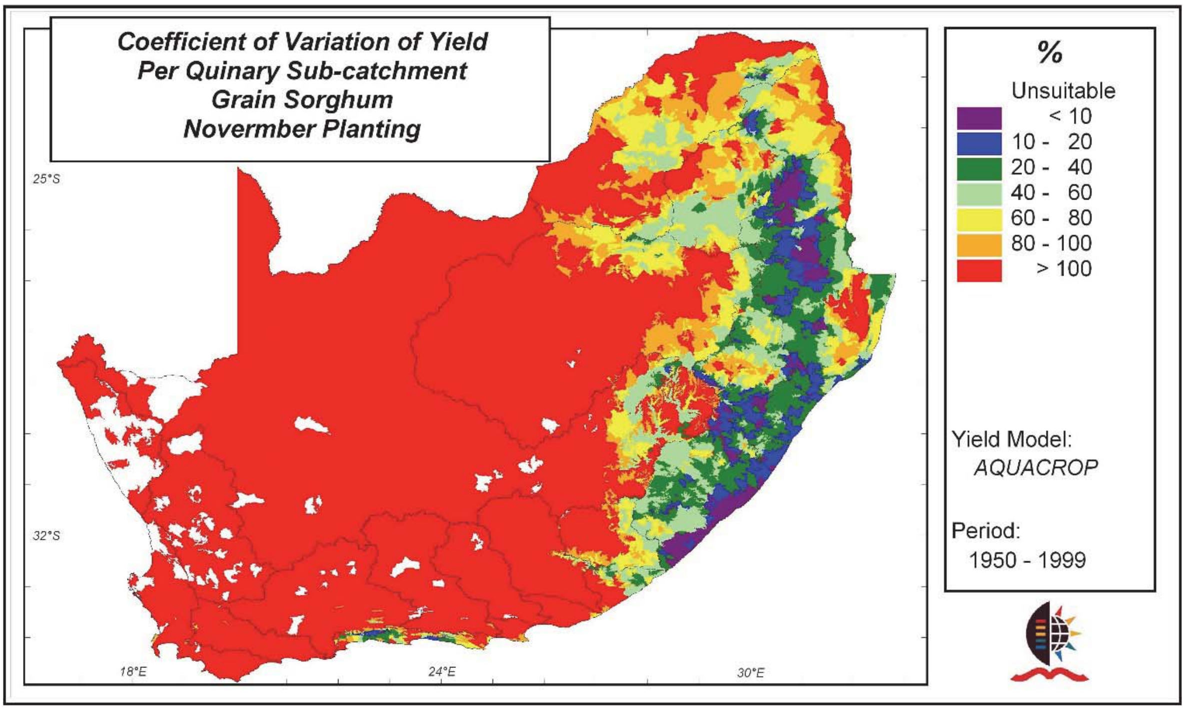
(b)


Coefficient of Variation of Yield
Per Quinary Sub-catchment
Sugarbeet
September Planting
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999

(c)

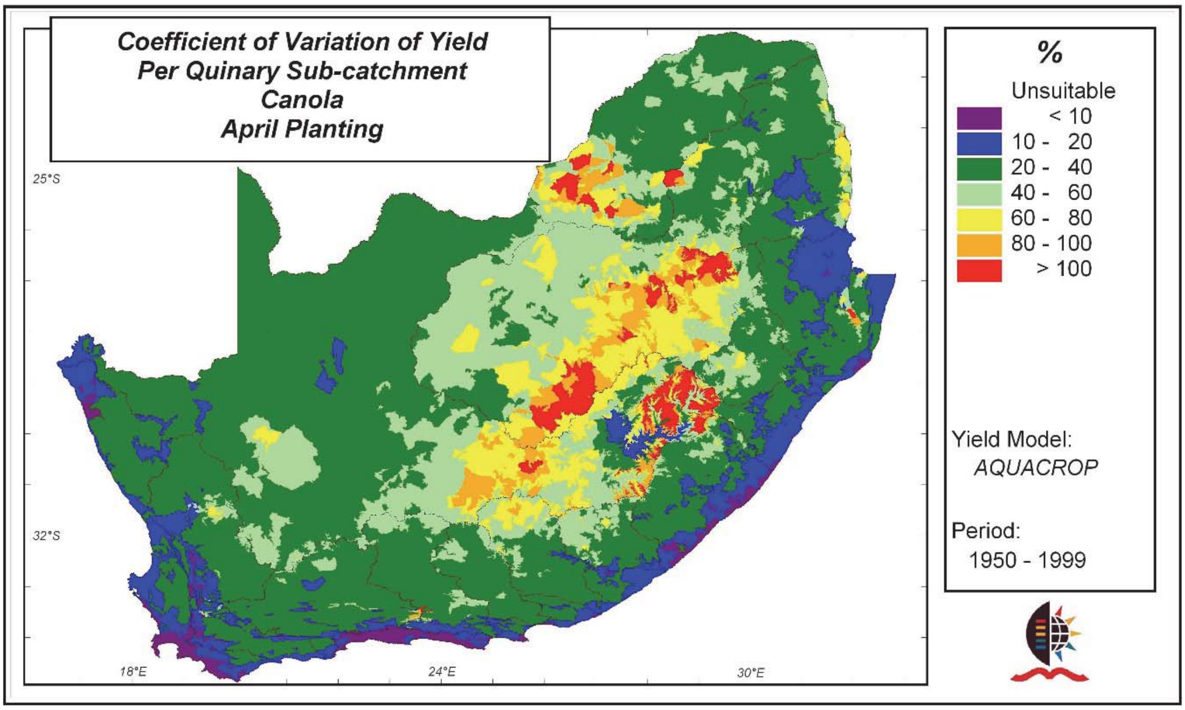

Coefficient of Variation of Yield
Per Quinary Sub-catchment
Sugarbeet
June Planting
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999

(d)

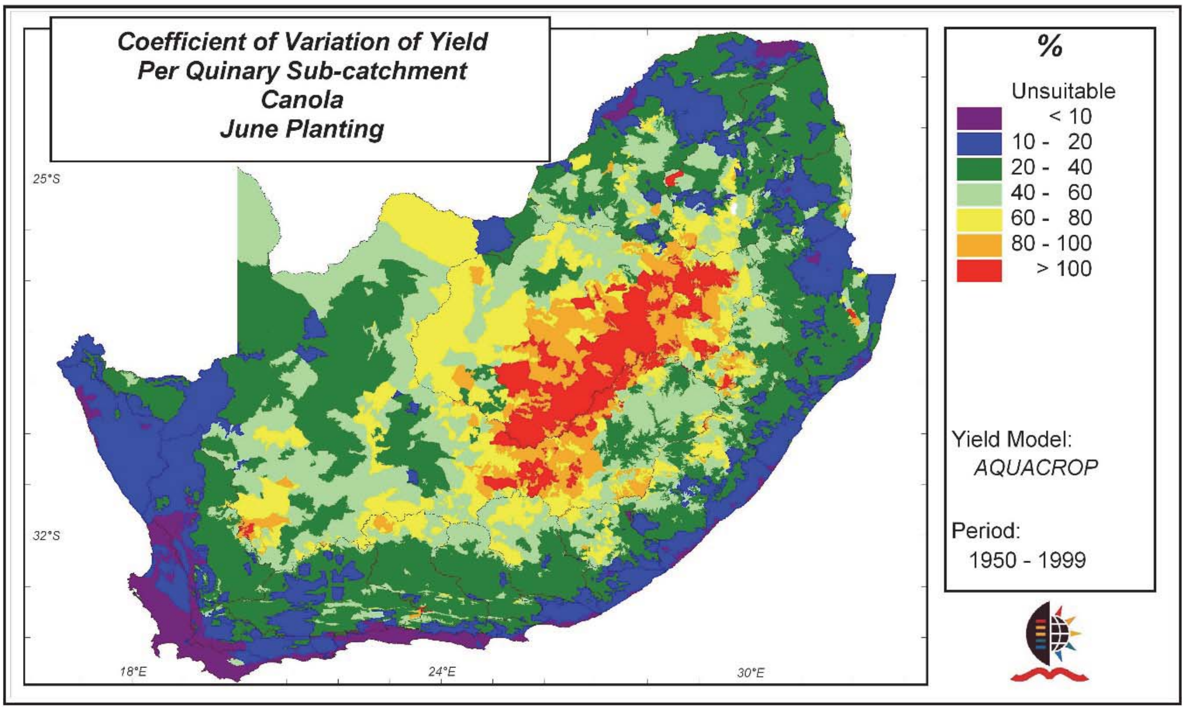


(e)

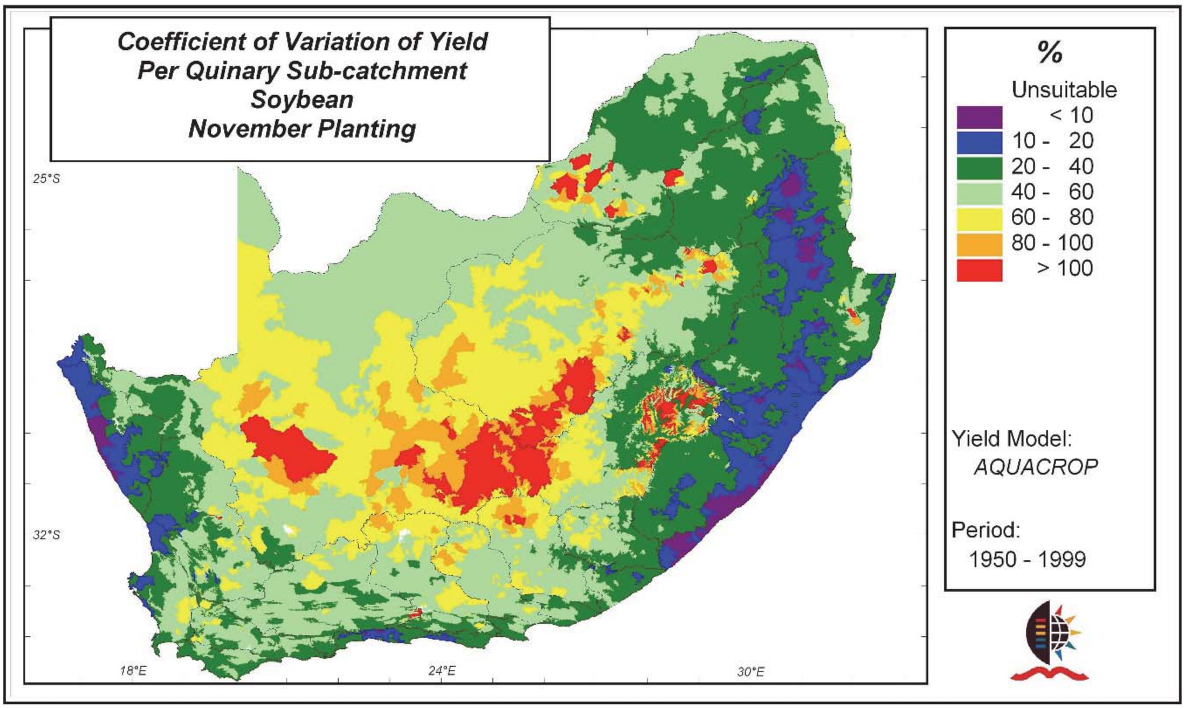
Figure 45 Variability of inter-seasonal yield (%) for selected bioethanol feedstocks (a-e) planted on different dates



(a)



(b)

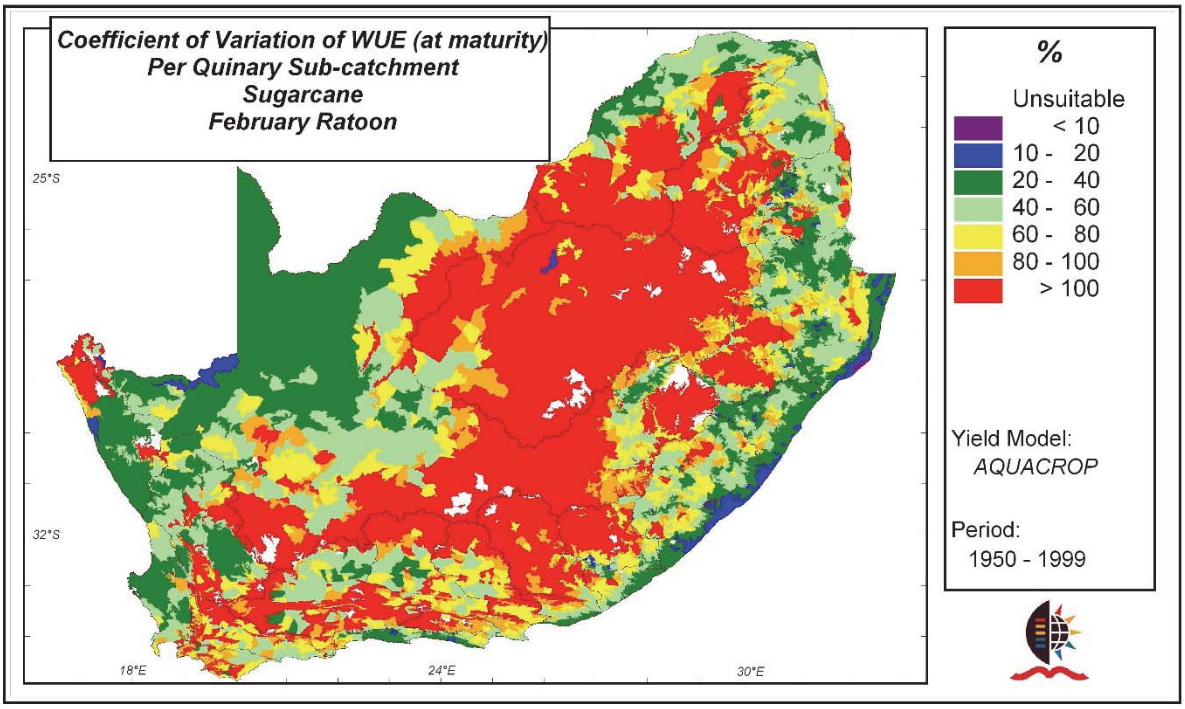


(c)

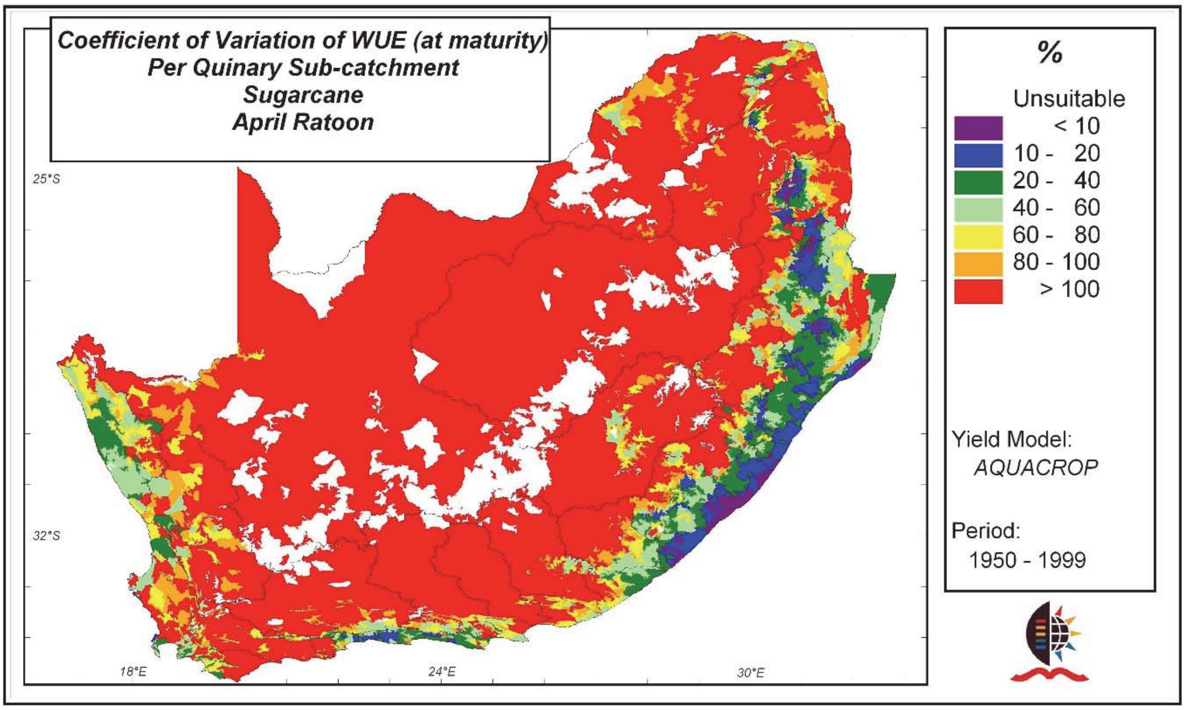
Figure 46 Variability of inter-seasonal yield (%) for selected biodiesel feedstocks (a-c) planted on different dates

4.2.3.9 WUE variation

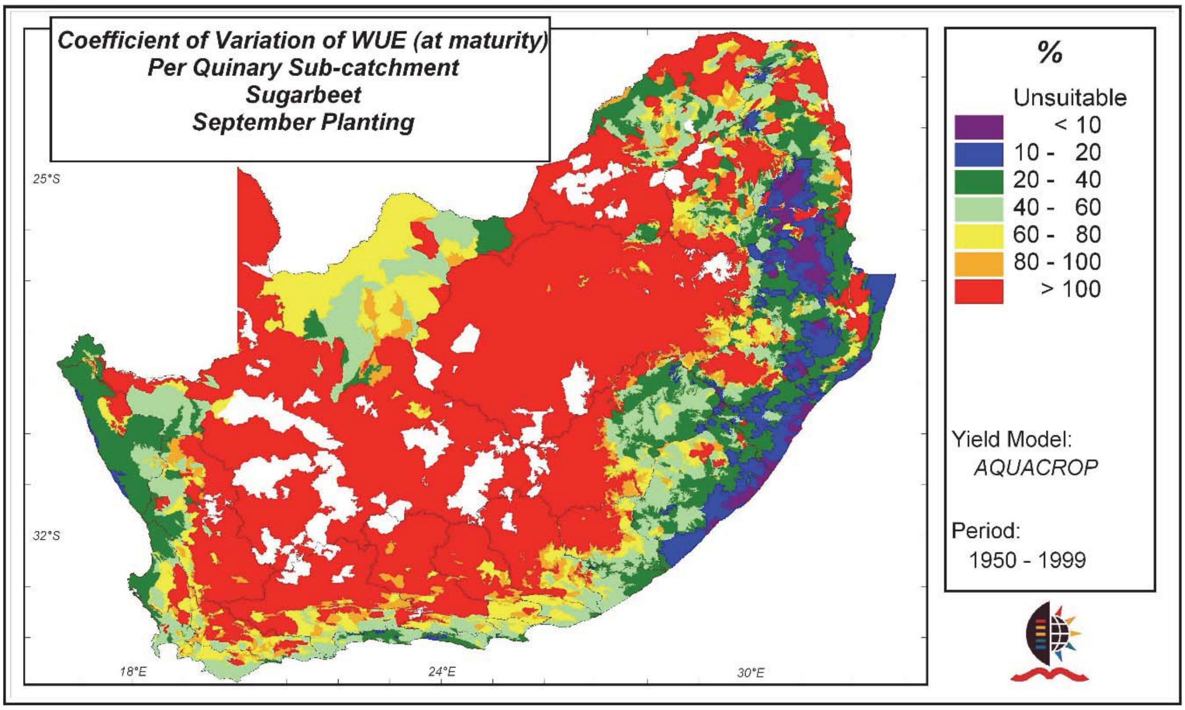
The inter-seasonal variation in WUE (at maturity) for the selected bioethanol and biodiesel crops in shown in **Figure 47** and **Figure 48** respectively. Similar maps for the variation in WUE (at peak) are given in **APPENDIX F** (c.f. **Figure 81** and **Figure 82**). Large differences in WUE (at maturity) and WUE (at peak) were noticed for sugarbeet (June) and sugarcane (February). Only slight differences were noticed for the biodiesel crops, mainly in the interior of the country. In general, variability of inter-seasonal WUE is highest in the interior regions of the country than compared to the coastal areas. If the variability in WUE (at maturity or peak) is high, the area should not be considered suitable for cultivation.



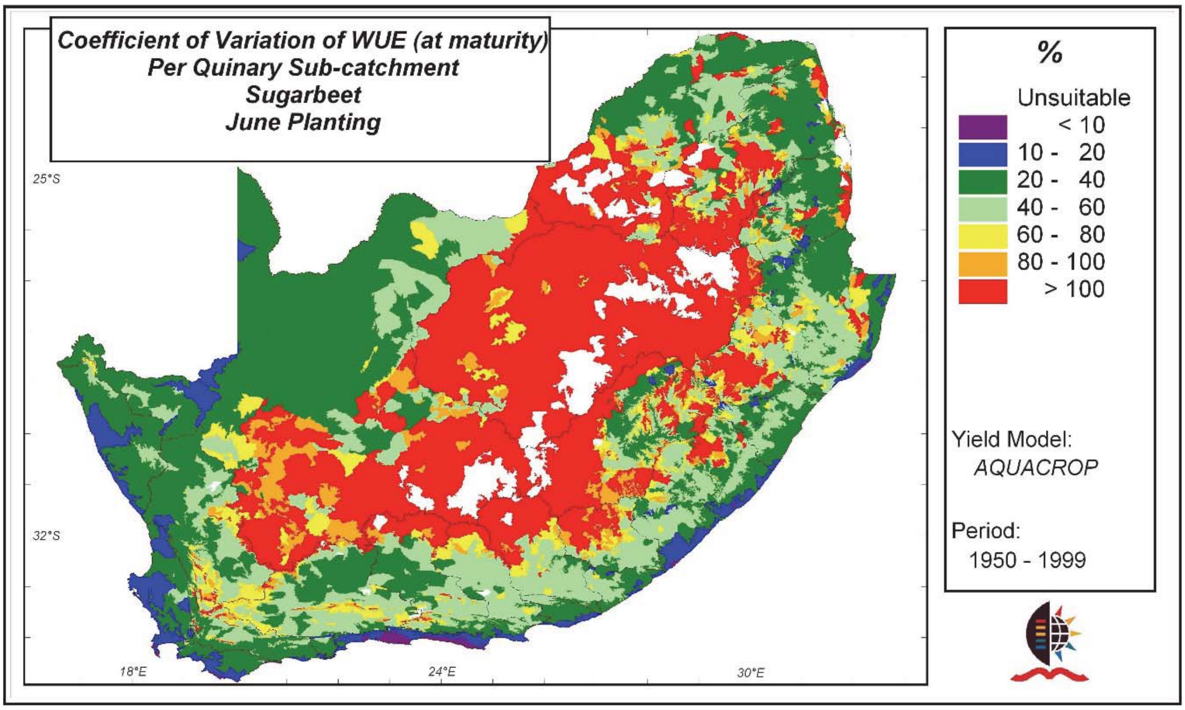
(a)


Coefficient of Variation of WUE (at maturity)
Per Quinary Sub-catchment
Sugarcane
April Ratoon
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999

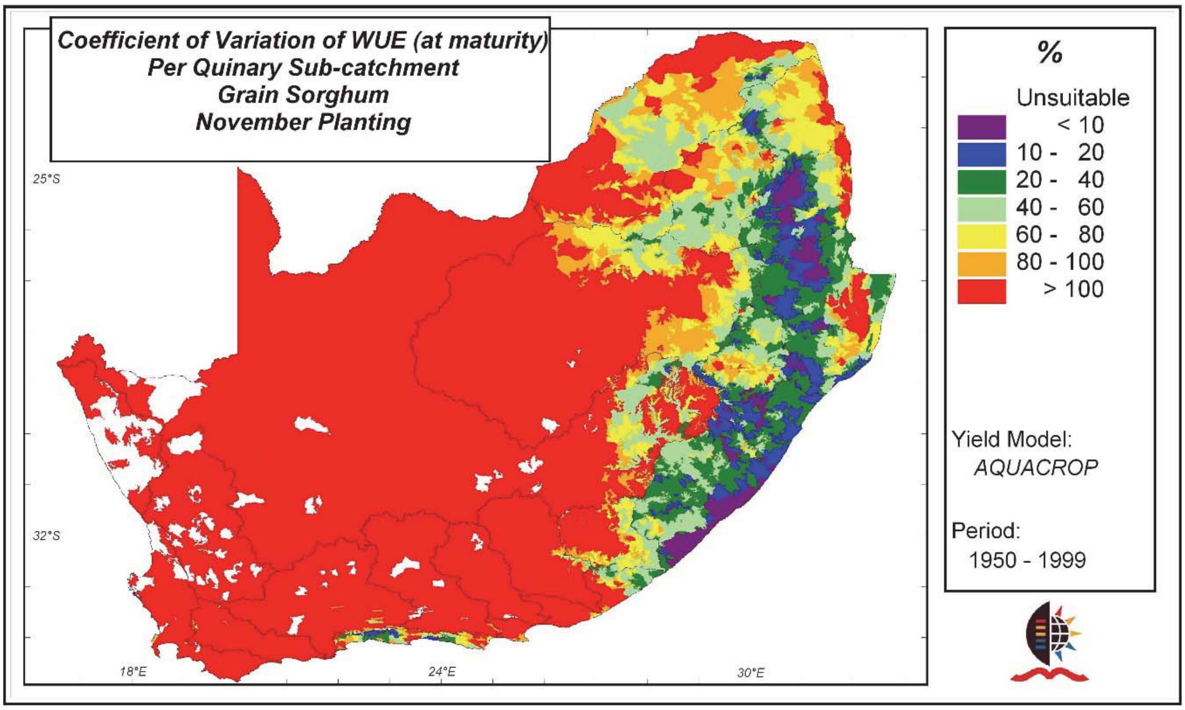
(b)


Coefficient of Variation of WUE (at maturity)
Per Quinary Sub-catchment
Sugarbeet
September Planting
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999

(c)

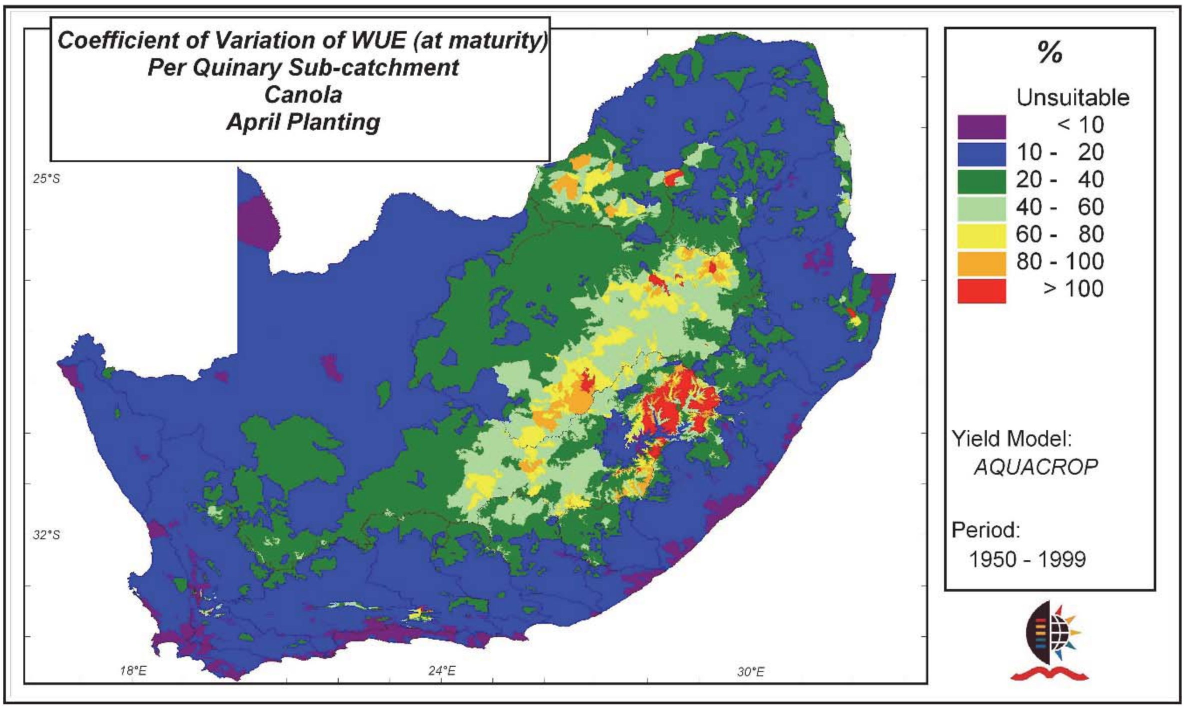


(d)

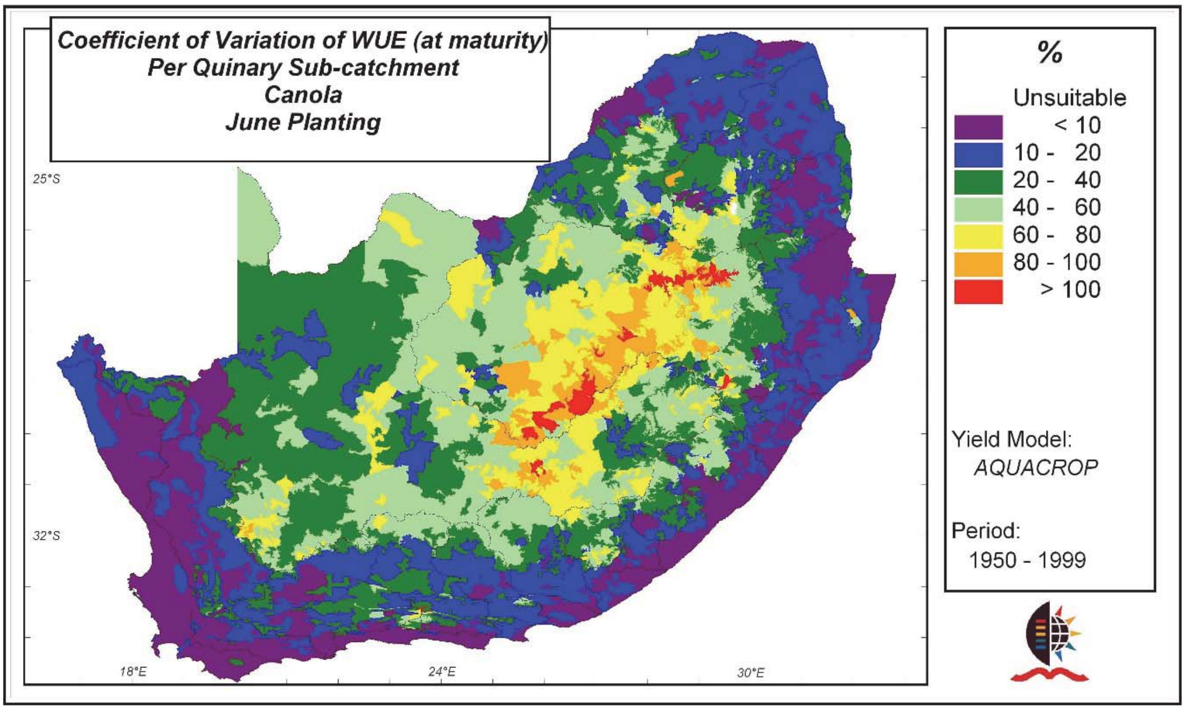


(e)

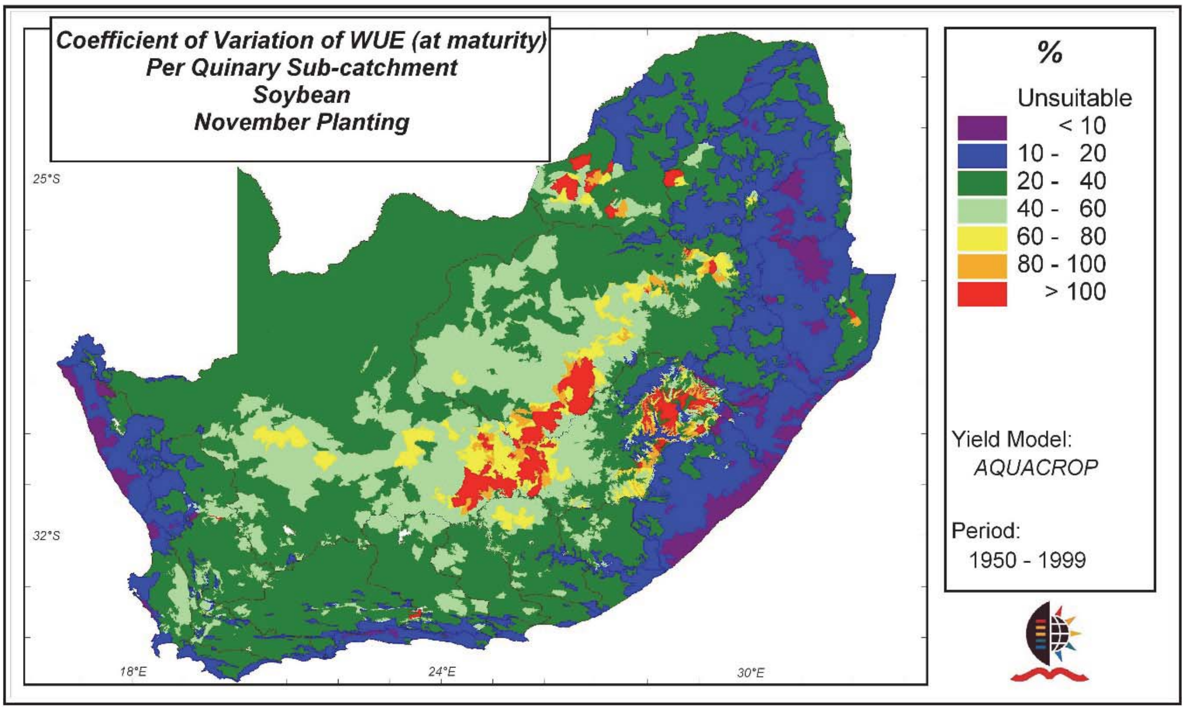
Figure 47 Variability of inter-seasonal WUE (%) calculated at maturity for selected bioethanol feedstocks (a-e) planted on different dates


Coefficient of Variation of WUE (at maturity)
Per Quinary Sub-catchment
Canola
April Planting
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)


Coefficient of Variation of WUE (at maturity)
Per Quinary Sub-catchment
Canola
June Planting
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



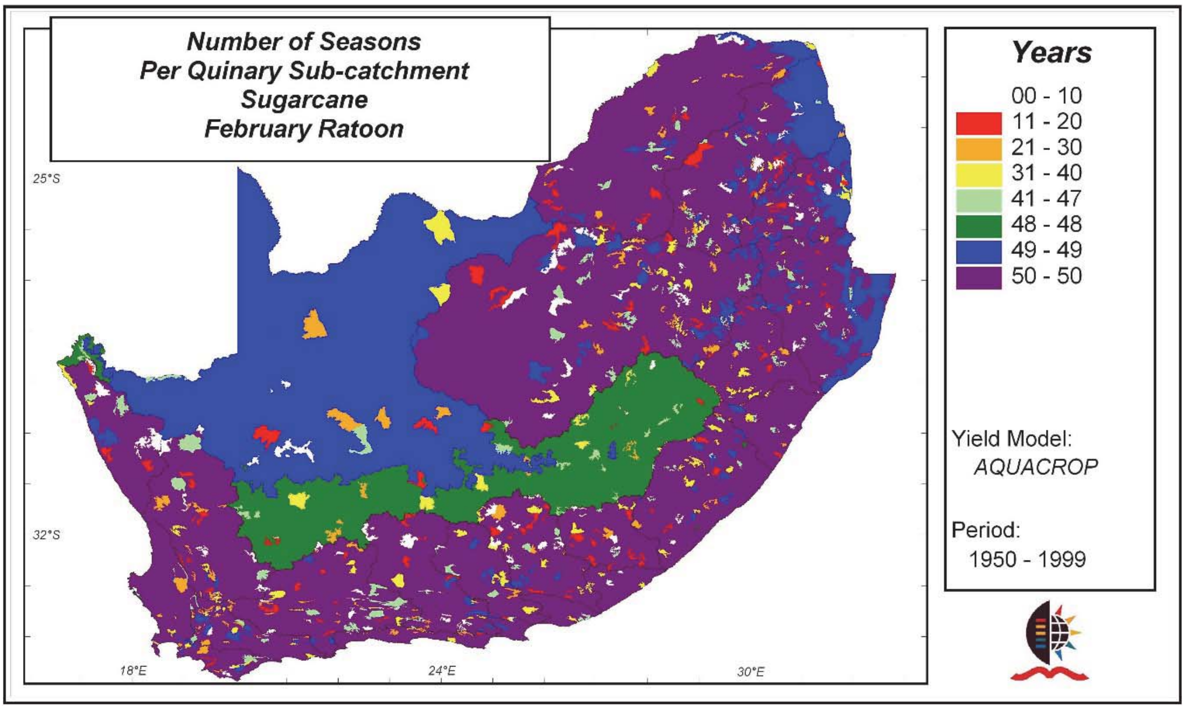
(c)

Figure 48 Variability of inter-seasonal WUE (%) calculated at maturity for selected biodiesel feedstocks (a-c) planted on different dates

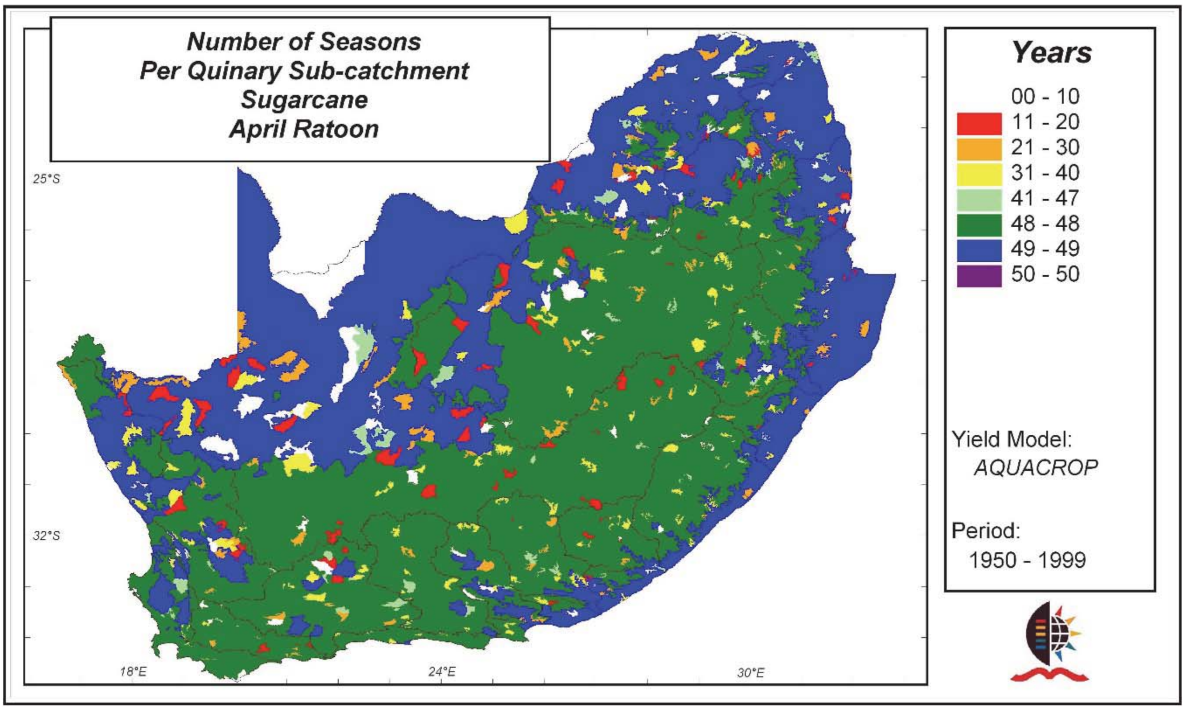
4.2.3.10 Number of seasons

The number of seasons (maximum 50) that was used to calculate the long-term attainable yield is shown in **Figure 49** and **Figure 50** for bioethanol and biodiesel crops respectively. For sugarcane transplanted in February, the map shows that the model successfully simulated 50 consecutive seasons for most of the quinary sub-catchments, which is incorrect. This result highlighted an error in the algorithm to determine the crop cycle length using thermal time. The length of the final growing season (i.e. planted in 1999) was incomplete for crops that had not physiologically matured before 31st December 1999 (i.e. the end of the climate record). The decision was made to discard the last season, thus limiting the number of seasons to 49. The error was corrected for sugarcane transplanted in April. Hence, the April map shows that the number of simulated seasons is 49 for the warmer regions of the country, but only 48 seasons for the cooler, higher altitude areas.

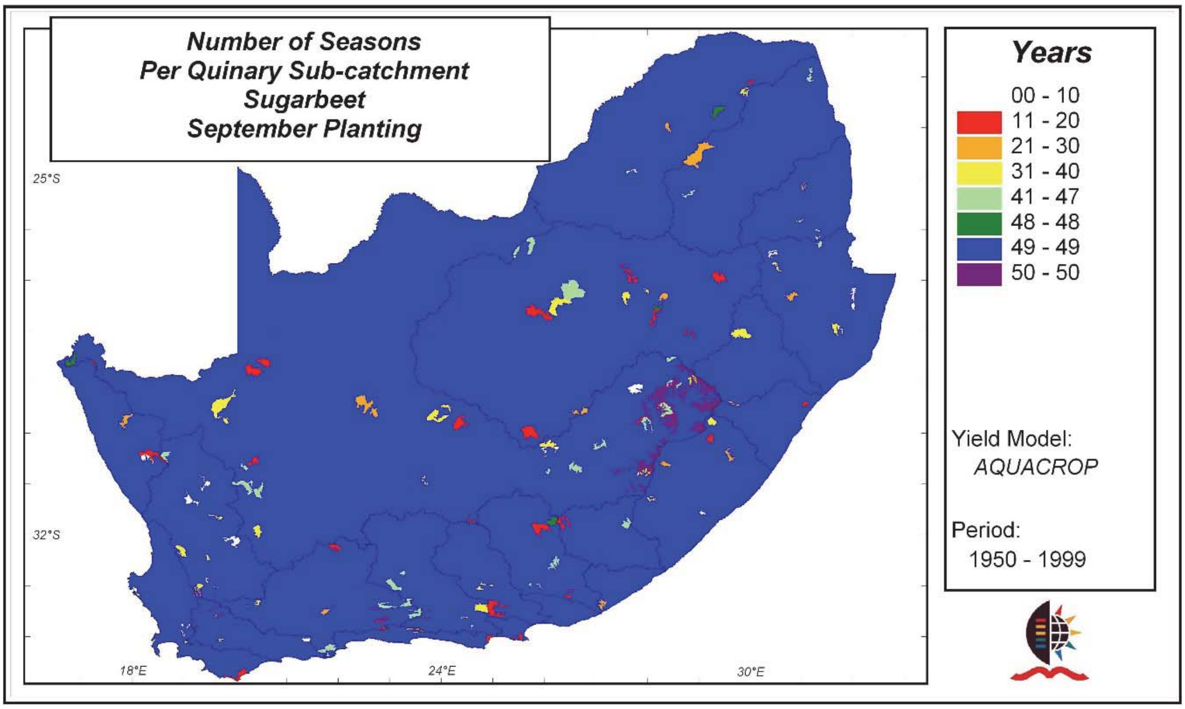
For sugarbeet (September) and grain sorghum (November), the maps illustrate that these crops mature in the following year for the majority of the country. On the other hand, canola (April or June planting) could be harvested in the same year it was planted. However, the maps shown in **Figure 49** and **Figure 50** highlight scattered quinaries in which less than 48 simulations were achieved. It indicates that *AQUACROP* ended "prematurely" whilst simulating consecutive seasons of yield data (due to the "division-by-zero" error discussed previously). Furthermore, quinary sub-catchments where the statistics were determined from less than 20 years of data must be interpreted with caution (and preferably discarded). Thus, if the model was unable to simulate more than 20 years of yield and WUE data, the sub-catchment should be considered unsuitable for the cultivation of that crop.


Number of Seasons
Per Quinary Sub-catchment
Sugarcane
February Ratoon
25°S
32°S
18°E
24°E
30°E
Years
00 - 10
11 - 20
21 - 30
31 - 40
41 - 47
48 - 48
49 - 49
50 - 50
Yield Model:
AQUACROP
Period:
1950 - 1999

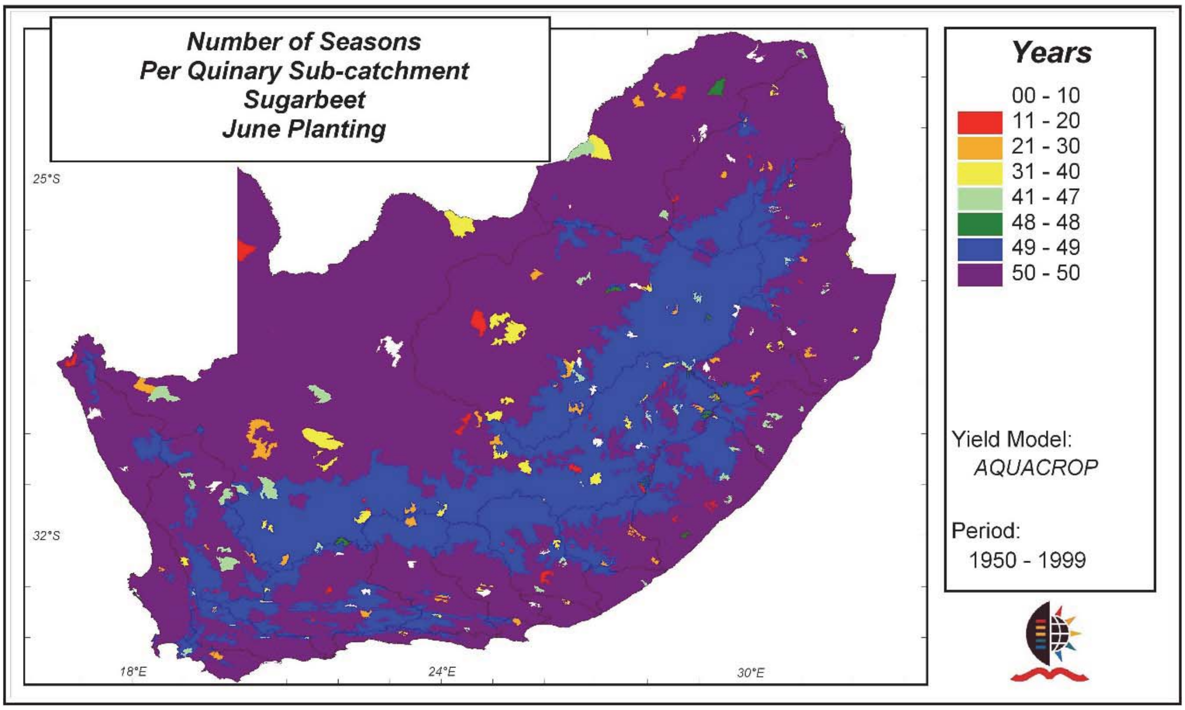
(a)


Number of Seasons
Per Quinary Sub-catchment
Sugarcane
April Ratoon
25°S
32°S
18°E
24°E
30°E
Years
00 - 10
11 - 20
21 - 30
31 - 40
41 - 47
48 - 48
49 - 49
50 - 50
Yield Model:
AQUACROP
Period:
1950 - 1999

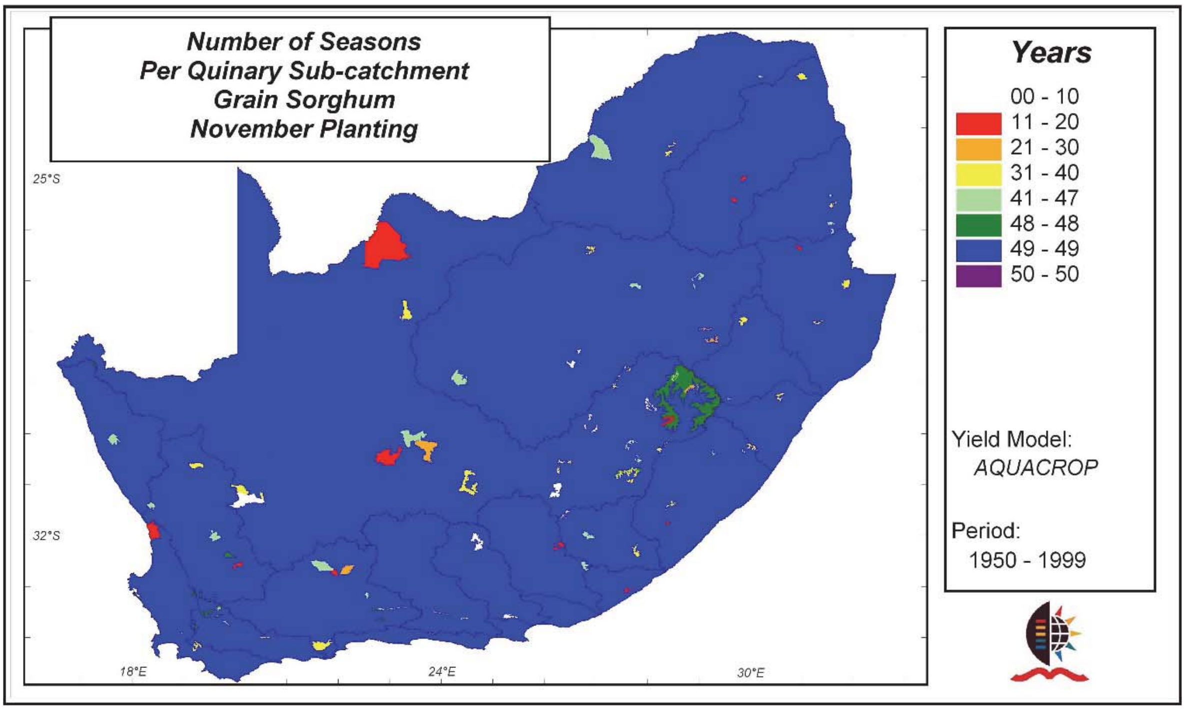
(b)


Number of Seasons
Per Quinary Sub-catchment
Sugarbeet
September Planting
25°S
32°S
18°E
24°E
30°E
Years
00 - 10
11 - 20
21 - 30
31 - 40
41 - 47
48 - 48
49 - 49
50 - 50
Yield Model:
AQUACROP
Period:
1950 - 1999

(c)

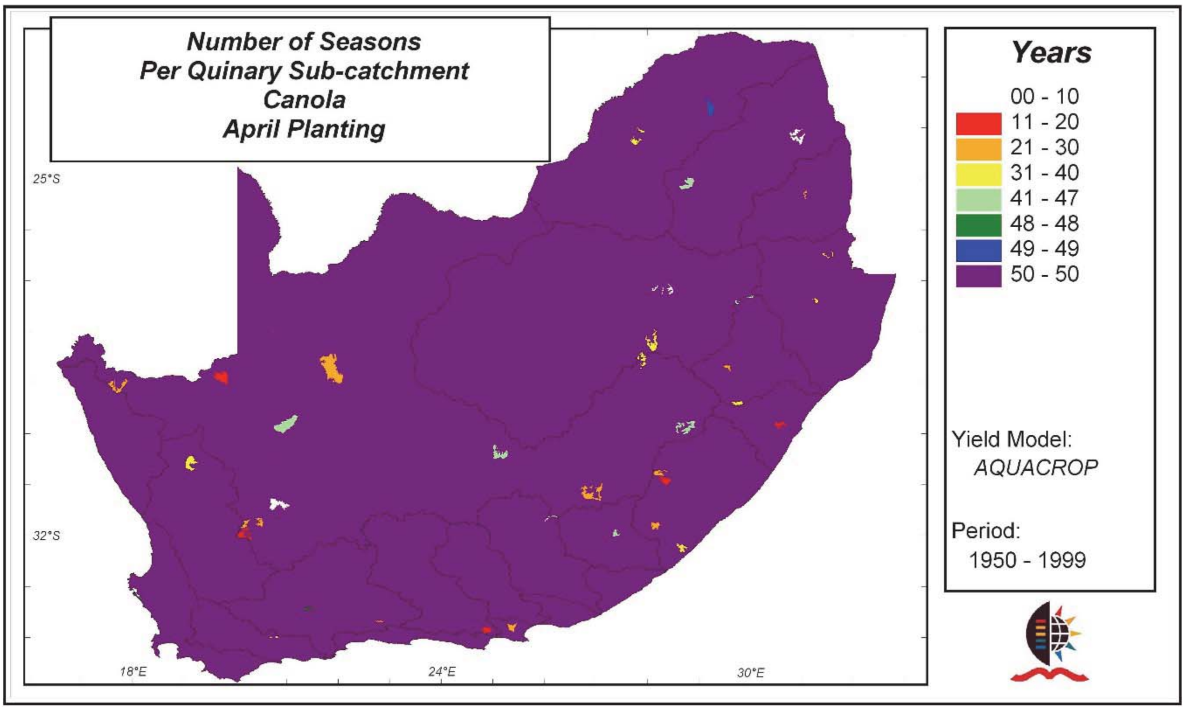

Number of Seasons
Per Quinary Sub-catchment
Sugarbeet
June Planting
25°S
32°S
18°E
24°E
30°E
Years
00 - 10
11 - 20
21 - 30
31 - 40
41 - 47
48 - 48
49 - 49
50 - 50
Yield Model:
AQUACROP
Period:
1950 - 1999

(d)

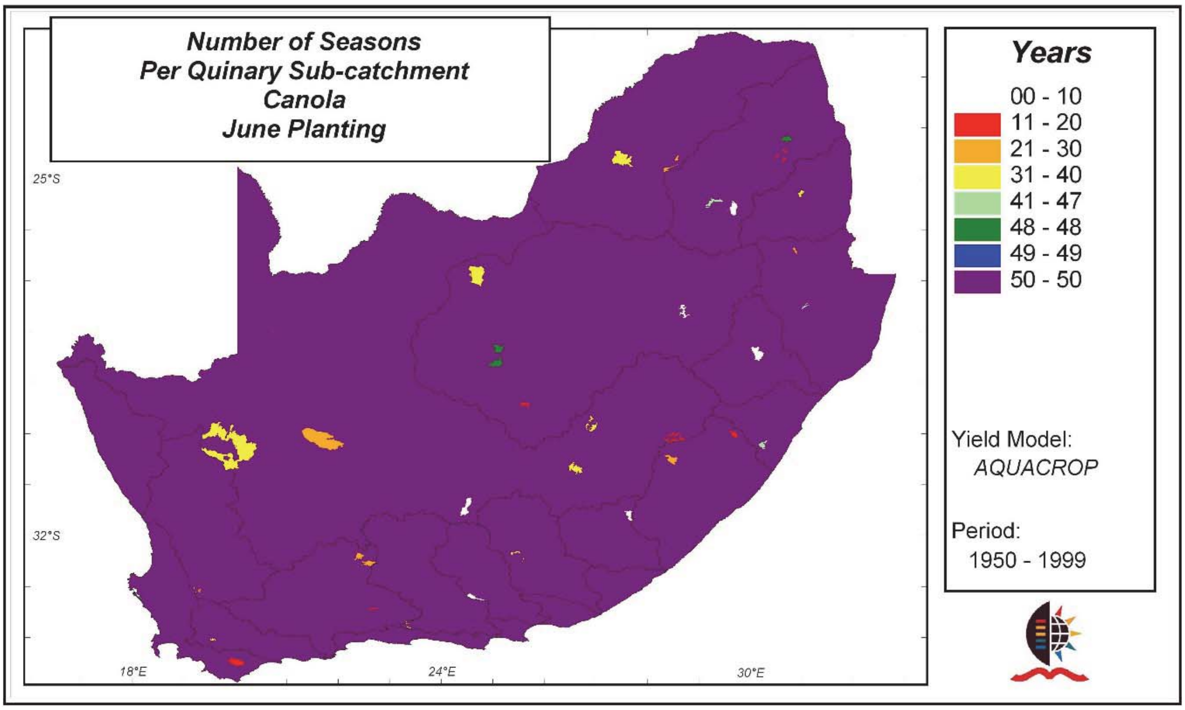


(e)

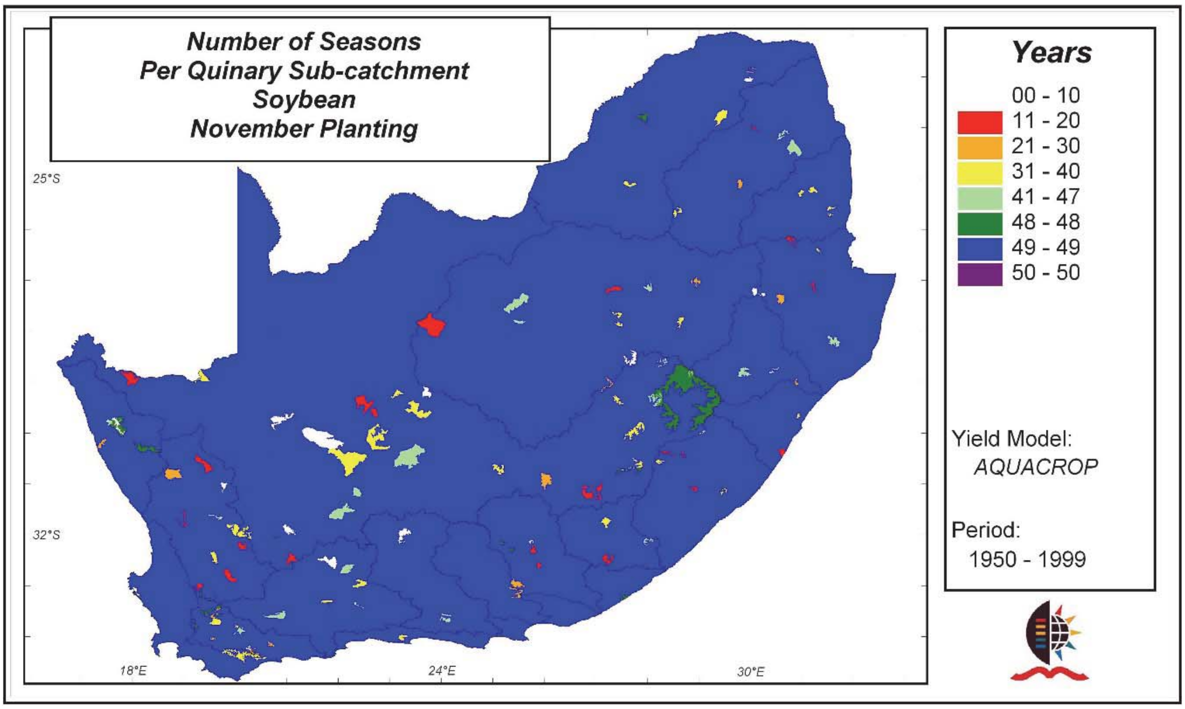
Figure 49 Number of seasons of data used to estimate the long-term yield and WUE for selected bioethanol feedstocks (a-e) planted on different dates



(a)



(b)



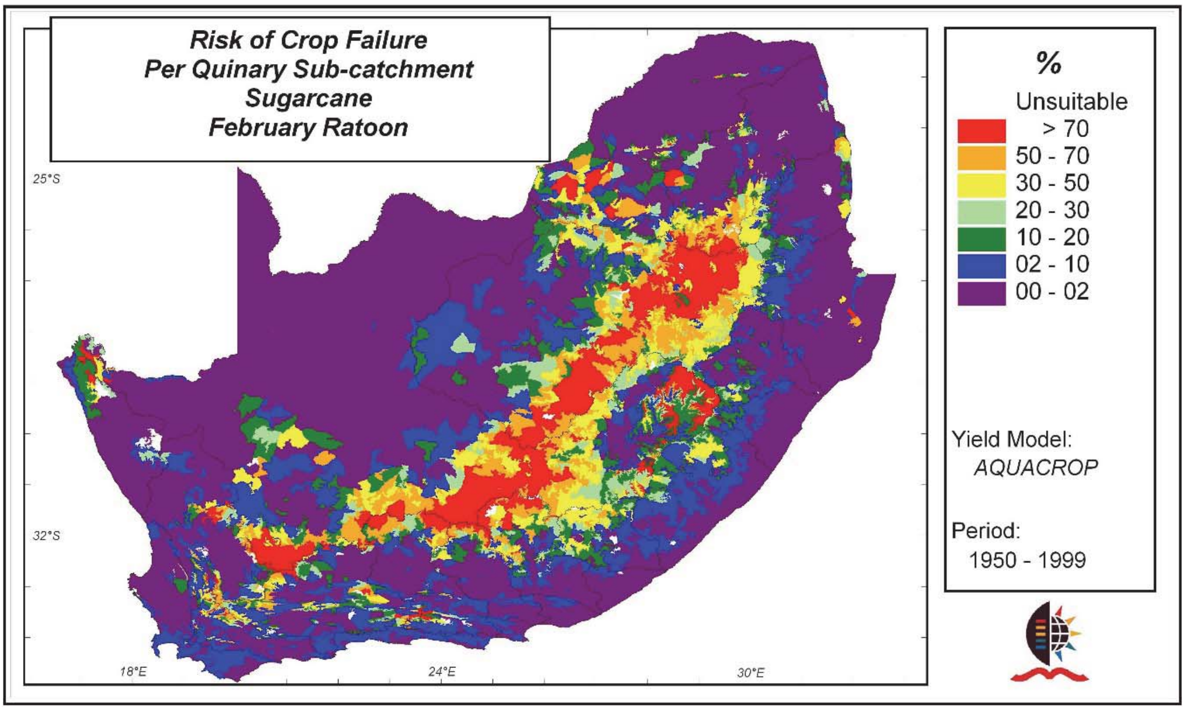
(c)

Figure 50 Number of seasons of data used to estimate the long-term yield and WUE for selected biodiesel feedstocks (a-c) planted on different dates

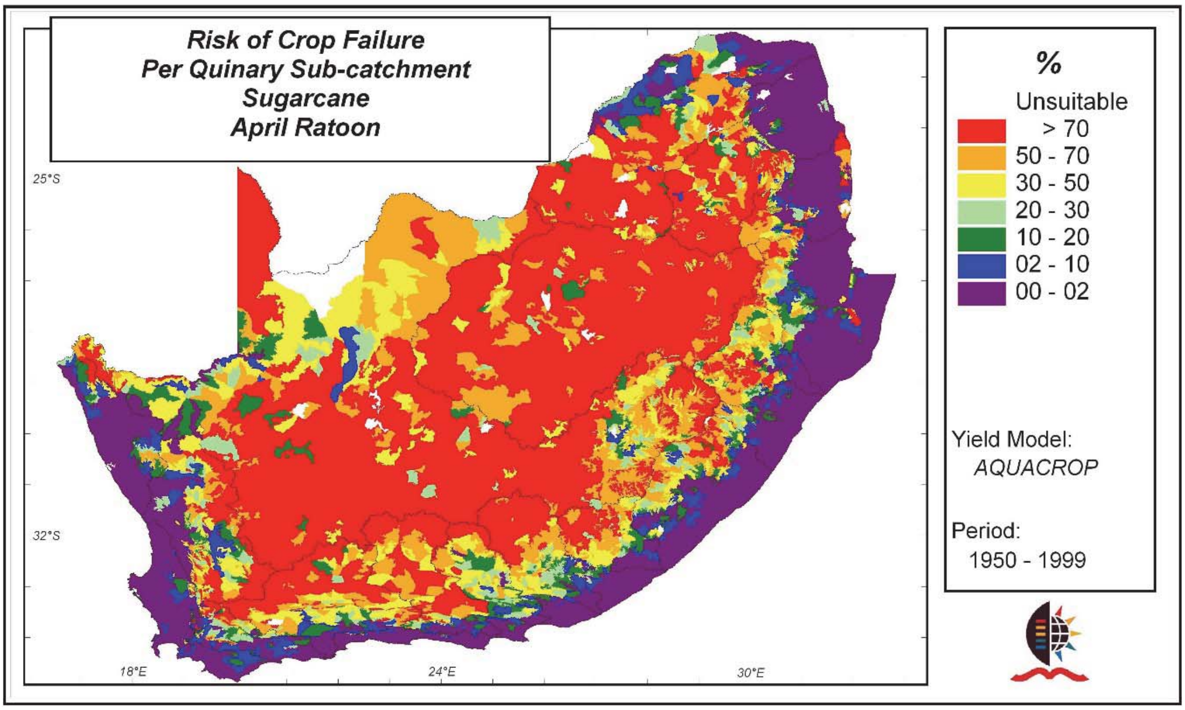
4.2.3.11 Risk of crop failure

The risk of crop failure simulated for selected bioethanol and biodiesel crops is given in **Figure 51** and **Figure 52** respectively. To re-cap, it represents the number of zero yields that were simulated over the maximum 50-year period, which is then doubled and expressed as a percentage. The maps show that the interior of the country is economically unviable for many feedstocks, in particular sugarcane and sugarbeet. Grain sorghum is not suitable for production in the western parts of the country, with the exception of the southern Cape coastal areas.

Canola represents the feedstock that can grow practically anywhere in the country, followed by soybean. For all other crops, a 20% risk means a total crop failure (i.e. zero yield) was simulated 10 times over the 50 (maximum) seasons. This equates to one crop failure every five years (on average), which may be considered high risk by some investors.

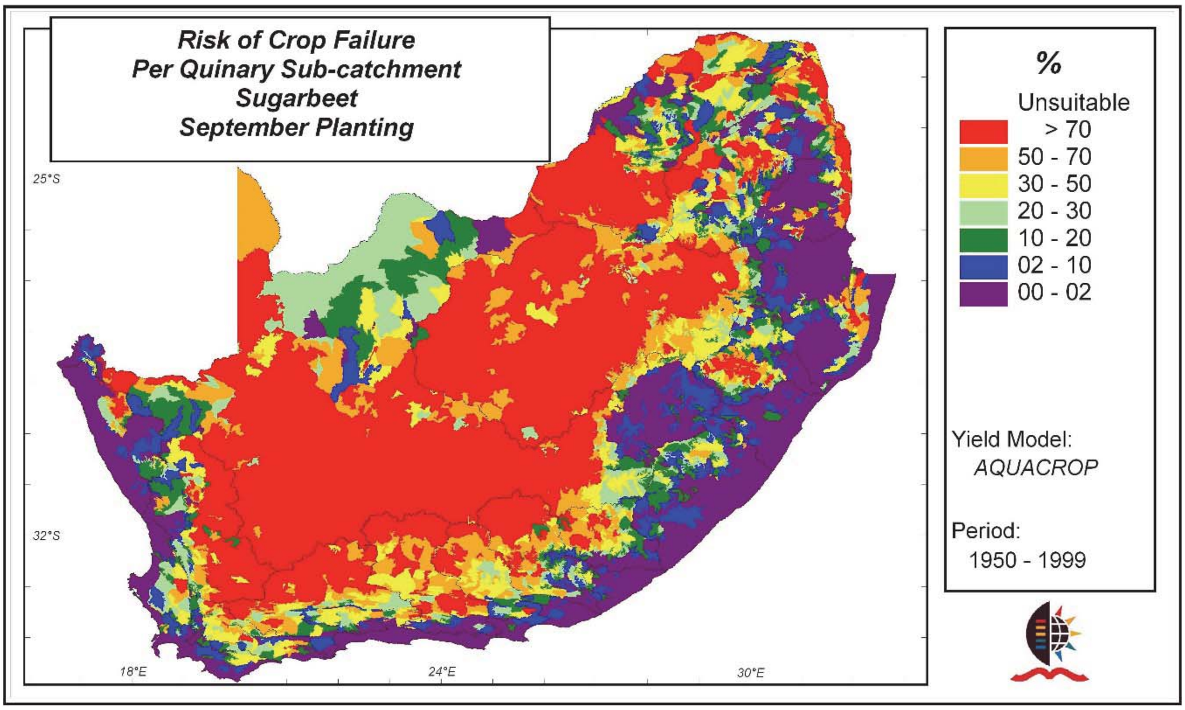


(a)



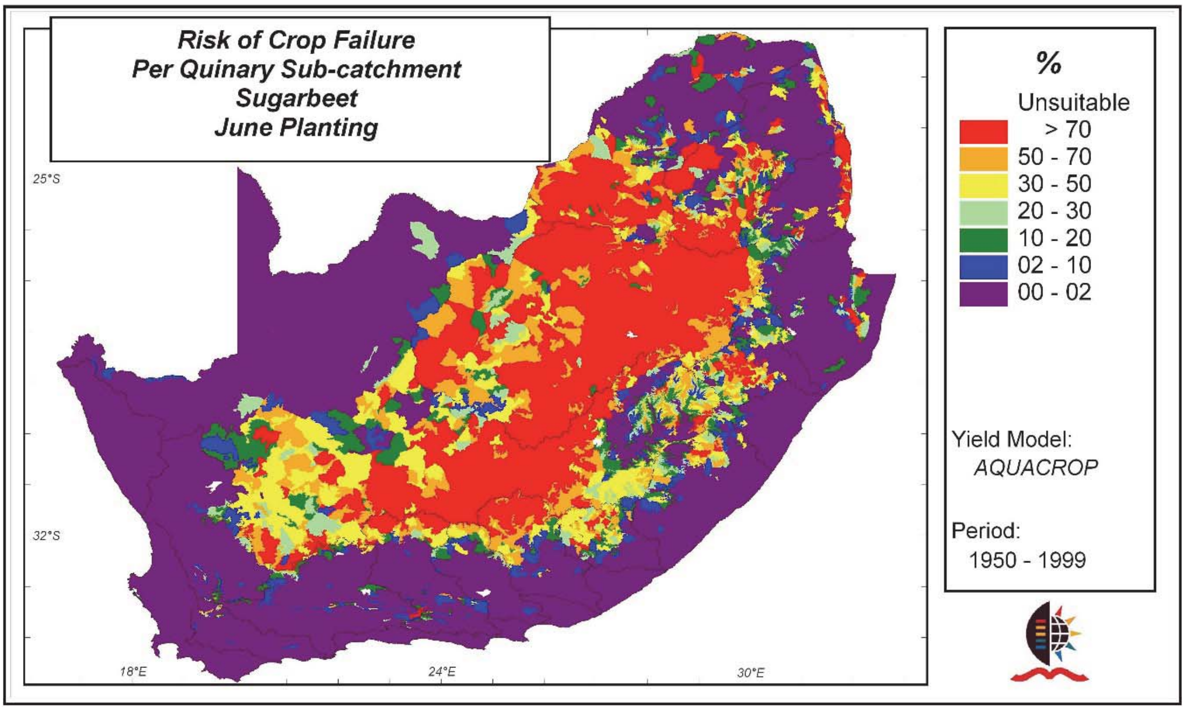
Risk of Crop Failure
Per Quinary Sub-catchment
Sugarcane
April Ratoon
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
> 70
50 - 70
30 - 50
20 - 30
10 - 20
02 - 10
00 - 02
Yield Model:
AQUACROP
Period:
1950 - 1999

(b)

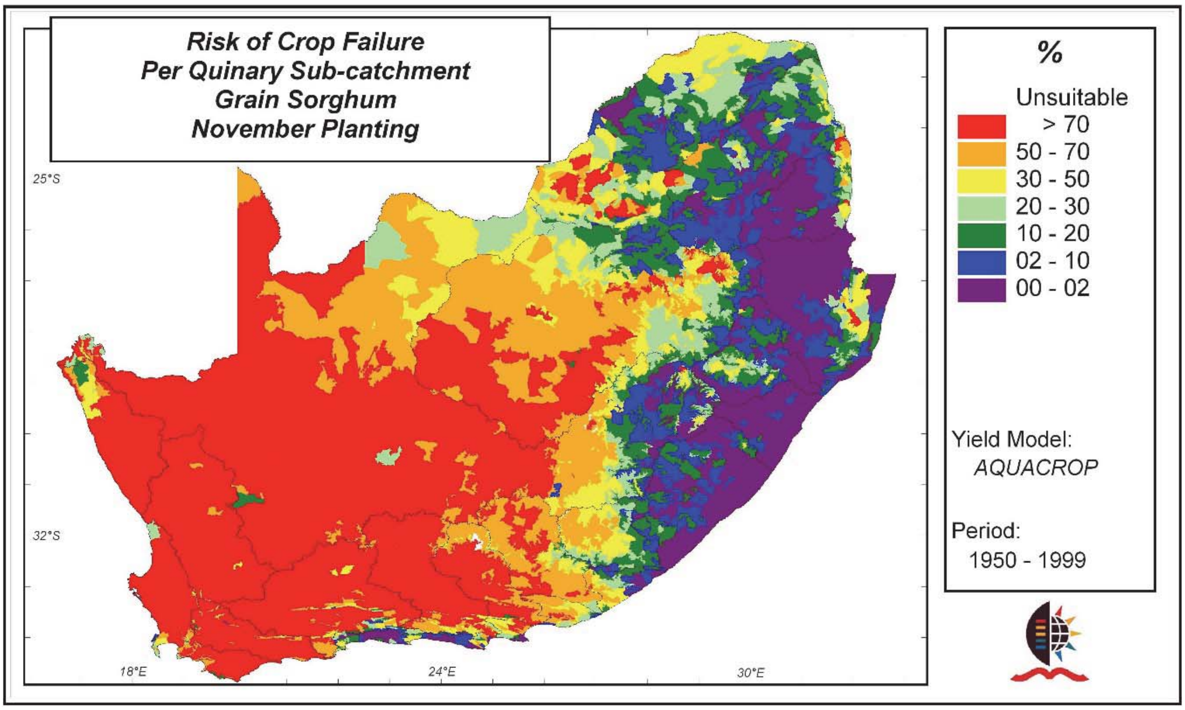


Risk of Crop Failure
Per Quinary Sub-catchment
Sugarbeet
September Planting
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
> 70
50 - 70
30 - 50
20 - 30
10 - 20
02 - 10
00 - 02
Yield Model:
AQUACROP
Period:
1950 - 1999

(c)

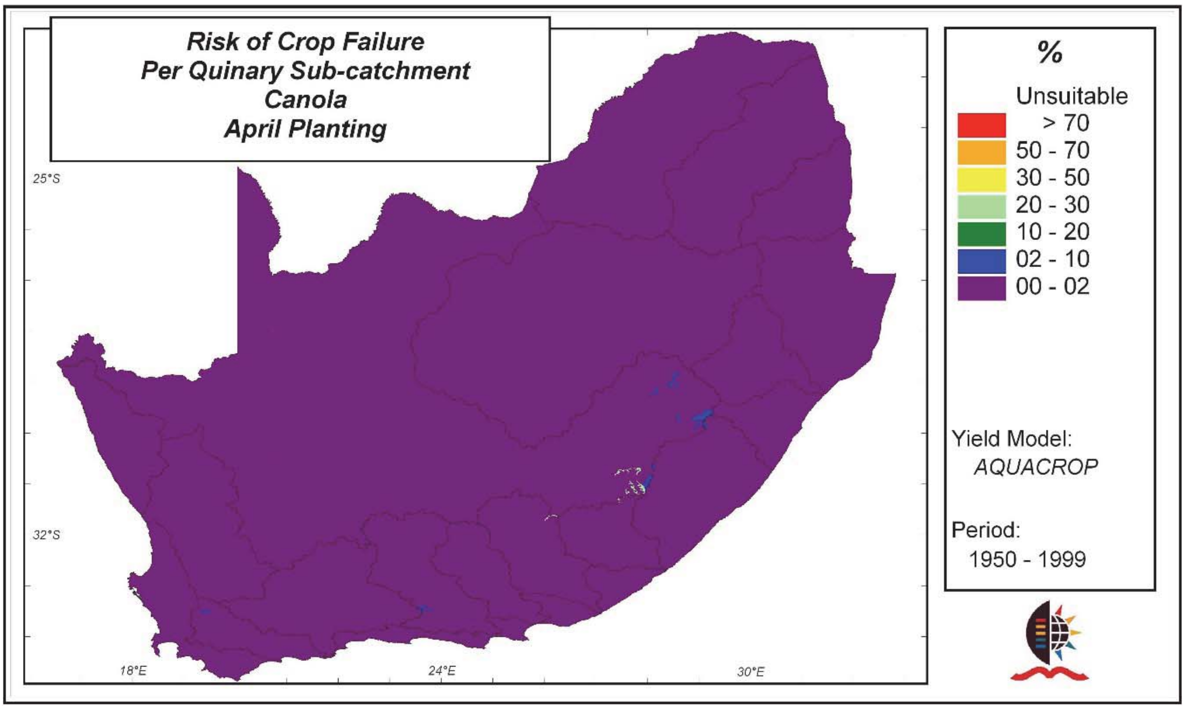


(d)



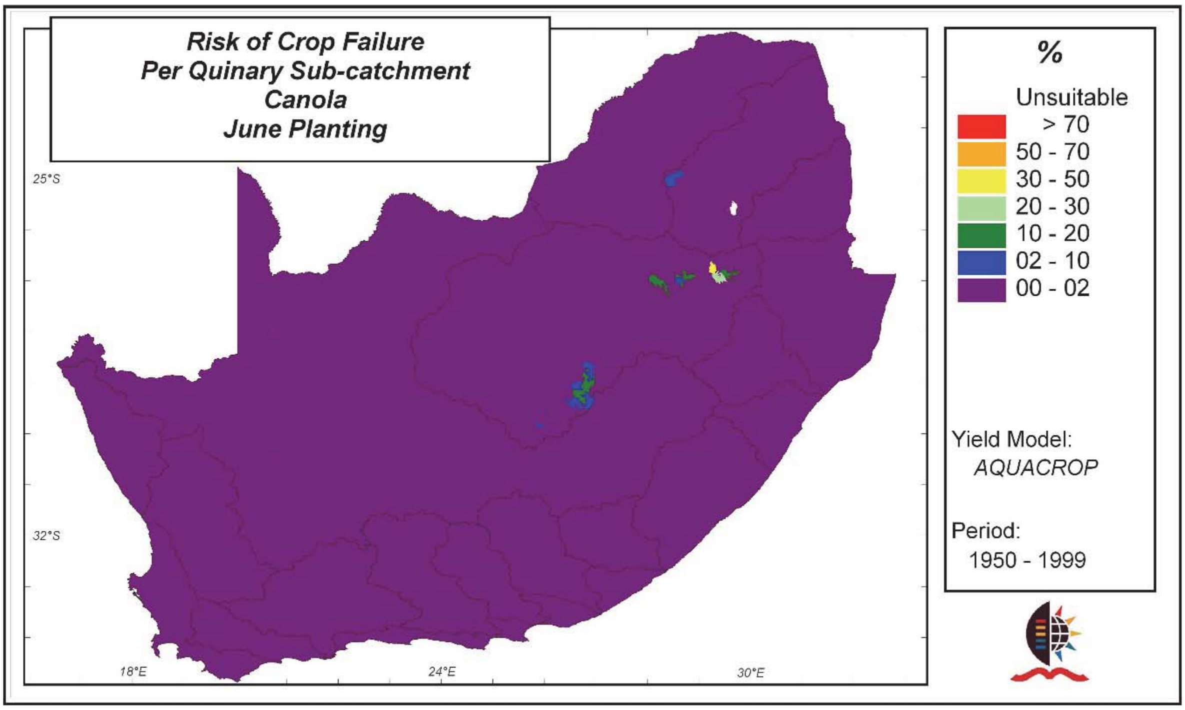
(e)

Figure 51 Number of crop failures over the 50-year period (expressed as a percentage) for selected bioethanol feedstocks (a-e) planted on different dates



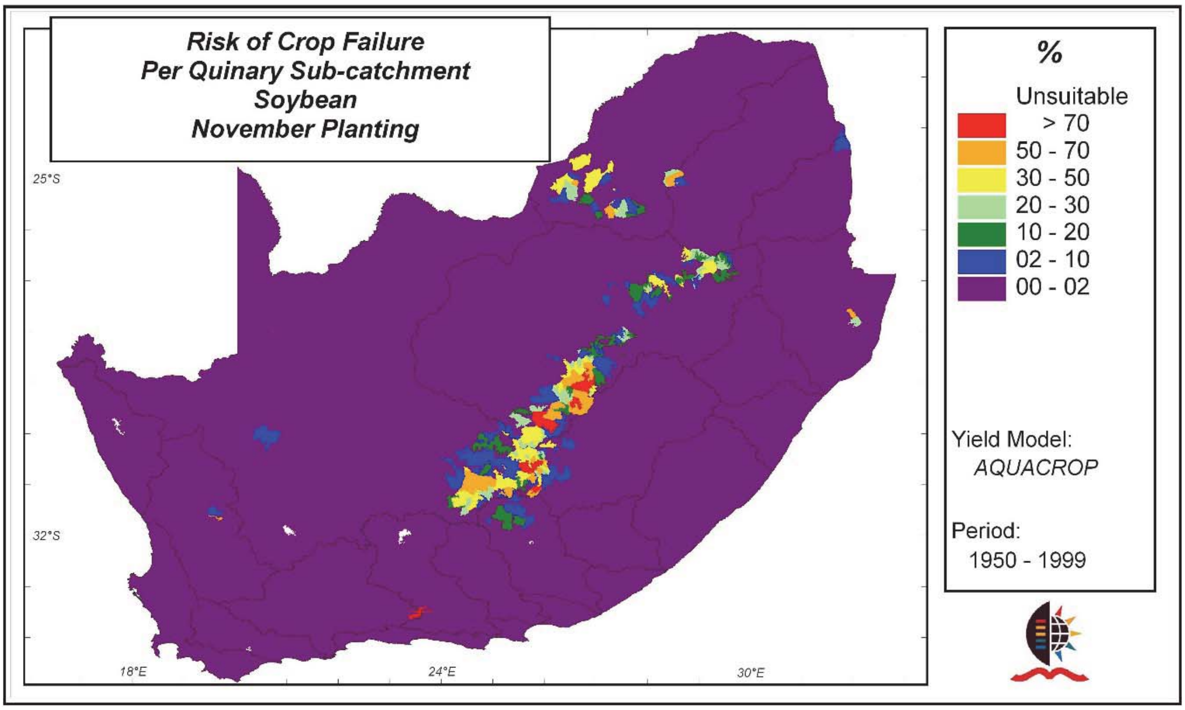
Risk of Crop Failure
Per Quinary Sub-catchment
Canola
April Planting
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
> 70
50 - 70
30 - 50
20 - 30
10 - 20
02 - 10
00 - 02
Yield Model:
AQUACROP
Period:
1950 - 1999

(a)



Risk of Crop Failure
Per Quinary Sub-catchment
Canola
June Planting
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
> 70
50 - 70
30 - 50
20 - 30
10 - 20
02 - 10
00 - 02
Yield Model:
AQUACROP
Period:
1950 - 1999

(b)



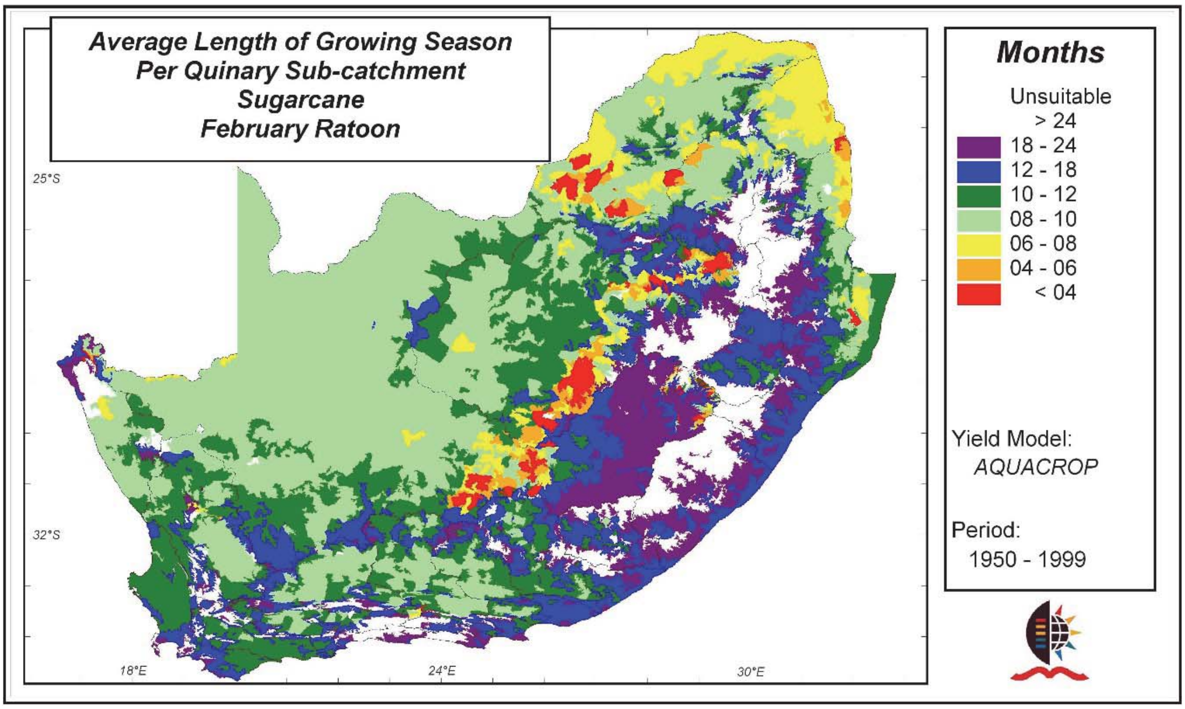
(c)

Figure 52 Number of crop failures over the 50-year period (expressed as a percentage) for selected biodiesel feedstocks (a-c) planted on different dates

4.2.3.12 Length of growing season (*CYC*)

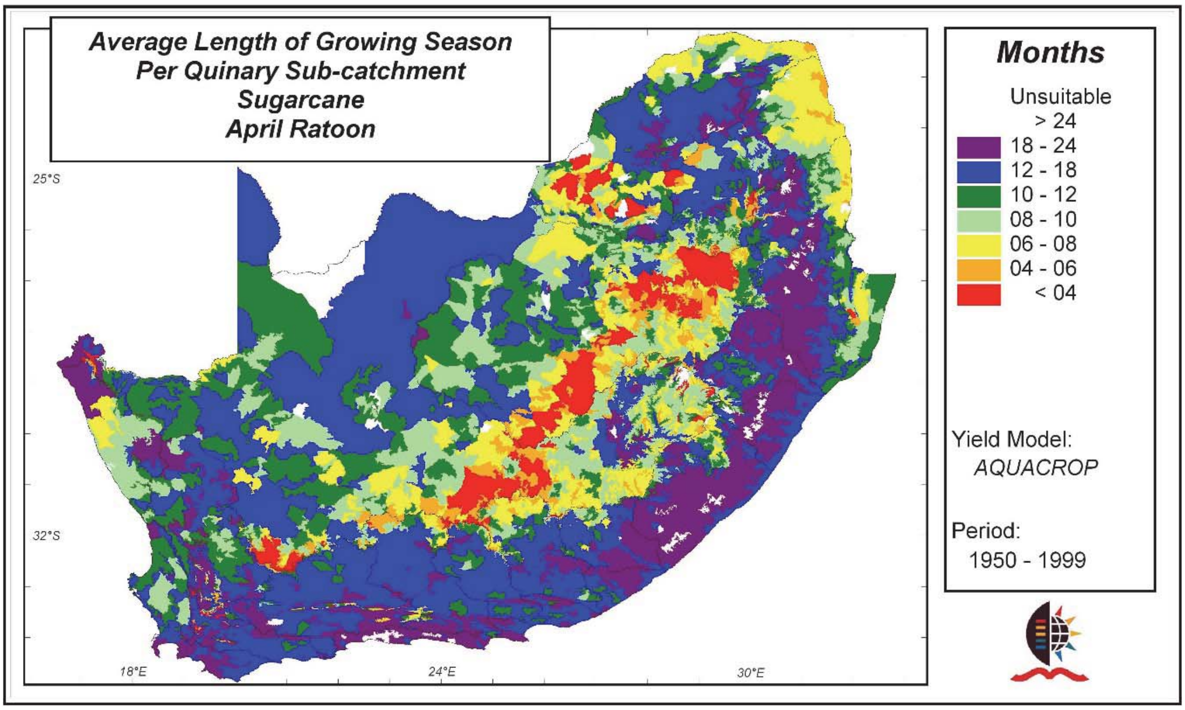
The length of the crop cycle (called *CYC* in this document) is presented in **Figure 53** and **Figure 54** for selected bioethanol and biodiesel crops respectively. To re-cap, *CYC* is the length of the crop cycle from germination to the date the peak (or maximum) yield is attained. The maps highlight those crops which should physiologically mature faster than others. More importantly, the maps identify areas which are deemed too cold to grow the crop in a reasonable season length. For example, a crop cycle length of 10 months or longer may be considered unviable for annual crops, which occurs in the Lesotho highlands and Drakensberg region. Similarly, a crop cycle length of more than 24 months for perennial crops such has sugarcane may also be considered economically unviable.

Maps of the median length of the growing season are given in **Figure 83** and **Figure 84** in **APPENDIX G**. The largest difference between the mean and median map versions occurred for sugarcane. Areas in white represent a crop cycle length of two years or more (i.e. > 730 days), which is considered unsuitable for viable production.



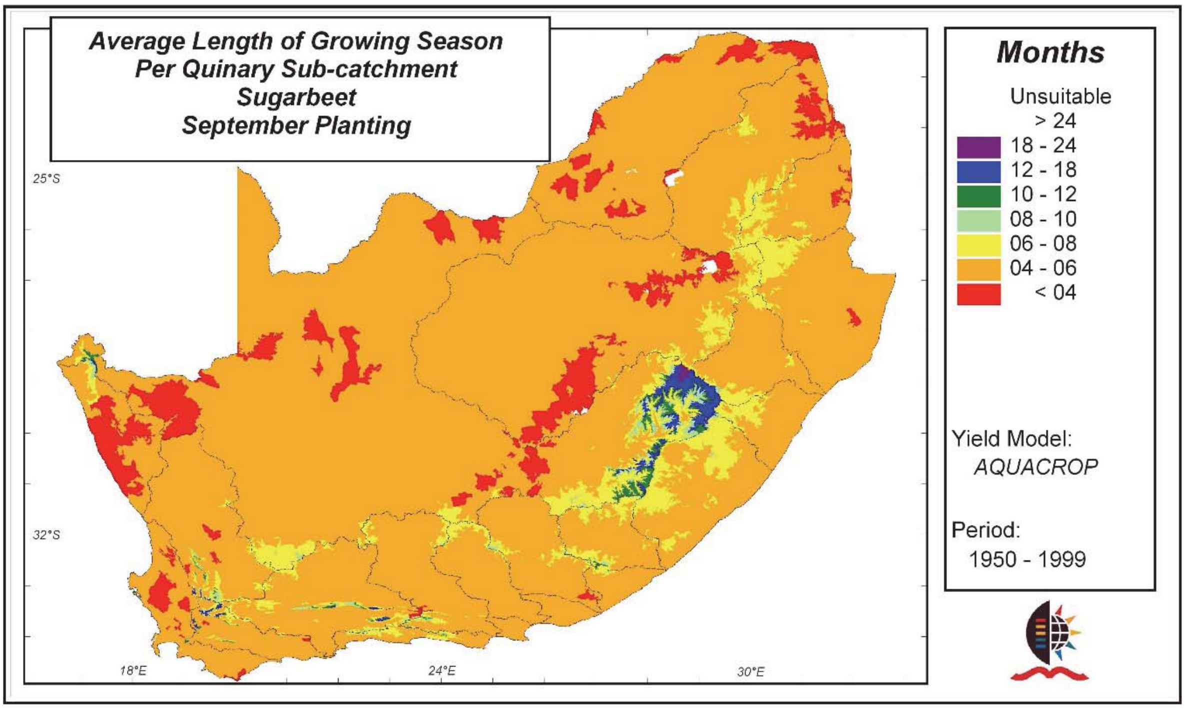
Average Length of Growing Season
Per Quinary Sub-catchment
Sugarcane
February Ratoon
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)

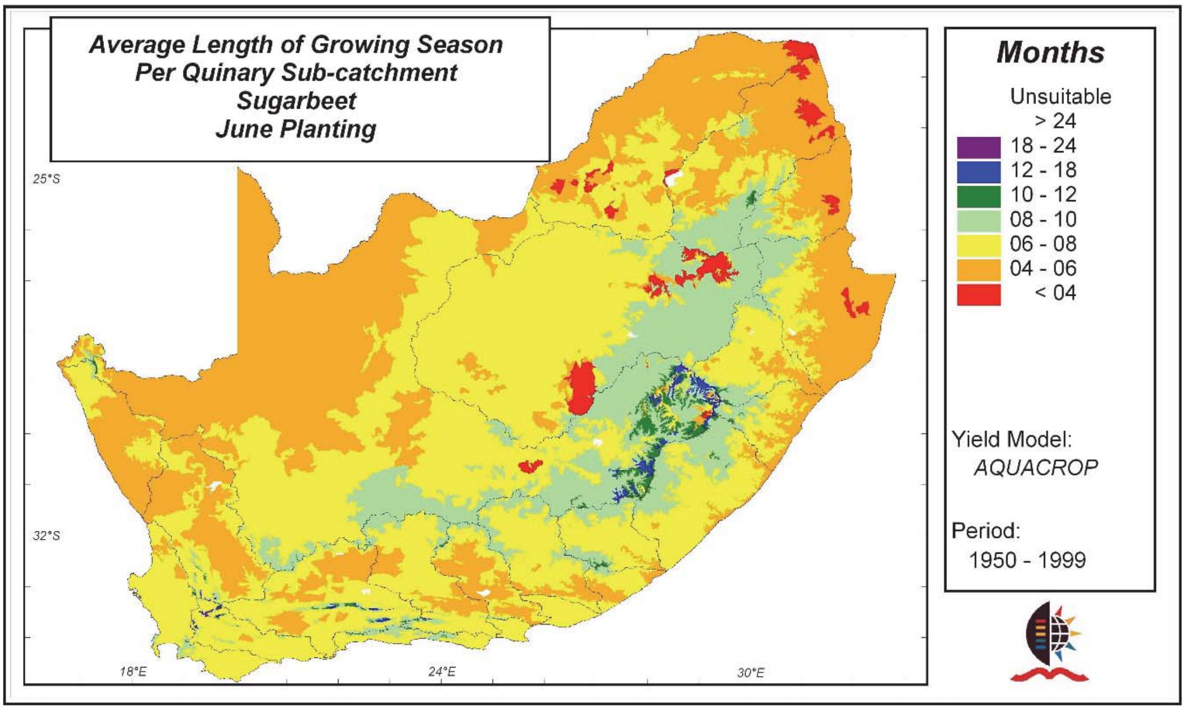


Average Length of Growing Season
Per Quinary Sub-catchment
Sugarcane
April Ratoon
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

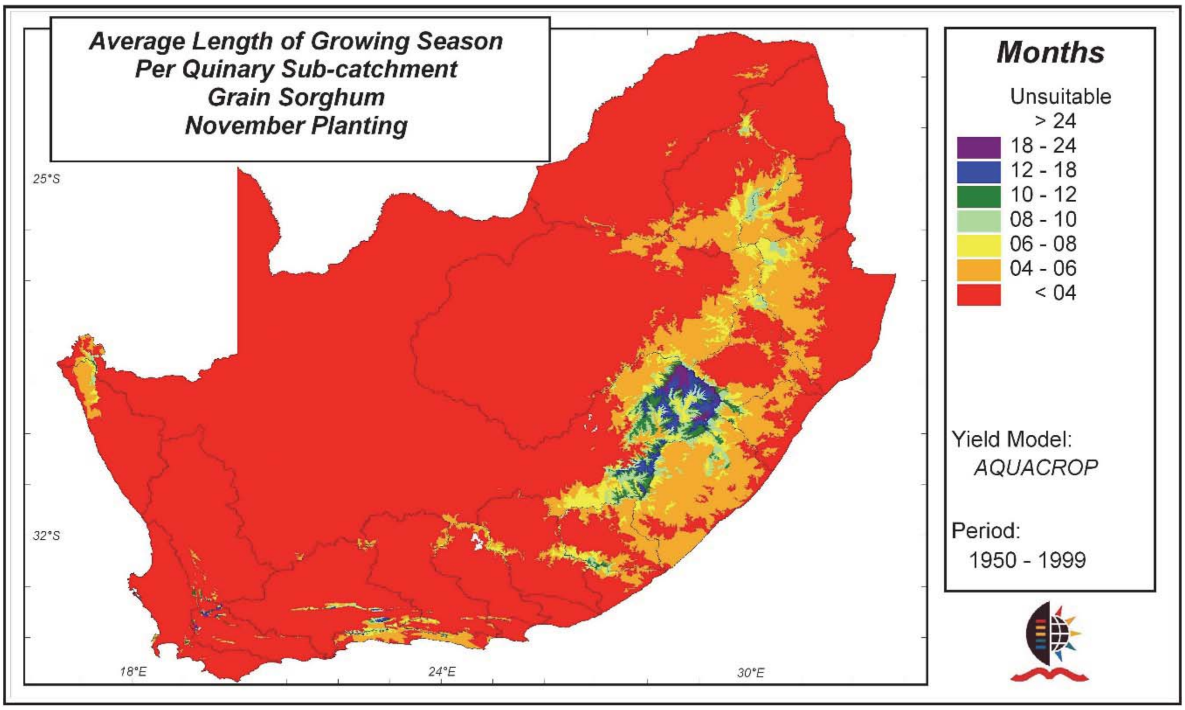
(b)


Average Length of Growing Season
Per Quinary Sub-catchment
Sugarbeet
September Planting
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)

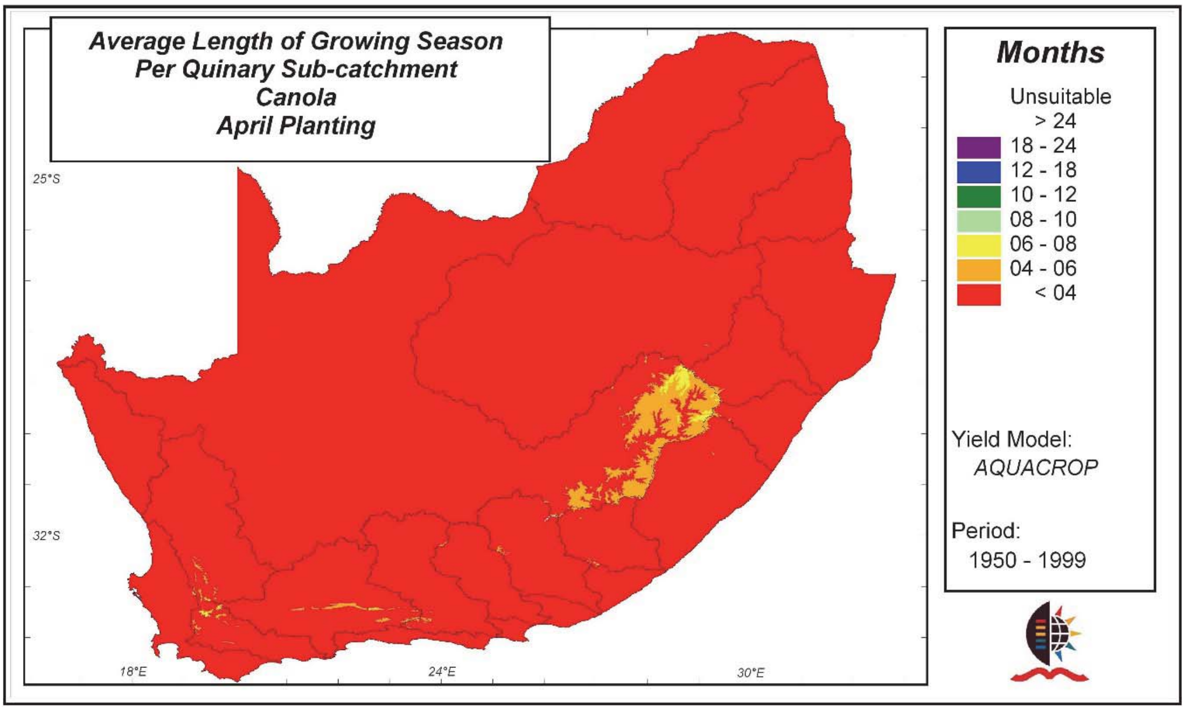

Average Length of Growing Season
Per Quinary Sub-catchment
Sugarbeet
June Planting
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

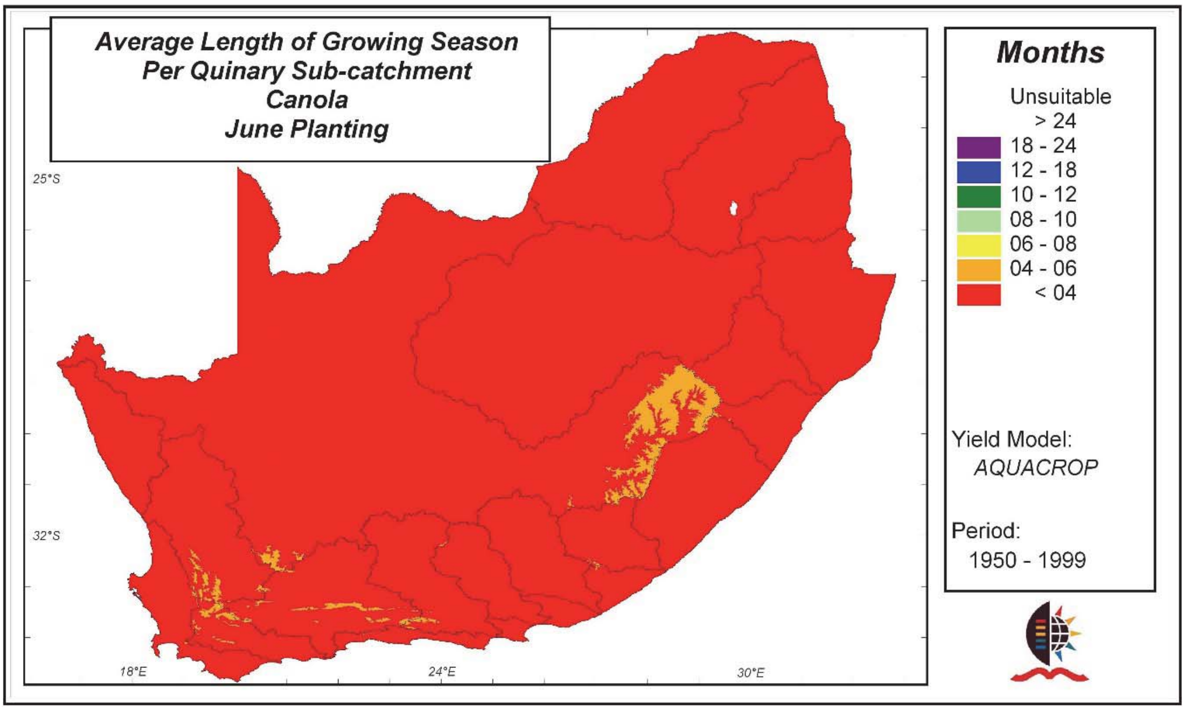


(e)

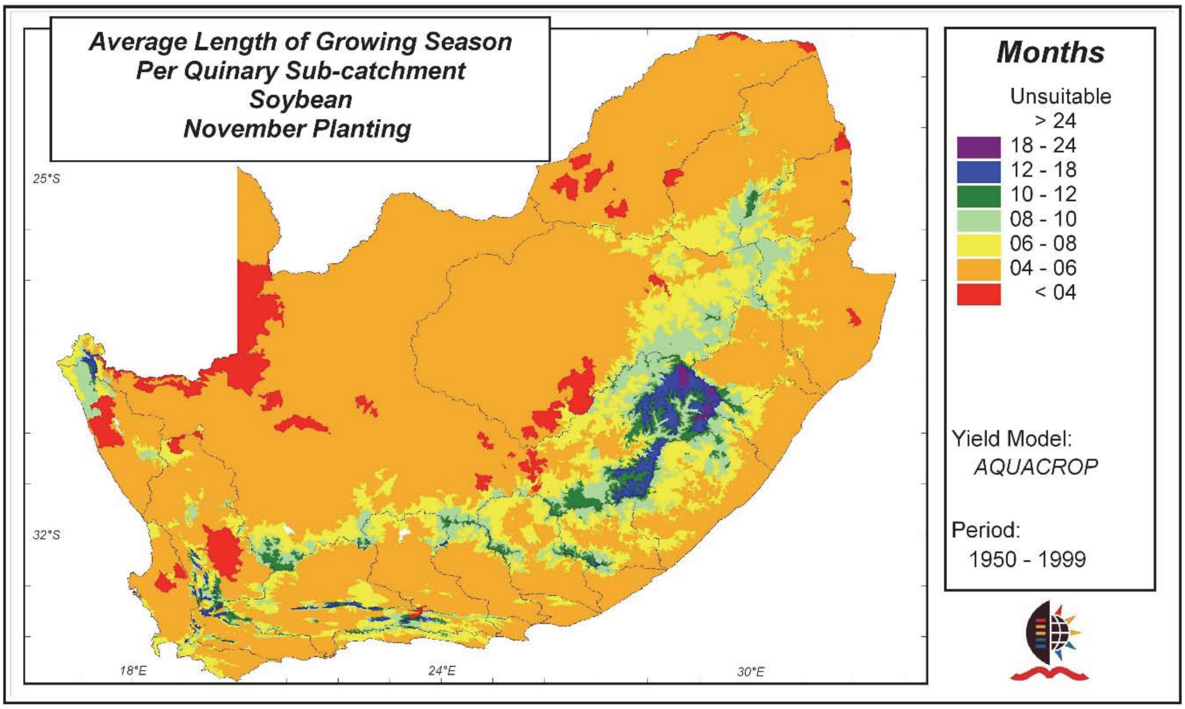
Figure 53 Average length of the growing season (from germination to peak yield) as determined by *AQUACROP* for selected bioethanol feedstocks (a-e) planted on different dates



(a)



(b)



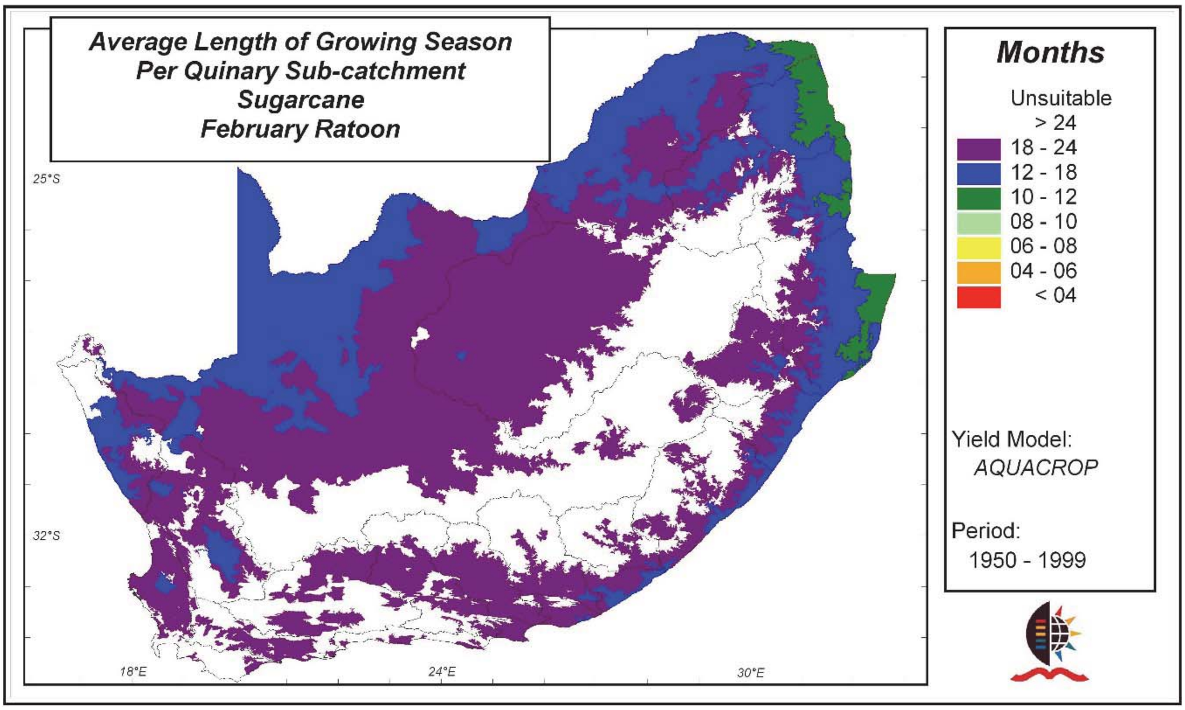
(c)

Figure 54 Average length of the growing season (from germination to peak yield) as determined by *AQUACROP* for selected biodiesel feedstocks (a-c) planted on different dates

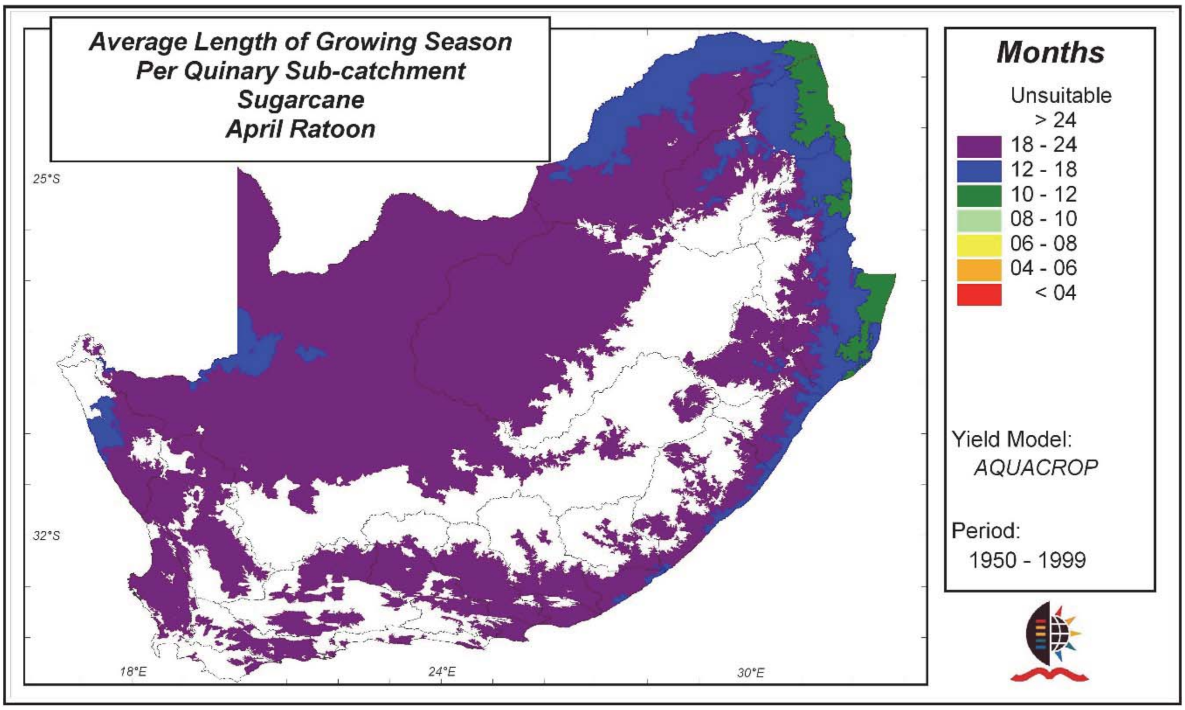
4.2.3.13 Length of growing season (*GRO*)

In this section, the length of the growing season is defined from the day of planting to the maturity date (or expected harvest date). It represents the variable *GRO* in this document. Maps of average season lengths are shown in **Figure 55** and **Figure 56** for selected bioethanol and biodiesel feedstocks respectively. For sugarcane, it highlights the short-season growing areas (12 months or less) associated with high temperatures (e.g. Zululand coastal area). For the majority of the cane producing areas, cane is typically cut once every 12 to 18 months. In the cooler, higher altitude sites, the season extends up to 24 months. Areas shown in white are considered too cold for viable sugarcane production as the season length is longer than 24 months.

The canola maps clearly identify mountain topography, with the Lesotho highlands and Drakensberg regions producing unreasonably long growing seasons for all crops (except canola). A comparison of **Figure 54** with **Figure 56** revealed that *CYC* is very similar to *GRO* for canola, which is not the case for all the other crops considered. The growing season length presented in this section (i.e. spatial variation in variable *GRO*) is considered superior to the maps shown in the previous section (i.e. based on the variable *CYC*). The median-based versions are given in **Figure 85** and **Figure 86** in **APPENDIX H**.

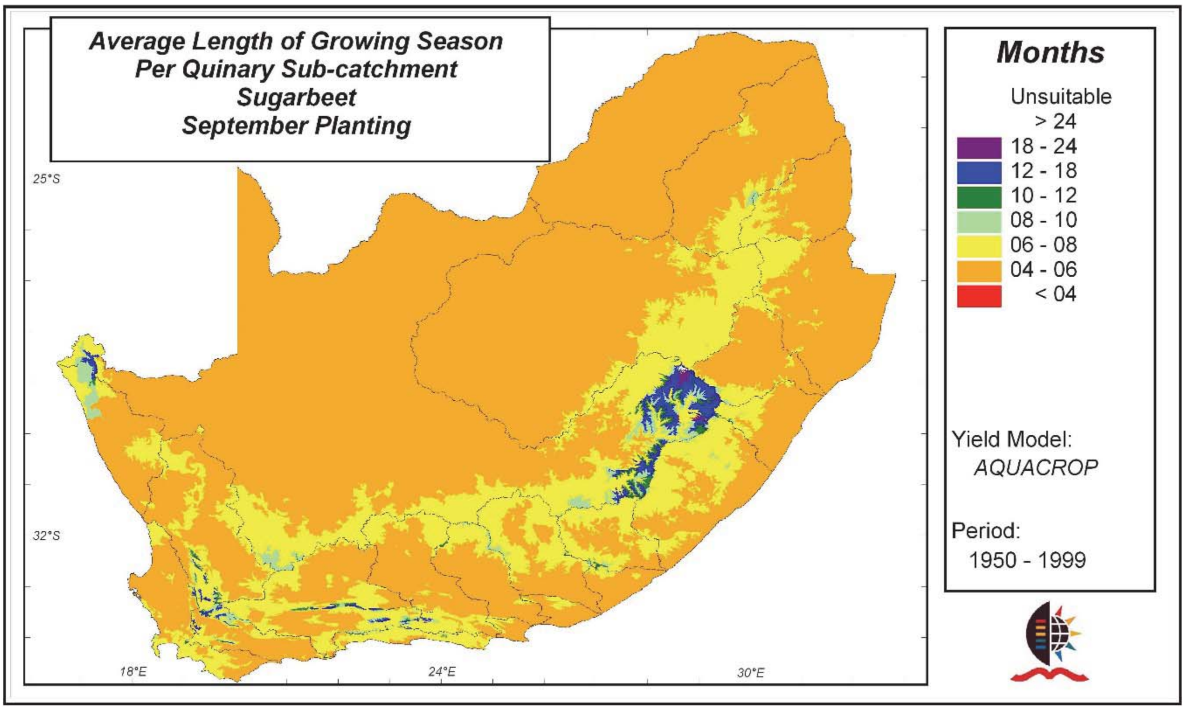


(a)



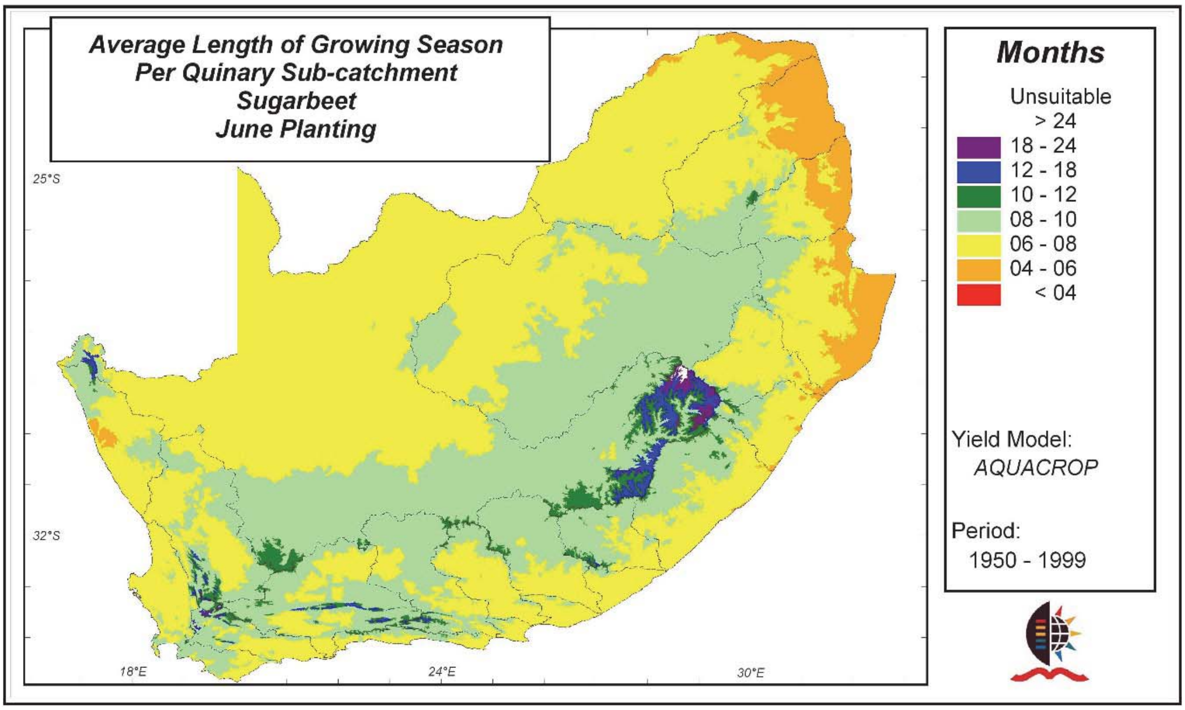
Average Length of Growing Season
Per Quinary Sub-catchment
Sugarcane
April Ratoon
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)

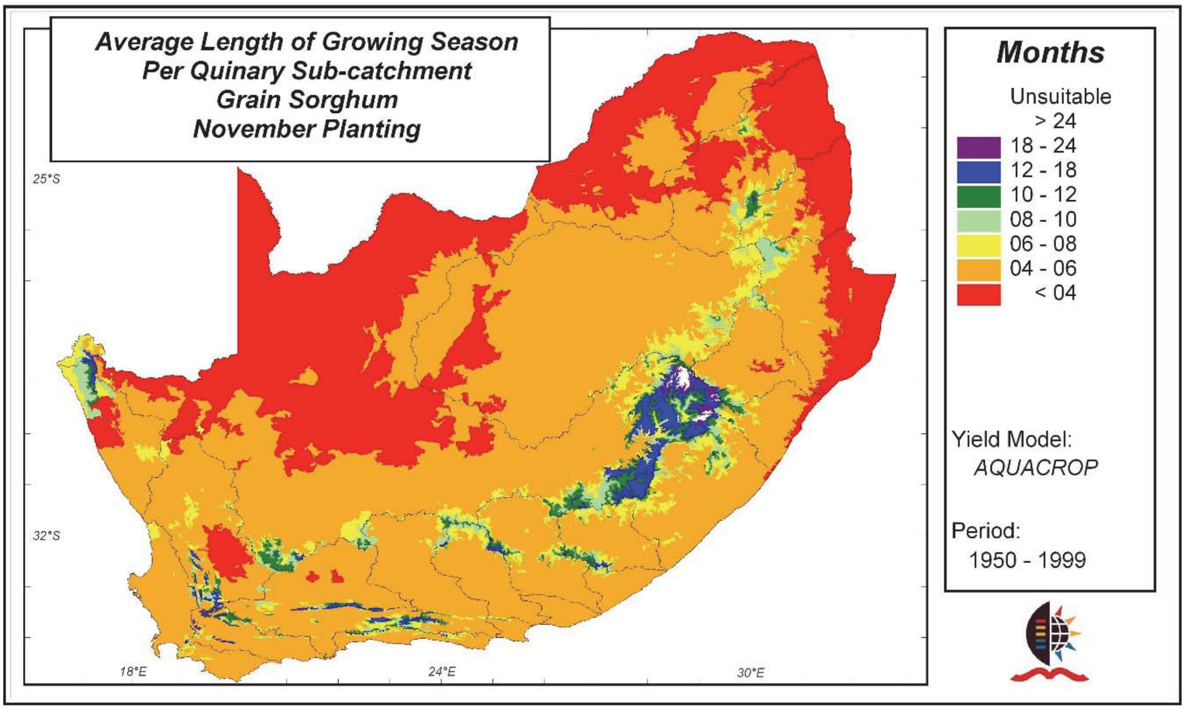


Average Length of Growing Season
Per Quinary Sub-catchment
Sugarbeet
September Planting
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)

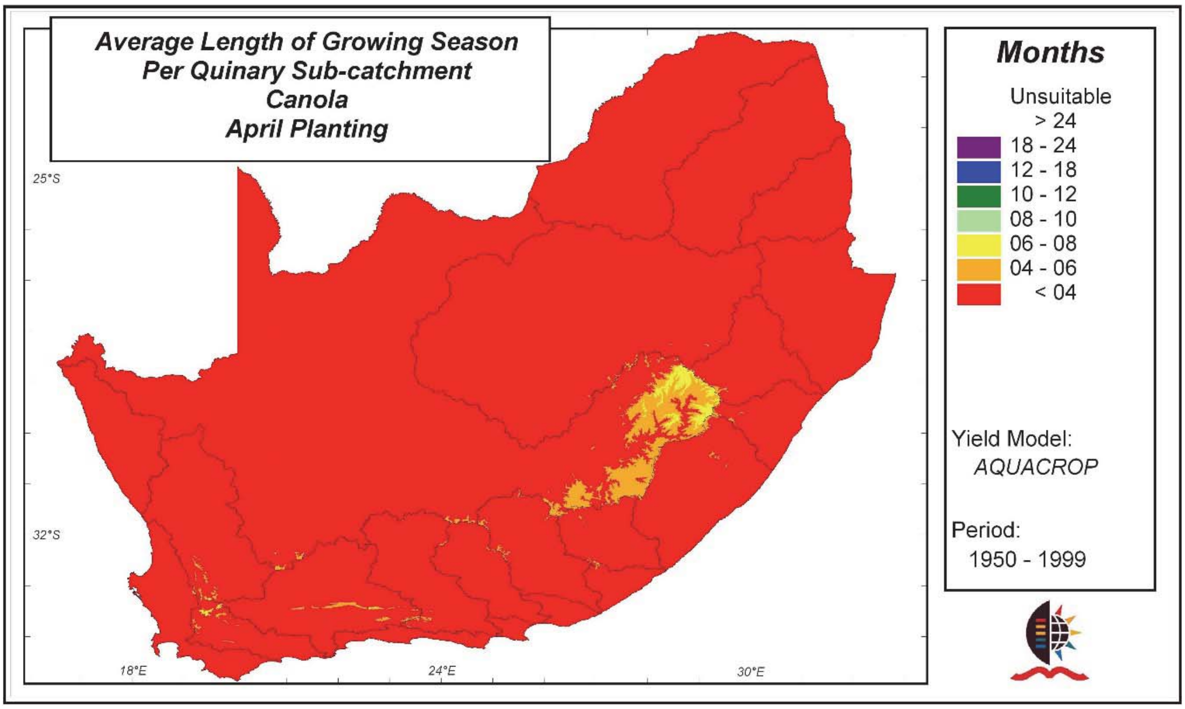


(d)

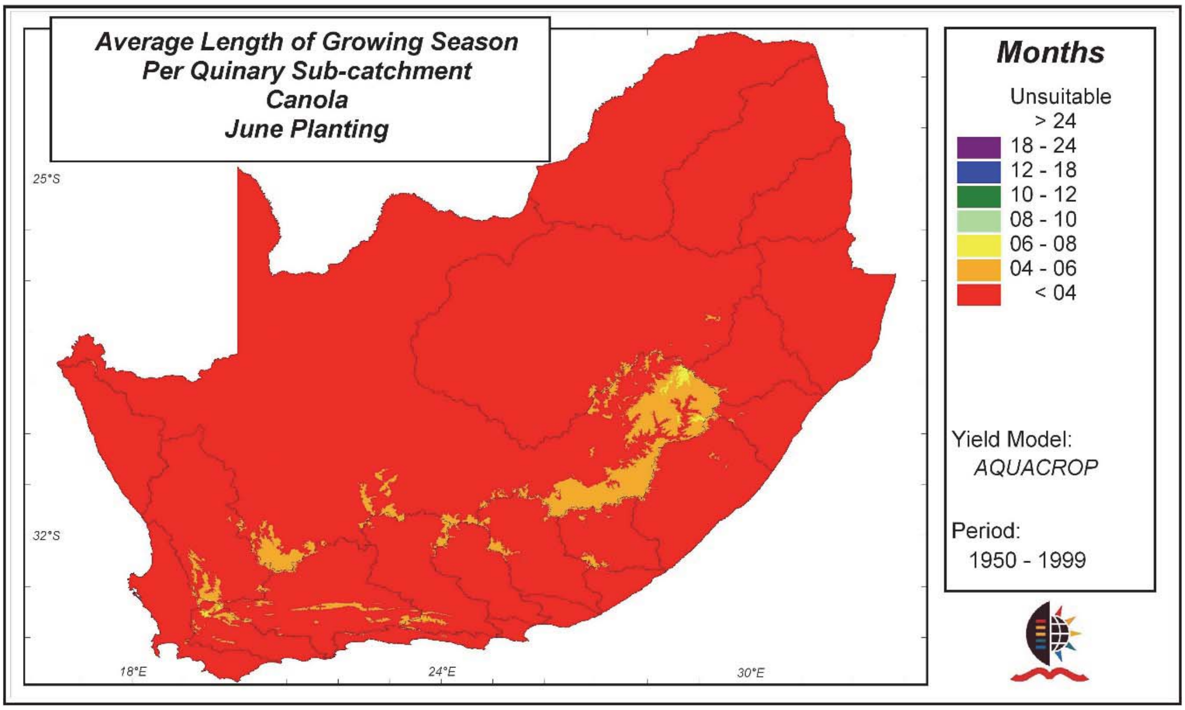


(e)

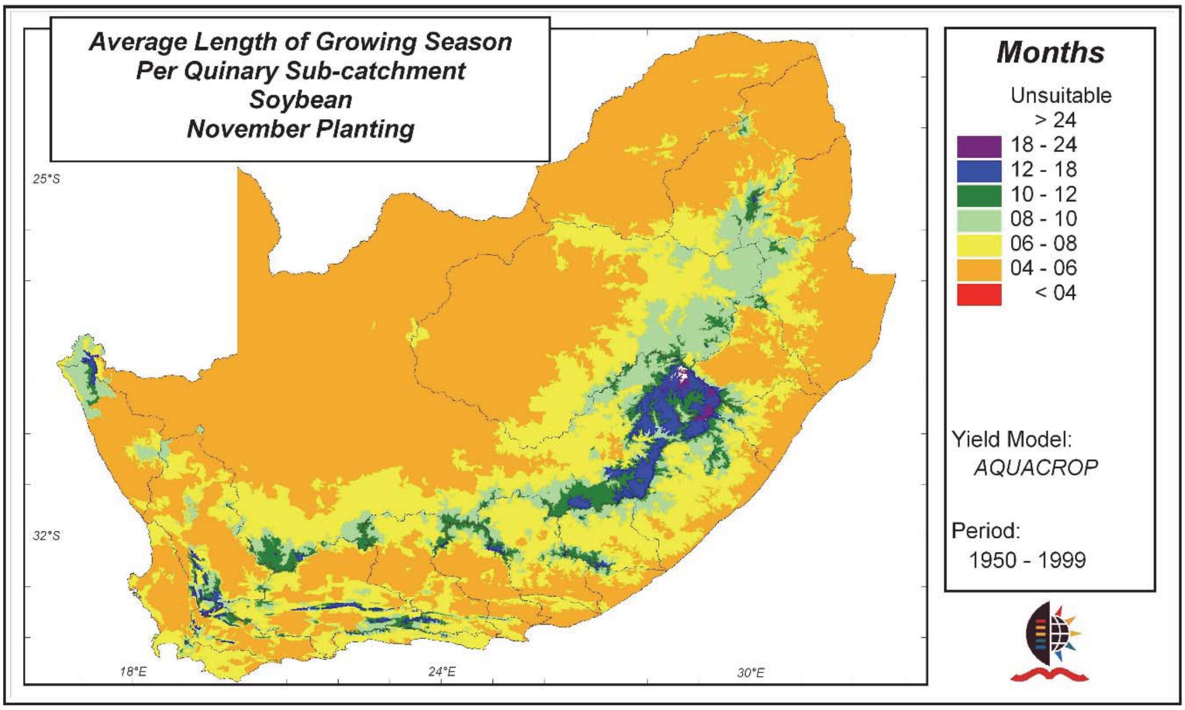
Figure 55 Average length of the growing season (from planting to maturity date) for selected bioethanol feedstocks planted on different dates


Average Length of Growing Season
Per Quinary Sub-catchment
Canola
April Planting
25°S
32°S
18°E
24°E
30°E
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999

(a)


Average Length of Growing Season
Per Quinary Sub-catchment
Canola
June Planting
25°S
32°S
18°E
24°E
30°E
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999

(b)



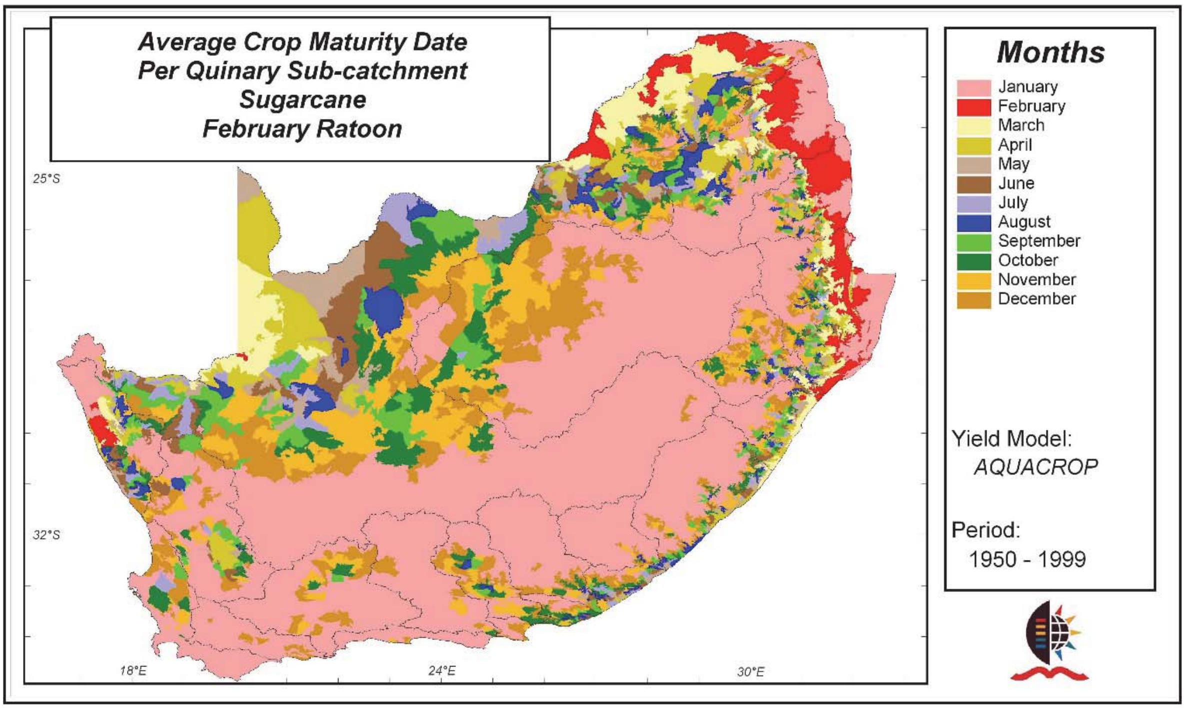
(c)

Figure 56 Average length of the growing season (from planting to maturity date) for selected biodiesel feedstocks planted on different dates

4.2.3.14 Crop maturity month

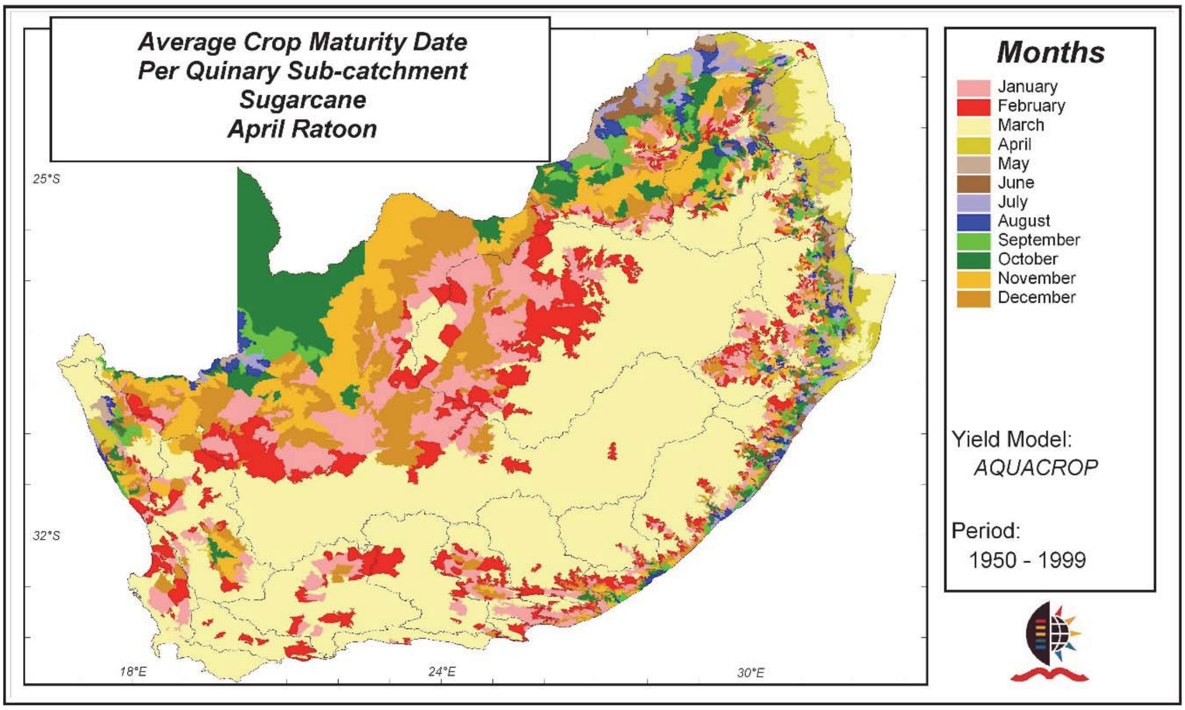
The final sets of maps produced from *AQUACROP* output provide the average month in which the crop matures (i.e. harvest month) in terms of GDD. As noted previously, the harvest month is particularly important for sugarcane, considering the sugar mills accept feedstock from April to about October. For a February transplanting of sugarcane in the Zululand coastal region of KwaZulu-Natal, the crop should mature in January or February, i.e. outside of the milling season (**Figure 57**). However, the crop should be ready for harvest in March or April if transplanted in April, which better coincides with the period that mills typically accept feedstock for processing.

The two sugarcane maps therefore highlight areas that neither a February nor an April transplanting is representative of the cane growing area. This means the yield model should be run for other planting dates, an exercise that was not undertaken due to the length of time required to produce a national run. In reality, sugarcane is harvested from different fields of the same farm, thus ensuring the supply of cane during the milling season. **Figure 57** also shows that if sugarbeet is planted on 1st September, it is likely to be ready for harvest in January or February the following year, or delayed till March for the colder sites.



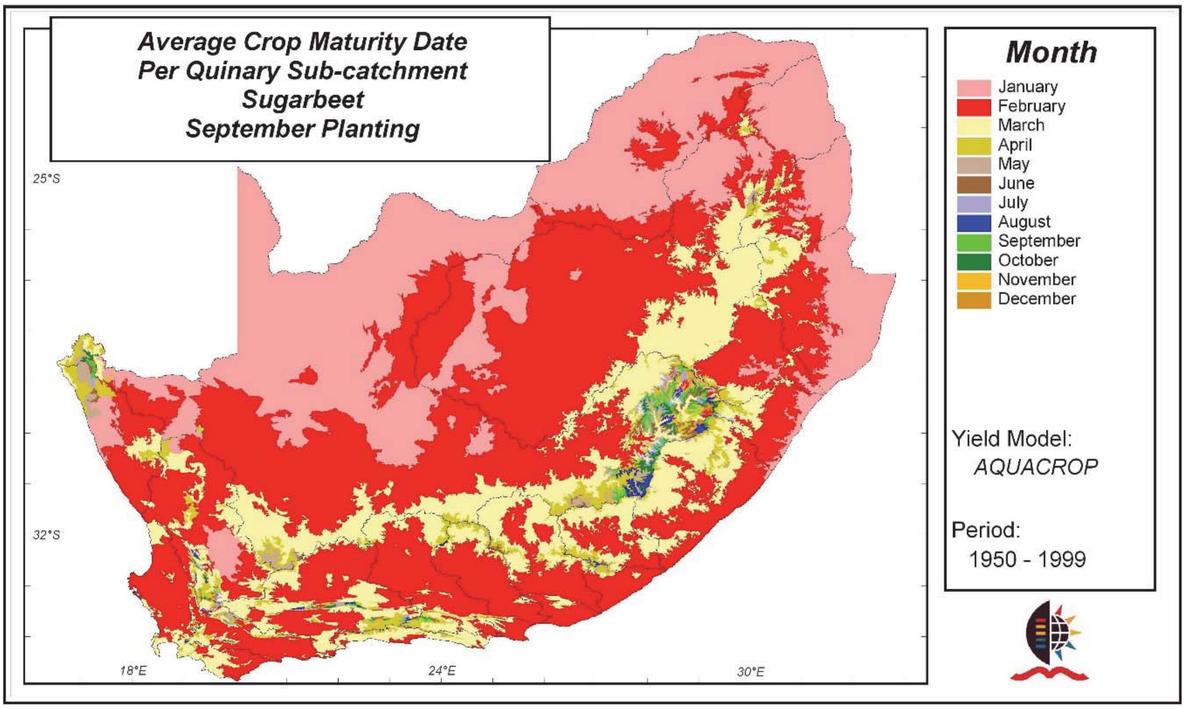
Average Crop Maturity Date
Per Quinary Sub-catchment
Sugarcane
February Ratoon
Months
January
February
March
April
May
June
July
August
September
October
November
December
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)



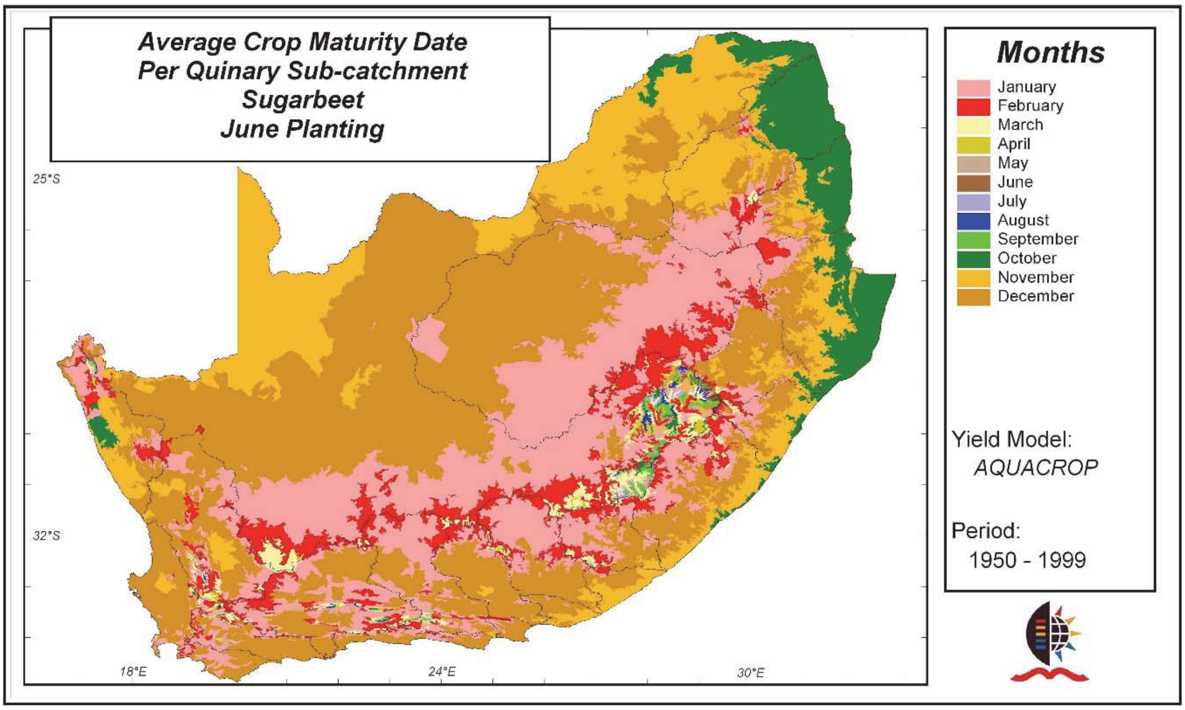
Average Crop Maturity Date
Per Quinary Sub-catchment
Sugarcane
April Ratoon
Months
January
February
March
April
May
June
July
August
September
October
November
December
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



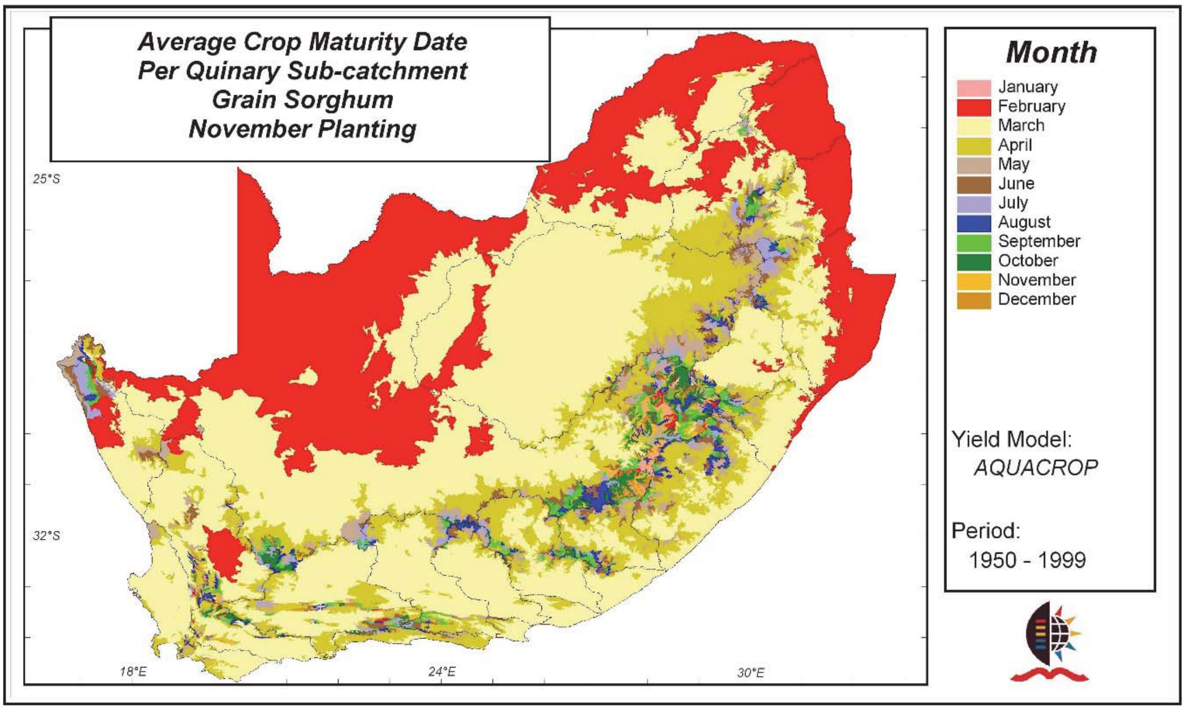
Average Crop Maturity Date
Per Quinary Sub-catchment
Sugarbeet
September Planting
Month
January
February
March
April
May
June
July
August
September
October
November
December
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)



Average Crop Maturity Date
Per Quinary Sub-catchment
Sugarbeet
June Planting
Months
January
February
March
April
May
June
July
August
September
October
November
December
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

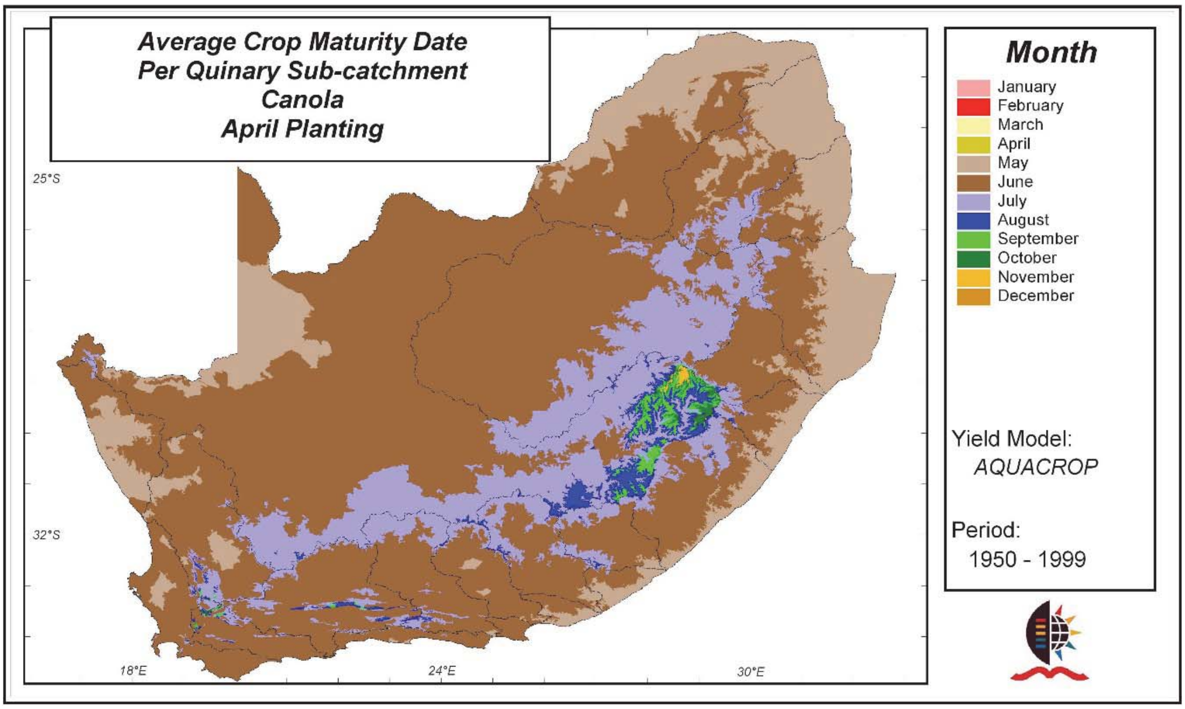


(e)

Figure 57 Average month in which the crop matures (i.e. expected harvest date) for selected bioethanol feedstocks (a-e) planted on different dates

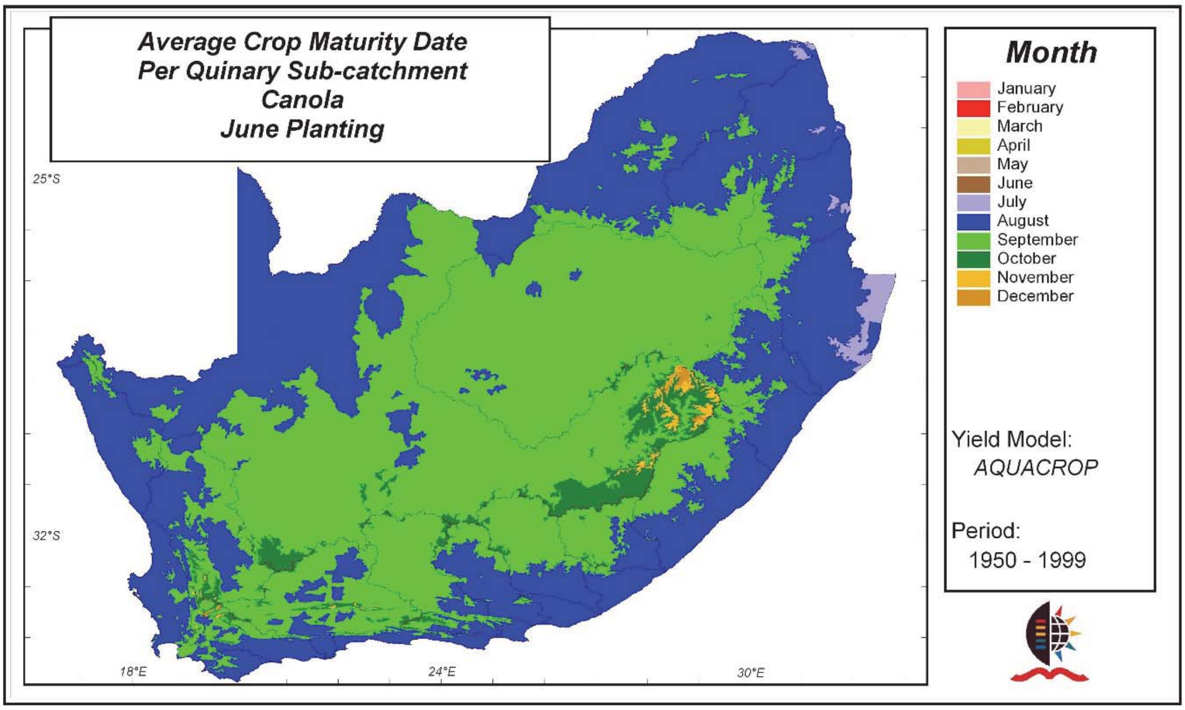
For the biodiesel crops shown in **Figure 58**, canola is ready for harvesting in late May (warmer areas) or early June (cooler areas) if planted on 1st April. However, the crop only matures in July for the col areas of the interior and even later (August) in the high altitude sites. For a June planting, the crop will typically mature in August or September for the majority of locations where canola could be grown (Western Cape, Eastern Cape, KwaZulu-Natal & Free State). If soybean is planted on the 1st November, it should typically mature in April for growing areas in the KwaZulu-Natal midlands. However, it is also noted that in reality, farmers tend to leave their crop in the field long after it has reached physiological and harvest maturity.

The median version of these maps is given in **APPENDIX I** (**Figure 87** and **Figure 88** for bioethanol and biodiesel crops respectively). The median months were similar to the mean months for most crops, except for the higher altitude, cooler sites and for sugarcane.



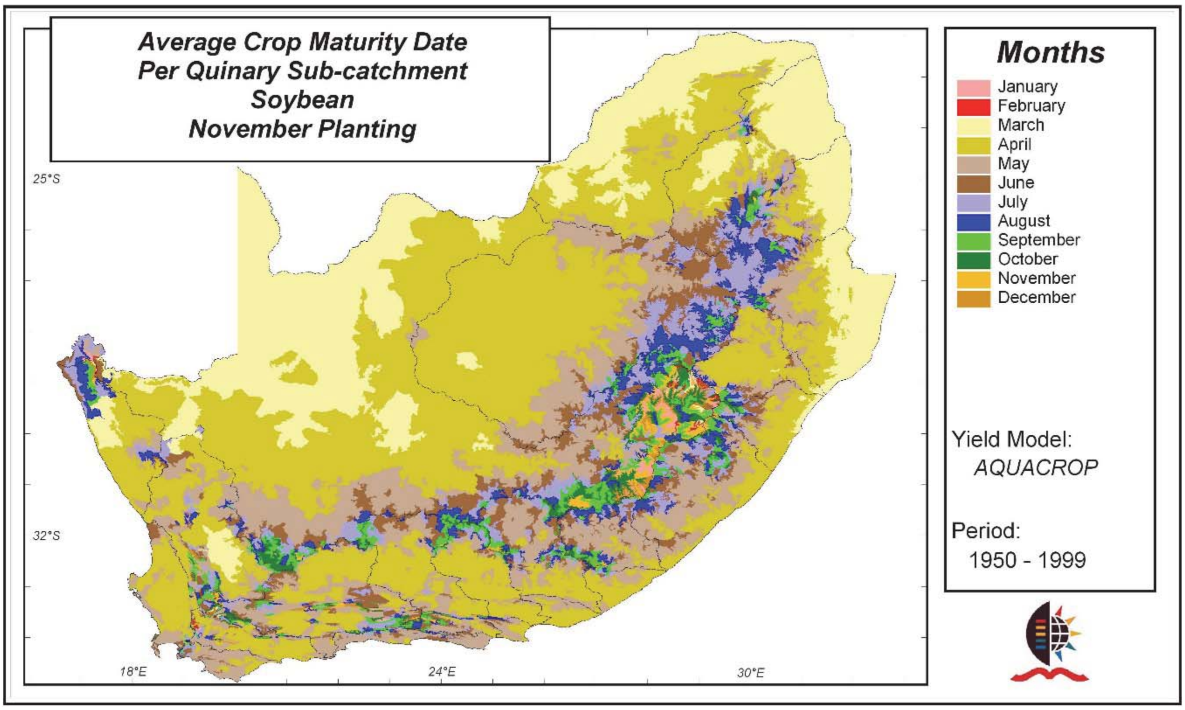
Average Crop Maturity Date
Per Quinary Sub-catchment
Canola
April Planting
Month
January
February
March
April
May
June
July
August
September
October
November
December
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)



Average Crop Maturity Date
Per Quinary Sub-catchment
Canola
June Planting
Month
January
February
March
April
May
June
July
August
September
October
November
December
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(b)



(c)

Figure 58 Average month in which the crop matures (i.e. expected harvest date) for selected biodiesel feedstocks (a-c) planted on different dates

4.2.4 Biofuel yield potential

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 yield provided in **Table 12**. The italicised reference represents the source of the extraction yield that is recommended for use. For sugar crops (e.g. sugarcane, sugarbeet & sweet sorghum), the yield first needs to be converted from dry tons to fresh (i.e. wet) tons. For sugarbeet, dry yields should be multiplied by a factor of 4 to 5 to obtain fresh (or green) yields (Raes *et al.*, 2012c). This factor ranges from 2.86 to 3.33 for sugarcane and is based on cane stalks containing approximately 30 to 35% dry matter. A typical factor of 3 is suggested for sugarcane in South Africa.

The extraction yield of 75 L t^{-1} obtained from Maclachlan (2012) compares favourably with that obtained from the 2010/11 (i.e. September planting) sugarbeet trial at Ukulinga. Calculations gave a theoretical bioethanol yield of 4 021 litres from a fresh tuber yield of 53.1 t ha^{-1} (14.9% Brix). However, the 2013/14 (June planting) sugarbeet trial at Ukulinga produced an extraction yield of 89.1 L t^{-1} (theoretical bioethanol yield of 4 046 litres from a fresh tuber yield of 45.4 t ha^{-1} and 17.1% Brix). This highlights the sensitivity of the extraction yield to the sugar content of the crop.

Table 12 Biofuel production in litres per ton of crop yield

Feedstock	Extraction yield ($L\ t^{-1}$)	Range ($L\ t^{-1}$)	Source
Sugarcane	80[a]	68.0 - 81.4	(DME, 2006a) Meyer *et al*. (2008) Garoma *et al*. (2011) *DoE (2014)*
Sugarbeet	75[a]	75.0 - 89.1	*Maclachlan (2012)*
Sweet sorghum	69[a]	54.4 - 74.8	Smith & Frederiksen (2000) *Prasad et al. (2007)* Almodares and Hadi (2009)
Yellow maize	402[b]	360.0 - 417.3	Smith & Frederiksen (2000) DME (2006a) *Meyer et al. (2008)* Drapcho *et al*. (2008) Garoma *et al*. (2011)
Grain sorghum	417[b]	370.0 - 417.0	Du Preez *et al*. (1985) Smith & Frederiksen (2000) BFAP (2008) Lemmer & Schoeman (2011) Kotze (2012b) *DoE (2014)*
Canola	413[b]		This study
Sunflower	398[b]		*Meyer et al. (2008)*
Soybean	185[b]	171.4 - 211.8	DME (2006a) Meyer *et al*. (2008) GAIN (2009) *DoE (2014)*

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

For canola, the yield extraction of 413 litres of biodiesel per ton of crop 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. For example, Sparks (2010) stated that 6% of the oil remains in the soybean oilcake after the crushing (or pressing) process. Similar extraction yields of 185.9 and 392.4 L t^{-1} can be obtained for soybean and sunflower respectively, which are comparable with those in **Table 12**. These figures are based on an oil content of 18% for soybean and 38% for sunflower.

Using the extraction yields provided in the previous table, the land area in hectares required to produced 1 000 m^3 of biofuels is shown in **Table 13**. The yield of 95 t ha^{-1} for sugarbeet represents the "bankable" yield in the Cradock region (Maclachlan, 2012). If this yield is halved which is then comparable with that measured at Ukulinga, then the harvest area doubles to 281 ha to produce 1000 m^3 of biofuel. In this study, the sugarcane yield from the 1998/99 to the 20011/12 season was averaged to produce 66.11 t ha^{-1}. Based on the theoretical bioethanol yield equation, the average extraction yield averaged 78.4 L t^{-1}, which equates to 193 ha of land area required to produce 1 000 m^3 of bioethanol (similar to the figure given in the above table).

Table 13 Land area required to produce 1 million litres of biofuel

Crop	Extraction yield (L t^{-1})	Crop mass (t)	Feedstock yield (t ha^{-1})	Harvest area (ha)
Sugarbeet	75[a]	13 333	95.00[c]	140
Sugarcane	80[a]	12 500	63.88[d]	196
Yellow maize	402[b]	2 488	4.63[e]	537
Grain sorghum	417[b]	2 398	2.66[e]	902
Canola	413[b]	2 421	2.00[f]	1 211
Sunflower	398[b]	2 513	1.27[e]	1 979
Soybean	185[b]	5 405	1.70[e]	3 179

[a] multiply by crop yield in fresh (i.e. wet) tons
[b] multiply by crop yield in dry tons
[c] Maclachlan (2012)
[d] SASA website: http://www.sasa.org.za/Files/Crop data 2012.pdf
[e] Lemmer and Schoeman (2011)
[f] Fouché (2015)

The land area required to produce one million litres of biofuel from each feedstock is shown in **Table 13**. It is evident that bioethanol feedstocks required a smaller "land footprint" to produce the equivalent volume of biofuel than compared to the biodiesel crops. Yellow maize requires ≈2.7 times more land area than sugarcane to produce the same volume of bioethanol. Similarly, grain sorghum requires ≈4.6 times more land than sugarcane. Due to the low extraction and feedstock yields associated with soybean, 3 179 ha of land area is required to produce 1 000 m^3 of biodiesel. Sunflower and soybean require 1.6 and 2.6 times the land area of canola to produce the same volume of biodiesel, respectively.

The proposed biodiesel plant at Coega requires 1.56 million tons of soybean per annum. Hence, an additional 916 000 ha of land must be planted to soybean to produce sufficient feedstock for this facility (**Table 14**). From this evidence, it may be argued that biodiesel production from soybean should be avoided, due to the large area of farmland required to produce the biofuel. The quantity of biodiesel produced (288 million litres) is approximately half (49.3%) of the projected biodiesel demand of 584 million litres in 2016.

Table 14 Additional arable land required to produce sufficient feedstock to meet the demand of each proposed biofuel facility

Company	Biofuel	Feedstock	Capacity (ML an^{-1})	Feedstock mass (t)	Additional land area (ha)
Mabele Fuels	Bioethanol	Sorghum	150	359 712	135 230
Arengo 316	Bioethanol	Sorghum	90	215 827	81 138
Arengo 316	Bioethanol	Sugarbeet	90	1 200 000	12 632
Ubuhle RE	Bioethanol	Sugarcane	50	625 000	9 784
PhytoEnergy	Biodiesel	Canola	455	1 100 594	550 297
Rainbow Nation	Biodiesel	Soybean	288	1 556 757	915 739

A minimum 2% blending rate requires the production of at least 240 million litres of bioethanol. This can be achieved when the 90- and 150-million litre capacity Cradock and Bothaville facilities are in full operation. If a ton of grain sorghum produces 417 litres of bioethanol (**Table 13**), approximately 576 000 tons of grain is required. Based on an average sorghum yield of 2.66 t ha^{-1} (**Table 13**), an additional 217 000 ha of land should be planted to sorghum (**Table 14**).

Lemmer and Schoeman (2011) estimated that 600 000 tons of additional grain sorghum is required (i.e. 400 L t^{-1}), with an expansion of 243 902 ha based on an average sorghum yield of 2.46 t ha^{-1}. Kotze (2012a) also reported that an estimated 600 000 tons of grain sorghum is required per annum for both bioethanol plants. Using an average yield of 2.82 t ha^{-1} for grain sorghum, he reported an additional 213 000 ha is required for sorghum cultivation.

From the above calculations, a minimum of 1.7 million ha of arable land should be dedicated to biofuel feedstock production in South Africa. Statistics provided by DAFF (2012a) indicate there is 16.738 million hectares of potentially arable land (or 13.7% of SA's total land), of which 84.79% is under commercial agriculture and 15.21% is developing agriculture (**Table 15**). Hence, sufficient arable land is available in the former homelands (i.e. developing land) for feedstock cultivation. However, the figures in **Table 15** were based on a study by the Development Bank of Southern Africa in 1991 and provide no indication of the land currently used by agriculture.

Since the national biofuels strategy (DME, 2007a) promotes the use of under-utilised land in the former homelands, the government "prefers" feedstock cultivation to occur in the North West Province, followed by Limpopo and the Eastern Cape. There is limited (developing) land available for feedstock production in the Free State and no available land in the Western and Northern Cape Provinces or Gauteng.

Table 15 Arable land potential in South Africa and land utilisation by commercial farms and developing farmers (DAFF, 2012a)

Province	Arable land in South Africa (ha)		
	Potential	Developing	Commercial
Free State	4 221 423	34 900	4 186 523
North West	3 360 459	951 975	2 408 484
Western Cape	2 454 788	0	2 454 788
Eastern Cape	1 172 901	529 400	643 501
Limpopo	1 700 442	530 700	1 169 742
Mpumalanga	1 734 896	137 898	1 596 998
KwaZulu-Natal	1 199 675	360 700	838 975
Gauteng	438 623	0	438 623
Northern Cape	454 465	0	454 465
Total	**16 737 672**	**2 545 573**	**14 192 099**

Lemmer and Schoeman (2011) estimated that approximately 1.5 million ha of commercial farmland should still be available for crop production. This figure is based on the total plantings of grain and oilseed crops in South Africa which has declined from 5.7 million ha in 1995/96 to an estimated 4.2 million hectares in 2010/11. However, this figure assumes that no arable land was "lost" to other land use needs such as urbanisation, mining and biodiversity protection. However, between 1994 and 2000, KwaZulu-Natal lost 3% of its land classified as high potential agricultural land and a 5% increase in productive land that has been permanently transformed (i.e. due to urbanisation). The goal of KZN's Provincial Growth and Development Plan (PGDP) is to achieve no further change in these figures (PGDP, 2012).

4.3 Summary

The revised quinary climate database was used to produce 5 838 climate files and relevant site information (i.e. location & altitude) for each quinary. In total, 17 514 (i.e. 5 838 * 3) climate files containing daily rainfall, temperature and FAO56 evaporation were developed. When compared to the original climate database derived by Schulze *et al*. (2011), the revised version exhibits higher A-pan equivalent evaporation estimates which result in lower runoff estimates.

The quinary soils database (Schulze *et al*., 2011) was used to produce 5 838 soils files containing the depth and soil water retention parameters for each of the two soil horizons. In addition, a pedotransfer function was developed to estimate the saturated hydraulic conductivity and soil texture for each horizon from the soil water retention parameters. *AQUACROP* is particularly sensitive to the saturated hydraulic conductivity of the topsoil.

It was discovered that setting the initial soil water content to 50% of PAW (i.e. half way between DUL and PWP) impacted the yield estimates considerably. Similarly, if the simulation is started before the planting date, the simulated yields were also much lower. Since *AQUACROP* is particularly sensitive to these two settings, it was decided to use the default options where the simulation starts:

- on the planting date (user-specified) and ends on the maturity date (based on GDD), and
- with the initial soil water content at field capacity.

For each crop, an *AQUACROP* multiple run project (or .PRM) file was produced for each quinary, which instructs the model to simulate yield over the growing season (i.e. from planting date to maturity date), for a maximum of 50 seasons. The .PRM file also indicates which input files to use for each quinary (i.e. climate, soil, crop parameter & CO_2 concentration files).

In total, over 5 000 lines of computer programming code was written to a) prepare the input files required by the model, and b) automate the running of the model at the national scale. The model run for a total of 1 100 hours and required almost 1 500 re-starts to produce yield maps for sugarcane, sugarbeet and grain sorghum as well as canola and soybean. Two planting dates were selected for sugarcane, sugarbeet and canola.

Other variations of standard output from *AQUACROP* were determined as part of this study. For example, the end-season WUE was calculated and compared to the peak WUE calculated by the model. If these two WUE estimates differ, it may indicate the location is not suitable for crop growth as the yield is peaking too early in the growing season. Similarly, two versions of the growing season length were also determined (i.e. version 1 based on standard model output *vs*. version 2 calculated from planting to maturity date).

A number of maps depicting the spatial variability in model output were produced. These include the yield and WUE as well the temporal variation of these two variables. In addition, maps showing the number of seasons which the yield and WUE calculations are based on, together with the number of crop failures were also produced. In the future, it is envisaged that this output may be combined to eliminate sub-catchments not considered suitable for crop production.

The model outputs yield in dry tons per hectare. However, for crops that contain sugar (e.g. sugarcane & sugarbeet), fresh yield is preferred for estimation of biofuel production. For sugarbeet, the dry yield can be multiplied by a factor ranging from 4 to 5 to obtain the fresh tonnage. Similarly, this factor ranges from 2.86 to 3.33 for sugarcane.

The yield model was run for all quinaries and not a subset of quinaries where the crop may grow (i.e. based on the land suitability maps). This will allow the national yield maps to help validate the land suitability maps in the future, especially since the latter maps differentiate low from high potential production sites.

5 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.

5.1 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. These 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**. 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. For additional information on the interim steps used to develop the sugarbeet and canola maps, the reader is referred to **Volume 1**. A brief summary of the approach used is given in this volume, using soybean as the example.

5.2 Weighted Site Criteria

5.2.1 Background

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 or relative humidity (index of disease risk),
- soil depth (index of moisture storage), and
- slope (e.g. eliminate areas with steep slopes).

5.2.2 Methodology

The four main steps followed in the land suitability assessment were as follows:

- determination of feedstock growth criteria,
- ranking of suitability criteria,
- weighting of each criterion, and finally
- calculating the suitability score.

5.2.2.1 Feedstock growth criteria

Rainfall, temperature, relative humidity and soil depth thresholds were obtained from a detailed review of available literature which distinguish between optimum (Opt), sub-optimum (Sub) and marginal (Abs) growing conditions as shown in **Table 16**. It is important to realise that the growth thresholds were derived from a subjective assessment of values gleaned from a literature review. Thus, these estimates are not absolute and should only be used as a definitive guide to where the crop may be grown in South Africa. In general, such estimates may "improve" with time as more data becomes available on each feedstock, especially if it is grown extensively in South Africa.

Table 16 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			

5.2.2.2 Ranking of criteria

A ranking was then assigned to each class. 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 17**).

5.2.2.3 Weighting of criteria

The five selected criteria were weighted according to their relative importance in determining feedstock survival at a particular location (**Table 18**). These subjective weightings were based on expert opinion, with rainfall deemed most important to crop survival. These weightings were then normalised to create a decimal weighting.

Table 17 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

Table 18 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**

5.2.2.4 Total suitability score

In **Table 19**, the suitability score is the product of the ranking and the decimal weighting. The five suitability scores were 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 19 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**

5.2.2.5 Normalised suitability score

The total suitability score ranges from 0 (not suitable) to 3 (optimally suited), which was then normalised. The normalised values were grouped into four classes for mapping purposes as shown in **Table 20**. 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. Each suitability class was then equated to the land suitability classification proposed in 1976 by the Food and Agriculture Organisation of the United Nations o FAO (c.f. **Section 5.3.2.1**).

Table 20 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

5.2.2.6 Rainfall distribution

Monthly crop coefficients (K_c) for Baynesfield were used to determine the optimum distribution of monthly rainfall over the growing season. The monthly values were normalised and then multiplied by each of the seasonal rainfall thresholds given in **Table 16**.

Table 21 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 22**). 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.

Table 22 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. The monthly crop coefficient was also used 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 23**).

Table 23 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**

Each monthly rainfall dataset (for November to December) was re-classified to produce five new datasets. For example, if the monthly rainfall in February ranged from 175 to 215 mm, it was re-classified as 3 (i.e. optimum). Each new re-classified rainfall dataset (called Rfl_Rec_xx; where xx = month) was weighted using the normalised crop coefficient, 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 2

The weighted rainfall map for soybean (**Figure 59**) shows that soybean cultivation under dryland conditions is best suited to the eastern parts of South Africa, and not the drier western and north-western regions.

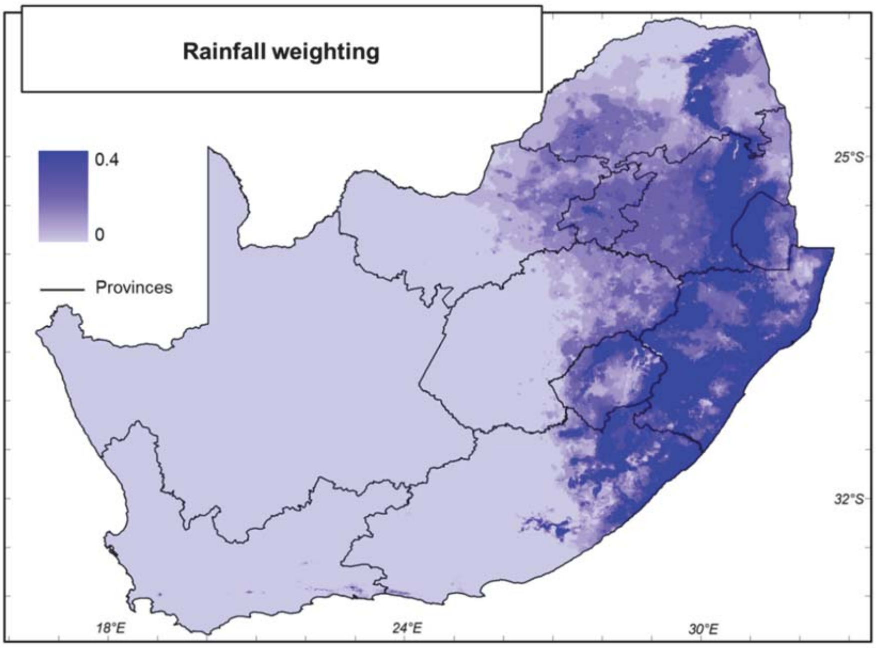


Figure 59 Normalised suitability score for seasonal rainfall which ranges from 0 (not suitable) to 0.4 (highly suited) for soybean cultivation, based on FAO crop coefficients (Khomo, 2014)

5.2.2.7 Temperature and relative humidity

This exercise was repeated for the other monthly climate datasets for temperature and relative humidity. The relative temperature weightings assigned to each month (**Table 24**) indicate soybean is more sensitive to temperature stress early in the season (i.e. November-January). Similarly, the risk of soybean rust outbreak is highest in January and February and declines in March.

Table 24 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**

5.2.2.8 Soil depth

Due to data limitations, only soil depth was evaluated in this study. **Table 25** summarises the soil depth suitability classes and rankings (i.e. scores) used for soybean. The depths were gleaned from the literature review undertaken for soybean.

Table 25 Ranking of each suitability class based on soil depth (mm) for soybean

Code	Suitability class	Soil depth (mm)	Ranking
Opt	S1	> 500	3
Sub	S2	300 - 500	2
Abs	S3	200 - 300	1
Not	N1	< 200	0

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 60** shows the coarseness of the soil depth data available for Lesotho and Swaziland. **Table 26** indicates that for a large portion (≈40%) of the country, soil depths are unsuitable for production of annual feedstocks. These areas mainly occur in the western parts of the country (**Figure 60**).

Table 26 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

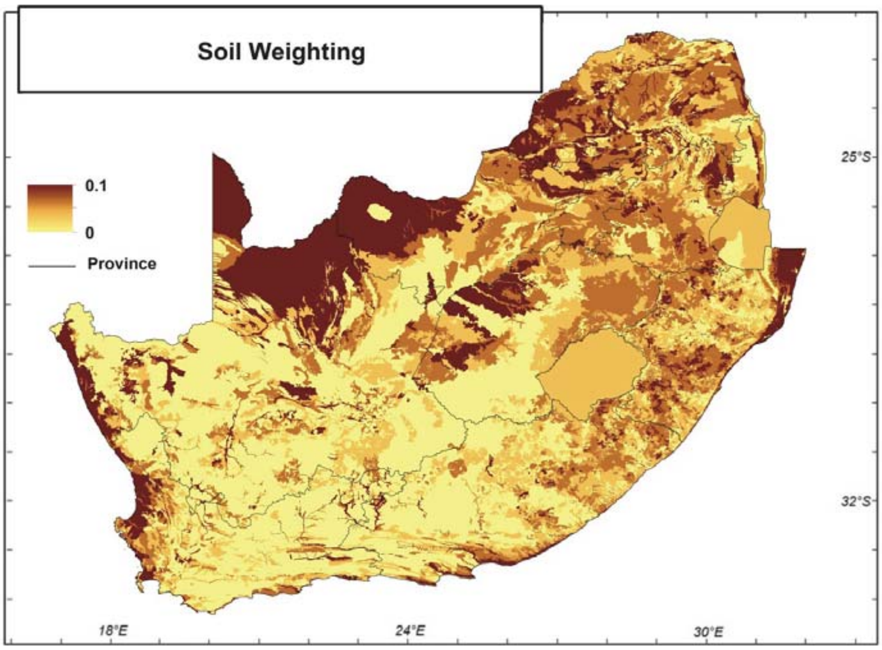


Figure 60 Soil depth suitability map for the cultivation of canola

5.2.2.9 Slope

Steeper areas (> 10% slope) are not suitable for cultivation due to the high risk of soil erosion from increased runoff. Furthermore, steeper slopes are more difficult and costly to cultivate than flat land (Santos *et al.,* 2000). **Table 27** summarises the slope suitability classes and rankings used in this study for all feedstocks.

Table 27 Ranking of each suitability class based on slope (%) for each feedstock (Russell, 1997)

Code	**Suitability class**	**Soil slope (%)**		**Ranking**
		Sugarcane	**All other crops**	
Opt	S1	< 10	< 4	3
Sub	S2	10 - 15	4 - 8	2
Abs	S3	15 - 30	8 - 10	1
Not	N2	> 30	> 10	0

The procedure followed to process slope is similar to that used for soil depth, in that there is only a single dataset (**Figure 61**). However, the final weighting of this dataset is 0.2, i.e. same influence as temperature.

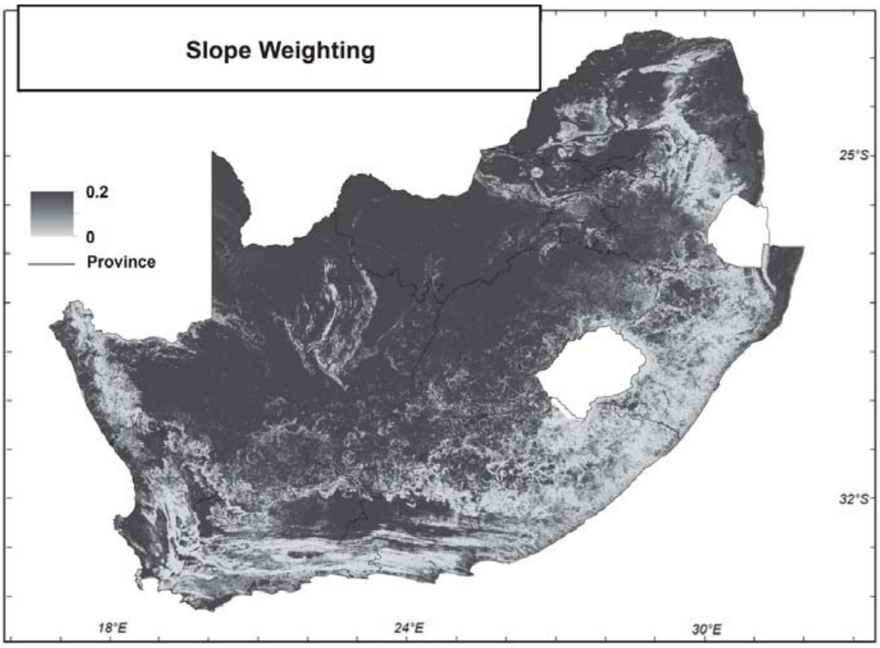


Figure 61 Slope suitability map for the cultivation of canola

With regard to slope constraints, **Table 28** shows that the majority of the country is deemed suitable for cultivation of annul crops. 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 28 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

5.3 Elimination of Unsuitable Production Areas

5.3.1 Background

The approach used in this study was further extended by considering the existing land use, which reduced the total arable land available for feedstock cultivation. This is considered important in order to produce land suitability maps which more realistically represent the biofuel feedstock production potential in South Africa. Land use describes how mankind utilises land, e.g. for urban living and agricultural food production. Areas deemed unsuitable for feedstock growth (i.e. “no-go” areas) were eliminated to provide a realistic estimate of the land area available for biofuel feedstock production.

5.3.2 Methodology

5.3.2.1 Land suitability classification

The definition of land suitability, as proposed by the Food and Agriculture Organisation of the United Nations (FAO) “is the fitness of a given type of land for a defined use”. According to FAO (1976), land can be classified as suitable (S) or unsuitable (N) for a particular use. Suitable means sustained use is expected to give positive results. Similarly, not suitable means land qualities are considered inappropriate for a particular use.

The degree of suitability is reflected by land suitability classes. The classes are numbered in a sequence where the highest number represents the least suitable and the lowest number represents the most suitable. According to FAO (1976), the relationship between inputs and benefits mainly determines the differences in the degree of suitability. The FAO recommends three suitability classes, with the following denominations:

- Class S1: Highly suitable
- Class S2: Moderately suitable
- Class S3: Marginally suitable

The land can be classified as not suitable based on, for example, environmental considerations (e.g. potential damage to biodiversity), technical considerations (e.g. soil depth and slope) or economic considerations (e.g. revenues). There are normally two classes for not suitable as follows:

- Class N1: Currently not suitable
- Class N2: Permanently not suitable

5.3.2.2 Present land use

The seven land cover classes of the NLC2009 dataset subdivided in two categories, *viz*. absolute “no-go” areas and functional “no-go” areas. Absolute no-go areas comprise of land covers that are physically unsuitable for feedstock production. According to the FAO classification (see **Section 5.3.2.1**), such areas are classed as N2 (i.e. permanently not suitable) and include mines, urban areas and water bodies (**Table 29**).

Functional no-go areas refer to land covers currently not suitable for feedstock cultivation (N1 class) and include, *inter alia*, forest plantations, orchards (i.e. citrus and avocado) & vineyards (i.e. Cape winelands). It is highly unlikely that these well-established industries would consider a change in land use to biofuel feedstock production.

Table 29 Classification of the 2009 national land cover dataset according to suitability for feedstock cultivation

Land cover class	FAO suitability class
Water bodies	N2
Urban built-up	N2
Mines	N2
Plantations	N1
Natural	N1
Degraded	N1
Cultivation	N1

Furthermore, in order to cultivate virgin land (i.e. natural vegetation), the land owner must be granted written permission by the Executive Officer (except if approval was granted under Section 4A of the 1972 Forest Act). Virgin soil is defined as land that has not been cultivated in the previous ten years and thus is referred to as "undeveloped" by the Executive Officer (Niemand, 2011). This is in accordance with the Conservation of Agricultural Resources Act (CARA) 43 of 1983. Thus, natural areas were classified as functional "no-go" (i.e. N1) areas.

It is reported in the literature that certain feedstocks may restore the productivity of degraded land. For example, the national biofuels feasibility study (DME, 2006a) suggested two indigenous plums (*Xiemenia Caffra* or sour plum; *Papia Capensis* or jacket plum) that have potential to stabilise degraded land with their strong rooting systems. Based on this suggestion, degraded areas were classified as functional "no-go" (i.e. N1) areas.

Cultivated areas were also classified as functional "no-go" areas since biofuel crops can be produced in rotation with food crops. However, an expansion of agricultural land is preferable for the cultivation of biofuel feedstocks. In terms of food security, existing cultivated areas are better utilised for food production.

5.3.2.3 Protected areas

The updated national land cover did not include boundaries of protected areas. Thus, the approach was again extended to consider this land use. According to the National Environmental Management: Protected Areas (Act 57 of 2003), the declaration of protected areas includes South Africa's threatened or rare species as well as areas which are vulnerable or ecologically sensitive. SANBI provides a number of useful datasets which describe areas that are protected or endangered. These datasets were used to eliminate areas not suitable for biofuel feedstock cultivation at the national scale.

Only the formerly protected areas (**Figure 2**; c.f. **Section 2.9**) were eliminated in this study. The boundaries of protected areas were reclassified as N2 (i.e. permanently not suitable for biofuels). Hence, all areas that were identified as suitable for feedstock cultivation (S1, S2 or S3), but overlapped with protected areas classified as N2, were excluded (or filtered out) using GIS.

5.3.3 Results

The land suitability map for canola before (**Figure 62**) and after (**Figure 63**) the exclusion of absolute "no-go" areas is illustrated next. The approach provides a more realistic estimate of the land available for feedstock cultivation, especially by eliminating the Kruger National Park and the world heritage site that borders with Lesotho. It is important to note that no land cover or protected areas data exists for Swaziland or Lesotho and thus, these land suitability maps are only applicable to South Africa.

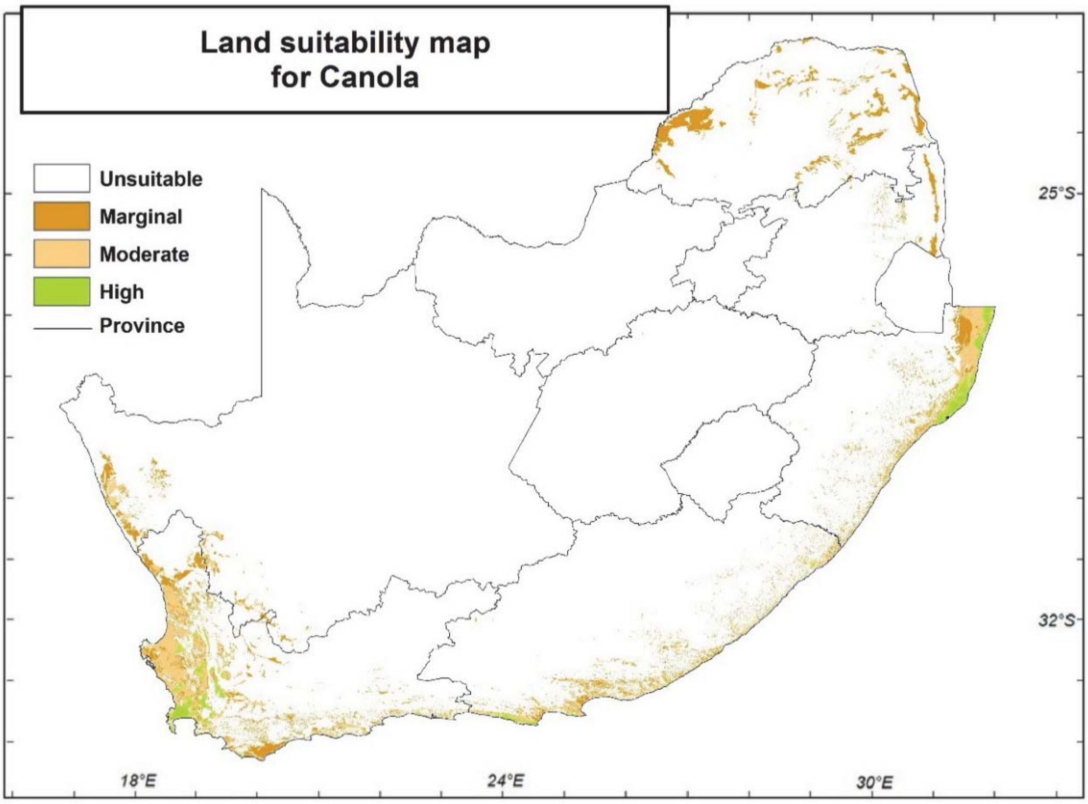


Figure 62 Land suitability map for canola production in South Africa, before the elimination of absolute "no-go" areas

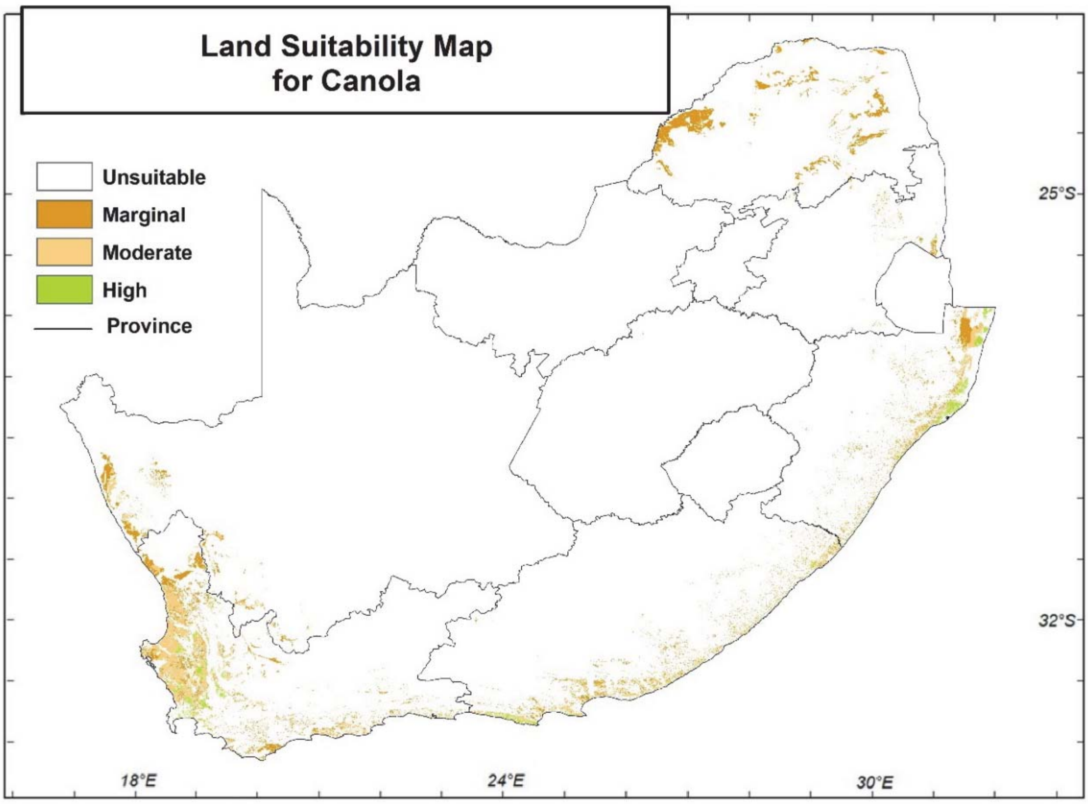


Figure 63 Land suitability map for canola production in South Africa, after the elimination of absolute "no-go" areas

5.4 Land Suitability Assessment

5.4.1 Background

A land suitability assessment identifies the land area suitable for feedstock production and then assesses the feedstock's potential yield in such areas. A land suitability map can be used to estimate South Africa's biofuel production potential. According to the German Advisory Council on Global Change (WBGU, 2004), there are five different types of energy resource potential as follows:

- Theoretical potential: identifies the physical upper limit of energy available from a certain renewable source (i.e. biomass). This potential does not account for a) land-use restrictions, or b) the efficiency of conversion technologies used.

- Technical potential: considers various restrictions related to the land realistically available for energy production. However, the criteria used in identifying potential land are not applied uniformly in the literature and hence this potential is dependent on a wide range of assumptions and conditions.

- Conversion potential: derived from the overall efficiency of the respective conversion technology. It is therefore not a strictly defined value, since the efficiency of a particular technology depends on technological advances and usually improves with time.

- Economic potential: describes the proportion of technical potential that can be utilised economically. For example, the quantity of biomass that can be exploited economically, taking into account competition from other products and land uses.

- Sustainable potential: limits the biofuel production potential based on evaluation of critical ecological and social factors. Sometimes, authors include sustainable criteria in their consideration of technical and/or economic potential. Hence, sustainable potential is not clearly defined and is also dependent on a wide range of assumptions and conditions.

Based on the definitions given above, the land suitability maps produced in this study highlight the country's technical potential to produce biofuel feedstocks. The approach that was developed is considered unique and innovative. However, the approach does not consider the future land uses needs (i.e. land required to house and feed the growing population, the need to expand current mining activities as well as protecting the country's rich biodiversity heritage).

5.4.2 Methodology

The overall aim was to map areas suitable for selected feedstocks and to improve the mapping approach used in previous land suitability studies. The methodology developed and implemented in this study is broadly similar to that adopted in four case studies reviewed in presented in **Volume 2**. To re-cap, a literature review of feedstock growth criteria added to that undertaken in previous studies (e.g. the biofuels scoping study). Spatial rainfall data were classified into different suitability classes according to each feedstock's crop water requirements, using the crop coefficient concept. Similarly, spatial temperature was also categorised into different classes to separate optimum from sub-optimum growing areas. The rainfall and temperature datasets were then combined and weighted in order to identify land climatically suited to feedstock production.

The approach then made use of a range of "filters" which were applied to the climatically suitable areas in order to highlight areas realistically suitable for crop production. For example, relative humidity was used (as a surrogate variable) to exclude areas with a high risk of disease incidence, thus minimising the risk of crop failure. Soil depth and slope data were also used to exclude areas with shallow soils and steep slopes that cannot support sustainable agriculture. Land use datasets were used to exclude areas that are classified as built-up, mining and water bodies as well as those areas protected by law for their biodiversity. It was important to eliminate these so-called "no-go" areas in order to identify land area realistically available to feedstock production. This approach helped to obtain a more realistic map of areas that can be planted to biofuel feedstocks. Although the latest available datasets were utilised, small patches of land may have been ignored (i.e. not highlighted as suitable) due to the coarseness of input climate data, which cannot account for microclimate effects.

The approach included relative humidity and soil depth, and is unique in that these two additional sites factors were not considered in previous GIS mapping studies. However, the most innovative aspect of this study is the use of crop coefficients to quantify the feedstock's optimum distribution of rainfall over the growing season. It is important to note that the methodology identifies three bio-climatic regions and not two as required by the project's Terms of Reference. These regions range from high potential to low potential and are called highly suitable, moderately suitable and marginally suitable.

5.4.3 Results

5.4.3.1 Sugarcane

The map showing areas suited to dryland sugarcane production is shown in **Figure 64**. This map is based on rainfall weightings derived using local crop coefficients (K_c) that were averaged for three sugarcane producing areas. These K_c values represent ratoon cane and not planted cane. This map was originally produced by Khomo (2014), but was re-produced to fix an error discovered in the soil depth data (this also applies to the grain sorghum and soybean maps presented in the sections that follow).

Figure 64 highlights areas suitable for sugarcane production, which correlates well with **Figure 65**. The latter is a simplified map of irrigated *vs*. dryland sugarcane production areas obtained from the South African Sugar Association (SASA, 2011). Approximately 68% of cane is grown within 30 km of the coast line, which extends from northern Pondoland (Eastern Cape) to the northern KwaZulu-Natal coastal region. Approximately 17% is grown in higher rainfall regions in KwaZulu-Natal, with the remainder grown in the northern irrigated areas that comprise the Pongola and Mpumalanga Lowveld regions (DAFF, 2011b).

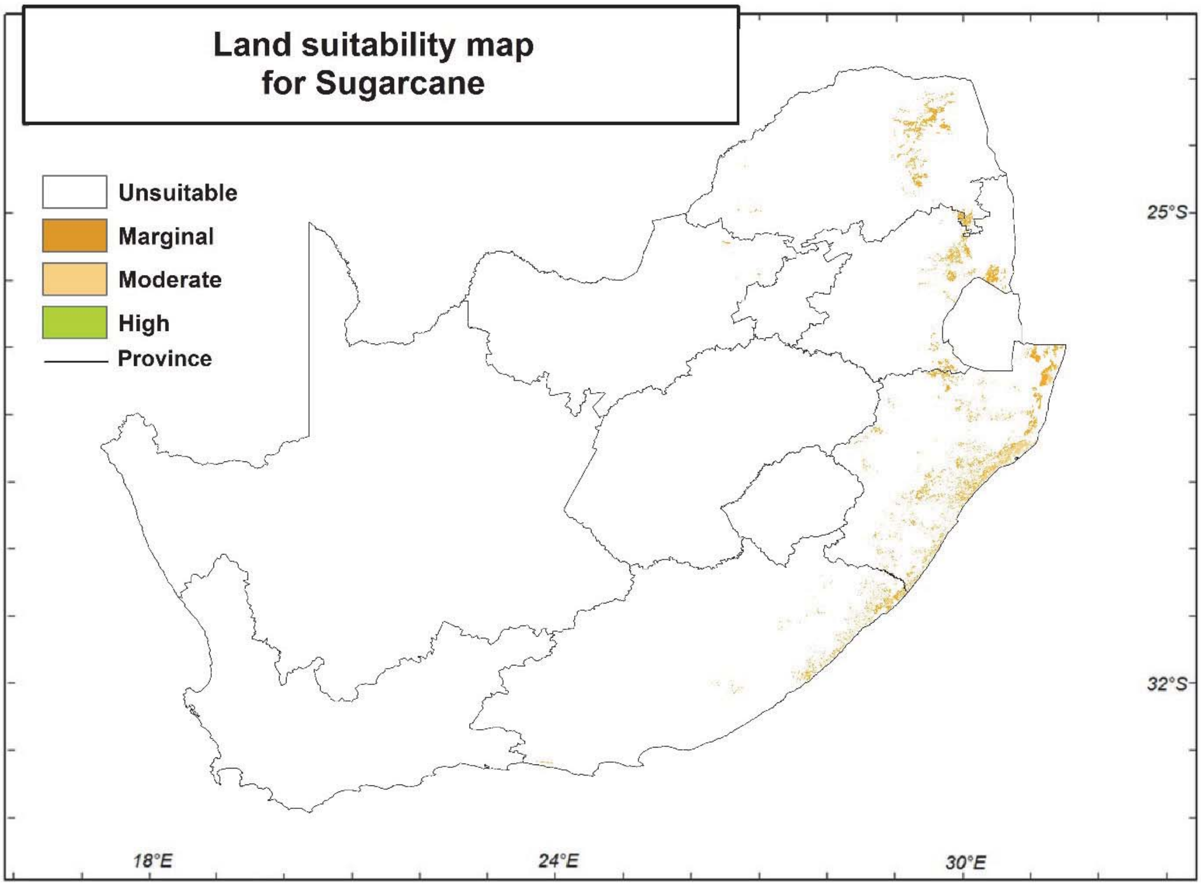


Figure 64 Overall suitability map for sugarcane production in South Africa (based on local crop coefficient weightings)

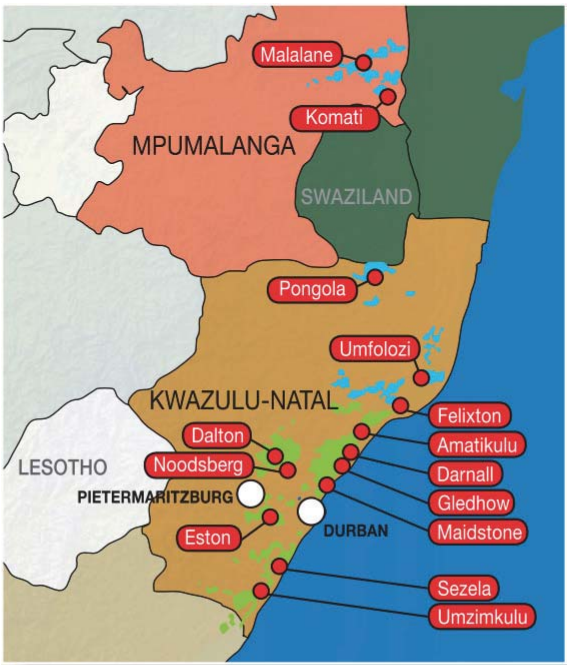


Figure 65 Rainfed (light green) and irrigated (light blue) sugarcane production areas in South Africa (SASA, 2011)

The suitability map shown in **Figure 64** highlights the northern coastal region of KwaZulu-Natal as ideally suited to cane production. This region is north of the Amatikulu sugar mill and south of the Umfolozi mill, with the Felixton mill in-between (**Figure 65**). The suitability map highlights the marginal areas near the Komatipoort mill (north of the Swaziland border in the Mpumalanga lowveld region). Due to the low rainfall conditions in the Mpumalanga lowveld region, sugarcane is produced under irrigated conditions.

The suitability map does not highlight all the irrigated sugarcane areas surrounding the Malelane mill (north west of the Komati mill in **Figure 65**). Similarly, the suitability map does not show all the irrigated sugarcane areas near the Pongola mill (south of the Swaziland border in **Figure 65**). The reason for this is **Figure 64** highlights areas where sugarcane can be grown under rainfed/dryland conditions (not irrigated). However, the suitability map does not show all the dryland production areas surrounding the Dalton, Noodesberg and Eston mills (in **Figure 65**) which are situated in the KZN midlands. Although the suitability map shows the Eastern Cape coastal regions as suitable for cane production, only a small fraction of cane is produced in the Eastern Cape Province (just south of the KZN provincial boundary).

Finally, it should be noted that frost-prone areas were not eliminated in this study. Hence, some areas classified as suitable for sugarcane cultivation in higher altitude regions will be at risk of severe frost damage. Such areas should rather be classified as unsuitable and not marginal. For further clarity, the reader is referred to Section 7.4.3 and Section 8.3.3.6 of **Volume 1**, as well as Section 7.5.2 of **Volume 2**.

5.4.3.2 Sugarbeet (summer)

The map showing areas suited to sugarbeet production is shown in **Figure 66** for a September (summer) planting. The map was produced using rainfall weightings based on crop coefficients obtained at Ukulinga during the 2010/11 season. Based on a summer planting, sugarbeet is better suited to the northern interior of the country, where optimum growing conditions exist. This is due to the seasonal rainfall occurring in these areas, which exceeds the lower threshold of approximately 400 mm per season (September to March) for sugarbeet. Coastal areas associated with higher humidity levels are not suited for sugarbeet production during the summer months. The individual maps that were combined to produce the final version are presented in **Volume 1**.

5.4.3.3 Sugarbeet (winter)

The map showing areas suited to sugarbeet production is shown in **Figure 67** for a June (winter) planting. The map was produced using rainfall weightings based on crop coefficients obtained at Ukulinga during the 2012/13 season. **Figure 67** illustrates that very few areas in South Africa can support dryland cultivation of sugarbeet planted in winter. Areas with sufficient rainfall from June to December exist along the Zululand coast, the Knysna coastal region and parts of the Western Cape where winter canola and wheat are currently grown. This finding indicates that supplemental irrigation is required to grow sugarbeet in winter, as is planned for the Cradock region. The individual maps that were combined to produce the final version are presented in **Volume 1**.

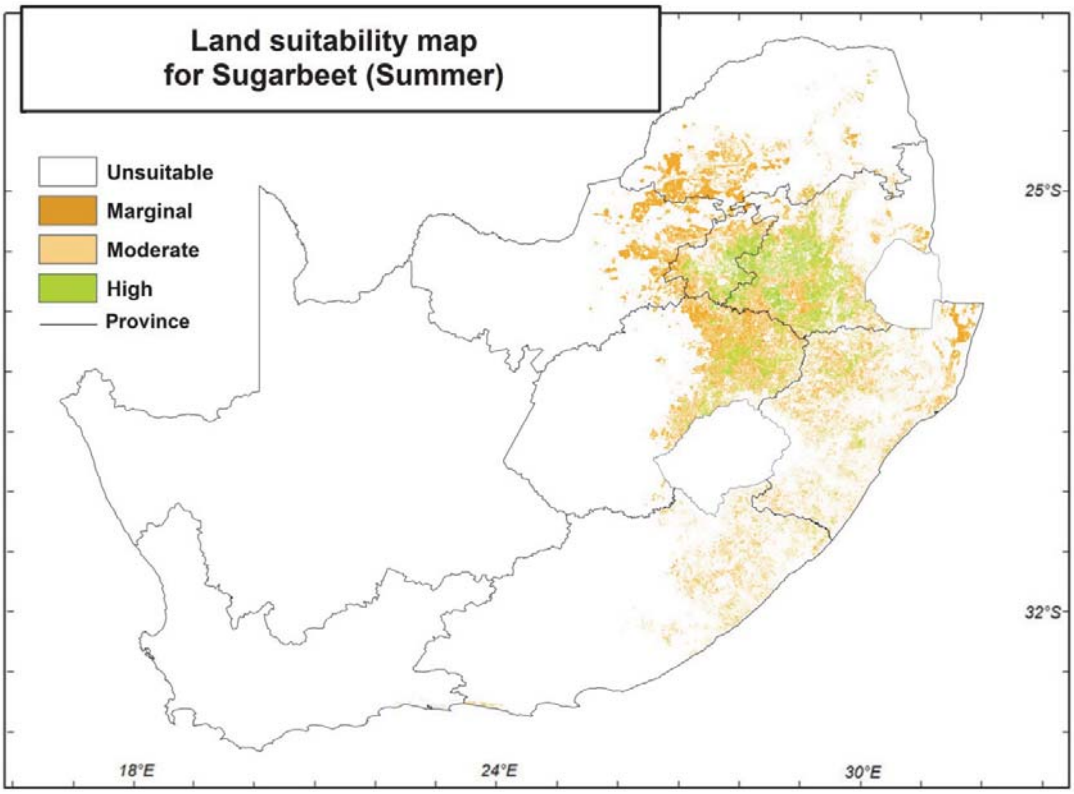


Figure 66 Overall suitability map for sugarbeet production in South Africa (based on crop coefficient weightings derived at Ukulinga from September 2010)

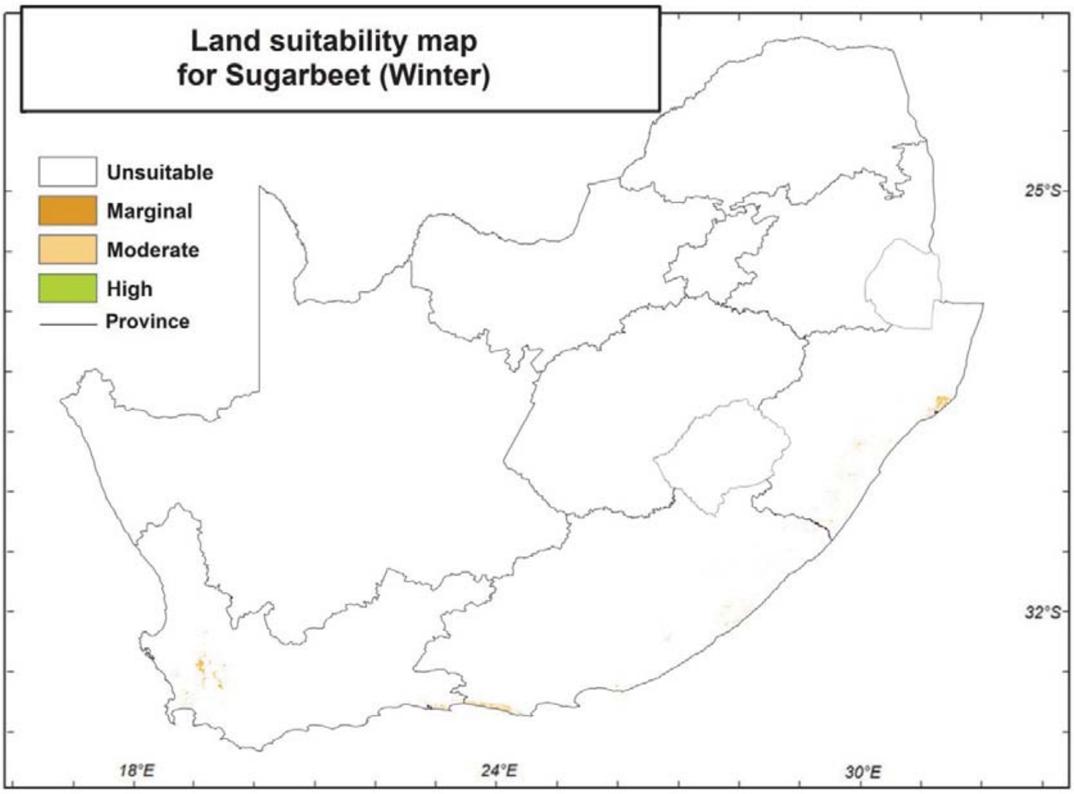


Figure 67 Overall suitability map for sugarbeet production in South Africa (based on crop coefficient weightings derived at Ukulinga from June 2013)

5.4.3.4 Grain sorghum

The map showing areas suited to grain sorghum production is shown in **Figure 68**. The map was produced using rainfall weightings based on crop coefficients that were averaged from two seasons of data obtained at Ukulinga in 2012/13 and 2013/14. According to Mashabela (2012), grain sorghum can be grown in all of South Africa's nine Provinces. However, the map does not highlight the Western Cape and Northern Cape Provinces as being suitable for sorghum production. This is due to the low average rainfall received in these regions. According to Mashabela (2012), grain sorghum is mainly produced on a commercial scale in the Free State (51.9%), Mpumalanga (24.3%) and Limpopo (15.3%) Provinces. Finally, the land suitability map does not identify the Free State as the largest producing grain sorghum area in the country.

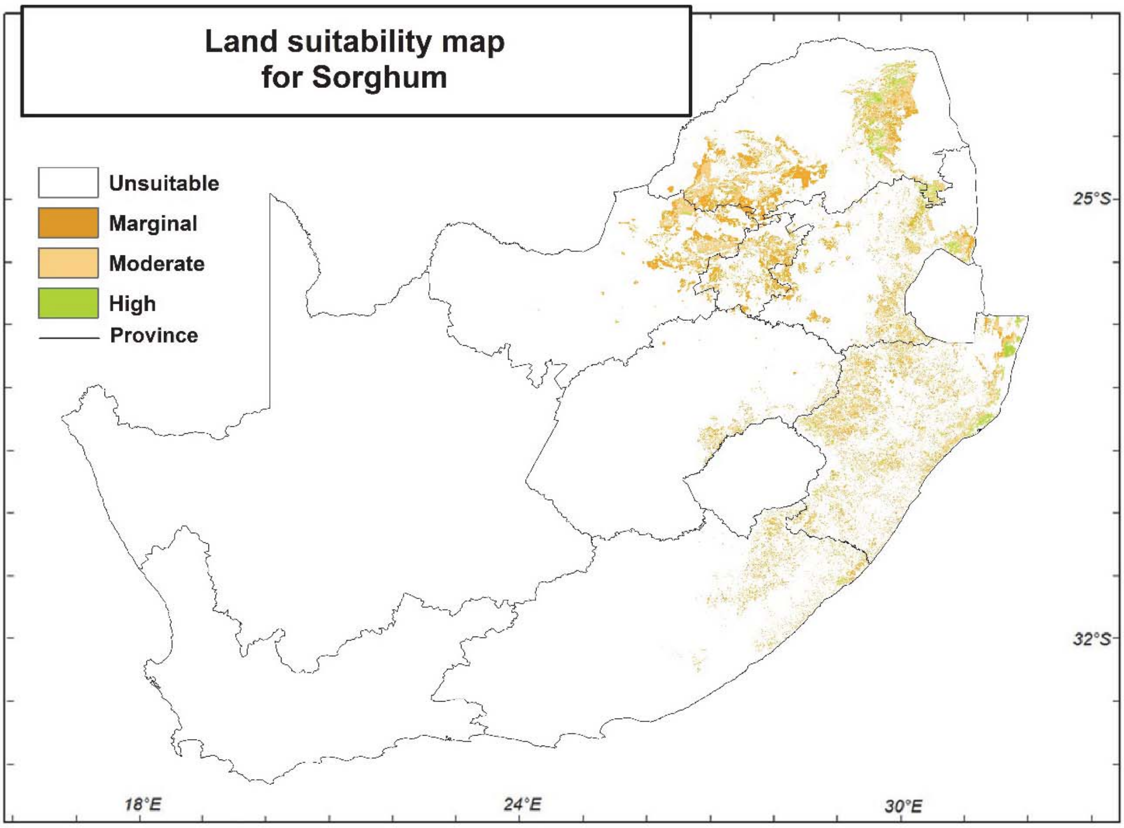


Figure 68 Overall suitability map for grain sorghum in South Africa (based on crop coefficient weightings derived at Ukulinga from November 2012)

5.4.3.5 Soybean

The overall soybean suitability map is shown in **Figure 69** and is based on the approach where the single crop coefficient (K_c) was used to weight monthly rainfall totals across the growing season. This map highlights areas optimally (i.e. highly) suited to soybean production, which are mainly situated in the KwaZulu-Natal, Mpumalanga and Limpopo Provinces. Compared to the map produced in the biofuels scoping study (Jewitt *et al*., 2009a), a relatively large increase in suitable growing areas in the Limpopo and Mpumalanga Provinces is noted in the new map. This result is expected since the scoping study used a smaller seasonal rainfall range of 550 to 700 mm to delineate optimum growth areas, compared to the 700 to 900 range adopted in this study.

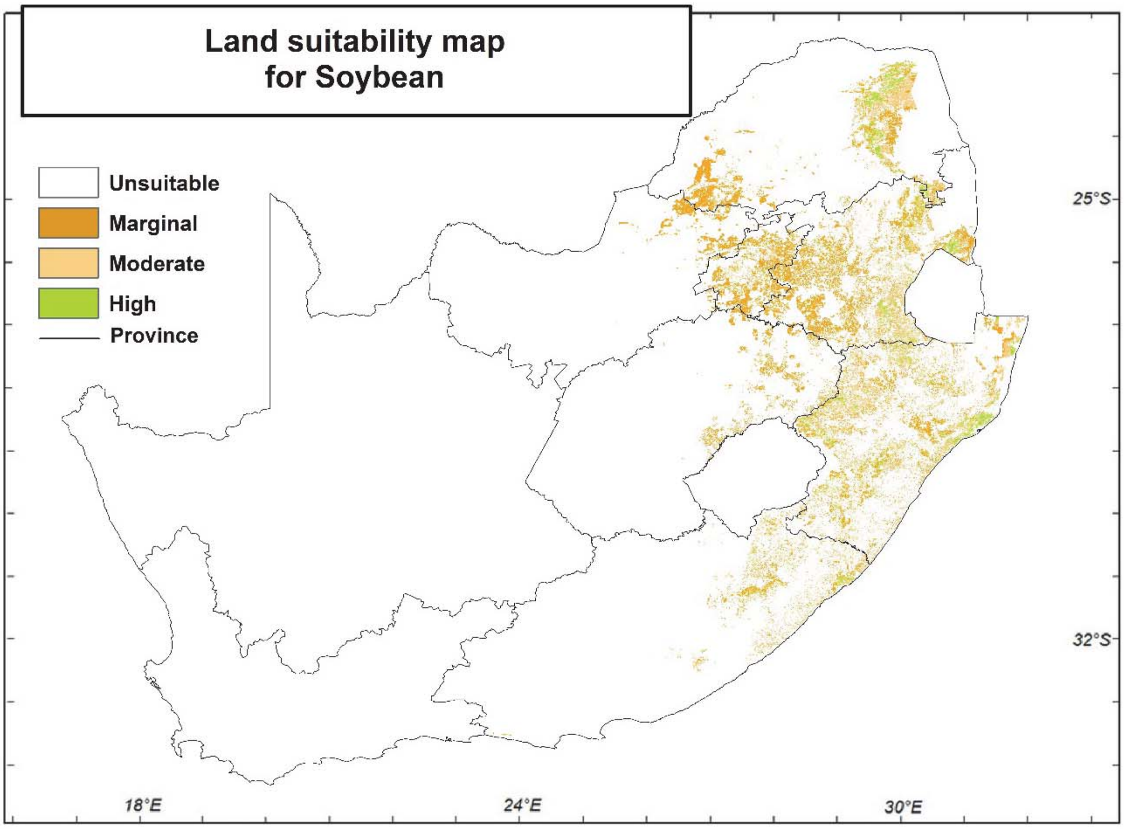


Figure 69 Overall suitability map for soybean production in South Africa (based on crop coefficient weightings derived at Baynesfield from October 2012)

The most notable difference in this map is the classification of the eastern Free State as moderately suitable for soybean production. In addition, more than half the areas highlighted in Mpumalanga are considered highly suitable for soybean. This is important considering that in 2010, 42.3% and 26.8% of soybean was produced in Mpumalanga and Free State respectively.

5.4.3.6 Canola (winter)

The map showing areas suited to canola production is shown in **Figure 70**. The map was produced using rainfall weightings based on crop coefficients obtained from Majnooni-Heris *et al*. (2012). According to DAFF (2014), the major production area for canola is the Western Cape (98%), with farmers in the North West and Limpopo Provinces slowly expanding canola's production (2%). According to DAFF (2014), the labour intensive nature of the post harvesting processes often renders the cultivation of canola unviable for many farmers. The land suitability map for canola underwent many iterations to complete, which is further explained in **Volume 2**. In addition, the individual maps that were combined to produce the final version are also presented in **Volume 2**.

The finalisation of the canola map was a major challenge due to the lack of information pertaining to this crop. The project resorted to expert opinion (and emailed DAFF, ARC, GRAIN SA and PhytoEnergy) to derive site criteria needed to produce the suitability map. Fouché (2015) states that canola can basically grow anywhere in South Africa since the crop is very drought tolerant. However, the above map does not indicate canola can be grown in the eastern parts of the Free State during winter, where PhytoEnergy plan to cultivate the crop for biodiesel production. Setting the lower limit of seasonal rainfall for canola was problematic which is explained further in **Volume 2**.

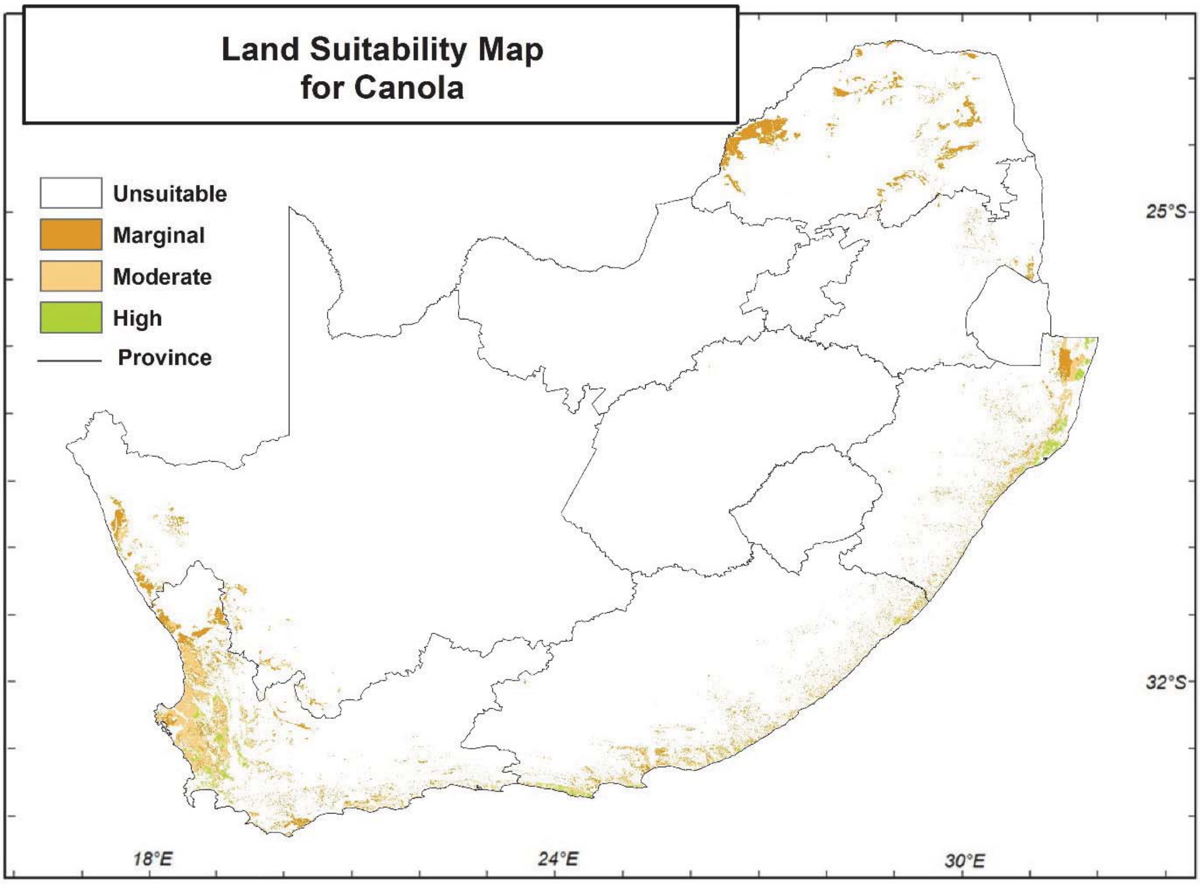


Figure 70 Overall suitability map for canola production in South Africa (based on crop coefficient weightings derived from Majnooni-Heris *et al*., 2012)

5.5 Summary

The overall aim was to map areas suitable for selected feedstocks and to improve the mapping approach used in previous land suitability studies. The methodology developed and implemented in this study is broadly similar to that adopted in four case studies that were reviewed (refer to **Section 7.3** in **Volume 2** for additional detail). To re-cap, a literature review of feedstock growth criteria added to that undertaken in previous studies (e.g. the biofuels scoping study). Spatial rainfall data were classified into different suitability classes according to each feedstock's crop water requirements, using the crop coefficient concept. Similarly, spatial temperature was also categorised into different classes to separate optimum from sub-optimum growing areas. The rainfall, temperature and relative humidity datasets were then combined and weighted in order to identify land climatically suited to feedstock production. This is illustrated in the first tier of **Figure 71**, where 0.4 (for example) represents that weighing assigned to rainfall (i.e. 40% as given in **Table 18** in **Section 5.2.2.3**).

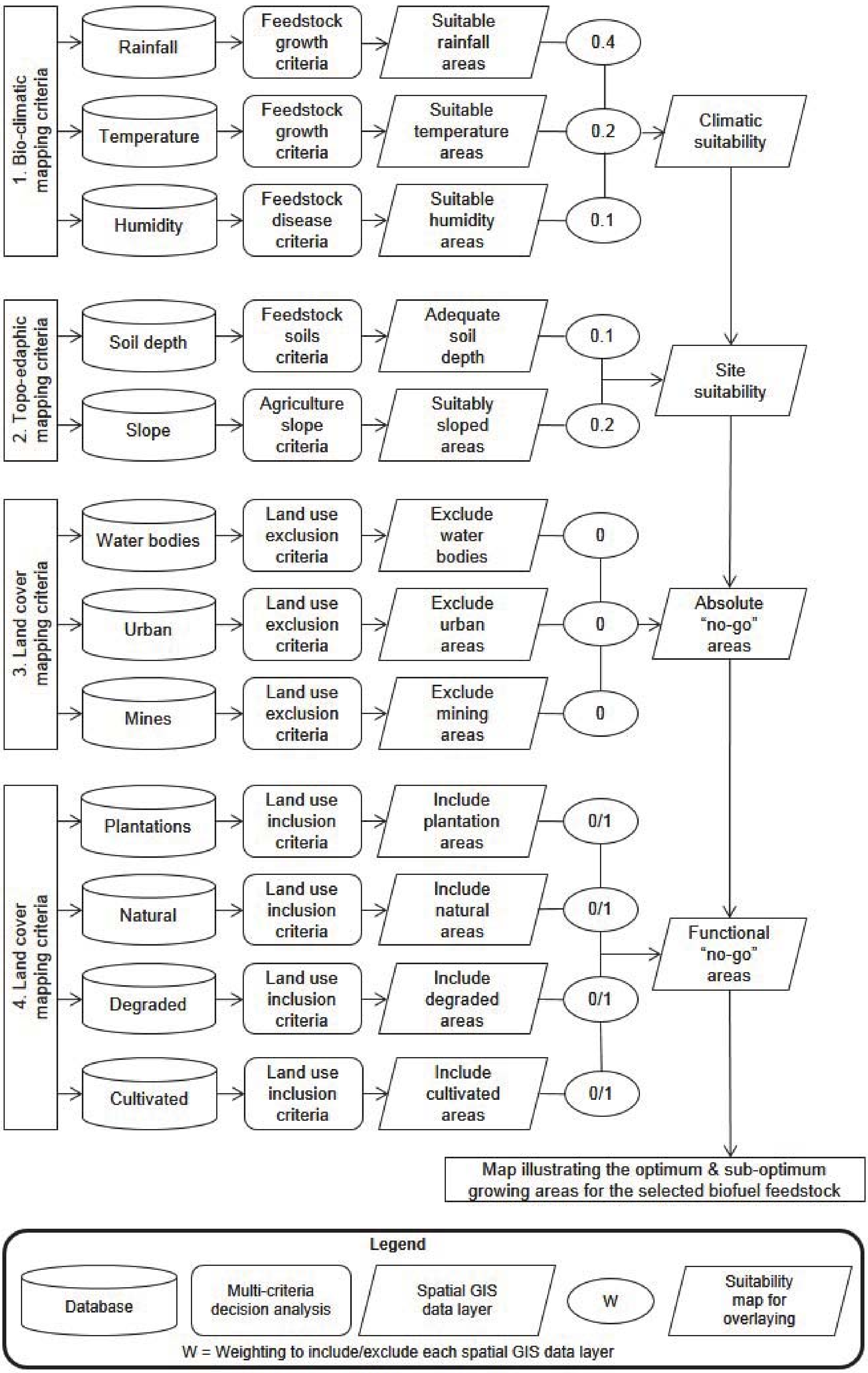


Figure 71 Decision tree flowchart highlighting various criteria considered when identifying areas suited to sustainable feedstock production

The approach then made use of a range of “filters” which were applied to the climatically suitable areas in order to highlight areas realistically suitable for crop production. For example, soil depth and slope data were used to prioritise areas with deep soils and gentle slopes that can support sustainable agriculture (second tier in **Figure 71**). Land use datasets were then used to exclude areas (i.e. weighting set to zero) that are classified as built-up, mining and water bodies as well as those areas protected by law for their biodiversity (third tier in **Figure 71**). It was important to eliminate these so-called absolute “no-go” areas in order to identify land area realistically available to feedstock production. The exclusion of function “no-go” areas was not considered in this study (i.e. the weighting was set to 1 in the fourth tier of **Figure 71**).

This approach helped to obtain a more realistic map of areas that can be planted to biofuel feedstocks. Although the latest available datasets were utilised, small patches of land may have been ignored (i.e. not highlighted as suitable) due to the coarseness of input climate data, which cannot account for microclimate effects. The approach included relative humidity and soil depth, and is unique in that these two additional sites factors were not considered in previous GIS mapping studies. However, the most innovative aspect of this study is the use of crop coefficients to quantify the feedstock’s optimum distribution of rainfall over the growing season. It is important to note that the methodology identifies three bio-climatic regions and not two as required by the project’s Terms of Reference. These regions range from high potential to low potential and are called highly suitable, moderately suitable and marginally suitable.

6 THE BIOFUELS ASSESSMENT UTILITY

6.1 Introduction

A utility was developed as part of the SFRA project (Jewitt *et al*., 2009b) to allow users to extract estimates of water use (defined as a reduction in stream flow) for different land uses at the quinary sub-catchment scale. This utility was written in the Microsoft .Net programming language and is packaged on a CD. This utility was modified to accommodate the requirements of this project as well as to disseminate the output from this project that is related to feedstock water use.

6.2 Overview of the Utility

The assessment utility has a user-friendly interface which allows the user to select a particular quinary sub-catchment. It then “zooms” into the area (or sub-catchment) of interest. Next, the user selects the baseline land use, as well as the proposed land use. The utility then displays a daily or monthly time series of simulated runoff (i.e. *SIMSQ*) generated under 1) baseline conditions and 2) the proposed land use. These two time series can be displayed in both tabular and graphical form, the latter producing a plot which helps to “visualise” the difference in runoff generated by the two land uses. In essence, the utility provides a time series of *ACRU* model output, whilst performing various calculations “on the fly”.

As noted in **Section 3.2.1**, feedstock water use is defined as the reduction in stream flow that may result from a land use change from the baseline to a particular feedstock. The simulated stream flow reduction (i.e. MAR_{base} - MAR_{crop}) is calculated “on the fly” and is easily exported if necessary. Estimates of stream flow reductions (SFR) can also be viewed as monthly or annual flow duration curves for user-selected time periods. The change in *SIMSQ* (mm) is plotted against the probability of exceedance, with low flows defined as those falling below the 75th percentile exceedance level. Various statistics can also be calculated (and exported) for the sub-catchment.

In terms of the current SFR legislation, the user would select Acocks Veld Types as the baseline land cover. Hence, stream flow reductions are assessed relative to the runoff generated under “pristine” or natural conditions. However, the utility also allows the user to select any land use as the baseline. This option is useful for the comparison of runoff reductions relative to the actual land use that the feedstock may be replacing. Finally, an updated user guide for the utility is provided in **APPENDIX J**.

6.3 Improvements Made to Utility

A number of improvements were made to version 1.0 of the biofuels assessment utility. Since then, the utility underwent a major revision to version 2.0. The most significant changes to the utility are briefly described next.

6.3.1 *ACRU* BIN files

For the SFRA project, the output from the *ACRU* model (daily stream flow or *SIMSQ* values) was stored in a structured database. This involved the conversion of *ACRU*'s binary output files for multiple quinaries into a single data "blob". Although this process simplified the packaging (and retrieval) of information by the SFRA utility, it significantly increased the time required to update the utility's database. The utility was modified to read an *ACRU* output (i.e. BIN) file directly, in its raw binary (non-ASCII) format. This improvement negated the need to "re-format" *ACRU*'s output, thus significantly reducing the time required to update the utility's database.

6.3.2 Exclusion of arid areas

An MAP threshold of 250 mm was selected as the absolute minimum annual rainfall required for dryland farming. Thus, the total number of quinaries is 5 018, with the whole of basin F excluded. This MAP threshold was derived by superimposing the canola farms with the quinary sub-catchment rainfall map. The canola farms were derived from an aerial census undertaken by the Department of Agriculture (Western Cape) in 2013. The farm-level data were obtained via Mr Andre Roux (Roux, 2015). Some canola farms in the southern Cape region, particularly near Ruens, are located in quinaries where the MAP is below 300 mm (e.g. 289 mm).

6.3.3 Exclusion using land suitability maps

Although the *ACRU* model was run at the national scale (i.e. for all 5 838 quinaries) for each feedstock, a particular quinary may not be ideally suited to the growth of certain feedstocks. Hence, the land suitability maps are used to "filter-out" sub-catchments were the feedstock may not be grown successfully (i.e. to produce an economically viable crop yield).

6.3.4 Default options

A number of "default" options have been set in the utility for the user's convenience:

- The utility initially displays all quinaries exhibiting an MAP ≥ 250 mm.
- The baseline land use is set to Acocks Veld Types.
- The *ACRU* output variable is set to simulated stream flow, excluding all upstream contributions (i.e. *SIMSQ*).
- The hydrological year for all statistics is set from October to September.

When the user selects the sugarcane land suitability map, the following occurs:

- The quinary sub-catchments not suited to the growth of this feedstock are eliminated.
- The proposed land use is to sugarcane automatically.
- The user then selects the quinary of interest and the utility calculates the statistics.

6.3.5 Inclusion of other variables

The calculation of statistics was modified to accommodate other *ACRU* output variables where daily values are either aggregated (i.e. summed) into monthly values (e.g. rainfall) or averaged to monthly values (e.g. crop coefficients).

6.3.6 Improved statistics

Another improvement made to the original SFRA utility is the option to calculate statistics with October as the start of the hydrological year (and not January as the start of a calendar year). In the summer rainfall region of South Africa, annual statistics calculated from October to September (and not January to December) are more intuitive from a hydrological viewpoint.

6.3.7 Installation issues

A Microsoft Access database file was originally used by the utility to, *inter alia*, link the quinary number (e.g. 0010) to its name (e.g. A21A1) as well as manage the list of feedstocks for which data are available. This utility required a driver to access the database file, which caused installation problems on certain PCs. This database file was converted to XML format, which negated the need to use the specialised driver to access the database.

6.3.8 *ACRU* output variables

At present, the user is able to display, query and analyse a number of *ACRU* output variables other than stream flow (e.g. *SIMSQ*). These are highlighted in

Table 32 in **APPENDIX J**. This list of variables can be changed without the need to update and re-package the utility for distribution.

6.3.9 Batch export

The batch export utility which re-written to improve the speed of extracting data from the *ACRU* binary (.BIN) file and re-formatting it to a more user-friendly comma separated (.CSV) file format. This feature allows the user to extract data for use in another software application and was used by the former Department of Water Affairs. Only the mean statistic is output at present.

6.3.10 Other improvements

Numerous "cosmetic" enhancements were made to the user interface that relate to the formatting of columns and numbers. In addition, the headings (e.g. *AET*, *SIMSQ*) and units (e.g. mm, %) that appear in tables and graphs were improved. The mean statistic is highlighted for stream flow reductions expressed as a percentage.

6.4 Dissemination of Data

The filtered (i.e. 5 018 quinaries) binary stream flow database compresses from ≈4.3 Gb to ≈2.5 Gb for each feedstock (average compression of 52.5%), which means it can be packaged on a single-layer DVD for distribution. Hence, each land use is written to a separate DVD or alternatively, all land uses written to a single layer Blu-ray disc.

An open data portal (e.g. SAEON) or web-based mapping utility would simplify access to the data by this project. A data portal would also streamline the dissemination of updated data (in particular .BIN files) and information (i.e. map-based output such as crop yield), as well as the inclusion of additional feedstocks and associated maps. In essence, this approach will facilitate the maintenance of a single database (consisting of data, tables & figures), that would be accessible by end-users via the Internet.

The SAEON (South African Environmental Observation Network) data portal could be used to disseminate the stream flow database required by the utility. Owing to the potential size of the data to be disseminated, SAEON suggested setting up a dedicated server so that data requests would not impact other portal functions.

7 REFERENCES

ABDULKAREEM AS, UTHMAN H, AFOLABI AS and AWENEBE OL (2011) Extraction and optimization of oil from *Moringa oleifera* seed as an alternative feedstock for the production of biodiesel. [Internet]. In: Nayeripour M & Kheshti M (Eds), *Sustainable growth and application in renewable energy sources,* 243-268. ISBN: 978-953-307-408-5. Available from:
http://www.intechopen.com/books/sustainable-growth-and-applications-in-renewable-energy-sources/extraction-and-optimization-of-oil-from-moringa-oleifera-seed-as-an-alternative-feedstock-for-the-pr
[Accessed 30 August 2013]

ABW (2008) Sweet sorghum: A new "smart biofuel crop". [Internet]. Agriculture Business Week (ABW) Online, 30th June 2008. Available from:
http://www.agribusinessweek.com/sweet-sorghum-a-new-smart-biofuel-crop/
[Accessed 16 October 2010]

ABW (2010) Sweet sorghum residues make good bio-organic fertilizer. [Internet]. Agriculture Business Week (ABW) Online, 11th October 2010.
http://www.agribusinessweek.com/sweet-sorghum-residues-make-good-bio-organic-fertilizer/
[Accessed 16 October 2010]

ACHTEN WMJ, VERCHOT L, FRANKEN YJ, MATHIJS E, SINGH VP, AERTS R and MUYS B (2008) Jatropha bio-diesel production and use. *Biomass and Bioenergy* 32(12): 1063-1084.
http://www.sciencedirect.com/science/article/pii/S0961953408000767

ACOCKS JPH (1953) Veld Types of South Africa (Second Edition). Botanical Research Institute, Pretoria, RSA. *Memoirs of the Botanical Society* 28.

ACOCKS JPH (1975) Veld Types of South Africa (Second Edition). Botanical Research Institute, Pretoria, RSA. *Memoirs of the Botanical Society* 40.

ACOCKS JPH (1988) Veld Types of southern Africa. Botanical Research Institute, Pretoria, RSA. *Botanical Survey of South Africa Memoirs* 57. 146 pp.

ADEOTI O (2010) Water use impact of ethanol at a gasoline substitution ratio of 5% from cassava in Nigeria. *Biomass and Bioenergy* 34(7): 985-992. ISSN: 0961-9534.
DOI:10.1016/j.biombioe.2010.02.006
http://www.sciencedirect.com/science/article/pii/S0961953410000619

ADETUNJI AI and TAYLOR JRN (2012) Development of a database on the quality attributes of released improved sorghum varieties and cultivars in southern Africa. *Journal of Quality Assurance and Safety of Crops & Foods* 4(3): 141-151.
http://dx.doi.org/10.1111/j.1757-837X.2012.00145.x

ALLEN RG, PEREIRA LS, RAES D and SMITH M (1998) Crop evapotranspiration - Guidelines for computing crop water requirements. [Internet]. Food and Agricultural Organisation (FAO), Rome, Italy. FAO Irrigation and drainage paper 56, Chapter 6. Available from:
http://www.fao.org/ag/agl/aglw/cropwater/docs/method.pdf
[Accessed 10 October 2007]

ALLEN RG, PEREIRA LS, HOWELL TA and JENSEN ME (2011a) Evapotranspiration information reporting: I. Factors governing measurement accuracy. *Agricultural Water management* 98: 899-920.
http://www.sciencedirect.com/science/article/pii/S0378377411000023
[Accessed 07 September 2011]

ALLEN RG, PEREIRA LS, HOWELL TA and JENSEN ME (2011b) Evapotranspiration information reporting: II. Recommended documentation. *Agricultural Water management* 98: 921-929.
http://www.sciencedirect.com/science/article/pii/S0378377411000035
[Accessed 7 September 2011]

ALLEN RG, PRUITT WO, WRIGHT JL, HOWELL TA, VENTURA F, SNYDER R, ITENFISU D, STEDUTO P, BERENGENA J, BASELGA YRISARRY J, SMITH M, PEREIRA LS, RAES D, PERRIER A, ALVES I, WALTER I and ELLIOTT R (2006) A recommendation on standardized surface resistance for hourly calculation of reference ET_o by the FAO56 Penman-Monteith method. *Agricultural Water Management* 81(1-2): 1-22. DOI:10.1016/j.agwat.2005.03.007
http://www.sciencedirect.com/science/article/pii/S037837740500154X

ALLEN RG, SMITH M, PEREIRA LS, RAES D and WRIGHT JL (2000) Revised FAO Procedures for Calculating Evapotranspiration - Irrigation and Drainage Paper No. 56 with Testing in Idaho. In: Flug M, Frevert D and Watkins DW (Eds), *ASCE Proceedings of Watershed Management and Operations Management*, 20-24 June 2000, Fort Collins, Colorado, USA. doi:10.1061/40499(2000)125
http://www.winrockwater.org/docs/Allen_Revised%20FAO%20procedures.pdf
[Accessed 23 August 2011]

ALLEN RG, WALTER IA, ELLIOTT RL, HOWELL TA, ITENFISU D, JENSEN ME and SNYDER RL (2005) *The ASCE Standardized Reference Evapotranspiration Equation.* American Society of Civil Engineers (ASCE). Reston, VA. 59 pp with supplemental appendices.

ALMODARES A and HADI MR (2009) Production of bioethanol from sweet sorghum: A review. *African Journal of Agricultural Research* 4(9): 772-780.
http://www.academicjournals.org/ajar/pdf/pdf%202009/Sep/Almodares%20and%20Hadi.pdf
[Accessed 05 October 2013]

AMINZADEH B, TORKIHARCHEGANI M, AHMADI A and GORGI MRN (2014) Modeling of climate effects on sugar beet growth in Kurdistan province. *International Journal of Advanced Biological and Biomedical Research* 2(4): 1217-1225.

AN P, INANAGA S, KAFKAFI U, LUX A and SUGIMOTO Y (2001) Different effect of humidity on growth and salt tolerance of two soybean cultivars. *Biologia Plantarum* 44(3): 405-410.
http://www.springerlink.com/content/h17472489473471t/

ANDERSON RL, TANAKA DL and MERRILL SD (2003) Yield and water use of broadleaf crops in a semiarid climate. *Agricultural Water Management* 58(3): 255-266. DOI:10.1016/S0378-3774(02)00085-9
http://www.sciencedirect.com/science/article/pii/S0378377402000859

ANGUS GR (1989) Sensitivity of ACRU model input. In: Schulze RE (Ed), ACRU: Background: Concepts and Theory. Water Research Commission (WRC), Pretoria, RSA. WRC Report 154/1/89. pp AT18-1 to AT18-21.

ANISKO T, NESMITH DS and LINDSTROM OM (1994) Time-domain Reflectometry for Measuring Water Content of Organic Growing Media in Containers. *Horticultural Science* 29(12): 1511-1513.
http://hortsci.ashspublications.org/content/29/12/1511.full.pdf

ANNANDALE JG, BENADÉ N, JOVANOVIC NZ, STEYN M and DU SAUTOY N (1999) Facilitating irrigation scheduling by means of the soil water balance model. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 753/1/99.

ANNANDALE JG, JOVANOVIC NZ, STEYN JM, SOUNDY P and BACKEBERG GR (2002) Technology transfer of the Soil Water Balance (SWB) model for irrigation scheduling. Workshop organised by FAO-ICID, 24th July 2002, Montreal, Canada. 23 pp.

ARC-GCI (1999) Sorghum production guide. Agricultural Research Council (ARC), Grain Crops Institute, Potchefstroom, RSA. 46 pp.

ARDEBILI MS, GHOBADIAN B, NAJAFI G and CHEGENI A (2011) Biodiesel production potential from edible oil seeds in Iran. *Renewable and Sustainable Energy Reviews* 15(6): 3041-3044.
http://www.sciencedirect.com/science/article/pii/S1364032111001031

ASHER MJC and HANSON LE (2006) Fungal and Bacterial Diseases. In: Draycott AP (Ed), *Sugar Beet*, Chapter 12, 286-315. Blackwell Publishing Ltd, Oxford, UK. Online ISBN: 9780470751114. DOI:10.1002/9780470751114.

ASIEDU JJ (1989) *Processing tropical crops - a technological approach*. Macmillan, London, UK.

ATABANI AE, MAHLIA TMI, BADRUDDIN IA, MASJUKI HH, CHONG WT and LEE KT (2013) Investigation of physical and chemical properties of potential edible and non-edible feedstocks for biodiesel production, a comparative analysis. *Renewable and Sustainable Energy Reviews* 21: 749-755. DOI:10.1016/j.rser.2013.01.027
http://www.sciencedirect.com/science/article/pii/S1364032113000580

AUGUSIAKA J, VAN DEN BRINK PJ and GRIMM V (2014) Merging validation and evaluation of ecological models to 'evaluation': A review of terminology and a practical approach. *Ecological Modelling* 280: 117-128.
http://www.sciencedirect.com/science/article/pii/S0304380013005450

BAHIZIRE FB (2007) Effect of Salinity on Germination and Seedling Growth of Canola (*Brassica napus L*). Study leader: Prof. GA Agenbag. Thesis in partial fulfilment of Degree of Master of Agricultural Sciences, University of Stellenbosch, RSA.

BALAT M and BALAT H (2010) Progress in biodiesel processing. *Applied Energy* 87(6): 1815-1835.
http://www.sciencedirect.com/science/article/pii/S0306261910000255

BALL-COELHO B, SAMPAIO EVSB, TIESSEN H and STEWART JWB (1992) Root dynamics in plant and ratoon crops of sugar cane. *Plant and Soil* 142(2): 297-305.
DOI:10.1007/BF00010975
http://link.springer.com/article/10.1007%2FBF00010975

BANERJEE S and KUNDU D (2013) A comparative overview of ethanol production from cereal grains and potato by enzymatic treatment. *International Journal of Research in Engineering and Advanced Technology* 1(2): 1-11.
http://www.ijreat.org/Papers%202013/Issue2/IJREATV1I2019.pdf

BARAN R, BASSEREAU D and GILLET N (1974) Measurement of available water and root development on an irrigated sugar cane crop in the Ivory Coast. *Proceedings of the International Society of Sugar Cane Technologists* 15: 726-735.

BASSAM NE (2010) *Handbook of Bioenergy Crops: A Complete Reference to Species, Development and Applications*. Earthscan Ltd, London, UK.

BERTLING I and ODINDO AO (2013) Personal communication. University of KwaZulu-Natal, Pietermaritzburg, RSA, 20th April 2013.

BEVEN KJ (2001) *Rainfall-runoff modelling, the primer.* John Wiley and Sons, Chichester, UK.

BFAP (2008) Impact analysis of the Biofuels Industrial Strategy on the South African Agricultural and Biofuel Subsectors. [Internet]. Bureau for Food and Agricultural Policy, Pretoria, RSA. BFAP Biofuels Report 03/2008. Available from:
http://www.bfap.co.za/reports/BFAP_Biofuels_report_no3.pdf
[Accessed 13 December 2009]

BHENGU S, SCHULZ C and GROBLER J (2008) GIS metadata: detailed report. [Internet]. South African National Biodiversity Institute (SANBI), Cape Town, RSA. Available from:
http://196.21.45.151/imf-aims50/sites/BGIS/nlc_metadata_2009.pdf
[Accessed 15 June 2014]

BLACKBURN F (1984) *Sugar-cane*. Longman, New York. ISBN: 0-582-46028-X. 414 pp.

BLÜMMEL M, RAO SS, PALANISWAMI S, SHAH L and REDDY BVS (2009) Evaluation of sweet sorghum (*Sorghum bicolor* L. Moench) used for bio-ethanol production in context of optimising whole plant utilisation. *Animal Nutrition and Feed Technology* 9(1): 1-10. http://openaccess.icrisat.org/bitstream/10731/1636/1/AniNutFeedTech%209_1_1-10_2009.pdf [Accessed 16 October 2010]

BOOTH EJ and GUNSTONE FD (2004) Rapeseeds and rapeseed oil: Agronomy, production, and trade. In: Gunstone FD (Ed), *Rapeseed and canola oil production, processing, properties and uses, 1-16*. Blackwell Publishing Ltd, Oxford, UK.

BOWEN HD, COLWICK RF and BATCHELDER DG (1973) Computer simulation of crop production: potential and hazards. *Agricultural Engineering* 54(10): 42-45.

BRADSHAW P (2010) GIS informal and formal protected areas metadata: Detailed report. [Internet]. South African National Parks (SANParks), Pretoria, RSA. Available from: http://bgis.sanbi.org/protectedareas/protectedAreas.asp [Accessed 24 June 2014]

BRANDLING J (2010) Production of ethanol from tropical sugar beet. Unpublished MSc thesis, Faculty of Engineering Sciences (Chemical and Minerals Engineering), North-West University, Potchefstroom, RSA.

BRISTOW KL and CAMPBELL GS (1984) On the relationship between incoming solar radiation and daily maximum and minimum temperature. *Agricultural and Forest Meteorology* 31(2): 159-166. http://www.sciencedirect.com/science/article/pii/0168192384900170

BROWN KF and BISCOE PV (1985) Fibrous root growth and water use of sugar beet. *Journal of Agricultural Science* 105: 679-691.

BULCOCK HH (2011) An assessment of canopy and litter interception in commercial forest plantations and an indigenous forest in the KwaZulu-Natal Midlands, South Africa. Unpublished PhD thesis. School of Bioresources Engineering and Environmental Hydrology. University of KwaZulu-Natal, Pietermaritzburg, RSA.

BULCOCK HH and JEWITT GPW (2012) Field data collection and analysis of canopy and litter interception in commercial forest plantations in the KwaZulu-Natal Midlands, South Africa. *Hydrology and Earth System Sciences* 16: 3717-3728. http://www.hydrol-earth-syst-sci.net/16/3717/2012/hess-16-3717-2012.html

BURGESS SSO, ADAMS MA, TURNER NC, BEVERLY CR, ONG CK, KHAN, AAH and BLEBY TM (2001) An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology* 21(9): 589-598.

CALDER IR (1990) *Evaporation in the uplands*. John Wiley and Sons, Chichester, UK.

CALDWELL PM, LAING MD and WARD J (2002) *The threat to SA soya crop continues*. Farmer's Weekly, Republican Press, Johannesburg, RSA.

CAMP KGT (1995) *Valley Bushveld of KwaZulu-Natal: Natural Resources and Management*. Department of Agriculture, Cedara, KwaZulu-Natal, RSA. Cedara Report No. N/A/95/2.

CAMP KG (1997) *The Bioresource Groups of KwaZulu-Natal*. Department of Agriculture, Cedara, KwaZulu-Natal, RSA. Cedara Report No. N/A/97/6.

CAMPBELL LG (2002) Sugarbeet Quality Improvement. *Journal of Crop Production* 5(1-2): 395-413. DOI:10.1300/J144v05n0116

CAMPBELL GS and VAN EVERT FK (1994) Light interception by plant canopies: Efficiency and architecture. p. 35-52. In: Monteith JL, Scott RK & Unsworth MH (Eds), *Resource Capture by Crops*. Nottingham University Press.

CANOLA ENCYCLOPAEDIA (2013a) Environmental effects. [Internet]. Available from:
http://www.canolacouncil.org/canola-encyclopedia/crop-development/growth-stages/
[Accessed 17 January 2015]

CANOLA ENCYCLOPAEDIA (2013b) Environmental effects. [Internet]. Available from:
http://www.canolacouncil.org/canola-encyclopedia/field-characteristics/effects-of-soil-characteristics/
[Accessed 17 January 2015]

CATTANACH AW, DEXTER AG and OPLINGER ES (1991) Alternative field crops manual: Sugarbeets. [Internet]. Available from:
http://www.hort.purdue.edu/newcrop/afcm/sugarbeet.html
[Accessed 27 March 2012]

CERNUSAK LA, ARANDA J, MARSHALL JD and WINTER K (2007) Large variation in whole-plant water-use efficiency among tropical tree species. *New Phytologist* 173: 294-305.

CHAN CY and KNIGHT RJ (1999) Determining water content and saturation from dielectric measurements in layered materials. *Water Resources Research* 35(1): 85-93.
http://onlinelibrary.wiley.com/doi/10.1029/1998WR900039/full

CHANDLER M, SEYFRIED M, MURDOCK M and MCNAMARA JP (2004) Field Calibration of Water Content Reflectometers. *Soil Science Society of America Journal* 68(5): 1501-1507.
https://dl.sciencesocieties.org/publications/sssaj/abstracts/68/5/1501

CHAPMAN RD (2004) Estimation of Vapour Pressure and Solar Radiation in South Africa. MSc dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.

CHARLESWORTH P (2005) Soil water monitoring. An information package, 2nd edition. [Internet]. National Program for Sustainable Irrigation. CSIRO/CRC Irrigation Futures - Land and Water Australia. Available from:
http://www.lwa.gov.au/downloads/publications_pdf/PR050832.pdf
[Accessed 17 June 2011]

CHIANU JN, OHIOKPEHAI O, VANLAUWE B, ADESINA A, DE GROOTE H and SANGINGA N (2009) Promoting a Versatile but yet Minor Crop: Soybean in the Farming Systems of Kenya. *Journal of Sustainable Development in Africa* 10(4): 1520-5509.

CHIREMBA C (2010) Personal Communication. Research Scientist, Agricultural Research Council, Potchefstroom, RSA.

CHRISTENSON DR and DRAYCOTT AP (2006) Nutrition - Phosphorus, Sulphur, Potassium, Sodium, Calcium, Magnesium and Micronutrients - Liming and Nutrient Deficiencies. In: Draycott AP (Ed), *Sugar Beet*, Chapter 9, 185-220. Blackwell Publishing Ltd, Oxford, UK. Online ISBN: 9780470751114. DOI:10.1002/9780470751114.

COLEMAN A (2012) R1,7 billion bio-ethanol plant in FS. [Internet]. Farmers Weekly, 30 March 2012.
http://www.farmersweekly.co.za/news.aspx?id=16363&h=Biofuels-Free-State
[Accessed 03 April 2012]

COMPETE (2009) Improved agricultural practices in farming systems of semi-arid and arid Africa in view of future possibilities for bioenergy production: Experiences from the COMPETE Network. Competence Platform on Energy Crop and Agroforestry Systems for Arid and Semi-arid Ecosystems: Africa (COMPETE), ANNEX2-2-1 of Deliverable D2.1, the Second Periodic Activity Report (January-December 2008). Dornburg V, Smeets E & Faaij A (Eds). Department of Science, Technology and Society, Copernicus Institute, Utrecht University, Utrecht, the Netherlands.

COOREVITS L (2010) Calibration and validation of green beans for the AquaCrop Model. Master Research. Inter-University Programme for Water Resources Engineering (IUPWARE), Brussels-Leuven, Belgium.

COWAN IR and FARQUHAR GD (1977) Stomatal function in relation to leaf metabolism and environment. In: Jennings DH (Ed), *Integration of Activity in the Higher Plant*. Cambridge University Press, Cambridge, UK, 471-505.

CUENCA RH (1989) *Irrigation system design: An engineering approach*. Prentice-Hall, Englewood Cliffs, New Jersey. 552 pp.

CUMMING C, HARDY M, BRAND T, LAMPRECHT S, TRIBE G, AGENBAG GA and LOMBARD P (2010) Canola Manual. [Internet]. Department of Agriculture, Western Cape, RSA. Available from:
http://www.overbergagri.co.za/documents/agri/Canola%20manual.pdf
[Accessed 30 September 2014]

CURT MD, FERNANDEZ J and MARTINEZ M (1995) Productivity and water use efficiency of sweet sorghum (*Sorghum bicolor* (L.) Moench) cv. "Keller" in relation to water regime. *Biomass and Bioenergy* 8(6): 401-409.
http://www.sciencedirect.com/science/article/pii/0961953495000364

DA SILVA JPV, SERRA TM, GOSSMANN M, WOLF CR, MENEGHETTI MR and MENEGHETTI SMP (2010) *Moringa oleifera* oil: Studies of characterization and biodiesel Production. *Journal of Biomass and Energy* 34(10): 1527-1530.
http://www.sciencedirect.com/science/article/pii/S0961953410001200

DAFF (2009) Canola. Department of Agriculture, Forestry and Fisheries (DAFF), Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/Brochures/canola.pdf
[Accessed 21 September 2012]

DAFF (2010a) Soya beans: production guideline. [Internet]. Department of Agriculture, Forestry and Fisheries (DAFF), Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/brochures/soya-beans.pdf
[Accessed 20 September 2012]

DAFF (2010b) Sorghum: production guideline. [Internet]. Department of Agriculture, Forestry and Fisheries, RSA. Available from:
http://www.nda.agric.za/docs/Brochures/prodGuideSorghum.pdf
[Accessed 27 September 2012]

DAFF (2010c) Sunflower: production guideline. [Internet]. Department of Agriculture, Forestry and Fisheries (DAFF), Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/Brochures/prodGuideSunflower.pdf
[Accessed 20 September 2012]

DAFF (2010d) Canola: production guideline. [Internet]. Department of Agriculture, Forestry and Fisheries (DAFF), Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/Brochures/prodGuideCanola.pdf
[Accessed 20 September 2012]

DAFF (2010e) Grain sorghum market value chain profile. [Internet]. National Department of Agriculture (NDA), Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/AMCP/GrnSorghumMVCP2009-2010.pdf
[Accessed 16 October 2010]

DAFF (2011a) Soybean market value chain profile 2010/2011. [Internet]. Department of Agriculture, Forestry and Fisheries (DAFF). Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/amcp/soyabeanmvcp2010-2011.pdf
[Accessed 20 September 2012]

DAFF (2011b) A profile of the South African sugar market value chain. [Internet]. Sector trade performance review (ATPR). Department of Agriculture, Forestry and Fisheries (DAFF). Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/AMCP/SUGARMVCP2011-12.pdf
[Accessed 21 September 2012]

DAFF (2012a) Abstract of agricultural statistics: 2012. [Internet]. Department of Agriculture, Forestry and Fisheries (DAFF). Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/statsinfo/Ab2012.pdf
[Accessed 21 September 2012]

DAFF (2012b) Canola market value chain profile 2011/2012. [Internet]. Department of Agriculture, Forestry and Fisheries (DAFF). Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/AMCP/CanolaMVCP2011.pdf
[Accessed 20 September 2012]

DAFF (2012c) Sugarcane. [Internet]. Department of Agriculture, Forestry and Fisheries (DAFF). Pretoria, RSA. Available from:
http://www.nda.agric.za/docs/Brochures/sugarcane.pdf
[Accessed 30 January 2013]

DAFF (2014) Canola Market Value Chain Profile. [Internet]. Department of Agriculture, Forestry and Fisheries (DAFF). Pretoria, RSA. Available from:
http://www.nda.agric.za/doaDev/sideMenu/Marketing/Annual%20Publications/Commodity%20Profiles/field%20crops/Canola%20Market%20Value%20Chain%20Profile%202014.pdf
[Accessed 21 July 2015]

DAWSON TE, MAMBELLI S, PLAMBOECK AH, TEMPLER PH and TU KP (2002) Stable isotopes in plant ecology. *Annual Review of Ecology and Systematics* 33: 507-559.
http://www.annualreviews.org/doi/abs/10.1146/annurev.ecolsys.33.020602.095451

DE BEER AS and DE KLERK N (2014) Soybean cultivar recommendations 2014/2015. [Internet]. ARC-Grain Crops Institute, Potchefstroom, RSA. Available from:
http://www.arc.agric.za/arc-gci/Documents/Soybeans/soyrecom14-15.pdf
[Accessed 24 August 2015]

DE JAGER JM (1994) Accuracy of vegetation evaporation ratio formulae for estimating final wheat yield. *Water SA* 20(4): 307-317.

DE VILLIERS G (1975) Reënvalonderskeppingsverliese in die Republiek van Suid Afrika - 'n Streekstudie. Unpublished PhD thesis. Department of Geography, University of the Orange Free State, Bloemfontein. 219 pp.

DEAT (2009) List 3: List Of Invasive Species In Terms Of Section 70 of the National Environmental Management: Biodiversity Act, 2004 (Act No. 10 of 2004). [Internet]. Government Gazette No. 32090, Notice 350 of 2009. Department of Environmental Affairs and Tourism (DAET), Pretoria, RSA. Available from:
http://acdb.co.za/uploads/File/Documents/Government%20Notice%20-%20Version%209.pdf
[Accessed 30 January 2013]

DENT MC, LYNCH SD and SCHULZE RE (1989) Mapping Mean Annual and Other Rainfall Statistics over Southern Africa. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 109/1/89. 230 pp.

DERCAS N, KAVADAKIS G and LIAKATAS A (2001) Evaluation of productivity, water and radiation use efficiency of two sweet sorghum varieties under Greek conditions. 1st World Conference on Biomass for Energy and Industry: Proceedings for the conference held in Sevilla, Spain, 5-9 June 2000. 1654-1657.

DICKO MH, GRUPPEN H, TRAORÉ AS, VORAGEN AGV and VAN BERKEL WJH (2006) Sorghum grain as human food in Africa: relevance of content of starch and amylase activities. *African Journal of Biotechnology* 5(5): 384-395.

DME (2006a) National Biofuels Study: An investigation into the feasibility of establishing a biofuels industry in the Republic of South Africa. [Internet]. Final report prepared to assist the development of an industrial strategy. 114 pp. Available from:
http://www.dme.gov.za/pdfs/energy/bio_feasible_study.pdf
[Accessed 17 November 2009]

DME (2006b) Draft biofuels industrial strategy of the Republic of South Africa. [Internet]. Department of Minerals and Energy (DME), Pretoria, RSA. 16 pp. Available from:
http://www.dme.gov.za/pdfs/energy/renewable/Biofuels_Strategy_SA.pdf
[Accessed 17 November 2009]

DME (2007a) *The South African National Biofuels Industrial Strategy*. [Internet]. Department of Minerals and Energy, Pretoria, RSA. Available from:
http://www.info.gov.za/view/DownloadFileAction?id=77830
[Accessed 19 March 2012]

DME (2007b) *Energy Security Master Plan - Liquid Fuels*. [Internet]. Annexure B released for public comment, Department of Minerals and Energy, RSA. 21st August 2007. Available from:
http://www.polity.org.za/article/energy-security-master-plan-liquid-fuels-august-2007-2007-08-21
[Accessed 25 September 2012]

DOBRIYAL P, QURESHI A, BADOLA R, and HUSSAIN SA (2012) A review of the methods available for estimating soil moisture and its implications for water resource management. *Journal of Hydrology* 458-459: 110-117.
http://www.sciencedirect.com/science/article/pii/S0022169412005069

DoE (2011) Draft regulations regarding the mandatory blending of biofuels with petrol and diesel. [Internet]. Government Gazette No. 34610, 16 September 2011. Amendment no. R.745 of the Petroleum Products Act of 1977, Pretoria, RSA. 3-7. Available from:
http://www.info.gov.za/view/DownloadFileAction?id=150835
[Accessed 26 September 2011]

DoE (2012a) Biofuels pricing and manufacturing economics. [Internet]. Department of Energy, Pretoria, RSA. Available from:
http://www.energy.gov.za/files/esources/renewables/BiofuelsPricingAndManufacturingEconomics.pdf
[Accessed 31 March 2013]

DoE (2012b) Regulations regarding the mandatory blending of biofuels with petrol and diesel. [Internet]. Government Gazette No. 35623, 23 August 2012. Amendment no. R.671 of the Petroleum Products Act of 1977, Pretoria, RSA. 3-7. Available from:
http://www.info.gov.za/view/DownloadFileAction?id=173022
[Accessed 29 August 2012]

DoE (2013) Presentation by Mr Mkhize (Chief Director: Hydrocarbons Policy) to the Portfolio Committee on Energy regarding an update on the biofuels industrial strategy. 13th August 2013. Available from:
http://slideplayer.com/slide/4730169/
[Accessed 18 January 2014]

DoE (2014) Draft position paper on the South Africa biofuels regulatory framework. [Internet]. Department of Energy (DoE), Pretoria, RSA. Government Gazette, Vol. 583 (No. 37232), Notice 24 of 2014, 15 January 2014. Available from:
http://www.energy.gov.za/files/policies/Draft_position_paper_on_the_SA_Biofuels_Reg_Frmwrk.pdf
[Accessed 20 January 2014]

DOORENBOS J and KASSAM AH (1979) *Crop water requirements*. FAO Irrigation and Drainage Paper No. 33. Food and Agricultural Organisation (FAO), Rome, Italy.

DOORENBOS J and PRUITT WO (1983) Yield response to water. FAO Irrigation and drainage paper, 2nd revised edition.

DRAPCHO CM, NGHIÊM NP and WALKER T (2008) Biofuel feedstocks. [Internet]. In: *Biofuels Engineering Process Technology*, Chapter 4. McGraw-Hill Publishers, USA. ISBN: 0071487492/9780071487498. Available from:
http://www.mhprofessional.com/downloads/products/0071487492/DrapchoCh4.pdf
[Accessed 29 September 2013]

DRAYCOTT AP (2006) *Sugar Beet*. Blackwell Publishing Ltd, Oxford, UK. Online ISBN: 9780470751114. DOI:10.1002/9780470751114.
http://onlinelibrary.wiley.com/book/10.1002/9780470751114

DRDLR (2013) Minister Nkwinti lambasts the lazy. [Internet]. Department of Rural Development and Land Reform (DRDLR), Pretoria, RSA. Available from:
http://www.dla.gov.za/phocadownload/stories/2013/sugar_hand_over_cradock090412.pdf
[Accessed 02 September 2013]

DU PLESSIS J (2008) Sorghum production. [Internet]. National Department of Agriculture, RSA. Available from:
http://www.nda.agric.za/docs/Infopaks/FieldCrops_Sorghum.pdf
[Accessed 07 May 2012]

DU PREEZ JC, DE JONG F, BOTS PJ and LATEGAN PM (1985) Fermentation alcohol from grain sorghum starch. *Biomass* 8(2): 101-117.
http://www.sciencedirect.com/science/article/pii/0144456585900216

DU TOIT JL (1954) Weather report for year 1st June 1953, to 31st May 1954. [Internet]. *Proceedings of the South African Sugar Technology Association* 1954: 62-66. Available from:
http://www.sasta.co.za/wp-content/uploads/Proceedings/1950s/1954_Du%20Toit_Weather%20Report%20For%20Year.pdf
[Accessed 07 October 2015]

DUGMORE H (2010) The great Fish River sugar beet plan. Farmers Weekly, 20th August 2010. 50-52.

DUGMORE H (2011) The great Fish River sugar beet plan. Farmers Weekly, 04th March 2011. 66-67.

DUKE JA (1983) Handbook of energy crops. [Internet]. Centre for New Crops and Plant Products, Purdue University. Available from:
http://www.hort.purdue.edu/newcrop/Indices/index_ab.html
[Accessed 12 August 2007]

DUKE CS, POUYAT RV, ROBERTSON GP and PARTON WJ (2013) *Ecological Dimensions of Biofuels.* [Internet]. Issues in Ecology, Report No. 17, The Ecological Society of America, Washington DC, USA. Available from:
http://www.esa.org/esa/wp-content/uploads/2013/03/issue17.pdf
[Accessed 12 August 2015]

DUNHAM RJ (1993) Water Use Requirements. In: Cooke DA & Scott RK (Eds), *The Sugarbeet Crop: Science into practice,* 279-309. Chapman and Hall, London, UK. 675 pp.

DWA (1986) *Management of the Water Resources of the Republic of South Africa*. Department of Water Affairs (DWA), Pretoria, RSA. CTP Book Printers, Cape Town. ISBN: 0 621 11004 3.

DYE PJ (2000) Water-use efficiency in South African Eucalyptus plantations: a review. *South African Forestry Journal* 189: 17-25.

DYE PJ and OLBRICH BW (1993) Estimating transpiration from 6-year-old *Eucalyptus grandis* trees: development of a canopy conductance model and comparison with independent sap flux measurements. *Plant Cell Environment* 16: 45-53.

DYE PJ, SOKO S and POULTER AG (1996) Evaluation of the heat pulse velocity method for measuring sap flow in *Pinus patula*. *Journal of Experimental Botany* 47: 975-981.

EFETHA A (2012) Irrigation Scheduling for Sugar Beet in Southern Alberta. [Internet]. Agdex 171/561-1. Alberta Agriculture and Rural Development. Available from:
http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex13524/$file/171_561-1.pdf?OpenElement
[Accessed 27 March 2015]

EHRENSING DT (2008) Canola. [Internet]. Department of Crop and Soil Science, Oregon State University, Oregon, USA. Available from:
http://extension.oregonstate.edu/catalog/pdf/em/em8955-e.pdf
[Accessed 01 May 2012]

ERASMUS D (2012) SA far from reaching biofuels target. [Internet]. Farmers Weekly, 29 September 2012. Available from:
http://www.farmersweekly.co.za/news.aspx?id=29229&h=SA-far-from-reaching-biofuels-target
[Accessed 08 October 2012]

ESCOBAR JC, LORA ES, VENTURINI OJ, YANEZ EE, CASTILLO EF and ALMAZAN O (2009) Biofuels: Environment, technology and food security. *Renewable and Sustainable Energy Reviews* 13: 1275-1287. DOI:10.1016/j.rser.2008.08.014
http://www.sciencedirect.com/science/article/B6VMY-4TMC2CG-2/2/b379897a8199e1f00d52c60c1e86d9b3
[Accessed 18 February 2011]

EVANS H (1964) The root system of sugarcane-an evaluation of its salient features. *Indian Journal of Sugarcane Research Development* 8: 161-171.

EVERSON C, EVERSON T and GHEZEHEI SB (2009) *Jatropha curcas,* the wonder biodiesel plant: Fact or fiction? 2nd World Congress of Agroforestry, Nairobi, Kenya, August 2009.

EVERSON CS, GHEZEHEI SB, EVERSON TM and ANNANDALE J (2012) Agroforestry systems for improved productivity through the efficient use of water. Water Research Commission (WRC). Pretoria, RSA. WRC Report No. 1480/1/12. ISBN: 978-1-4312-0261-4.
http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/1480-1-12.pdf
[Accessed 25 November 2012]

FAGET M, LIEDGENS M, STAMP P, FLÜTSCH P and HERRERA JH (2010) A minirhizotron imaging system to identify roots expressing the green fluorescent protein. *Computers and Electronics in Agriculture* 74(1): 163-167.
http://www.sciencedirect.com/science/article/pii/S0168169910001274

FANOURAKIS GC (2012) Estimating soil plasticity properties from pedological data. *Journal of the South African Institution of Civil Engineering* 54(2): 117-125.
http://reference.sabinet.co.za/sa_epublication_article/civileng_v54_n2_a14

FAO (1976) *A Framework for Land Evaluation*. Food and Agricultural Organisation (FAO), Rome, Italy. FAO Soils Bulletin No. 32.

FAO (1983) Guidelines: Land Evaluation for Rainfed Agriculture. Food and Agricultural Organisation (FAO), Rome, Italy. FAO Soils Bulletin No. 52.

FAO (2002) Crop water information. [Internet]. Available from: http://ecocrop.fao.org/
[Accessed 13 October 2007]

FAO (2006) Ecocrop info. [Internet]. Food and Agricultural Organisation (FAO), Rome, Italy. Available from: http://ecocrop.fao.org/
[Accessed 12 September 2007]

FAO (2007) Land evaluation: Towards a revised framework. [Internet]. Food and Agricultural Organisation (FAO), Rome, Italy. Available from: http://www.fao.org/
[Accessed 23 May 2013]

FAO (2012a) Soybean. [Internet]. Food and Agricultural Organisation (FAO), Rome, Italy. Available from:
http://www.fao.org/ag/AGP/AGPC/doc/gbase/data/soybean.htm
[Accessed 18 March 2012]

FAO (2012b) Sugarbeet. [Internet]. Food and Agricultural Organisation (FAO) Rome, Italy. Available from: http://www.fao.org/nr/water/cropinfo_sugarbeet.html
[Accessed 07 March 2012]

FAO (2012c) A compilation of tools and methodologies to assess the sustainability of modern bioenergy. In: Beall E, Cadoni P & Rossi A (Eds), *Environment and Natural Resources*. [Internet]. Working Paper No. 51, Food and Agricultural Organisation (FAO), Rome, Italy. 127 pp. ISBN: 978-92-5-107150-2. Available from:
http://www.fao.org/docrep/015/i2598e/i2598e.pdf
[Accessed 28 September 2012]

FAO-IIASA (2007) *Mapping biophysical factors that influence agricultural production and rural vulnerability*. Food and Agriculture Organisation-International Institute for Applied Systems (FAO-IIASA). Poverty Mapping, Rome.

FAOSTAT (2009) Food Balance Sheet for South Africa: 2009. [Internet]. Food and Agricultural Organisation (FAO), Rome, Italy. Available from:
http://faostat.fao.org/site/368/DesktopDefault.aspx?PageID=368#ancor
[Accessed 01 November 2012]

FARAHANI HJ, IZZI G and OWEIS TY (2009) Parameterization and evaluation of the AquaCrop model for full and deficit irrigated cotton. *Agronomy Journal* 101(3): 469-476.
https://dl.sciencesocieties.org/publications/aj/abstracts/101/3/469

FARLEY RF and DRAYCOTT AP (1974) Growth and yield of sugar beet in relation to potassium and sodium supply. *Journal of the Science of Food and Agriculture* 26: 385-392.

FARQUHAR GD and RICHARDS RA (1984) Isotopic composition of plant carbon correlates with water use efficiency of wheat genotypes. *Australian Journal of Plant Physiology* 11: 539-552.

FARQUHAR GD, O'LEARY MH and BERRY JA (1982) On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. Australian *Journal of Plant Physiology* 9: 121-137.

FORNSTROM KJ and POCHOP LO (1976) Climatic Periods and Thresholds Important to Sugarbeet Production. *Journal of the American Society of Sugar Beet Technologists* 19(1), Fort Collins, Colorado, USA.

FOUCHÉ P (2012) Best practice canola farming: The means towards economic growth for the farmers of South Africa. [Internet]. PhytoEnergy Group, Höhenkirchen, Germany. Available from:
http://config.phyto-energy.me-cms.de/index.php?id=/imageconvert&dlid=108
[Accessed 02 December 2014]

FOUCHÉ P (2015) Personal communication. Chief Executive Officer, PhytoFarming (Pty) Limited, Strand, RSA. 12th August 2015.

FRIEDMAN SP (1998) A saturation degree-dependent composite spheres model for describing the effective dielectric constant of unsaturated porous media. *Water Resources Research* 34(11): 2949-2961.
http://onlinelibrary.wiley.com/doi/10.1029/98WR01923/abstract

GALE MR and GRIGAL DF (1987) Vertical root distributions of northern tree species in relation to successional status. *Canadian Journal of Forestry Research* 17: 829-834.
http://www.nrcresearchpress.com/doi/abs/10.1139/x87-131

GAIN (2009) Biofuels annual report. [Internet]. Report prepared by Dirk Esterhuizen for the Global Agricultural Information Network (GAIN), USDA Foreign Agricultural Service. Available from:
http://gain.fas.usda.gov/Recent_GAIN_Publications/General_Report_Pretoria_South_Africa_-Republic_of_5-28-2009.pdf
[Accessed 13 November 2009]

GAN Y, CAMPBELL CA, LIU L, BASNYAT P and MCDONALD CL (2009) Water use and distribution profile under pulse and oilseed crops in semiarid northern high latitude areas. *Agricultural Water Management* 96(2): 337-348.
http://www.sciencedirect.com/science/article/pii/S0378377408002047

GARCÍA-VILA M, FERERES E, MATEOS L, ORGAZ F, STEDUTO P (2009) Deficit irrigation optimization of cotton with AquaCrop. *Agronomy Journal* 101(3): 477-487.
https://dl.sciencesocieties.org/publications/aj/abstracts/101/3/477

GARY C, JONES JW and TCHAMITCHIAN M (1998) Crop modeling in horticulture: state of the art. *Scientia Horticulturae* 74**:** 3-20.

GAROMA T, BEN-KHALED M and BEYENE A (2011) Comparative resource analyses for ethanol produced from corn and sugarcane in different climatic zones. *International Journal of Energy Research* 36(10): 1065-1076. DOI:10.1002/er.1853
http://onlinelibrary.wiley.com/doi/10.1002/er.1853/abstract

GEE GW and BAUDER JW (1986) Particle size analysis. In: Klute A (Ed), *Methods of Soil Analysis*, *Part 1*, Agronomy No. 9 (2nd edition), 383-411. American Society of Agronomy, Madison, Wisconsin.

GLOVER J (1967) The simultaneous growth of sugarcane roots and tops in relation to soil and climate. *Proceedings of the South African Sugar Technologists Association 42: 133-135.* Mount Edgecombe, RSA.

GOLDEMBERG J (2008) The Brazilian biofuels industry. *Biotechnology for Biofuels* 1(6): 1-7. DOI:10.1186/1754-6834-1-6. http://www.biotechnologyforbiofuels.com/content/1/1/6
[Accessed 26 July 2011]

GÖRGENS J (2013) Personal communication. Professor of Chemical Engineering, Department of Process Engineering, Stellenbosch University. 16th January 2013.

GOSSE G, VARLET-GRANCHER C, BONHOMME R, CHARTIER M, ALLIRAND JM and LEMAIRE G (1986) Maximum dry matter production and solar radiation intercepted by a canopy. *Agronomie* 6: 47-56.

GTZ (2009) Jatropha Reality Check: A field assessment of the agronomic and economic viability of Jatropha and other oilseed crops in Kenya. [Internet]. Study conducted by Endelevu Energy in collaboration with the World Agroforestry Centre and Kenya Forestry Research Institute. German Technical Cooperation (GTZ), Germany. Available from:
http://www.worldagroforestry.org/downloads/publications/PDFs/B16599.PDF
[Accessed 28 October 2010]

GUIYING L, WEIBIN G, HICKS A and CHAPMAN KR (2003) Training manual for sweet sorghum. [Internet]. FAO Project TCP/CPR/0066. Available from:
http://ecoport.org/ep?SearchType=earticleView&earticleId=172&page=-2
[Accessed 29 September 2012]

GUSH M (2008) Measurement of water use by *Jatropha curcas* L. using the heat pulse velocity technique. *Water SA* 34(5): 579-583.
http://www.wrc.org.za/Knowledge%20Hub%20Documents/Water%20SA%20Journals/Manuscripts/2008/04/WaterSA_2008_04_2211.pdf

GUSH MB and DYE PJ (2009) Water-use efficiency within a selection of indigenous and exotic tree species in South Africa as determined using sap flow and biomass measurements. ISHS *Acta Horticulturae* 846: 323-330.
http://www.actahort.org/books/846/846_37.htm

GYENGE J, FERNÁNDEZ ME, SARASOLA M and SCHLICHTER T (2008) Testing a hypothesis of the relationship between productivity and water use efficiency in Patagonian forests with native and exotic species. *Forest Ecology and Management* 255: 3281-3287.
http://www.sciencedirect.com/science/article/pii/S0378112708001515

HATTON TJ and WU HI (1995) Scaling theory to extrapolate individual tree water use to stand water use. *Hydrological Processes* 9: 527-540.
http://onlinelibrary.wiley.com/doi/10.1002/hyp.3360090505/abstract

HEATON E, VOIGT T and LONG SP (2004) A quantitative review comparing the yields of two candidate C_4 perennial biomass crops in relation to nitrogen, temperature and water. *Biomass and Bioenergy* 27(1): 21-30.
http://www.sciencedirect.com/science/article/pii/S0961953403001910

HENG LK, HSIAO TC, EVETT SR, HOWELL TA and STEDUTO P (2009) Testing of FAO AquaCrop model for rainfed and irrigated maize. *Agronomy Journal* 101(3): 488-498.
https://dl.sciencesocieties.org/publications/aj/abstracts/101/3/488

HEWITT A (2004) Soil properties for plant growth: a guide to recognising soil attributes necessary to plant growth and selection. Landcare Research Science Series No. 26. Manaaki Whenua Press, Lincoln, New Zealand. ISBN: 0-478-09362-4.
http://www.mwpress.co.nz/store/downloads/LRSciSeries26_4web.pdf

HILL RJ (1997) Algorithms for obtaining atmospheric surface-layer fluxes from scintillation measurements. *Journal of Atmospheric and Oceanic Technology* 14: 456-467.

HILL J, NELSON E, TILMAN D, POLASKY S and TIFFANY D (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences (PNAS)* 103(30): 11206-11210.
http://www.pnas.org/cgi/doi/10.1073/pnas.0604600103/
[Accessed 17 November 2009]

HOEKSTRA AY, CHAPAGAIN AK, ALDAYA MM and MEKONNEN MM (2011) *The water footprint assessment manual: Setting the global standard*. [Internet]. Earthscan, Washington, DC, USA. Available from:
http://doc.utwente.nl/78458/1/TheWaterFootprintAssessmentManual.pdf
[Accessed 30 November 2015]

HOFF H, FALKENMARK M, GERTEN D, GORDON L, KARLBERG L and ROCKSTRÖM J (2010) Greening the global water system. *Journal of Hydrology* 384(3-4): 177-186.
http://www.sciencedirect.com/science/article/pii/S0022169409003576

HOLL MA, GUSH MB, HALLOWES J and VERSFELD DB (2007) Jatropha curcas in South Africa: An assessment of its water use and bio-physical potential. [Internet]. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1497/1/07. ISBN: 978-1-77005-593-3.
http://www.wrc.org.za/Knowledge Hub Documents/Research Reports/1497-1-07.pdf
[Accessed 04 February 2010]

HOWARD PJA (1965) The carbon-organic matter factor in various soil types. *Oikos* 15: 229-236. DOI:10.2307/3565121.
http://www.jstor.org/stable/3565121?origin=crossref&seq=1#page_scan_tab_contents

HSIAO TC, LEE H, STEDUTO B, BASILIO RL, RAES D and FERERES E (2009) AquaCrop - The FAO crop model to simulate yield response to water: III. Parameterization and testing for maize. *Agronomy Journal* 101(3): 448-459.
https://dl.sciencesocieties.org/publications/aj/abstracts/101/3/448

IDC (2011) Expressions of interest for grain sorghum feedstock supply for the Cradock ethanol project. [Internet]. Industrial Development Corporation (IDC), Johannesburg, RSA. Available from:
http://www.agbiz.co.za/LinkClick.aspx?fileticket=7TuUUJnWjZc%3D&tabid=362
[Accessed 30 January 2012]

IDC (2013) Request for proposals for the blasting and excavation for the Cradock ethanol project. [Internet]. Tender document T41/06/13 issued by the Industrial Development Corporation of SA Ltd (IDC), Johannesburg, RSA. Available from:
http://www.idc.co.za/tenders/T41-06-13_RFP_Blasting_and_Excavation_for_the_Cradock_Ethanol_Project.pdf
[Accessed 02 September 2013]

IEA (2004) *Biofuels for transport: an international perspective*. Organisation for Economic Cooperation & Development (OECD), Paris, France. ISBN-10: 9264015124. ISBN-13: 978-9264015128. 216 pp.

IEA (2010) *Energy Technology Perspectives 2010: Scenarios and strategies to 2050*. The International Energy Agency Publications (IEA), France. ISBN: 978-92-64-08597-8. 706 pp.

IJE (2006) *Biomass Handbook*. Institution of Japan Energy (IJE), Chemistry Industry Press, Beijing, 166-167, 172 (in Chinese). Hua ZZ and Shi ZP (Translators).

JACKSON RB, CANADELL J, EHLERINGER JR, MOONEY HA, SALA OE and SCHULZE ED (1996) A global analysis of root distributions for terrestrial biomes. *Oecologia* 108(3): 389-411.
http://link.springer.com/article/10.1007/BF00333714

JARVIE JA (2009) A review of soybean rust from a South African perspective. *South African Journal of Science* 105(3-4): 103-108.
http://www.sajs.co.za/index.php/SAJS/article/view/55

JARVIS PG (1981) Stomatal conductance, gaseous exchange and transpiration. In: Grace J, Ford ED & Jarvis PG (Eds), *Plants and their atmospheric environment*. Blackwell Publishing Ltd, Oxford, UK.

JEWITT GPW, KUNZ RP, WEN HW and VAN ROOYEN AM (2009a) Scoping study on water use of crops/trees for biofuels in South Africa. [Internet]. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1772/1/09. ISBN: 978-1-77005-884-2. Available from:
http://www.wrc.org.za/Knowledge Hub Documents/Research Reports/1772-1-09 Agricltural Water Management.pdf
[Accessed 08 May 2012]

JEWITT GPW, LORENTZ SA, GUSH MB, THORNTON-DIBB S, KONGO V, WILES L, BLIGHT J, STUART-HILL SI, VERSFELD D and TOMLINSON K (2009b) Methods and guidelines for the licensing of SFRAs with particular reference to low flows. [Internet]. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1428/1/09. ISBN: 978-1-77005-877-4. Available from:
http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/1428-1-09.pdf
[Accessed 08 May 2012]

JOHL SS (1980) *Irrigation and Agricultural Development*. Pergamon Press.

JOHNSON F and SHARMA A (2010) A comparison of Australian open water body evaporation trends for current and future climates estimated from class A evaporation pans and general circulation models. *Journal of Hydrometeorology* 11: 105-121. DOI:10.1175/2009JHM1158.1
http://journals.ametsoc.org/doi/abs/10.1175/2009JHM1158.1

JØKER D and JEPSEN J (2003) *Jatropha curcas* L. Danida Forest Seed Centre (DFSC), Seed Leaflet 83.

JONES H (2004) What is water use efficiency? In: Bacon MA (Ed), *Water use efficiency in plant biology*. Blackwell Publishing Ltd, Oxford, UK, 27-41.

JONES SB, WRAITH JM and OR D (2002) Time domain reflectometry measurement principles and applications. *Hydrological Processes* 16(1): 141-153.
http://onlinelibrary.wiley.com/doi/10.1002/hyp.513/abstract

JONGSCHAAP REE, BLESGRAAF RAR, BOGAARD TA, VAN LOO EN and SAVENIJE HHG (2009) The water footprint of bioenergy from *Jatropha curcas* L. *Proceedings of the National Academy of Sciences USA (PNAS*) 106(35): E92.
http://www.pnas.org/content/106/35/E92.full

JONGSCHAAP REE, CORRÉ WJ, BINDRABAN PS and BRANDENBURG WA (2007) Claims and facts on *Jatropha curcas* L.: Global *Jatropha curcas* evaluation, breeding and propagation programme. [Internet]. Report 158. Plant Research International BV, Wageningen, The Netherlands and Stichting Het Groene Woudt, Laren, The Netherlands.
http://library.wur.nl/way/bestanden/clc/1858843.pdf
[Accessed 17 October 2010]

JOVANOVIC NZ and ANNANDALE JG (1999) An FAO type crop factor modification to SWB for inclusion of crops with limited data: Examples for vegetable crops. *Water SA* 25(2): 181-189.
http://www.wrc.org.za/Lists/Knowledge%20Hub%20Items/Attachments/4287/1999_April_apr99_p181_ABSTRACT.pdf

JOVANOVIC NZ, ANNANDALE JG and MHLAULI NC (1999) Field water balance and SWB parameters determination of six winter vegetable species. *Water SA 25(2):* 191-196.
http://www.wrc.org.za/Knowledge%20Hub%20Documents/Water%20SA%20Journals/Manuscripts/1999/02/WaterSA_1999_02_apr99_p191.pdf

JOVANOVIC NZ, ANNANDALE JG and NEL AA (2000) Calibration and validation of the SWB model for sunflower (*Helianthus annuus* L.). *South African Journal of Plant and Soil* 17(3): 117-123. DOI:10.1080/02571862.2000.10634881
http://www.tandfonline.com/doi/pdf/10.1080/02571862.2000.10634881

KANDEL H (2010) Soybean Production Field Guide for North Dakota and Northwestern Minnesota. [Internet]. NDSU Extension Services, North Dakota State University, Fargo, North Dakota, USA. Available from:
http://www.ag.ndsu.edu/pubs/plantsci/rowcrops/a1172.pdf
[Accessed 07 May 2012]

KARUNARATNE S, AZAM-ALI SN, IZZI G and STEDUTO P (2011) Calibration and validation of FAO-AquaCrop model for irrigated and water deficient bambara groundnut. *Experimental Agriculture* 47(3): 509-527.
http://dx.doi.org/10.1017/S0014479711000111

KAWUKI RS, ADIPULA E, LAMO J and TUKAMUHABWA P (2003) Responding to the soybean rust epidemic in sub-Saharan Africa: A review. *African Crop Science Journal* 11(4): 301-318.
http://www.ajol.info/index.php/acsj/article/view/27580

KENTER C, HOFFMANN CM and MÄRLÄNDER B (2006) Effects of weather variables on sugar beet yield development (*Beta vulgaris* L.). *European Journal of Agronomy* 24(1): 62-69.
http://www.sciencedirect.com/science/article/pii/S1161030105000547

KHOMO T (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

KIDD M (2011) *Environmental Law*. 2nd edition, Juta and Company, Ltd., Cape Town, RSA. 368 pp. ISBN: 9780702185458.

KINGS S (2012) Biofuel plant backfires on community. [Internet]. Mail & Guardian Online, Johannesburg, RSA. Available from:
http://mg.co.za/article/2012-07-12-biofuel-plant-backfires-on-community
[Accessed 02 September 2013]

KIPTUM CK, KIPKORIR EC, MUNYAO TM and NDAMBUKI JM (2013) Application of AquaCrop model in deficit irrigation management of cabbages in Keiyo Highlands. *International Journal of Water Resources and Environmental Engineering* 5(7): 360-369.
http://www.academicjournals.org/journal/IJWREE/article-abstract/C5B33D21381

KIENZLE S (2015) Personal communication. Professor at the Department of Geography, University of Lethbridge, Lethbridge, Alberta, Canada. 10th March 2015.

KIKER GA and CLARK DJ (2001) *The development of a java-based, object-oriented modeling system for simulation of southern African hydrology*. Proceedings of the American Society of Agricultural Engineers (ASCE). ASCE Meeting Paper No. 01-2030. St. Joseph, Michigan, USA.

KIKER GA, CLARK DJ, MARTINEZ CJ and SCHULZE RE (2006) A java-based, object-orientated modelling system for southern African hydrology. *Transactions of the ASABE* 49(5): 1419-1433. DOI:10.13031/2013.22057
https://elibrary.asabe.org/abstract.asp?aid=22057

KLOPPERS R (2002) New soybean disease in South Africa. [Internet]. Available from:
http://www.saspp.org/new_disease/soybean_2001.php
[Accessed 02 June 2012]

KOHLER MA, NORDENSON TJ and FOX WE (1955) Evaporation from pans and lakes. [Online]. US Department of Commerce, Washington, DC. Research Paper 38. 19 pp. Available from:
http://docs.lib.noaa.gov/rescue/wb_researchpapers/QC852U55no38.pdf
[Accessed 02 March 2015]

KOIKAI JS (2008) Utilizing GIS-based suitability modelling to assess the physical potential of bioethanol processing plants in western Kenya. [Internet]. Volume 10, Papers in Resource Analysis. 12 pp. Saint Mary's University of Minnesota University Central Services Press, Winona, MN. Available from:
http://www.gis.smumn.edu/
[Accessed 28 November 2012]

KOTZE C (2012a) DoE's mandatory blending regulations welcomed by grain producers. [Internet]. Engineering News 32(06), 21-27 September 2012, p 67. Creamer Media (Pty) Ltd, Johannesburg, RSA. Available from:
http://www.engineeringnews.co.za/article/does-mandatory-blending-regulations-welcomed-by-grain-producers-2012-09-21
[Accessed 22 September 2012]

KOTZE C (2012b) SA biofuels industry awaits implementation of regulations. Engineering News 32(06), 21-27 September 2012, p 68. Creamer Media (Pty) Ltd, Johannesburg, RSA.

KRISHNAN P, BLACK TA, GRANT NJ, BARR AG, HOGG EH, JASSAL RS and MORGENSTERN K (2006) Impact of changing soil moisture distribution on net ecosystem productivity of a boreal aspen forest during and following drought. *Agricultural and Forest Meteorology* 139(3-4): 208-223.
http://www.sciencedirect.com/science/article/pii/S0168192306001626

KRUGER FJ and BOSCH JM (2002) Criteria for identifying activities that qualify as Stream Flow Reduction Activities. Department of Water Affairs and Forestry, Pretoria, RSA.

KUNZ RP (1994) Techniques to assess possible impacts of climate change in southern Africa. Unpublished MSc dissertation. University of Natal, Pietermaritzburg, Department of Agricultural Engineering. 172 pp.

KUTTI V (2010) Moringa: world highest yield Moringa variety PKM 1 seeds. [Internet]. Available from:
http://moringaseed.blogspot.com/2010/01/world-highest-yield-moringa-variety-pkm.html
[Accessed 15 May 2012]

LAMAUD E, BRUNET Y and BERBIGIER P (1997) Radiation and water use efficiencies of two coniferous forest canopies. *Physics and Chemistry of the Earth* 21(5-6): 361-365.
http://www.sciencedirect.com/science/article/pii/S007919469781124X

LAW BE, FALGE E, GU L, BALDOCCHI DD, BAKWIN P, BERBIGIER P, DAVIS K, DOLMAN AJ, FALK M, FUENTES JD, GOLDSTEIN A, GRANIER A, GRELLE A, HOLLINGER D, JANSSENS IA, JARVIS P, JENSEN NO, KATUL G, MAHLI Y, MATTEUCCI G, MEYERS T, MONSON R, MUNER W, OECHEL W, OLSON R, PILEGAARD KP, THORGEIRSSON H, VALENTINI R, VERMA S, VESALA T, WILSON K and WOFSY S (2002) Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. *Agricultural and Forestry Meteorology* 113: 97-120.
http://www.sciencedirect.com/science/article/pii/S0168192302001041

LEDIEU J, DE RIDDER P, DE CLERCK P and DAUTREBANDE S (1986) A method of measuring soil moisture by time-domain reflectometry. *Journal of Hydrology* 88(3-4): 319-328.
http://www.sciencedirect.com/science/article/pii/0022169486900971

LEMMER W (2009) The impact of biofuels production on food security on biofuels production. [Internet]. Food vs. Fuel Debate Forum, Halevy Heritage Hotel, Bloemfontein, RSA, 11-12 March 2009. Available from:
http://www.saba.za.org/export/sites/saba/content/downloads/Lemmer_FOOD_VS_FUEL_DEBATE_FORUM_FINAL_PRESENTATION.ppt
[Accessed 14 November 2011]

LEMMER W and SCHOEMAN B (2011) *An assessment of the food security impact in South Africa and the world due to the South African Biofuels industry rollout.* [Internet]. Report by Grain SA, Bothaville, Free State, RSA. September 2011. Available from:
http://www.mabelefuels.com/wp-content/uploads/2011/12/Sorghum.pdf
[Accessed 03 September 2013]

LERNER A, MATUPA O, MOTHLATHLEDI F, STILES G and BROWN R (2010) SADC biofuels state of play study: An assessment of the biofuel sector development in the Southern African Development Community. [Internet]. Study commissioned by the SADC Biofuel Taskforce, funded by the German Technical Cooperation (GTZ) and their Programme for Basic Energy Conservation (ProBEC). Available from:
http://www.probec.org/fileuploads/fl11092010040316_SADC_BIOFUELS_STATE_OF_PLAY_STUDY.pdf
[Accessed 05 March 2011]

LI-COR (2009) LAI-2200 Plant Canopy Analyzer. Instruction manual. [Internet]. LI-COR, Inc. Lincoln, Nebraska, USA. Publication Number 984-10633.
http://www.licor.co.za/manuals/LAI-2200_Manual.pdf
[Accessed 14 May 2014]

LINACRE ET (1992) *Climate Data and Resources*. Routledge. 366 pp.

LINACRE ET (1993) Data-sparse estimation of lake evaporation, using a simplified Penman equation. *Agricultural and Forest Meteorology* 64(3-4): 237-256.
http://www.sciencedirect.com/science/article/pii/016819239390031C

LINACRE ET (1994) Estimating U.S. Class A pan evaporation from few climate data. *Water International* 19(1): 5-14.
http://www.tandfonline.com/doi/abs/10.1080/02508069408686189

LINDROTH A and CIENCIALA E (1996) Water use efficiency of short-rotation *Salix viminalis* at leaf, tree and stand scales. *Tree Physiology* 16: 257-262.

LIPINSKI ES (1978) *Sugar crops as a source of fuels*, vol. II. Processing and Conversion, Research Dept. of Energy. Final Report. Battelle Columbus Labs, OH, USA.

LIU R, LI J and SHEN F (2008) Refining bioethanol from stalk juice of sweet sorghum by immobilized yeast fermentation. *Renewable Energy* 33(5): 1130-1135.
DOI:10.1016/j.renene.2007.05.046
http://www.sciencedirect.com/science/article/pii/S0960148107002121

LOPES DC and STEIDLE NETO AJ (2011) Potential Crops for Biodiesel Production in Brazil: A Review. *World Journal of Agricultural Sciences* 7(2): 206-217.
http://www.idosi.org/wjas/wjas7(2)/17.pdf

LORENTZ S, GOBA P and PRETORIUS J (2001) Hydrological processes research: experiments and measurements of soil hydraulic characteristics. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 744/1/01. 69 pp.

LORITE IJ, GARCÍA-VILA M, SANTOS C, RUIZ-RAMOS M and FEDERES E (2013) AquaData and AquaGIS: two computer utilities for temporal and spatial simulations of water-limited yield with AquaCrop. *Computers and Electronics in Agriculture* 96: 227-237.
http://www.sciencedirect.com/science/article/pii/S0168169913001300

LU X and ZHUANG Q (2010) Evaluating evapotranspiration and water-use efficiency of terrestrial ecosystems in the conterminous United States using MODIS and AmeriFlux data. *Remote Sensing of Environment* 114(9): 1924-1939.
http://www.sciencedirect.com/science/article/pii/S0034425710001124

LUMSDEN TG, KUNZ RP, SCHULZE, RE, KNOESEN DM and BARICHIEVY KR (2011) Methods 4: Representation of grid and point scale regional climate change scenarios for national and catchment level hydrological impacts assessments. In: Schulze RE, Hewitson BC, Barichievy KR, Tadross M, Kunz RP, Horan MJC & Lumsden TG. Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa, Chapter 9, 89-99. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1562/1/10. ISBN: 978-1-4312-0050-4.

LUMSDEN TG and SCHULZE RE (2012) Development and applications of rainfall forecasts for agriculturally-related decision-making in selected catchments of South Africa. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. TT 538/12. ISBN: 978-1-4312-0333-8. 207 pp.

LYNCH SD (2004) Development of a raster database of annual, monthly and daily rainfall for southern Africa. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1156/1/04. 78 pp.

MABHAUDHI T, MODI AT and BELETSE YG (2013) Parameterization and testing of AquaCrop for a South African bambara groundnut landrace. *Agronomy Journal* 106(1): 243-251.
https://dl.sciencesocieties.org/publications/aj/abstracts/106/1/243

MABHAUDHI T, MODI AT and BELETSE YG (2014) Parameterisation and evaluation of the FAO-AquaCrop model for a South African taro (*Colocasia esculenta* L. Schott) landrace. *Agricultural and Forest Meteorology 192/193*: 132-139.
http://www.sciencedirect.com/science/article/pii/S0168192314000811

MABHAUDHI T (2015) Personal communication. Post-doctoral student at the University of KwaZulu-Natal, Pietermaritzburg, RSA. 3th July 2015.

MACLACHLAN R (2012) Personal communication. Senior Farm Support and Development Manager, Agrarian Research & Development Agency (ARDA), Eastern Cape, RSA.

MACVICAR CN, DE VILLIERS JM, LOXTON RF, VERSTER E, LAMBRECHTS JJN, MERRYWEATHER FR, LE ROUX J, VAN ROOYEN TH and HARMSE HJ von M (1977) Soil Classification - A Binomial System for South Africa. Department of Agricultural Technical Services, Soil and Irrigation Research Institute, Pretoria, RSA. 150 pp.

MAJNOONI-HERIS A, SADRADDINI AA, NAZEMI AH, SHAKIBA MR, NEYSHABURI MR and TUZEL IH (2012) Determination of single and dual crop coefficients and ratio of transpiration to evapotranspiration for canola. *Annals of Biological Research* 3(4): 1885-1894.
http://scholarsresearchlibrary.com/ABR-vol3-iss4/ABR-2012-3-4-1885-1894.pdf

MAKENETE A, LEMMER W and KUPKA J (2007) The impact of biofuel production on food security: A briefing paper with a particular emphasis on maize-to-ethanol production. [Internet]. South Africa Biofuels Association, Gauteng, RSA. Available from:
http://www.saba.za.org/export/sites/saba/content/downloads/impact_of_biofuels_on_food_security.pdf
[Accessed 13 December 2009]

MALCZEWSKI J (2004) GIS-based land-use suitability analysis: a critical overview. *Progress in Planning* 62(1): 3-65. DOI:10.1016/j.progress.2003.09.002
http://www.sciencedirect.com/science/article/pii/S0305900603000801

MANETAS Y, GRAMMATIKOPOULOS G and KYPARISSIS A (1998) The use of the portable, non-destructive, SPAD-502 (Minolta) chlorophyll meter with leaves of varying trichome density and anthocyanin content. *Journal of Plant Physiology* 153(3-4): 513-516.
http://www.sciencedirect.com/science/article/pii/S017616179880182X

MANSKE LL (2001) Grassland ecosystem monitoring: A non-quantitative procedure for assessing rangeland performance status. [Internet]. Dickinson Research Extension Center, North Dakota State University, Fargo, North Dakota, USA. Range Management Report DREC 01-1034. 16 pp. Available from:
http://www.ag.ndsu.edu/archive/dickinso/research/2001/range01j.htm
[Accessed 15 November 2013]

MARKHAM CG (1970) Seasonality of precipitation in the United States. *Annals of the Association of American Geographers* 60: 593-597.

MARSHALL DC (1958) Measurement of sap flow in conifers by heat transport. *Plant Physiology* 33: 385-396.

MARSHALL JD and ZHANG J (1994) Carbon isotope discrimination and water-use efficiency in native plants of the north-central Rockies. *Ecology* 75: 1887-1895.

MARVEY BB (2008) Sunflower-based feedstocks in non-food applications: Perspectives from Olefin Metathesis. *International Journal of Molecular Sciences* 9(8): 1393-1406. DOI:10.3390/ijms9081393
http://www.mdpi.com/1422-0067/9/8/1393

MASHABELA T (2012) *An analysis of South African's grain sorghum industry*. Industrial Development Corporation of South Africa Limited, Johannesburg, RSA. IDC Report No. 987-1-920639-02-0.

MASTRORILLI M, KATERJI N and RANA G (1999) Productivity and water use efficiency of sweet sorghum as affected by soil water deficit occurring at different vegetative growth stages. *European Journal of Agronomy* 11: 207-215.
http://publications.tamu.edu/FORAGE/PUB_forage_Economic%20Benefits%20of%20Forage.pdf

MBOHWA C. and MYAKA N (2011) Social Life Cycle Assessment of Biodiesel in South Africa: An Initial Assessment sugar cane. [Internet]. Department of Quality and Operations Management, University of Johannesburg, RSA. Available from:
http://www.lcm2011.org/papers.html?file=tl_files/pdf/paper/13_Session_Life_Cycle_Sustainability_Assessement_I/8_MbohwaSocial_Life_Cycle_Assessment_of_Biodiesel_in_South_Africa-769_b.pdf
[Accessed 14 April 2012]

MCCORKLE D, HANSELKA D, BEAN B, MCCOLLUM T, AMOSSON S, KLOSE S and WALLER M (2007) *The economic benefits of sorghum silage as an alternative crop*. MKT-3557L 05/07. AgriLife Extension, Texas A&M System.

MCMAHON TA, PEEL MC, LOWE L, SRIKANTHAN R and MCVICAR TR (2013) Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. *Hydrology and Earth System Sciences* 17:1331-1363.
http://www.hydrol-earth-syst-sci.net/17/1331/2013/hess-17-1331-2013.html

MCMASTER GS and WILHELM WW (1997) Growing degree-days: one equation, two interpretations. *Agricultural and Forestry Meteorology* 87(4): 291-300.
http://www.sciencedirect.com/science/article/pii/S0168192397000270

MCRAE SG and BURNHAM CP (1981) *Land Evaluation*. Oxford University Press, New York, USA.

MCVICAR TR, VAN NIEL TG, LI L-T, HUTCHINSON MF, MU X-M and LIU Z-H (2007) Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographical influences. *Journal of Hydrology* 338(3-4): 196-220.
http://www.sciencedirect.com/science/article/pii/S002216940700114X

MENGISTU MG, EVERSON CS, MOYO NC and SAVAGE MJ (2014) The validation of the variables (evaporation and soil moisture) in hydrometeorological models. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 2066/1/13.
http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/2066-1-13.pdf

MENZ MA, KLEIN RR, MULLET JE, OBERT JA, UNRUH NC and KLEIN PE (2002) A high-density genetic map of *Sorghum bicolor* (L.) Moench based on 2926 AFLP, RFLP and SSR markers. *Plant Molecular Biology* 48(5): 483-499.
http://link.springer.com/article/10.1023%2FA%3A1014831302392

MEYER F, STRAUSS PG and FUNKE T (2008) Modelling the impacts of macro-economic variables on the South African biofuels industry. *Agrekon* 47(3): p 1-19.
http://www.up.ac.za/dspace/bitstream/2263/8427/1/Meyer_Modelling%282008%29.pdf
[Accessed 12 December 2009]

MEYERS TP and BALDOCCHI DD (2005) Current micrometeorological flux methodologies with applications in agriculture. In: Hatfield JL & Baker JM (Eds), *Micrometeorology in Agricultural Systems Agronomy Monograph* 47: 381-396.

MILLER AN and OTTMAN MJ (2010) Irrigation frequency effects on growth and ethanol yield in sweet sorghum. *Agronomy* 102(1):60-70. DOI:10.2134/agronj2009.0191
https://www.agronomy.org/publications/aj/abstracts/102/1/60
[Accessed 05 March 2012]

MOKONOTO O (2012) Mapping areas potentially suitable for soybean feedstock growth for biodiesel production. Unpublished Hydrology Honours project, School of Agricultural, Earth and Environmental Sciences (SAEES), University of KwaZulu-Natal, Pietermaritzburg, RSA.

MOKONOTO O (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.

MOLDEN D (1997) Accounting for water use and productivity. SWIM Paper 1. International Irrigation Management Institute, Colombo, Sri Lanka.

MONTEITH JL (1972) Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology* 9: 747-766.

MONTEITH JL (1977) Climate and efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society London* 281: 277-294.

MONTES GN, ODVODY GN and WILLIAMS AH (2003) Relationship between climatic variables and *Claviceps africana* incidence on sorghum hybrids in northern Mexico. In: Leslie JF (Ed), *Sorghum and Millets Diseases*, Chapter 20, 111-112. Iowa State Press, Iowa, USA.

MONTES GN, PROM LK, WILLIAMS AH and ISAKEIT T (2009) Effect of temperature and relative humidity on sorghum ergot development in northern Mexico. *Australasian Plant Pathology* 38(6): 632-637.
http://link.springer.com/article/10.1071%2FAP09049#page-1

MOODLEY M, JOHNSTON MA, HUGHES JC and TITSHALL LW (2004) Effects of water treatment residues, lime, gypsum, and polyacrylamide on the water retention and hydraulic conductivity of two contrasting soils under field conditions in KwaZulu-Natal, South Africa. *Australian Journal of Soil Research* 42: 273-282.

MORGAN J (2012) Crop file tuning for local conditions. [Internet]. Food and Agricultural Organisation (FAO), Land and Water Division, Rome Italy. Available from:
http://www.fao.org/nr/water/docs/aquacrop_exd_crop_solution.pdf
[Accessed 01 August 2015]

MORILLO-VERLADE R and OBER ES (2006) Water Use and Irrigation. In: Draycott AP (Ed), *Sugar Beet*, Chapter 10, 221-255. Blackwell Publishing Ltd, UK.

MORRIS C (2015) Personal communication. Agricultural Research Council - Animal Production Institute (ARC-API). School of Life Sciences, University of KwaZulu-Natal. 25th August 2015.

MOYO NC and SAVAGE MJ (2014) Energy flux and water use efficiency measurements in a maize and soybean cropping system. Poster presented at the Post-graduate Research Day, University of KwaZulu-Natal, Durban, RSA in December 2014.

MUCINA L and RUTHERFORD MC (2006) The vegetation of South Africa, Lesotho and Swaziland. *Strelitzia* 19, South African National Biodiversity Institute, Pretoria, RSA. 807 pp.

MUOK BO, NYABENGE M, OUMA BO, ESILABA AO, NANDOKHA T and OWUOR B (2010) [Internet]. Environmental suitability and agro-ecological zoning of Kenya for biofuel production. UNEP Publication, Nairobi, Kenya. Available from:
http://www.acts.or.ke/dmdocuments/books/PISCES_UNEP_ZONING_Study_Book.pdf
[Accessed 25 June 2013]

MYBURGH J (1985) Criteria for Vegetables. Estimated Irrigation Requirements of Crops in South Africa. Part1: Eastern Cape Region, Karoo Region, Natal Region, Winter Rainfall Region. In: Green GC (Ed), Memoirs on the Agricultural Natural Resources of South Africa No. 2. Soil and Irrigation Research Institute. Department of Agriculture and Water Supply, Pretoria, RSA.

NAIDOO B (2011) Tongaat sees big potential for jobs in ethanol and power projects. [Internet]. Engineering News, Creamer Media (Pty) Ltd. 14th November 2011. Available from:
http://www.engineeringnews.co.za/article/ethanol-and-power-projects-from-sugarcane-could-save-and-create-local-jobs-2011-11-14
[Accessed 21 September 2012]

NDONG R, MONTREJAUD-VIGNOLES M, GIRONS OS, GABRIELLE B, PIROT R, DOMERGUE M and SABLAYROLLES C (2009) Life cycle assessment of biofuels from *Jatropha curcas* in West Africa: a field study. *GCB Bioenergy* 1: 197-210.
http://onlinelibrary.wiley.com/doi/10.1111/j.1757-1707.2009.01014.x/pdf

NEL A (2015) Personal communication. Grains Crop Institute, Agricultural Research Council, Potchefstroom, RSA. 28th January 2015.

NGALAMU T, MESEKA S and ASHRAF M (2012) Performance of soybean (*Glycine max* L Merrill) genotypes under different planting dates in Sennar State of the Sudan. *Journal of Applied Biosciences* 49: 3363-3370.

NIELSEN DC (1997) Water use and yield of canola under dryland conditions in the central Great Plains. *Journal of Production Agriculture* 10(2): 307-313.
https://dl.sciencesocieties.org/publications/jpa/abstracts/10/2/307

NIEMAND B (2011) Transformation of agricultural and undeveloped land in the Boland region of the Western Cape. Unpublished MSc dissertation. University of Stellenbosch, Stellenbosch, RSA.

NIEUWENHUIS R and NIEUWELINK J (2002) Soya and other leguminous crops. Agromisa Foundation, Wageningen, The Netherlands. ISBN: 90-77073-28-0.
http://teca.fao.org/sites/default/files/technology_files/Soya%20and%20other%20leguminous%20.pdf

NJOBENI S (2012) Oil companies to spend R39bn on refineries as SA moves to cleaner fuels. [Internet]. Business Day Live (Online), BDFM Publishers (Pty) Ltd. 20th August 2012. Available from:
http://www.bdlive.co.za/business/energy/2012/08/20/oil-companies-to-spend-r39bn-on-refineries-as-sa-moves-to-cleaner-fuels
[Accessed 29 August 2012]

NOLTE M (2007) Commercial biodiesel production in South Africa: A preliminary economic feasibility study. Unpublished MSc Eng dissertation. Department of Process Engineering, University of Stellenbosch, Cape Town, RSA.
http://scholar.sun.ac.za/handle/10019.1/1797

NUNKUMAR A (2006) Studies on *Phakopsora pachyrizi*, the causal organism for soybean rust. Unpublished MSc dissertation, Discipline of Plant Pathology, School of Biochemistry, Genetics, Microbiology and Plant Pathology, University of KwaZulu-Natal, Pietermaritzburg, RSA. Available from:
http://researchspace.ukzn.ac.za/xmlui/bitstream/handle/10413/4503/Nunkumar_Archana_2006.pdf
[Accessed 17 October 2012]

NYAKUDYA IW and STROOSNIJDER L (2014) Effect of rooting depth, plant density and planting date on maize (*Zea mays* L.) yield and water use efficiency in semi-arid Zimbabwe: Modelling with AquaCrop. Agricultural Water Management 146: 280-296.
http://www.sciencedirect.com/science/article/pii/S0378377414002637

OLIVIER F (2014) Irrigation Scientist. Plant and Environment Resource Centre, Mpumalanga Research Station, Komatipoort. 21st August 2014.

ORESKES N and BELITZ K (2001) Philosophical issues in model assessment. In: Anderson MG & Bates PD (Eds), Model validation: *Perspectives in Hydrological Science*, Chapter 3, 23-41. John Wiley and Sons Ltd.
http://history.ucsd.edu/_files/faculty/oreskes-naomi/PhilIssuesModelAssessOreskes.pdf

ORMEROD P and ROSEWELL B (2006) Validation and Verification of Agent-Based Models in the Social Sciences. In: Squazzoni F (Ed), *Epistemological Aspects of Computer Simulation in the Social Sciences*, 130-140. Springer-Verlag, Berlin, Germany.

ORTEGA-FARIAS S, IRMAK S and CUENCA RH (2009) Special issue on evapotranspiration measurement and modelling. *Irrigation Science* 28: 1-3. DOI:10.1007/s00271-009-0184-x012
http://www.springerlink.com/content/m517k10k7305kxur/fulltext.pdf

PALMER T and AINSLIE A (2006) South Africa: Country pasture/forage resource profiles. [Internet]. Food and Agricultural Organisation (FAO), Rome, Italy. Available from:
http://www.fao.org/ag/AGP/AGPC/doc/Counprof/PDF%20files/SouthAfrica_English.pdf
[Accessed 20 September 2012]

PANNAR (2003) Know the maize plant. [Internet]. Pannar Seed (Pty) Ltd, Greytown, South Africa. Available from:
http://www.pannar.com/admin/tech_article/Know%20the%20Maize%20Plant.pdf
[Accessed 23 August 2011]

PANNAR (2011) Grain sorghum production guide. [Internet]. Pannar Seed (Pty) Ltd, Greytown, RSA. Available from:
http://www.flipbookcafe.com/pdfs/pannarseed_528372393c74d.pdf
[Accessed 14 June 2013]

PAREDES P, DE MELO-ABREU JP ALVES I and PEREIRA LS (2014) Assessing the performance of the FAO AquaCrop model to estimate maize yields and water use under full and deficit irrigation with focus on model parameterization. *Agricultural Water Management* 144: 81-97.
http://www.sciencedirect.com/science/article/pii/S0378377414001784

PATTERSON DE and SMITH MW (1985) Unfrozen water content in saline soils: Results using time domain reflectometry. *Canadian Geotechnical Journal* 22(1): 95-101.
http://www.nrcresearchpress.com/doi/abs/10.1139/t85-009#.VnVJUfl97RY

PATZEK TW (2006) A statistical analysis of the theoretical yield of ethanol from corn starch. *Natural Resources Research* 15(3): 205-212.
http://link.springer.com/article/10.1007%2Fs11053-006-9022-5

PENMAN HL (1948) Natural evaporation from open water, bare soil and grass. *Proceedings of the Royal Society London* A(194)S, 120-145.

PEREIRA AR, GREEN S and VILLA NOVA NA (2006) Penman-Monteith reference evapotranspiration adapted to estimate irrigated tree transpiration. *Agricultural Water Management* 83(1-2): 153-161.
http://www.sciencedirect.com/science/article/pii/S0378377405003616

PERRY C, STEDUTO P, ALLEN RG and BURT CM (2009) Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. *Agricultural Water Management* 96(11): 1517-1524.
http://www.sciencedirect.com/science/article/pii/S0378377409001668

PESSARAKLI M (1994) *Handbook of Plant and Crop Physiology*. Marcel Dekker, Inc., New York, 1024 pp.

PETKEVICIENE B (2009) The effects of climate factors on sugar beet early sowing timing. *Agronomy Research* 7(1): 436-443.
http://agronomy.emu.ee/vol07Spec1/p7sI46.pdf

PGDP (2012) Provincial Growth and Development Plan: February 2012. [Internet]. KwaZulu-Natal Provincial Planning Commission. Office of the Premier, Pietermaritzburg, KwaZulu-Natal, RSA. Available from:
http://www.kznppc.gov.za/Portals/0/Documents/12-05-21 PGDPFinalPrinted Version 17.pdf
[Accessed 17 October 2012]

PHILLIPS TP, TAYLOR DS, SANNI L and AKORODA MO (2004) A cassava industrial revolution in Nigeria: the potential for a new industrial crop. [Internet]. Available from:
http://www.fao.org/docrep/007/y5548e/y5548e00.htm
[Accessed 09 September 2012]

PICCINNI G, JONGHAN KO, MAREK T and HOWELL T (2009) Determination of growth-stage-specific crop coefficients (K_c) of maize and sorghum. *Agricultural Water Management* 96(12): 1698-1704.
http://www.sciencedirect.com/science/article/pii/S0378377409001954

PIKE A and SCHULZE RE (1995) AUTOSOIL Version 3: A Soils Decision Support System for South African soils. Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

PILKEY OH and PILKEY-JARVIS L (2007) *Useless Arithmetic: Why Environmental Scientists Can't Predict the Future*. Columbia University Press, New York, USA.

PINKARD EA, PATEL V and MOHAMMED C (2006) Chlorophyll and nitrogen determination for plantation-grown *Eucalyptus nitens* and *E. globulus* using a non-destructive meter. *Forest Ecology and Management* 223(1-3): 211-217.
http://www.sciencedirect.com/science/article/pii/S0378112705007103

PORTMANN FT, SIEBERT S and DÖLL P (2010) MIRCA2000-Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modelling. *Global Biogeochemical Cycles* 24: 1011-1034.
http://onlinelibrary.wiley.com/doi/10.1029/2008GB003435/abstract

POTT A, BERNADÉ N, VAN HEERDEN PS, GROVÉ B, ANNANDALE JG and STEYN M (2008) Technology transfer and the integrated implementation of Water Management models in commercial farming. Water Research Commission, Pretoria, RSA. WRC Report TT 267/08. 122 pp.

PRASAD S, SINGH A, JAIN N and JOSHI HC (2007) Ethanol production from sweet sorghum syrup for utilization as automotive fuel in India. *Energy Fuels* 21: 2415-2420.
http://pubs.acs.org/doi/abs/10.1021/ef060328z

PRETORIUS ZA, KLOPPERS FJ and FREDERICK RD (2001) First Report of Soybean Rust in South Africa. *Plant Disease* 85(12): 1288. DOI:10.1094/PDIS.2001.85.12.1288C
http://apsjournals.apsnet.org/doi/abs/10.1094/PDIS.2001.85.12.1288C

PRICHARD T, HANSON B, SCHWANKL L, VEREGAAL P and SMITH R (2004) Deficit irrigation of quality winegrapes using micro-irrigation techniques. [Internet]. University of California Cooperative Extension, Department of Land, Air and Water Resources, University of California Davis, USA.
http://cesanluisobispo.ucanr.edu/files/89518.pdf
[Accessed 08 May 2014]

PRUITT WO, FERERES E and SYNDER RL (1986) *Reference evapotranspiration (ET_o) for California*. Division of Agricultural and Natural Resources Bulletin 1922. University of California.

RADEBE H (2013) Oilseed processing investment rises in SA amid higher demand. [Internet]. Business Day Online, BDFM Publishers (Pty) Ltd, Johannesburg, RSA. 24th September 2013. Available from:
http://www.bdlive.co.za/business/agriculture/2013/09/24/oilseed-processing-investment-rises-in-sa-amid-higher-demand
[Accessed 30 September 2013]

RAES D, STEDUTO P, HSIAO TC and FERERES E (2009) AquaCrop-The FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agronomy Journal* 101(3): 438-447.
https://dl.sciencesocieties.org/publications/aj/pdfs/101/3/438

RAES D, STEDUTO P, HSIAO TC and FERERES E (2011) FAO crop water productivity model to simulate yield response to water. [Internet]. AquaCrop Reference Manual, Chapter 1, 19 pp. Food and Agriculture Organisation of the United Nations, Rome, Italy. Available from:
http://www.fao.org/nr/water/docs/aquacropv31pluschapter1.pdf
[Accessed 22 October 2015]

RAES D, STEDUTO P, HSIAO TC and FERERES E (2012a) AquaCrop Version 4.0 Reference Manual: Chapter 2 (Users guide). [Internet]. Food and Agricultural Organisation (FAO), Land and Water Division, Rome Italy. Updated June 2012. Available from:
http://www.fao.org/nr/water/docs/aquacropv40chapter2.pdf
[Accessed 11 March 2014]

RAES D, STEDUTO P, HSIAO TC and FERERES E (2012b) AquaCrop Version 4.0 Reference Manual: Chapter 3 (Calculation procedures). [Internet]. Food and Agricultural Organisation (FAO), Land and Water Division, Rome Italy. Updated June 2012. Available from:
http://www.fao.org/nr/water/docs/aquacropv40chapter3.pdf
[Accessed 11 March 2014]

RAES D, STEDUTO P, HSIAO TC and FERERES E (2012c) AquaCrop Version 4.0 Reference Manual: Annex I (Crop parameters). [Internet]. Food and Agricultural Organisation (FAO), Land and Water Division, Rome Italy. Updated June 2012. Available from:
http://www.fao.org/nr/water/docs/aquacropv40annexes.pdf
[Accessed 11 March 2014]

RAES D, STEDUTO P, HSIAO TC and FERERES E (2012d) AquaCrop Version 4.0 Reference Manual: Annex II (Indicative values for lengths of cop development stages). [Internet]. Food and Agricultural Organisation (FAO), Land and Water Division, Rome Italy. Updated June 2012. Available from:
http://www.fao.org/nr/water/docs/aquacropv40annexes.pdf
[Accessed 11 March 2014]

RAES D, STEDUTO P, HSIAO TC and FERERES E (2013) AquaCrop Version 4.0 Reference Manual: Update of Section 2.21 on Input Files (Chapter 2). [Internet]. Food and Agricultural Organisation (FAO), Land and Water Division, Rome Italy. Updated August 2013. Available from:
http://www.fao.org/nr/water/docs/Section2_21InputFiles_3_.pdf
[Accessed 11 March 2014]

RAJABI A, OBER ES and GRIFFITHS H (2009) Genotypic variation for water use efficiency, carbon isotope discrimination and potential surrogate measures in sugar beet. *Field Crops Research* 112(3-5): 172-181. DOI:10.1016/j.fcr.2009.02.015
http://www.sciencedirect.com/science/article/pii/S0378429009000653

RAMIREZ-VILLEGAS J, CHALLINOR AJ, THORNTON PK and JARVIS A (2013) Implications of regional improvement in global climate models for agricultural impact research. *Environmental Research Letters* 8(2): 12 pp. IOP Publishing (open access). DOI:10.1088/1748-9326/8/2/024018.
http://iopscience.iop.org/article/10.1088/1748-9326/8/2/024018

RANA G and KATERJIL N (2008) Direct and indirect methods to simulate the actual evapotranspiration of an irrigated overhead table grape vineyard under Mediterranean conditions. *Hydrological Processes* 22: 181-188. DOI:10.1002/hyp.6570
http://onlinelibrary.wiley.com/doi/10.1002/hyp.6570/pdf

RANKINE D, COHEN JE, TAYLOR MA, COY AD, SIMPSON LA, STEPHENSON T and LAWRENCE JL (2015) Parameterizing the FAO AquaCrop model for rainfed and irrigated field-grown sweet potato. *Agronomy Journal* 107(1): 375-387.
https://dl.sciencesocieties.org/publications/citation-manager/prev/zt/aj/107/1/375

RASHID U, ANWAR F, MOSER BR and KNOTHE G (2008) *Moringa oleifera* oil: A possible source of biodiesel. *Bioresource Technology* 99(17): 8175-8179.
DOI:10.1016/j.biortech.2008.03.066
http://www.sciencedirect.com/science/article/pii/S0960852408003039

RAYMER PL (2002) Canola: An emerging oilseed crop. In: Janick J & Whipkey A (Eds), *Trends in new crops and new uses*, 122-126. ASHS Press, Alexandria, VA, USA.

RAYNER DP (2007) Wind run changes: the dominant factor affecting pan evaporation trends in Australia. *Journal of Climate* 20: 3379-3394. DOI:10.1175/JCLI4181.1.
http://journals.ametsoc.org/doi/abs/10.1175/JCLI4181.1

REDDY BVS, KUMAR AA and RAMESH S (2007) Sweet sorghum: A Water Saving Bio-Energy Crop. [Internet]. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India. Available from:
http://www.icrisat.org/Biopower/BVSReddyetalSweetSorghumWatersavingJan2007.pdf
[Accessed 16 October 2010]

REDDY PS, REDDY BVS, KUMAR AA and RAO PS (2008) Standardisation of nitrogen fertiliser rate for sugar yield optimisation in sweet sorghum. *Journal of SAT Agricultural Research* 6. An open access journal published by ICRISAT (ejournal.icrisat.org)
http://openaccess.icrisat.org/bitstream/10731/157/1/standardizationofnitrogen6%281%29.pdf
[Accessed 16 October 2010]

REEEP (2007) REEEP looks at complexity of producing biofuels in South Africa. [Internet]. REEEP, Pretoria, RSA. Available from:
http://www.reeep.org/publications
[Accessed 25 August 2013]

REFAY YA (2010) Root yield and quality traits of three sugar beet (*Beta vulgaris* L.) varieties in relation to sowing date and stand density. *World Journal of Agricultural Sciences* 6(5): 589 -594.
http://www.idosi.org/wjas/wjas6(5)/17.pdf

REFSGAARD JC and HENRIKSEN HJ (2004) Modelling guidelines - terminology and guiding principles. *Advances in Water Resources* 27(1): 71-82.
http://www.sciencedirect.com/science/article/pii/S0309170803001489

RILEY JJ (1966) The heat balance of a class A evaporation pan. *Water Resources Research* 2: 223-226.

RINALLDI M and VONELLA AV (2006) The response of autumn and spring sown sugar beet (*Beta vulgaris* L.) to irrigation in Southern Italy: Water and radiation use efficiency. *Field Crops Research* 95(2-3): 103-114.
http://www.sciencedirect.com/science/article/pii/S0378429005000973

RITCHIE JT (1972) Model for predicting evaporation from a row crop with incomplete cover. *Water Resources Research* 24: 1121-1213.

RODERICK ML (1999) Estimating the diffuse component from daily and monthly measurements of global radiation. *Agricultural and Forest Meteorology* 95(3): 169-185.
http://www.sciencedirect.com/science/article/pii/S0168192399000283

RODERICK ML, ROTSTAYN LD, FARQUHAR GD and HOBBINS MT (2007) On the attribution of changing pan evaporation, *Geophysical Research Letters* 34: L17403-L174408. DOI:10.1029/2007GL031166
http://www.agu.org/pubs/crossref/2007/2007GL031166.shtml

ROSENZWEIG C, JONES JW, HATFIELD JL, RUANE AC, BOOTE KJ, THORBURN P, ANTLE JM, NELSON GC, PORTER C, JANSSEN S, ASSENG S, BASSO B, EWERT F, WALLACH D, BAIGORRIA G and WINTER JM (2013) The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agricultural and Forest Meteorology* 170: 166-182.
http://www.sciencedirect.com/science/article/pii/S0168192312002857

ROTH K, SCHULIN R, FLUHLER H and ATTINGER W (1990) Calibration of time domain reflectometry for water content measurements using a composite dielectric approach. *Water Resources Research* 26(10): 2267-2273.
http://onlinelibrary.wiley.com/doi/10.1029/WR026i010p02267/abstract

ROTSTAYN LD, RODERICK ML and FARQUHAR GD (2006) A simple pan-evaporation model for analysis of climate simulations: Evaluation over Australia. *Geophysical Research Letters* 33(17), L17715 (5 pages). DOI:10.1029/2006GL027114.
http://onlinelibrary.wiley.com/doi/10.1029/2006GL027114/abstract

ROUX A (2015) Director of Sustainable Resource management. Department of Agriculture, Western Cape Government, Elsenburg. 20th March 2015.

ROYAL SOCIETY (2008) Sustainable biofuels: prospects and challenges. Royal Society Policy Document 01/08. ISBN: 978 0 85403 662 2.
http://royalsociety.org/WorkArea/DownloadAsset.aspx?id=5501
[Accessed 09 February 2011]

RUSSELL WB (1997) Reducing rainfall and runoff erosion on cultivated land. [Internet]. KwaZulu-Natal Department of Agriculture, Pietermaritzburg, RSA. Available from: http://agriculture.kzntl.gov.za/publications/production_guidelines
[Accessed 17 December 2013]

SAKELLARIOU-MAKRANTONAKI M, PAPALEXIS D, NAKOS N and KALAVROUZIOTIS IK (2007) Effects of modern irrigation methods on growth and energy production of sweet sorghum (var. Keller) on a dry year in central Greece. *Agricultural Water Management* 90(3): 181-189.
http://www.sciencedirect.com/science/article/pii/S0378377407000698

SANTOS HR, THUROW AP and THUROW TL (2000) Linkages between investment in extension services and farmers, adoption of soil conservation practices in Sothern Honduras. Technical Bulletin No. 2000-2, USAID-Soil Management CRSP/Texas and M university, Texas, USA.

SAPIA (2009a) SAPIA 2008 Annual Report. [Internet]. South African Petroleum Industry Association (SAPIA), Johannesburg, RSA. Available from:
http://www.sapia.co.za/_literature_48414/SAPIA_2008_Annual_Report
[Accessed 21 September 2011]

SAPIA (2009b) SAPIA position on the uptake of biofuels into the liquid fuels market. [Internet]. South African Petroleum Industry Association (SAPIA), Cape Town, RSA. Published September 2009. Available from:
http://www.sapia.co.za/ffuels/docs/SAPIA-Position-on-the-uptake-of-Biofuels-into-the-Liquid-Fuels-Market.pdf
[Accessed 21 December 2009]

SAPIA (2012) SAPIA 2011 Annual Report. [Internet]. South African Petroleum Industry Association (SAPIA), Johannesburg, RSA. Available from:
http://www.sapia.co.za/_literature_141171/SAPIA_2011_Annual_Report
[Accessed 25 September 2012]

SARGENT RG (2011) Verification and validation of simulation models. In: Jain S, Creasey RR, Himmelspach J, White KP & Fu M (Eds), *Proceedings of the 2011 Winter Simulation Conference*, 183-198. Phoenix, Arizona, USA. 11-14 December 2011. ISBN: 9781457721076.
http://www.informs-sim.org/wsc11papers/014.pdf

SASA (2011) The South African Sugar Industry Directory. [Internet]. An annual publication produced by the South African Sugar Association (SASA), Mt. Edgecombe, KwaZulu-Natal, RSA. Available from:
http://www.sasa.org.za/files/Industry%20Directory%202011-2012.pdf
[Accessed 23 August 2011]

SASA (2012) The South African Sugar Industry Directory. [Internet]. An annual publication produced by the South African Sugar Association (SASA), Mt Edgecombe, KwaZulu-Natal, RSA. Available from:
http://www.sasa.org.za/Files/Industry%20Directory%202013%20-%202014.pdf
[Accessed 01 May 2013]

SAVAGE MJ, EVERSON CS, ODHIAMBO GO, MENGISTU MG and JARMAIN C (2004) Theory and practice of evapotranspiration measurement, with special focus on SLS as an operational tool for the estimation of spatially-averaged evaporation. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1335/1/04. 204 pp. ISBN: 1-77005-247-X.

SAVENIJE HHG (2004) The importance of interception and why we should delete the term evapotranspiration from our vocabulary. *Hydrological Processes* 18(9): 1507-1511. DOI:10.1002/hyp.5563. http://onlinelibrary.wiley.com/doi/10.1002/hyp.5563/abstract

SAXTON KE and SAWLS WJ (2006) Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal* 70(5): 1569-1578. DOI:10.2136/sssaj2005.0117
https://dl.sciencesocieties.org/publications/sssaj/abstracts/70/5/1569

SCHULZE RE (1995) Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System. Water Research Commission (WRC), Pretoria, RSA. WRC Report TT 69/9/95.

SCHULZE RE (2004) Determination of Baseline Land Cover Variables for Applications in Assessing Land Use Impacts on Hydrological Responses in South Africa. In: Schulze RE & Pike A (Eds), Development and Evaluation of an Installed Hydrological Modelling System, Chapter 2, 37-50. Water Research Commission (WRC), Pretoria, RSA. WRC Report 1155/1/04.

SCHULZE RE (2007) Relative humidity: General Background. In*:* Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Section 12.1. Water Research Commission (WRC), Pretoria, RSA. WRC Report 1489/1/06.

SCHULZE RE (2008) Personal communication. School of Bioresources Engineering and Environmental Hydrology, Pietermaritzburg, University of KwaZulu-Natal, RSA. 14th August 2008.

SCHULZE RE (2011) Methods 3: Modelling impacts of climate change on the hydrological system: Model requirements, selection of the ACRU model, its attributes and computations of major state variables and outputs. In: Schulze RE, Hewitson BC, Barichievy KR, Tadross M, Kunz RP, Horan MJC & Lumsden TG (2011) Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa, Chapter 8, 75-88. Water Research Commission (WRC), Pretoria, RSA. WRC Report 1562/1/10. ISBN: 978-1-4312-0050-4.

SCHULZE RE (2014) Personal communication. Centre for Water Resources Research (CWRR), University of KwaZulu-Natal (UKZN), Pietermaritzburg, RSA. 14th August 2014.

SCHULZE RE and CHAPMAN RD (2007) Estimation of Daily Solar Radiation over South Africa. In: Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Section 5.2. Water Research Commission (WRC), Pretoria, RSA. WRC Report 1489/1/07.

SCHULZE RE and HORAN MJC (2007a) Altitude and relative relief. In*:* Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Section 3.1. Water Research Commission (WRC), Pretoria, RSA. WRC Report 1489/1/06.

SCHULZE RE and HORAN MJC (2007b) Soils: Hydrological attributes. In*:* Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Section 4.2. Water Research Commission (WRC), Pretoria, RSA. WRC Report 1489/1/06.

SCHULZE RE and HORAN MJC (2011) Methods 1: Delineation of South African Lesotho and Swaziland into quinary catchments. In: Schulze RE, Hewitson BC, Barichievy KR, Tadross M, Kunz RP, Horan MJC & Lumsden TG (Eds), Methodological Approaches to Assessing Eco-Hydrological Responses to Climate Change in South Africa, Chapter 6, 55-62. Water Research Commission (WRC), Pretoria, RSA. WRC Report 1562/1/10. ISBN: 978-1-4312-0050-4.

SCHULZE RE and KUNZ RP (2010a) Climate Change 2010 and Rainfall Concentration. In: Schulze RE (Ed), Atlas of Climate Change and the South African Agricultural Sector: A 2010 Perspective, Chapter 3.9. Department of Agriculture, Forestry and Fisheries, Pretoria, RSA.

SCHULZE RE and KUNZ RP (2010b) Climate change and 2010 and sugarcane production. In: Schulze RE (Ed), Atlas of Climate Change and South African Agricultural Sector: A 2010 Perspective, Chapter 5.5. Department of Agriculture, Forestry and Fisheries, Pretoria, RSA.

SCHULZE RE and KUNZ RP (2010c) Climate change and 2010 and sorghum yields. In: Schulze RE (Ed), Atlas of Climate Change and South African Agricultural Sector: A 2010 Perspective, Chapter 5.3. Department of Agriculture, Forestry and Fisheries, Pretoria, RSA.

SCHULZE RE and KUNZ RP (2010d) Climate change and 2010 and soybean yields. In: Schulze RE (Ed), Atlas of Climate Change and South African Agricultural Sector: A 2010 Perspective, Chapter 5.4. Department of Agriculture, Forestry and Fisheries, Pretoria, RSA.

SCHULZE RE and MAHARAJ M (2004) Development of a database of gridded daily temperatures for Southern Africa. Water Research Commission (WRC), Pretoria, RSA. WRC Report 1156/2/04. 83 pp.

SCHULZE RE and MAHARAJ M (2007a) Daily mean temperatures. In: Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Section 7.7. Water Research Commission (WRC), Pretoria, RSA. WRC Report No 1489/1/06.

SCHULZE RE and MAHARAJ M (2007b) Rainfall concentration. In: Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Section 6.4. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1489/1/06.

SCHULZE RE and MAHARAJ M (2007c) Sorghum yield estimation. In: Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Chapter 16.4. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1489/1/06.

SCHULZE RE and MAHARAJ M (2007d) Soybean yield estimation. In: Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Chapter 16.8. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1489/1/06.

SCHULZE RE and MAHARAJ M (2007e) Rainfall seasonality. In: Schulze RE (Ed), *South* African Atlas of Climatology and Agrohydrology, Section 6.5. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1489/1/06.

SCHULZE RE and SCHÜTTE S (2015) Local and accumulated downstream impacts of dryland sugarcane on streamflows in three South African catchments: Can a case be made for sugarcane to become a "stream flow reduction activity"? *Proceedings of the South African Sugar Technologists' Association*. In press. Paper at the SASTA Congress, 18-20 August 2015, Durban South Africa.

SCHULZE RE, HUTSON JL and CASS A (1985) Hydrological characteristics and properties of soils in Southern Africa: Soil water retention models. *Water SA*: 11, 129-135.

SCHULZE RE, CHAPMAN RD and MAHARAJ M (2007a) Daily minimum, maximum and mean relative humidity. In: Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Section 12.2. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1489/1/07.

SCHULZE RE, HORAN MJC, LUMSDEN TG and WARBURTON ML (2007b) Runoff and Streamflow and their Variability. In: Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Section 21.4. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1489/1/07.

SCHULZE RE, HULL PJ and MAHARAJ M (2007c). Sugarcane yield estimation. In: Schulze RE (Ed). South African Atlas of Climatology and Agrohydrology, Section 16.3. Water Research Commission, Pretoria, RSA. WRC Report 1489/1/06.

SCHULZE RE, MAHARAJ M and MOULT N (2007d) Reference Crop Evaporation by the Penman-Monteith Method. In: Schulze RE (Ed), South African Atlas of Climatology and Agrohydrology, Section 13.3. Water Research Commission (WRC), Pretoria, RSA. WRC Report 1489/1/07.

SCHULZE RE, KUNZ RP and HULL PJ (2010a) Climate change 2010 and the spotted sugarcane stalk borer, *Chilo sacchariphagus*. In: Schulze RE (Ed), Atlas of Climate Change and the South African Agricultural Sector: A 2010 Perspective, Chapter 8.2. Department of Agriculture, Forestry and Fisheries, Pretoria, RSA.

SCHULZE RE, KUNZ RP and HULL PJ (2010b) Climate change 2010 and the African Sugarcane stalk borer, *Eldana saccharina*. In: Schulze RE (Ed), Atlas of Climate Change and the South African Agricultural Sector: A 2010 Perspective, Chapter 8.3. Department of Agriculture, Forestry and Fisheries, Pretoria, RSA.

SCHULZE RE, ANGUS GR and GUY RM (1995) Soils. In: Schulze RE (Ed), A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System, Chapter 5, AT5-1 to AT5-28*.* Water Research Commission (WRC), Pretoria, RSA. WRC Report TT 69/9/95.

SCHULZE RE, HORAN MJC, KUNZ RP, LUMSDEN TG and KNOESEN DM (2011) Methods 2: Development of the southern African quinary catchments database. In: Schulze RE, Hewitson BC, Barichievy KR, Tadross M, Kunz RP, Horan MJC & Lumsden TG (Eds), Methodological approaches to assessing eco-hydrological responses to climate change in South Africa*,* Chapter 7, 63-74*.* Water Research Commission (WRC), Pretoria, RSA. Report No. 1562/1/10. ISBN: 978-1-4312-0050-4.

SCHULZE RE, MAHARAJ M, LYNCH SD, HOWE B and MELVIL-THOMSON B (1997) South African Atlas of Agrohydrology and Climatology. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. TT82/96.

SCOTT DF and SMITH RE (1997) Preliminary empirical models to predict reductions in annual and low flows resulting from afforestation. *Water SA* 23(2): 135-140. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Water%20SA%20Journals/Manuscripts/1997/02/WaterSA_1997_02_1042%20abstract.pdf

SCWG (1991) Soil Classification - Taxonomic System for South Africa. Soil Classification Working Group (SCWG). Department of Agricultural Development, Pretoria, RSA. 257 pp.

SECKLER D (2003) Appendix A: A note on transpiration. In: Kijne, JW, Barker, R & Molden D (Eds), *Water Productivity in Agriculture: Limits and Opportunities.* CAB International, Wallingford, UK.

SEETSENG KA (2008) Effect of water application and plant density on Canola (*Brassica napus* L.) in the Free State. Unpublished MSc Agriculture dissertation. Department of Soil, Crop and Climate Sciences, Faculty of Natural and Agricultural Sciences, University of the Free State, Bloemfontein, RSA.

SHABALALA MM (2015) Modelling the impact of different reference crop evaporation standards on streamflow response. Unpublished BSc (Honours) project. University of KwaZulu-Natal, Pietermaritzburg.

SHUGART HH (1984) *A Theory of Forest Dynamics: The Ecological Implications of Forest Succession Models*. Springer-Verlag, New York, NY, USA.

SHULER ML and KARGI F (2002) *Bioprocess Engineering: Basic concepts.* 2nd edition. Prentice Hall, Upper Saddle River, NJ.

SHUTTLEWORTH WJ (1993) Evaporation. In: Maidment DR (Ed), *Handbook of Hydrology,* Chapter 4, 4.1-4.53. McGraw-Hill, New York, USA.

SHUTTLEWORTH WJ (2007) Putting the "vap" into evaporation. *Hydrological and Earth System Sciences* 11(1): 210-244. http://www.hydrol-earth-syst-sci.net/11/210/2007/hess-11-210-2007.pdf

SHUTTLEWORTH WJ (2010) Back to the basics of understanding ET. In: Khan S, Savenije HHG, Demuth S & Hubert P (Eds), *Hydrocomplexity: New Tools for Solving Wicked Water Problems*, Chapter 1, 13-34. IAHS Publication No. 338. ISBN: 978-1-907161-11-7.

SIBANDA DP (2008) A land suitability assessment of Zimbabwe for sugarcane and sweet sorghum as bioenergy crops. Unpublished MSc dissertation. University of KwaZulu-Natal, Durban, RSA.

SIEBERT S and DÖLL P (2010) Quantifying blue and green virtual water content using global crop production as well as potential production losses without irrigation. *Journal of Hydrology* 384: 198-217. DOI:10.1016/j.jhydrol.2009.07.031 http://www.sciencedirect.com/science/article/pii/S0022169409004235

SINCLAIR TR and MUCHOW RC (1999) Radiation Use Efficiency. *Advances in Agronomy* 65: 215-265.

SINCLAIR TR and SELIGMAN N (2000) Criteria for publishing papers on crop modelling. *Field Crops Research* 68(3): 165-172.
http://www.sciencedirect.com/science/article/pii/S0378429000001052

SINGELS A (2014) Personal communication. South African Sugarcane Research Institute (SASRI), Mt. Edgecombe, RSA. 23rd October 2014.

SINGELS A (2015) Personal communication. South African Sugarcane Research Institute (SASRI), Mt. Edgecombe, RSA. 25th November 2015.

SINGH R (2005) Water productivity analysis from field to regional scale: Integration of crop and soil modelling, remote sensing and geographical information. [Internet]. Unpublished PhD thesis. Wageningen University, Wageningen, The Netherlands. 160 pp. Available from:
http://edepot.wur.nl/121640
[Accessed 24 August 2011]

SINGH VP, SINGH P, HARITASHYA UK (2011) *Encyclopedia of Snow, Ice and Glaciers.* Springer, The Netherlands. ISBN: 978-90-481-2642-2
http://www.springer.com/978-90-481-2641-5

SIRI (1987) Land Type Series. Department of Agriculture and Water Supply, Pretoria, RSA, Soil and Irrigation Research Institute. Memoirs on the Agricultural Natural Resources of South Africa.

SMITH JMB (1994) Crop, Pasture and Timber Yield Index. Natal Agricultural Research Institute, Cedara, RSA. Cedara Report, N/A/94/4. 82 pp.

SMITH JMB (1998) Handbook for Agricultural Advisors in KwaZulu-Natal. KwaZulu-Natal Department of Agriculture, Cedara, RSA. 277 pp.

SMITH B (2006) *The Farming Handbook*. University of KwaZulu-Natal Press, Pietermaritzburg, RSA.

SMITH CW and FREDERIKSEN RA (2000) *Sorghum: Origin, history, technology, and production*. John Wiley and Sons, New York, USA

SMITH DM, INMAN-BAMBER NG and THORBURN PJ (2005) Growth and function of the sugarcane root system. *Field Crops Research* 92(2-3): 169-183.
DOI:10.1016/j.fcr.2005.01.017
http://www.sciencedirect.com/science/article/pii/S0378429005000298

SMITHERS JC and SCHULZE RE (1995) ACRU Agrohydrological Modelling System: User Manual Version 3.00. Water Research Commission (WRC), Pretoria, RSA. WRC Report TT 70/95.

SMITHERS JC, SCHULZE RE, LECLER NL, KIENZLE SW, LORENTZ SA and KUNZ RP (1995) User guidelines for setting up information. In: Smithers JC and Schulze RE (Eds), A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System, Chapter 6, AM6-1 to AM6.27-190. Water Research Commission (WRC), Pretoria, RSA. WRC Report TT 69/9/95.

SNYDER RL (1992) Equation for evaporation pan to evapotranspiration conversion. *Journal of Irrigation and Drainage Engineering* 118(6): 977-980. DOI:10.1061/(ASCE)0733-9437(1992)118:6(977)

SNYDER RL, SPANO D and PAW U KT (1996) Surface renewal analysis for sensible heat and latent heat flux density. *Boundary-Layer Meteorology* 77(3): 249-266. http://link.springer.com/article/10.1007%2FBF00123527

SNYDER RL, ORANG M, MATYAC S and GRISMER ME (2005) Simplified estimation of reference evapotranspiration from pan evaporation data in California. *Journal of Irrigation and Drainage Engineering* 131(3): 249-253. http://ascelibrary.org/doi/pdf/10.1061/(ASCE)0733-9437(2005)131:3(249)

SOLTANI A (2013) Modelling regional land use e the quest for the appropriate method. PhD Research. CT de Wit Graduate School for Production Ecology and Resource Conservation, Wageningen University, The Netherlands.

SPARKS GD (2010) The economic feasibility of on-farm biodiesel production in KwaZulu-Natal, South Africa. Unpublished MSc dissertation. [Internet]. School of Agricultural Sciences and Agribusiness. University of KwaZulu-Natal, Pietermaritzburg, RSA. Available from: http://researchspace.ukzn.ac.za/xmlui/handle/10413/8543 [Accessed 23 May 2011]

SQUIRE GR (1990) *The Physiology of Tropical Crop Production*. CABI, Wallingford, 236 pp.

SRINIVASA RAO P, RAO SS, SEETHARAMA N, UMAKANTH AV, REDDY PS, REDDY BVS and GOWDA CLL (2009) Sweet sorghum for biofuel and strategies for its improvement. [Internet]. Information Bulletin No. 77. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Andhra Pradesh, India. 83 pp. ISBN: 978-92-9066-518-2. http://oar.icrisat.org/1354/1/295_2009_IB77_SS_for_biofuel.pdf [Accessed 16 October 2010]

STEDUTO P (2006) Biomass water productivity: comparing the growth engines of crop models. [Internet]. Land & Water Development Division, FAO, Rome, Italy. http://www.distagenomics.unibo.it/wuemed/P_steduto_biomass.pdf [Accessed 24 August 2011]

STEDUTO P, HSIAO TC, RAES D and FERERES E (2009) AquaCrop - The FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal* 101(3): 426-437. https://dl.sciencesocieties.org/publications/aj/abstracts/101/3/426

STEDUTO P, HSIAO TC, FERERES E and RAES D (2012) Crop yield response to water. [Internet]. FAO Irrigation and Drainage Paper No. 66. Rome, Italy. Available from: http://www.fao.org/docrep/016/i2800e/i2800e00.htm
[Accessed 04 December 2012]

STEWART BA, MUSICK JT and DUSEK DA (1983) Yield and water use efficiency of grain sorghum in a limited irrigation-dryland farming system. *Agronomy Journal* 75(4): 629-634. DOI:10.2134/agronj1983.00021962007500040013x

STEYN AJ (2011) Farmers urged to report queleas. [Internet]. Farmers Weekly, 16 November 2011.
http://www.farmersweekly.co.za/article.aspx?id=10946&h=Farmersurgedtoreportqueleas
[Accessed 08 October 2012]

SUMNER DM and JACOBS JM (2005) Utility of Penman-Monteith, Priestley-Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. *Journal of Hydrology* 308(1-4): 81-104.
DOI:10.1016/j.jhydrol.2004.10.023
http://www.sciencedirect.com/science/article/pii/S0022169404005244

SWANSON RH and WHITFIELD DWA (1981) A numerical analysis of heat pulse velocity theory and practice. *Journal of Experimental Botany* 32: 221-239.

SWART WJ (2012) The economic feasibility of commercial biodiesel production in South Africa including sensitivity analyses of important production and related parameters. [Internet]. Unpublished PhD thesis. Chemical Engineering, Faculty of Engineering, University of Stellenbosch. Available from:
http://scholar.sun.ac.za/handle/10019.1/19998
[Accessed 18 July 2012]

SYS IC, VAN RANST E and DEBAVEYE IJ (1991) *Land Evaluation. Part I-III*. Agricultural Publications, General Administration for Development Cooperation, Brussels, 199 pp.

TAIT B (2005) Requirements and viability for biofuels in South Africa. [Internet]. Manager of Alternative Energy, Sasol Technology. Paper presented at the FSSA 6th Annual Congress, 27th May 2005, Pretoria. Available from:
http://www.fssa.org.za/pebble.asp?relid=317&t=33
[Accessed 02 December 2009]

TAMMISOLA J (2010) Towards much more efficient biofuel crops - Can sugarcane pave the way? [Internet]. Department of Agricultural Sciences, University of Helsinki, Helsinki, Finland. Available from:
http://www.landesbioscience.com/journals/gmcrops/02TammisolaGMC1-4.pdf
[Accessed 21 April 2012]

TANNER CB and SINCLAIR TR (1983) Efficient water use in crop production: research or re-search. In: Taylor, HM, Jordan, WR & Sinclair TR (Eds), *Limitations to efficient water use in crop production*, 1-27. American Society of Agronomy.

TARIMO AJP and TAKAMURA YT (1998) Sugarcane production, processing and marketing in Tanzania. *African Study Monographs* 19(1): 1-11.

TAYLOR NJ and GUSH MB (2014) The water use of selected fruit tree orchards (Volume 1): Review of available knowledge. [Internet]. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. 1770/1/14. ISBN: 978-1-4312-0574-5.
http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/1770-1-14.pdf
[Accessed 16 October 2015]

TAYLOR N, ANNANDALE J, ETISSA E and GUSH M (2008) Draft report on potential evapotranspiration models. Deliverable of Project K5/1770 to the Water Research Commission (WRC), Pretoria, RSA.

TESFAMARIAM EH (2004) Modelling the soil water balance of canola *Brassica napus* L. (Hyola 60). [Internet]. Unpublished MSc (Agric) dissertation. Department of Plant Production and Soil Science, University of Pretoria, Pretoria, RSA. Available from:
https://www.crops.org/publications/aj/abstracts/102/2/658
[Accessed 14 June 2012]

TESFAMARIAM EH, ANNANDALE JG and STEYN JM (2010) Water stress effects on winter canola growth and yield. *Agronomy* 102(2): 658-666. DOI:10.2134/agronj2008.0043.
https://dl.sciencesocieties.org/publications/aj/abstracts/102/2/658

TEIXEIRA AH DE C (2008) Measurements and modelling of evapotranspiration to assess agricultural water productivity in basins with changing land use patterns: A case study in the São Francisco river basin, Brazil. Unpublished PhD thesis, Wageningen University and the International Institute for Geo-information Science and Earth Observation (ITC).
http://www.itc.nl/PDF/Research/MWS/decastroteixeira.pdf
[Accessed 23 August 2011]

THIERMANN V and GRASSL H (1992) The measurement of turbulent surface-layer fluxes by use of bichromatic scintillation. *Boundary-Layer Meteorology* 58(4): 367-389.
http://link.springer.com/article/10.1007%2FBF00120238

THOM AS, THONY JL and VAUCLIN M (1981) On the proper employment of evaporation pans and atmometers in estimating potential transpiration, *Quarterly Journal of the Royal Meteorological Society* 107: 711-736.

TOHIDLOO G, GHALEBI S, TALEGHANI D, SADEGHIAN SY and CHEGINI MA (2004) Poster presentation at the 4th International Crop Science Congress. [Internet]. 26th September to 1st October 2004, Brisbane, Australia. Available from:
http://www.cropscience.org.au/icsc2004/poster/1/5/1090_tohidloog.htm
[Accessed 09 June 2010]

TOPP GC, DAVIS JL and ANNAN AP (1980) Electromagnetic determination of soil water content using TDR: I. Applications to wetting fronts and steep gradients. *Soil Science Society of America Journal* 46(4): 672-678.

TOPP GC, DAVIS JL and ANNAN AP (2003) The early development of TDR for Soil measurements. *Vadose Zone Journal* 2(4): 492-499.
https://dl.sciencesocieties.org/publications/vzj/abstracts/2/4/492

TOXOPEUS H and MVERE B (2004) *Brassica napus* L. [Internet]. Record from PROTA4U. In: Grubben GJH & Denton OA (Eds), *Plant Resources of Tropical Africa*, PROTA, Wageningen, The Netherlands. Available from:
http://www.prota4u.org/search.asp
[Accessed 01 July 2015]

TU K, KNOHL A, MAMBELLI S, MA S, BALDOCCHI D and DAWSON T (2008) Observations and scaling of water use efficiency from leaf to globe. *Geophysical Research Abstracts* 10: EGU2008-A-07012.

TURHOLLOW AF, WEBB EG and DOWNING ME (2010) Review of sorghum production practices: Applications for bioenergy. [Internet]. ORNL/TM-2010/7. Oak Ridge National Laboratory, Tennessee, USA. Available from:
http://info.ornl.gov/sites/publications/files/Pub22854.pdf
[Accessed 02 June 2011]

USDoE (2011) U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. RD Perlack and BJ Stokes (Leads), ORNL/TM-2011/224. United States Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN. 227 pp.

VAN ATTA CW. 1977. Effect of coherent structures on structure functions of temperature in the atmospheric boundary layer. *Archives of Mechanics* 29: 161-171.

VAN BURICK N (2006) Biobrandstof: Staatsbeleid nou dringend nodig. Landbouweekblad No. 87, p 71. 6th October 2006.

VAN DER WESTHUIZEN L (2013) Biofuel industry struggling in South Africa. [Internet]. Frontier Market Network. Global Africa Network Pty Ltd, Cape Town, RSA. Available from:
http://www.frontiermarketnetwork.com/article/1858-biofuel-industry-struggling-in-south-africa
[Accessed 06 September 2013]

VAN HEERDEN P (2013) Personal communication. SAPWAT3 Database, Bloemfontein, RSA. 12th April 2013.

VAN HEERDEN PS, CROSBY CT, GROVÉ B, BENADÉ N, THERON E, SCHULZE RE and TEWOLDE MH (2009) Integrating and upgrading of SAPWAT and PLANWAT to create a powerful and user-friendly irrigation water planning tool. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. TT 391/08.
http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/TT-391-08.pdf

VAN NIEKERK LM (2009) Development of climatic soybean rust model and forecasting framework. Unpublished MSc Eng dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, RSA.
http://researchspace.ukzn.ac.za/xmlui/handle/10413/2115

VANUYTRECHT E, RAES D, STEDUTO P, HSIAO TC, FERERES E, HENG LK, GARCÍA-VILA M and MORENO PM (2014) AquaCrop: FAO's crop water productivity and yield response model. *Environmental Modelling and Software* 62:351-360.
http://www.sciencedirect.com/science/article/pii/S136481521400228X

VASILAKOGLOU I, DHIMA K, KARAGIANNIDIS N and GATSIS T (2011) Sweet sorghum productivity for biofuels under increased soil salinity and reduced irrigation. *Field Crops Research* 120(1): 38-46.
http://www.sciencedirect.com/science/article/pii/S0378429010002285

VILJOEN A (2014) Time to talk biofuels. *Wheels Supplement, Witness*. 6th February 2014. p 10.

WAHAB AA and SALIH AA (2012) Water requirements of Sugar Beet *Beta vulgaris* under heavy cracking clay soils. *Journal of Agricultural Science and Technology* B 2: 865-874.
http://www.davidpublishing.com/davidpublishing/Upfile/9/23/2012/2012092382884673.pdf

WANG W (2002) Cassava production for industrial utilization in China - present and future perspectives. [Internet]. Available from:
http://www.ciat.cgiar.org/asia_cassava/pdf/proceedings_workshop_02/33.pdf
[Accessed 21 July 2013]

WANG D, BEAN S, MCLAREN J, SEIB P, MADL R, TUINSTRA, M, SHI Y, LENZ M, WU X and ZHAO R (2009) Grain sorghum is a viable feedstock for ethanol production. *Journal of Industrial Microbiology and Biotechnology* 35(5): 313-320.
http://link.springer.com/article/10.1007%2Fs10295-008-0313-1

WATSON HK, GARLAND GG, PURCHASE B, JOHNSON FX, GRIFFEE P and DERCAS N (2008) Bioenergy for Sustainable Development and Global Competitiveness: the case of Sugar Cane in southern Africa. Thematic Report 1. Stockholm Environment Institute, Stockholm, Sweden.

WBGU (2004) *World in Transition: Towards Sustainable Energy Systems*. German Advisory Council on Global Change (WBGU). Earthscan, London, UK.

WEEPENER HL, VAN DEN BERG HM, METZ M and HAMANDAWANA H (2011) The development of a hydrologically improved Digital Elevation Model and derived products for South Africa based on the SRTM DEM. Water Research Commission (WRC), Pretoria, RSA. WRC Report No. K5/1908.

WELLENS J, RAES D, TRAORE F, DENIS A, DJABY B and TYCHON B (2013) Performance assessment of the FAO AquaCrop model for irrigated cabbage on farmer plots in a semi-arid environment. *Agricultural Water Management* 127: 40-47.
http://www.sciencedirect.com/science/article/pii/S0378377413001315

WENT FW. 1957. *Environmental Control of Plant Growth*. Ronald Press Company, New York, USA.

WHITEHEAD D (1998) Regulation of stomatal conductance and transpiration in forest Canopies. *Tree Physiology* 18: 633-644.

WHITEHEAD ENC (2010) Personal communication. Regional Agricultural Economist, KwaZulu-Natal Department of Agriculture, Environmental Affairs and Rural Development, Cedara, South Africa.

WICKE B (2011) Bioenergy production on degraded and marginal land: Assessing its potentials, economic performance, and environmental impacts for different settings and geographical scales. [Internet]. Published PhD Dissertation, Faculty of Science, Copernicus Institute, Group Science, Technology and Society, Utrecht University, Netherlands. ISBN: 978-90-8672-050-7. Available from:
http://igitur-archive.library.uu.nl/dissertations/2011-0412-200703/UUindex.html
[Accessed 15 November 2013]

WOOD DW, SCOTT RK and LONGDEN PC (1980) The effects of mother plant temperature on seed quality in *Beta vulgaris* L. (sugar beet). In: Hebblethwaite PD (Ed), *Seed Production,* 257-270. Butterworths, London, UK.

WORLDWATCH INSTITUTE (2006) Biofuels for transport: global potential and implications for energy and agriculture. Prepared by Worldwatch Institute for the German Ministry of Food, Agriculture and Consumer Protection in coordination with the German Agency for Technical Cooperation and the German Agency of renewable resources. Earthscan, London, UK.

WRC (2010) Abridged Knowledge Review 2009/10 - Growing Knowledge for South Africa's Water Future. Water Research Commission (WRC), Pretoria, RSA. 59-60.

WULLSCHLEGER SD, MEINZER FC and VERTESSY RA (1998) A review of whole-plant water use studies in trees. *Tree Physiology* 18: 499-512.

YEH S, BERNDES G, MISHRA GS, WANI SP, NETO AE, SUH S, KARLBERG L, HEINKE J and GARG KK (2011) Evaluation of water use for bioenergy at different scales. *Biofuels, Bioproduction and Biorefining* 5:361-374. DOI:10.1002/bbb.308
http://onlinelibrary.wiley.com/doi/10.1002/bbb.308/abstract
[Accessed 14 July 2011]

ZEGADA-LIZARAZU W and MONTI A (2012) Are we ready to cultivate sweet sorghum as a bioenergy feedstock? A review on field management practices. *Biomass and Bioenergy* 40: 1-12. DOI:10.1016/j.biombioe.2012.01.048.
http://www.sciencedirect.com/science/article/pii/S0961953412000700

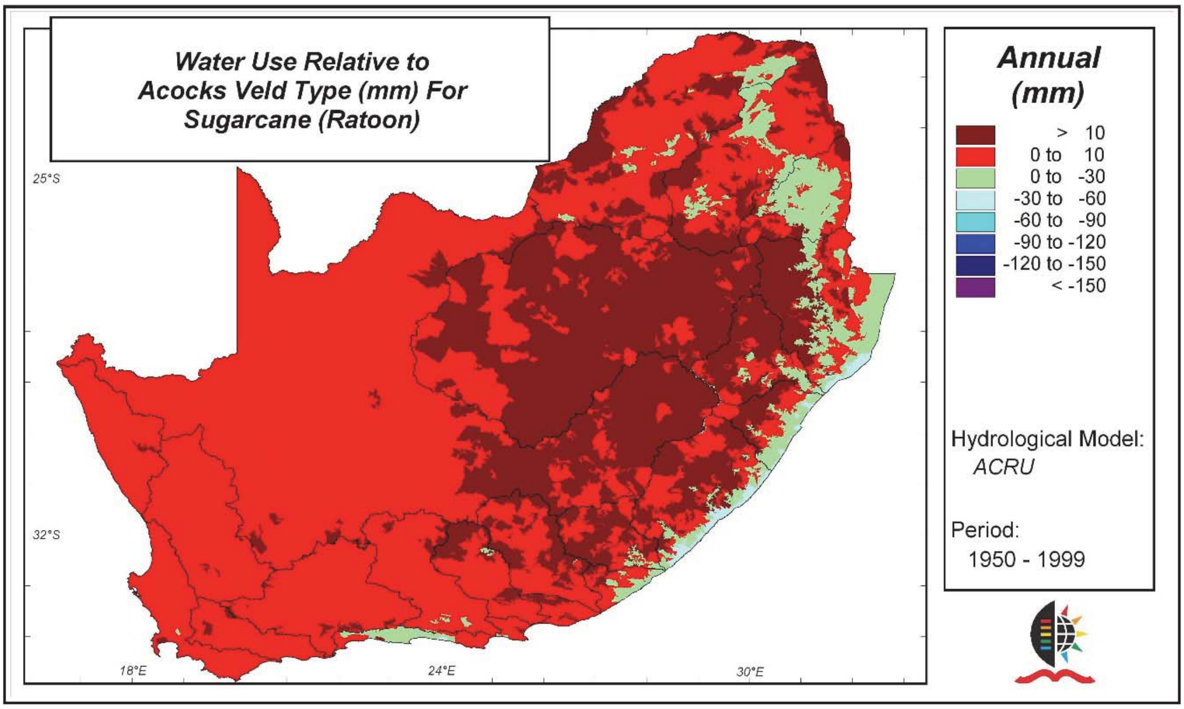
ZELEKE KT and WADE LJ (2012) Evapotranspiration estimation using soil water balance, weather and crop data. In: Irmak A (Ed), *Evapotranspiration - Remote Sensing and Modeling*, Chapter 3, 41-58. InTech Europe, Croatia. ISBN: 978-953-307-808-3.
http://cdn.intechweb.org/pdfs/26099.pdf
[Accessed 01 October 2012]

ZELEKE KT, LUCKETT D and COWLEY R (2011) Calibration and testing of the FAO AquaCrop Model for canola. *Agronomy Journal* 103(6): 1610-1618. https://dl.sciencesocieties.org/publications/aj/abstracts/103/6/1610

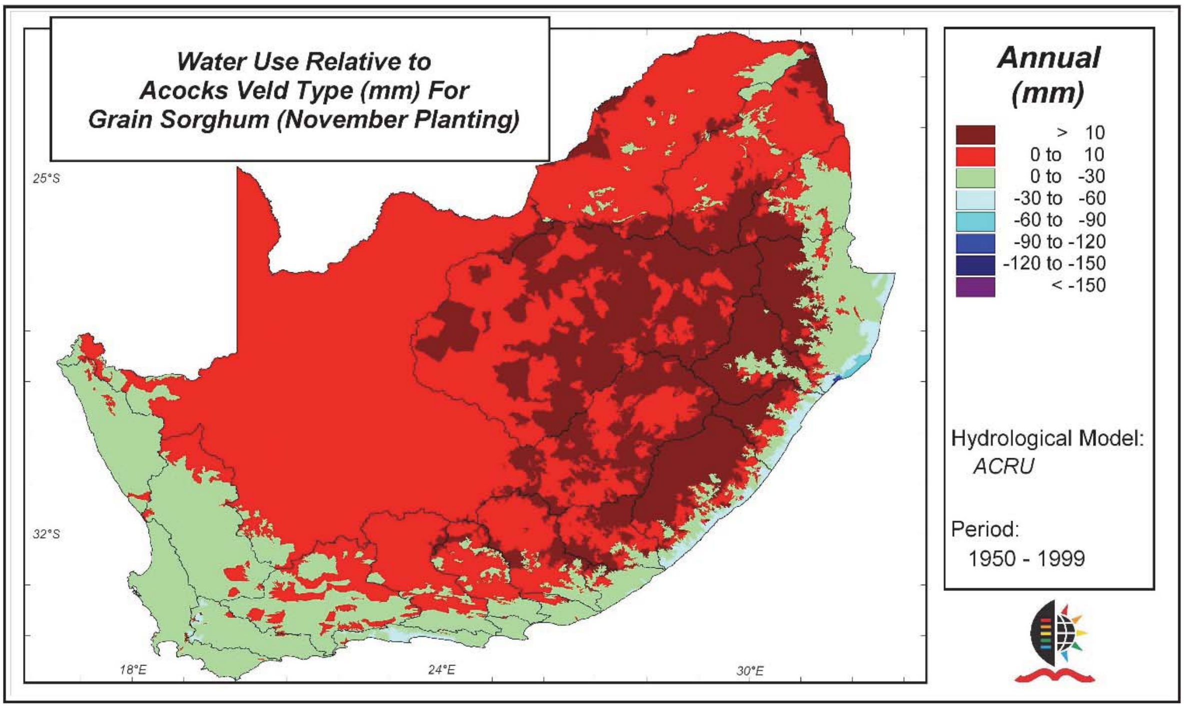
ZHANG X, CHEN S, SUN H, WANG Y and SHAO L (2010) Water use efficiency and associated traits in winter wheat cultivars in the North China Plain. *Agricultural Water Management* 97(8): 1117-1125. DOI:10.1016/j.agwat.2009.06.003. http://www.sciencedirect.com/science/article/pii/S0378377409001632

ZHAO YL, DOLAT A, STEINBERGER Y, WANG X, OSMAN A and XIE GH (2009) Biomass yield and changes in chemical composition of sweet sorghum cultivars grown for biofuel. *Field Crops Research* 111(1-2): 55-64. http://www.sciencedirect.com/science/article/pii/S0378429008002116

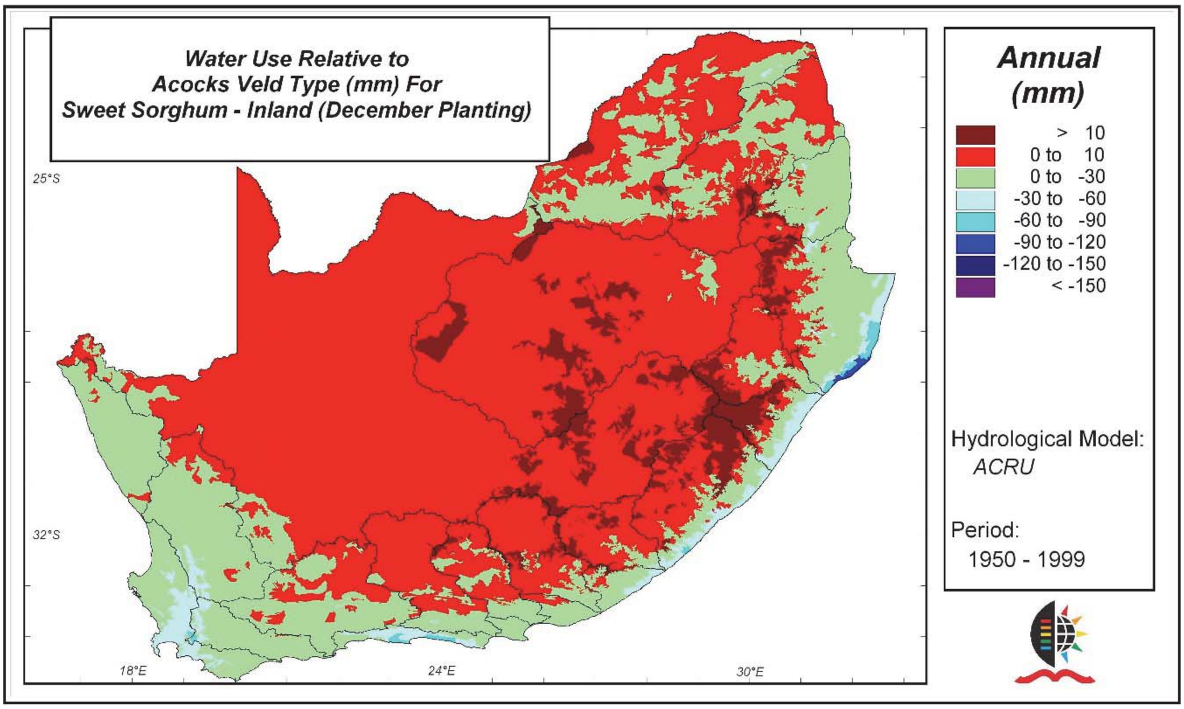
8 APPENDIX A



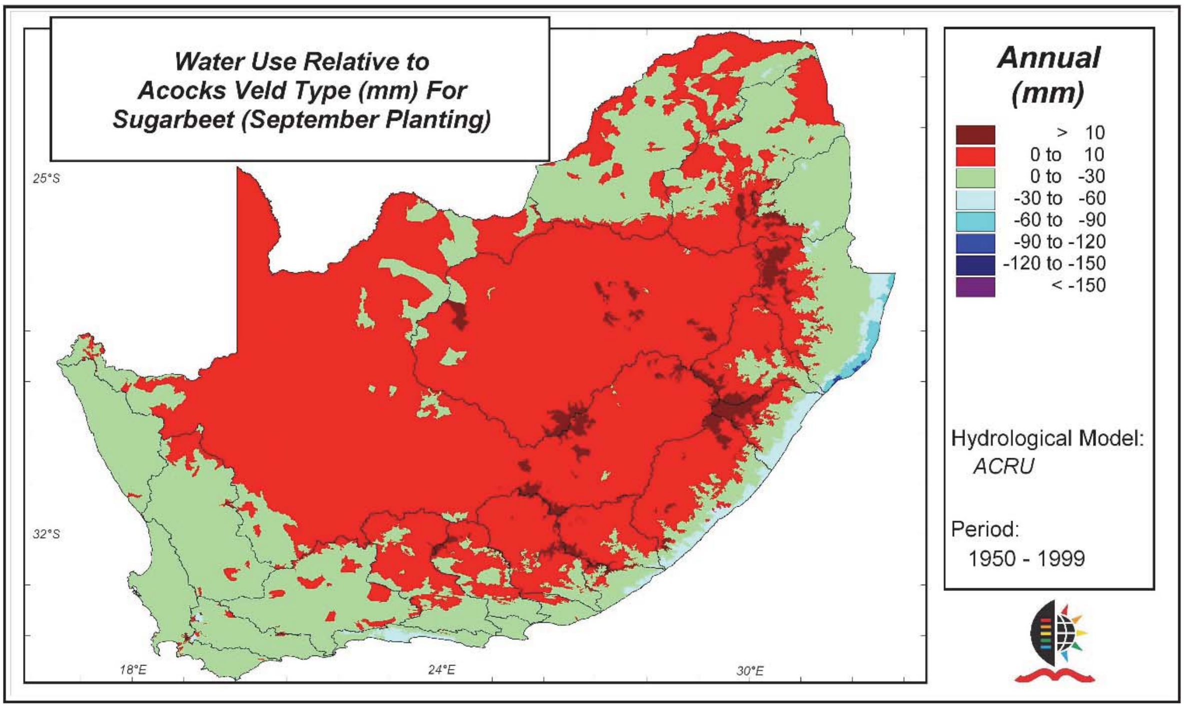
(a)



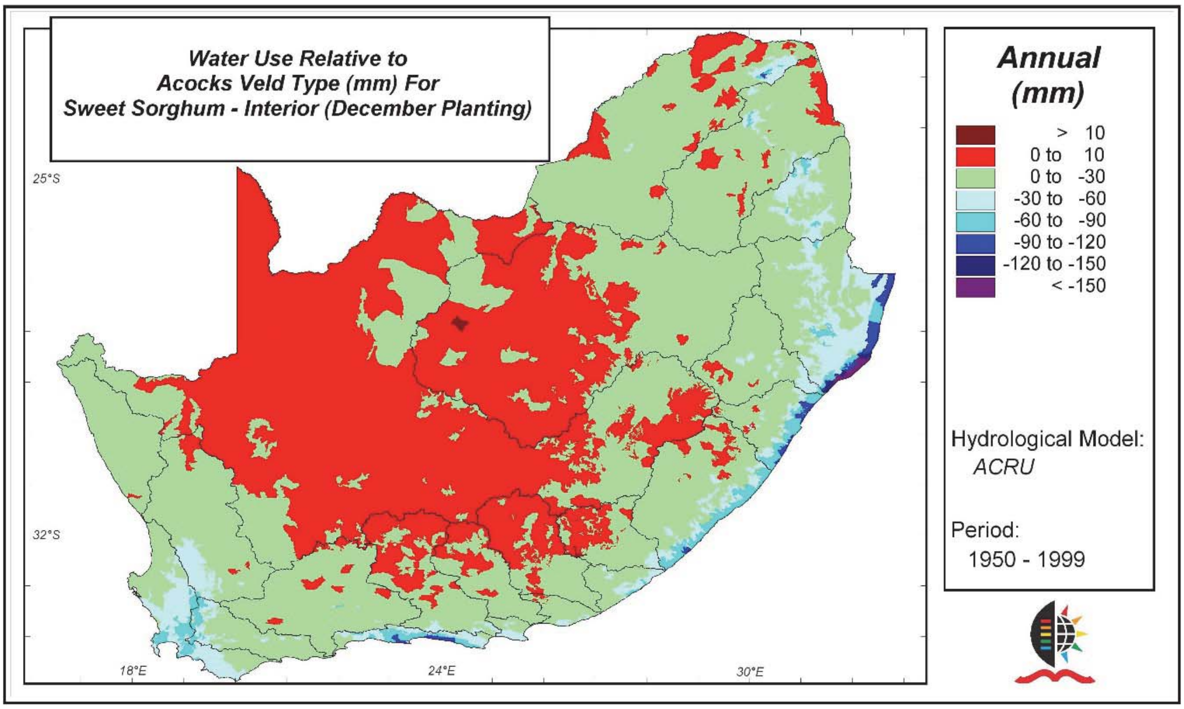
(b)


Water Use Relative to
Acocks Veld Type (mm) For
Sweet Sorghum - Inland (December Planting)
25°S
32°S
18°E
24°E
30°E
Annual
(mm)
> 10
0 to 10
0 to -30
-30 to -60
-60 to -90
-90 to -120
-120 to -150
< -150
Hydrological Model:
ACRU
Period:
1950 - 1999

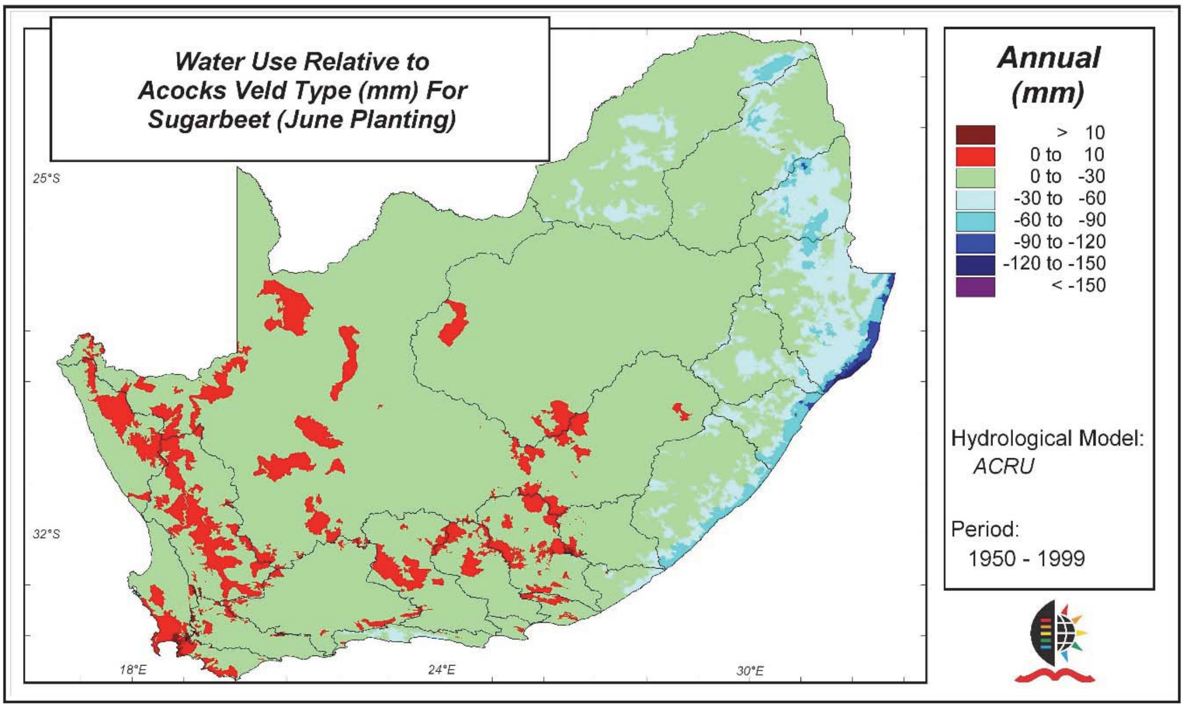
(c)


Water Use Relative to
Acocks Veld Type (mm) For
Sugarbeet (September Planting)
25°S
32°S
18°E
24°E
30°E
Annual
(mm)
> 10
0 to 10
0 to -30
-30 to -60
-60 to -90
-90 to -120
-120 to -150
< -150
Hydrological Model:
ACRU
Period:
1950 - 1999

(d)

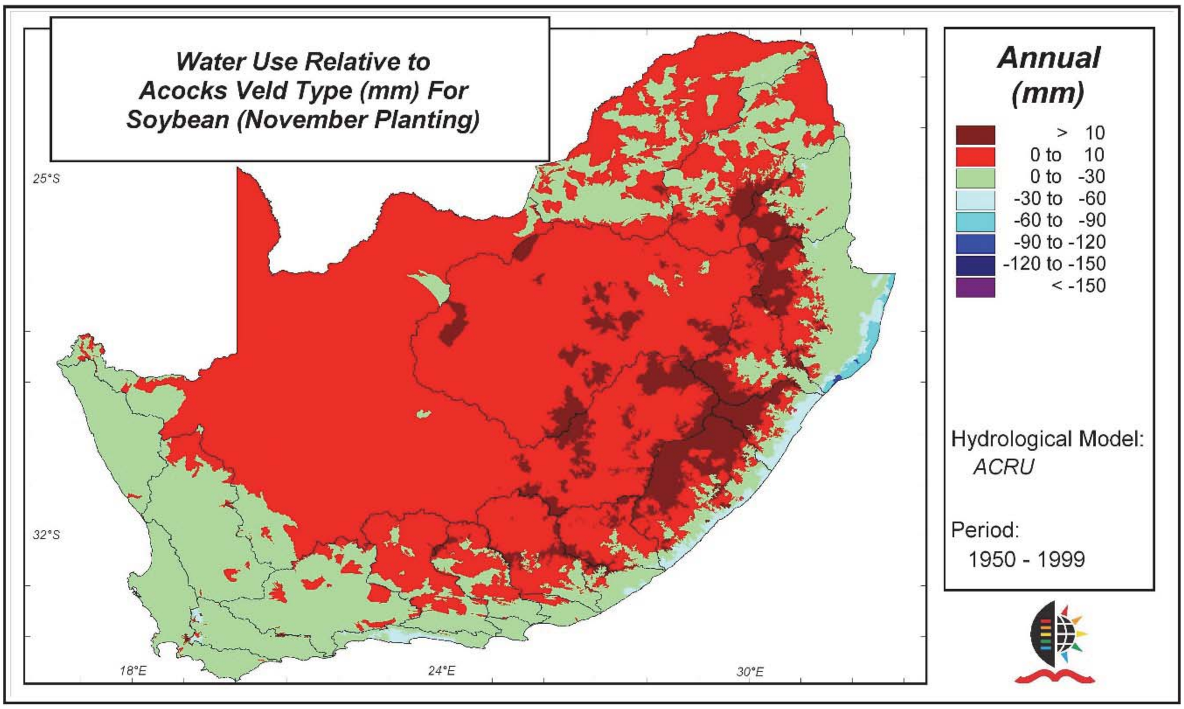


(e)



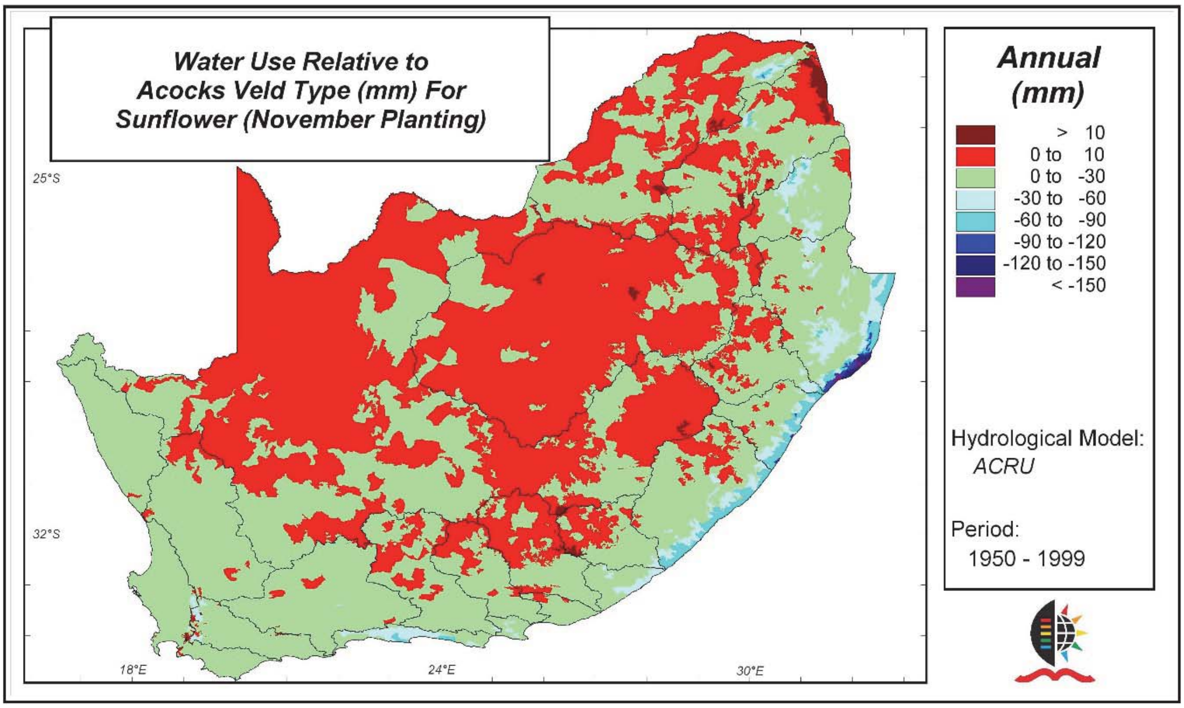
(f)

Figure 72 Water use (expressed in mm) of each bioethanol feedstock relative to the baseline (i.e. MAR_{base} - MAR_{crop})



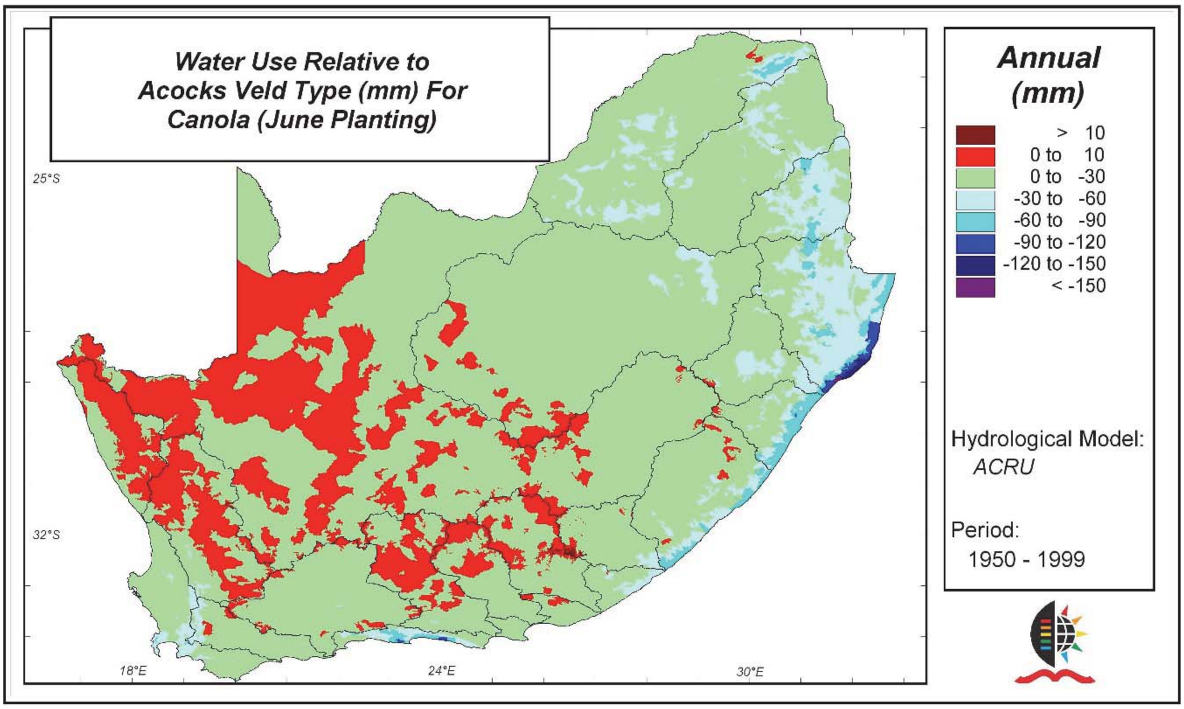
Water Use Relative to
Acocks Veld Type (mm) For
Soybean (November Planting)
Annual
(mm)
> 10
0 to 10
0 to -30
-30 to -60
-60 to -90
-90 to -120
-120 to -150
< -150
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(a)



Water Use Relative to
Acocks Veld Type (mm) For
Sunflower (November Planting)
Annual
(mm)
> 10
0 to 10
0 to -30
-30 to -60
-60 to -90
-90 to -120
-120 to -150
< -150
Hydrological Model:
ACRU
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

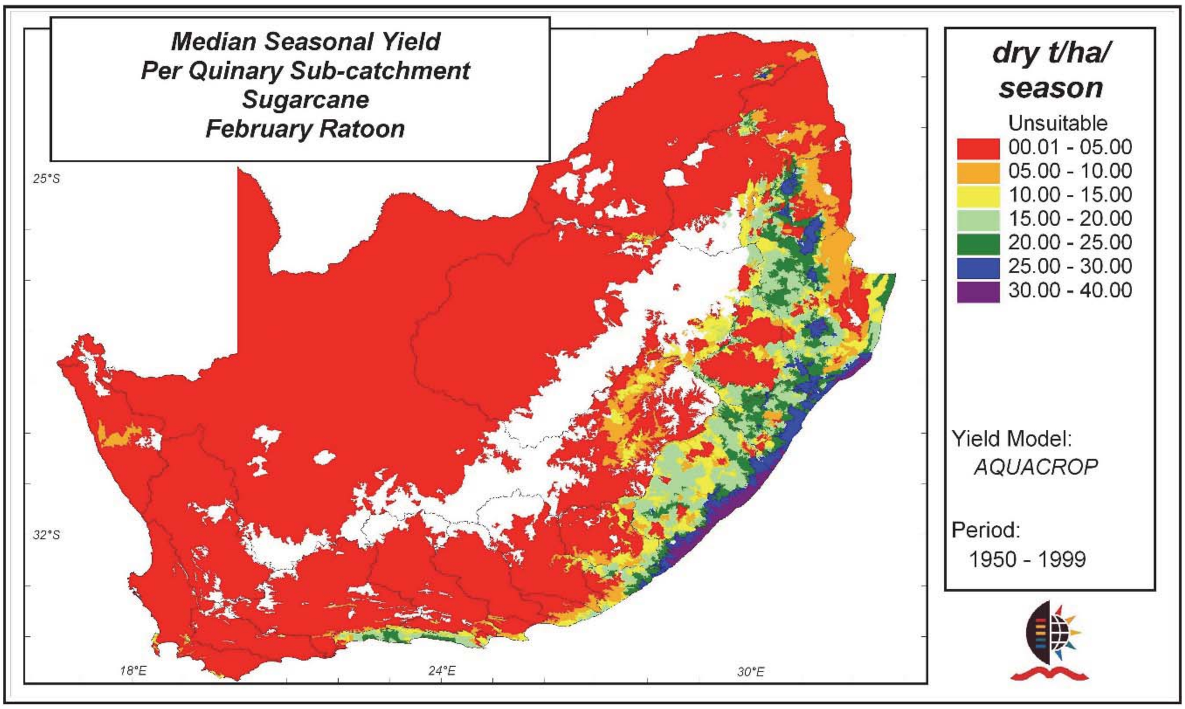
(b)



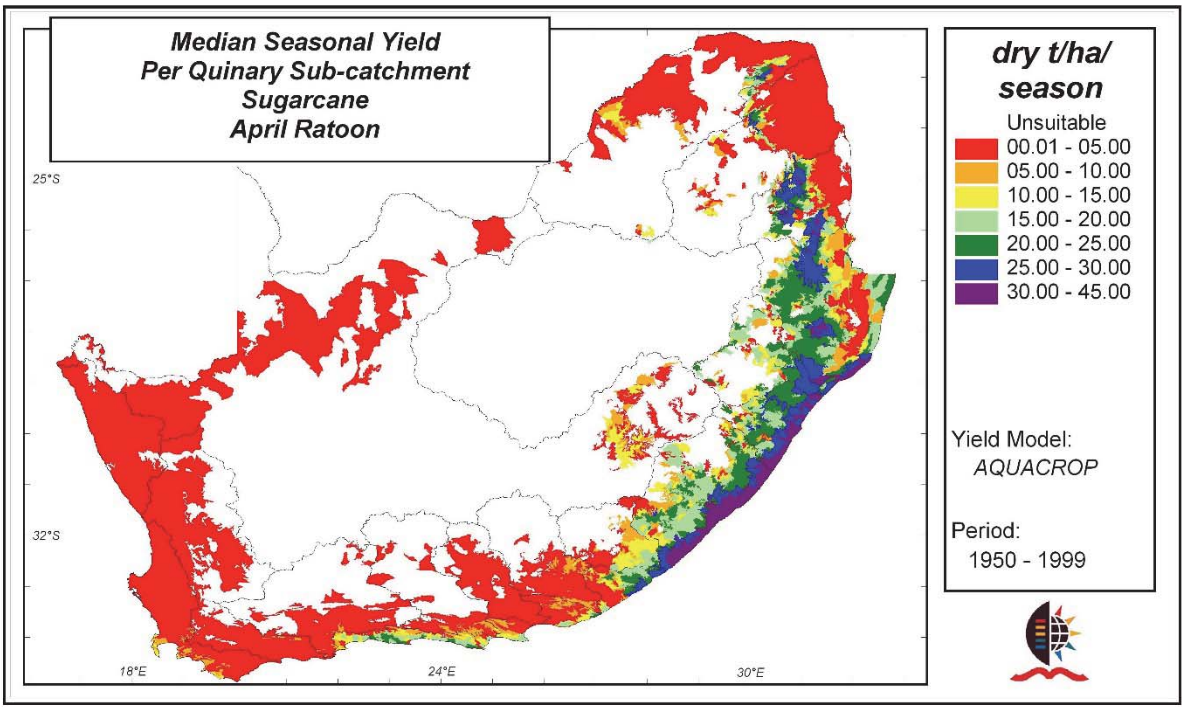
(c)

Figure 73 Water use (expressed in mm) of each biodiesel feedstock relative to the baseline (i.e. MAR_{base} - MAR_{crop})

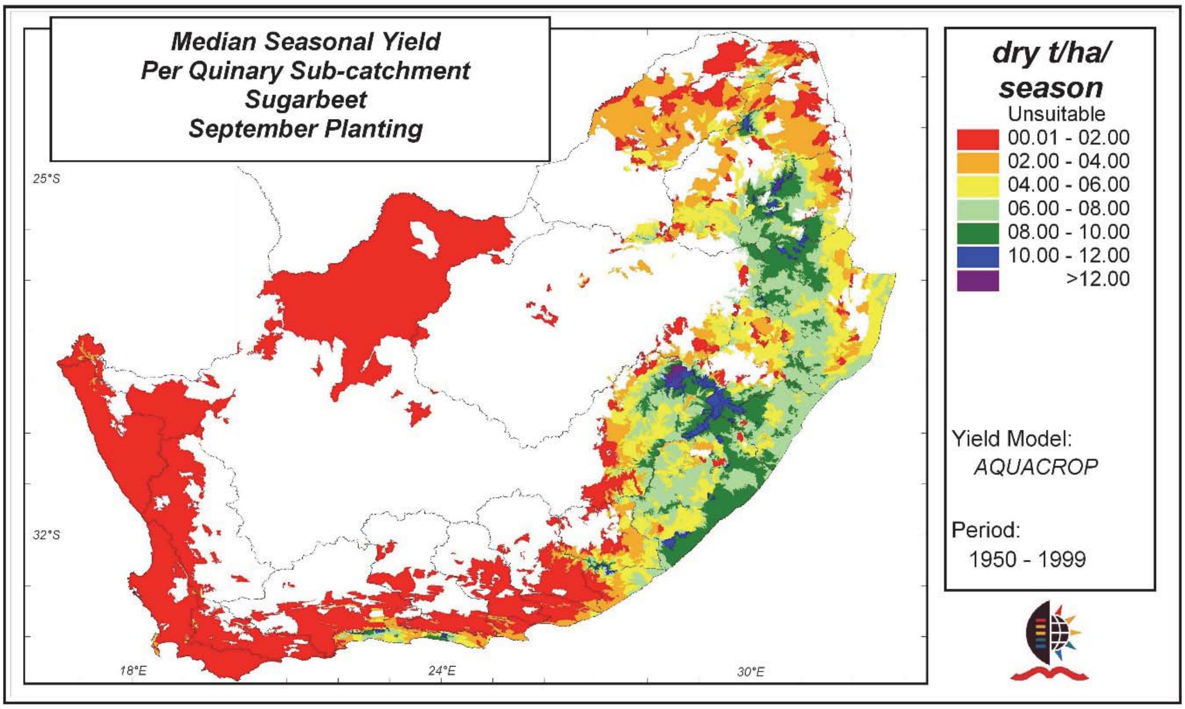
9 APPENDIX B



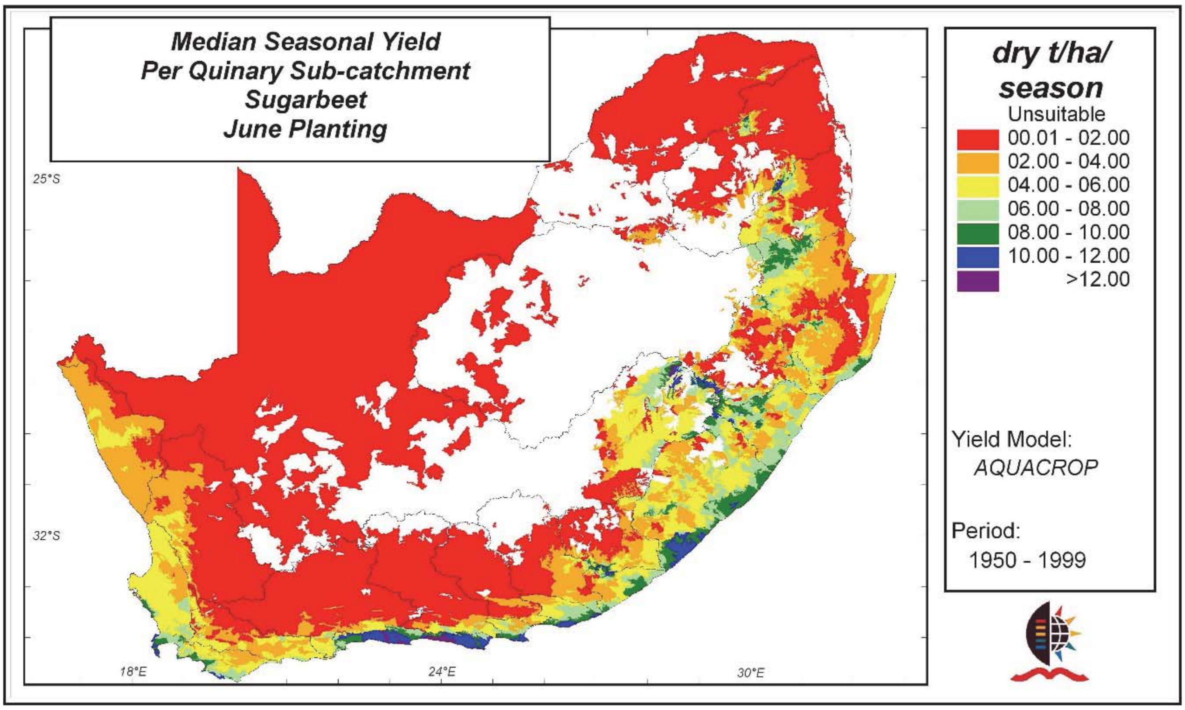
(a)



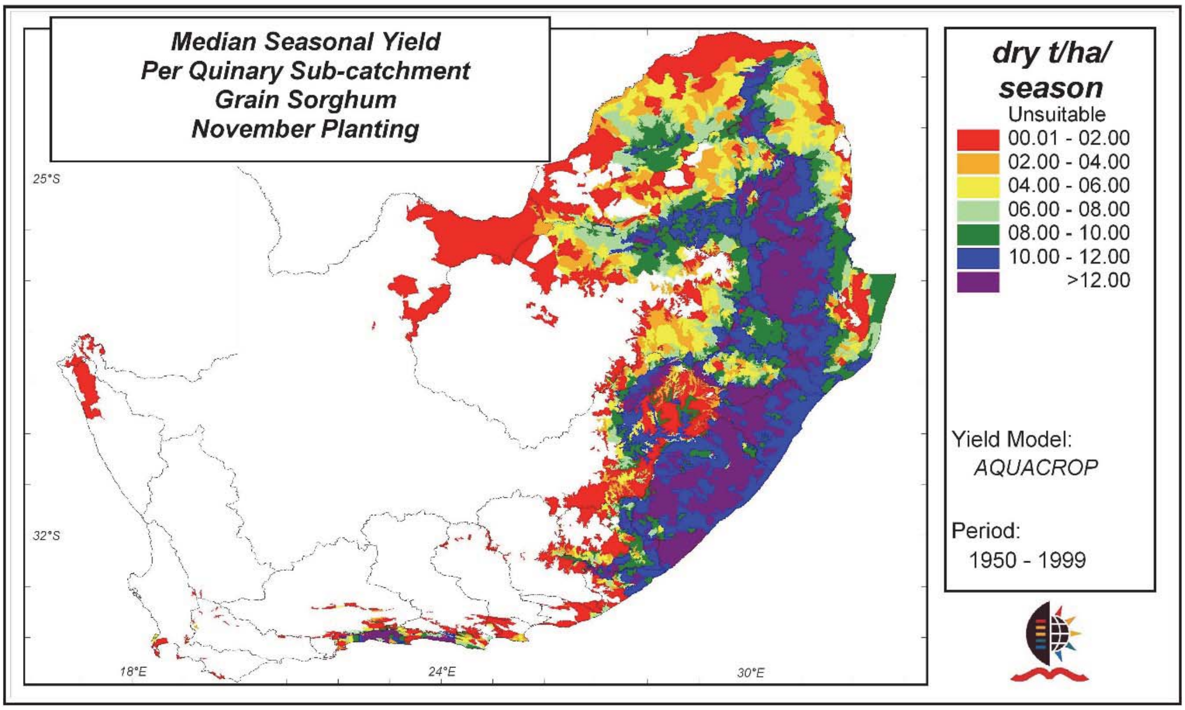
(b)


Median Seasonal Yield
Per Quinary Sub-catchment
Sugarbeet
September Planting
dry t/ha/ season
Unsuitable
00.01 - 02.00
02.00 - 04.00
04.00 - 06.00
06.00 - 08.00
08.00 - 10.00
10.00 - 12.00
>12.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)

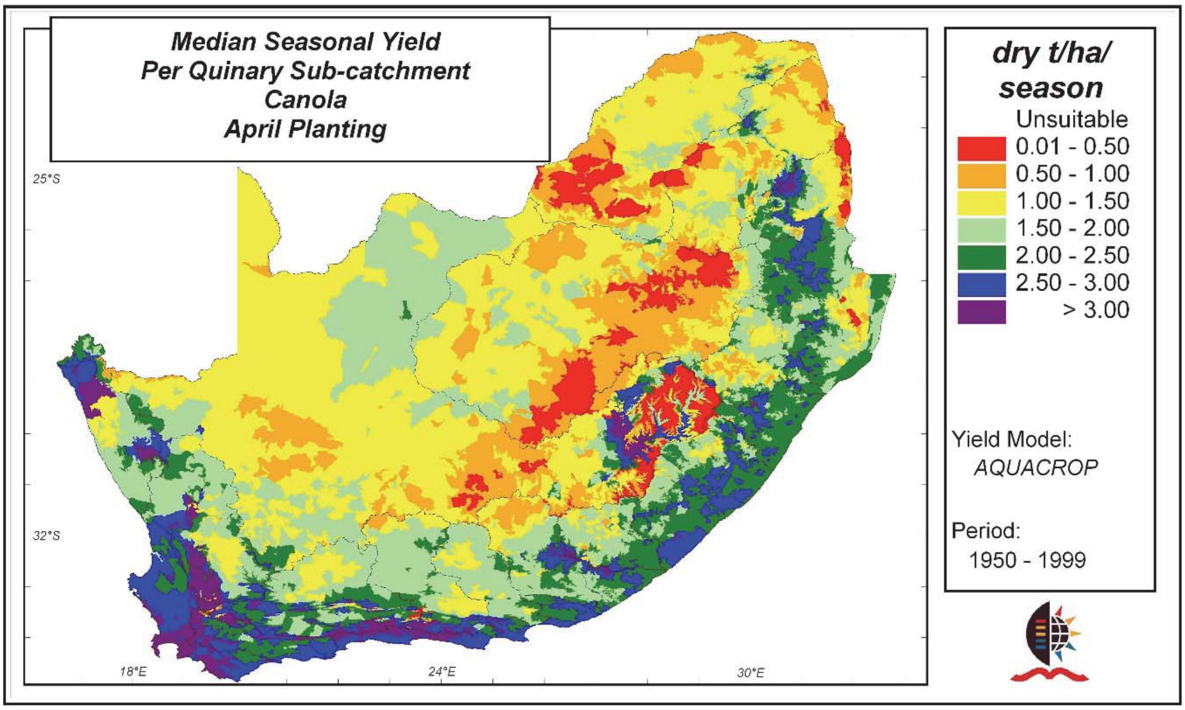

Median Seasonal Yield
Per Quinary Sub-catchment
Sugarbeet
June Planting
dry t/ha/ season
Unsuitable
00.01 - 02.00
02.00 - 04.00
04.00 - 06.00
06.00 - 08.00
08.00 - 10.00
10.00 - 12.00
>12.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

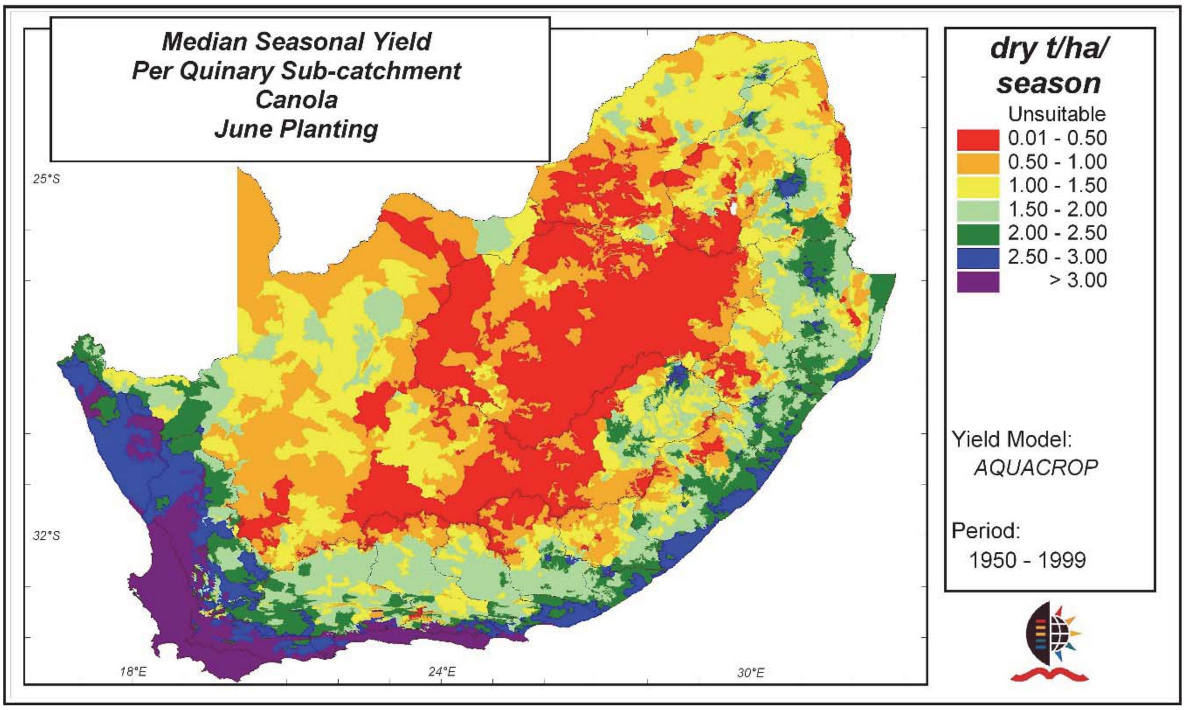


(e)

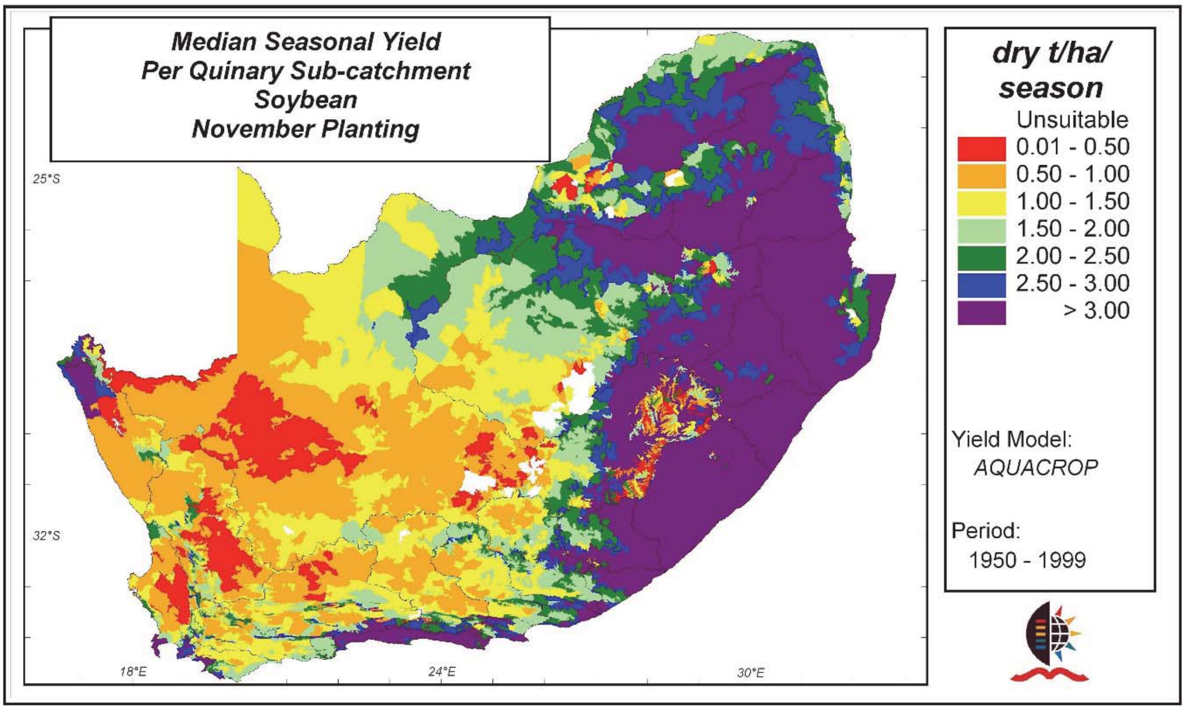
Figure 74 Median seasonal yield (dry t ha^{-1}) estimated using *AQUACROP* for selected bioethanol feedstocks (a-e) planted on different dates



(a)



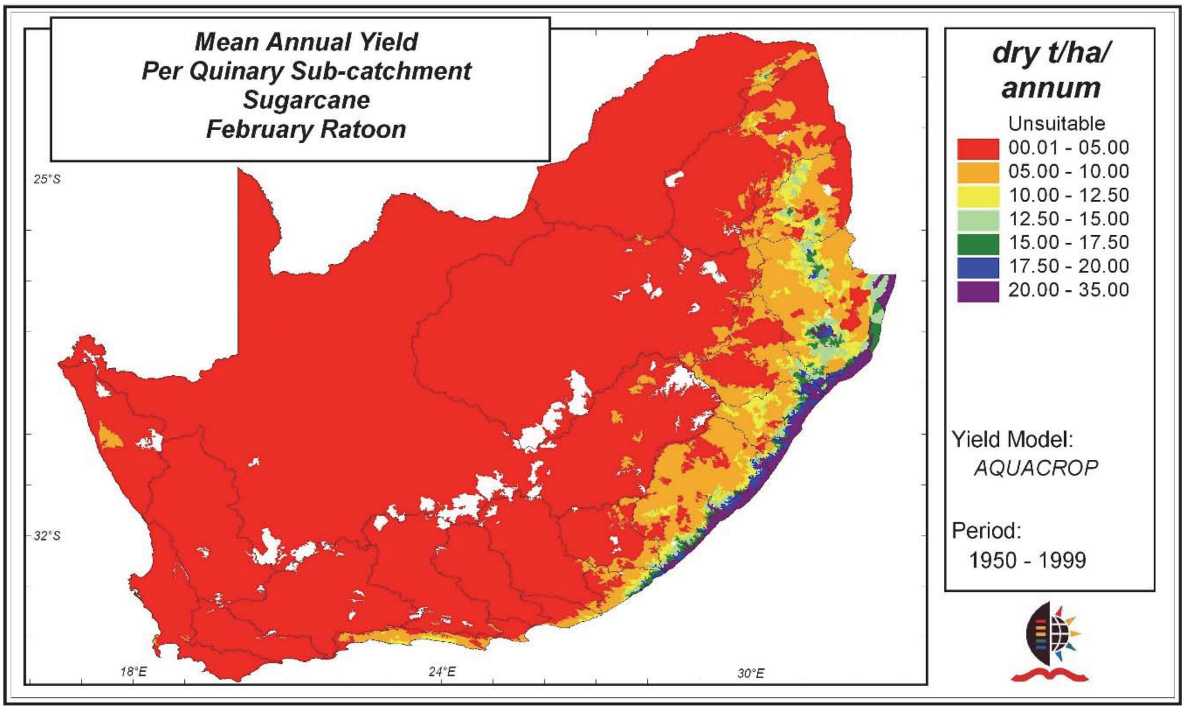
(b)



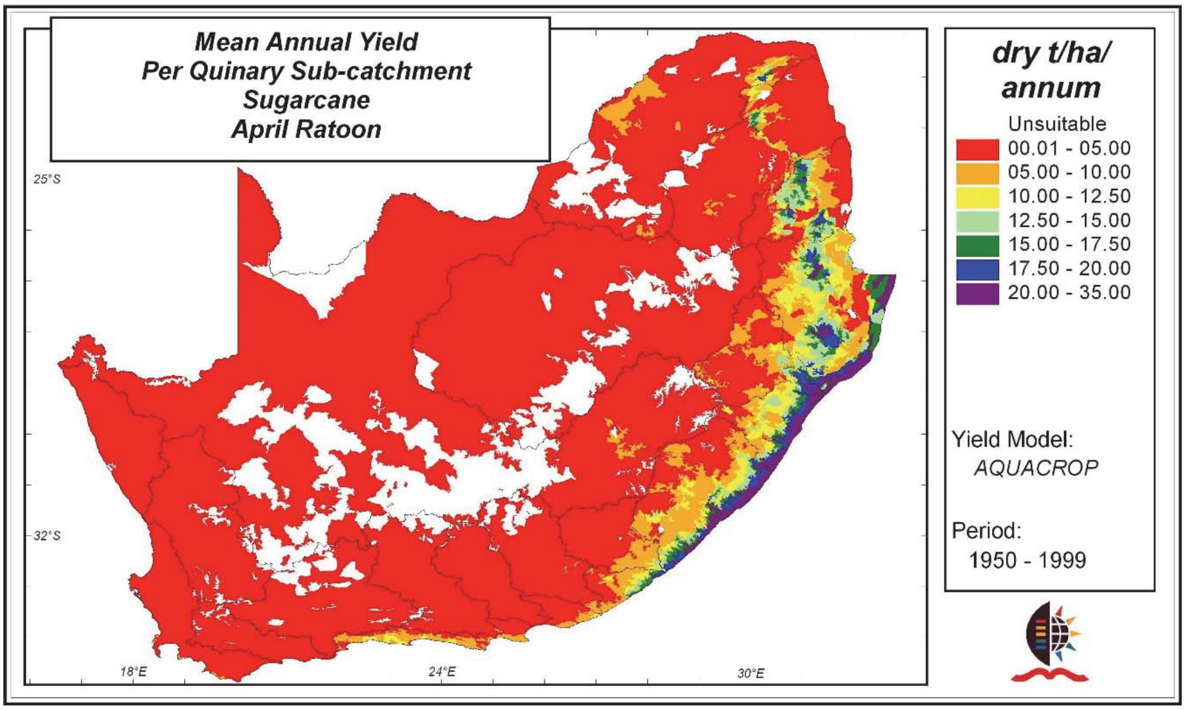
(c)

Figure 75 Median seasonal yield (dry t ha^{-1}) estimated using *AQUACROP* for selected biodiesel feedstocks (a-c) planted on different dates

10 APPENDIX C



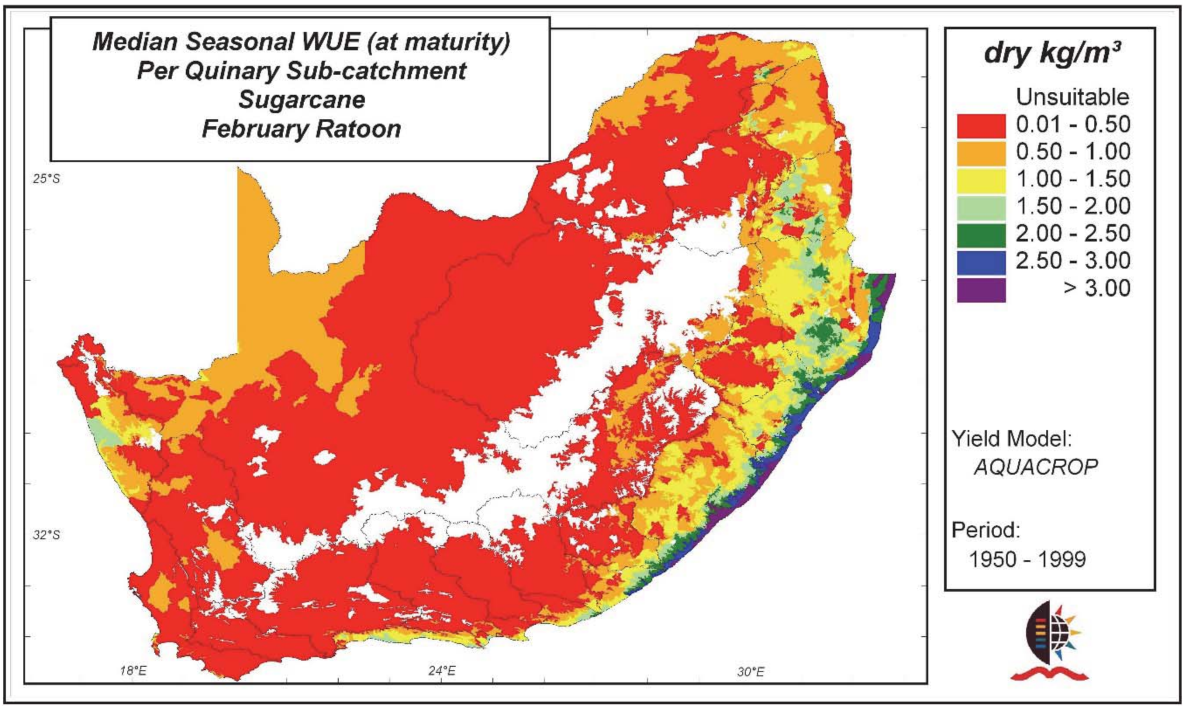
(a)



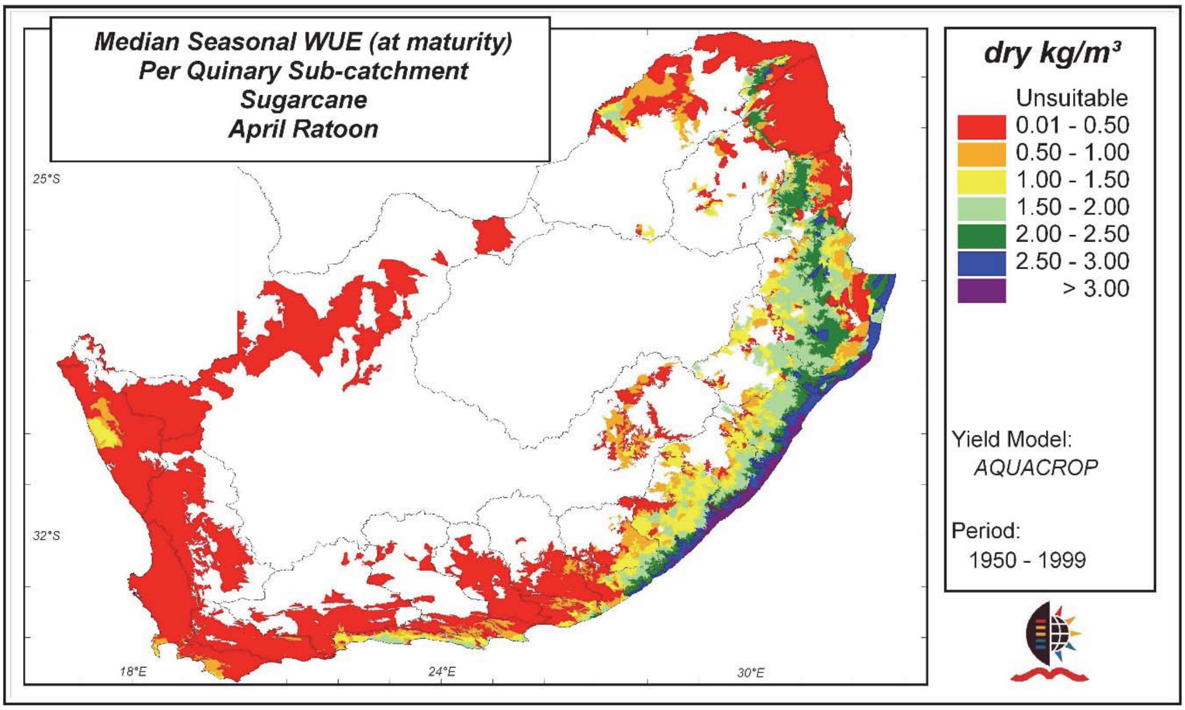
(b)

Figure 76 Mean annual sugarcane yield (dry t ha^{-1}) for sugarcane transplanted in February (a) and April (b)

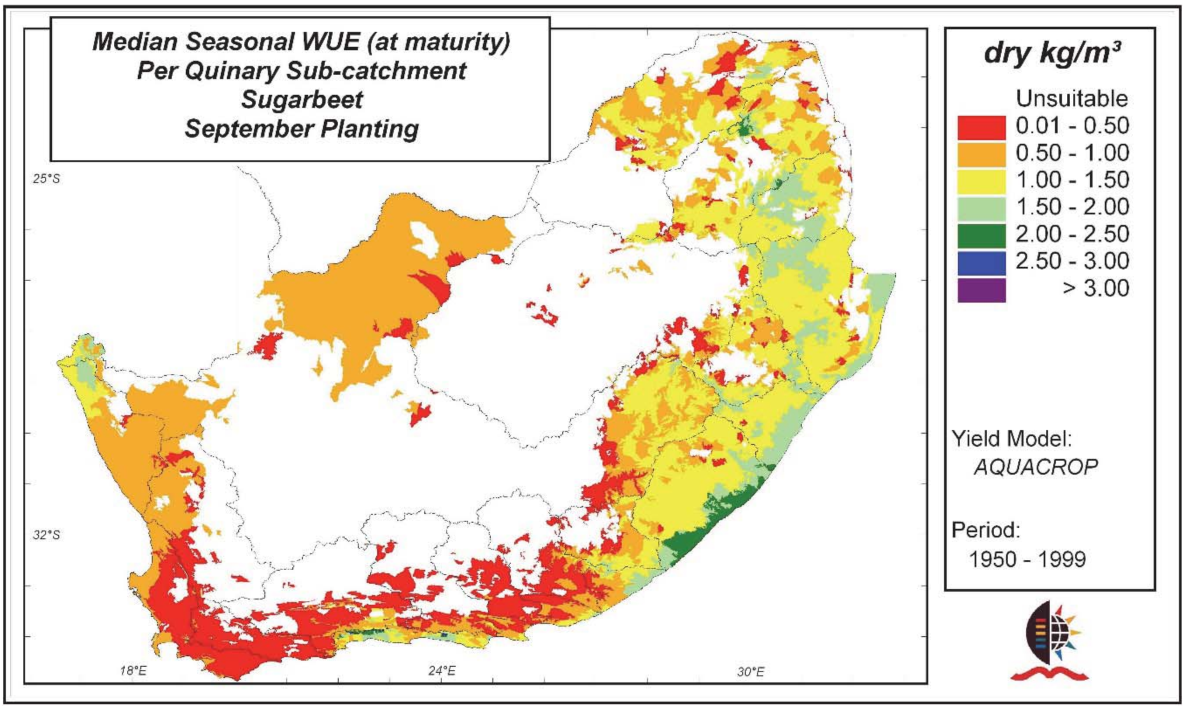
11 APPENDIX D



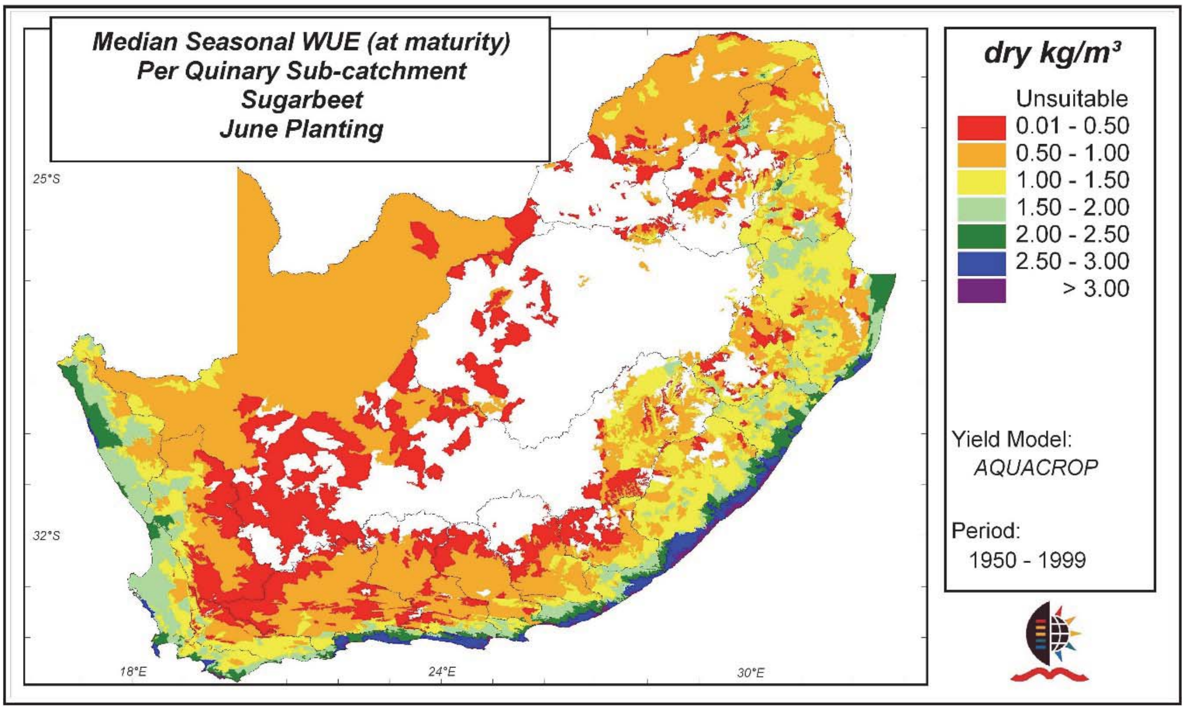
(a)



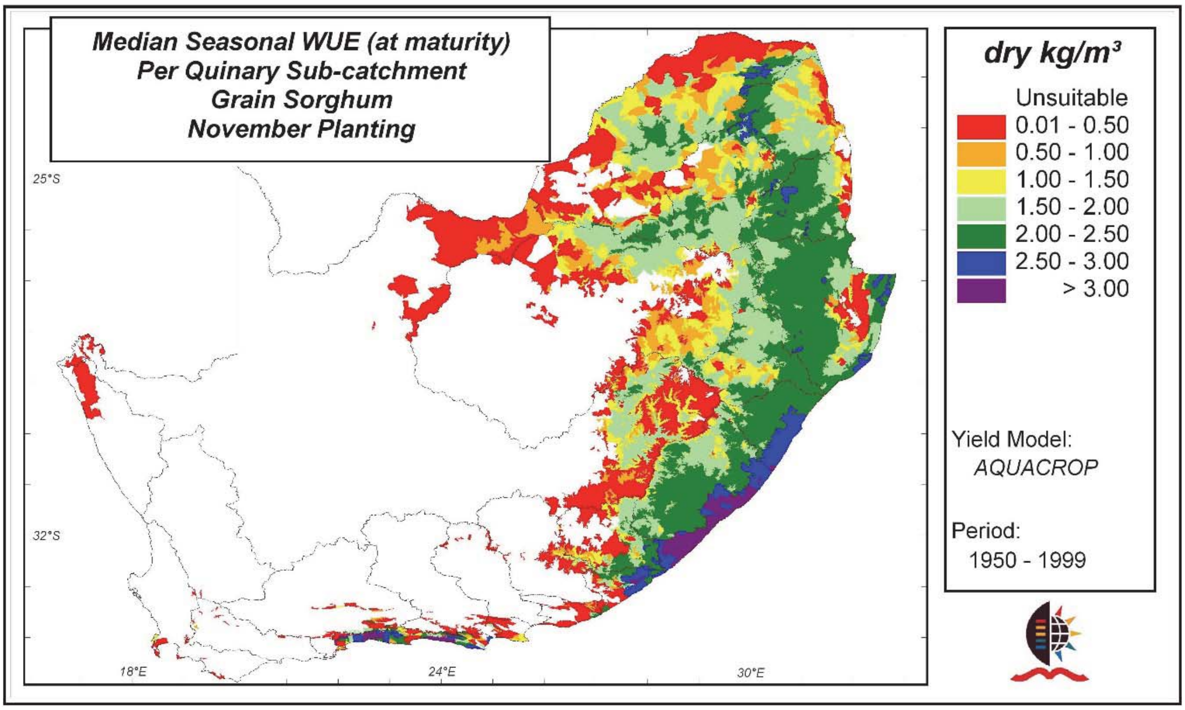
(b)


Median Seasonal WUE (at maturity)
Per Quinary Sub-catchment
Sugarbeet
September Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)

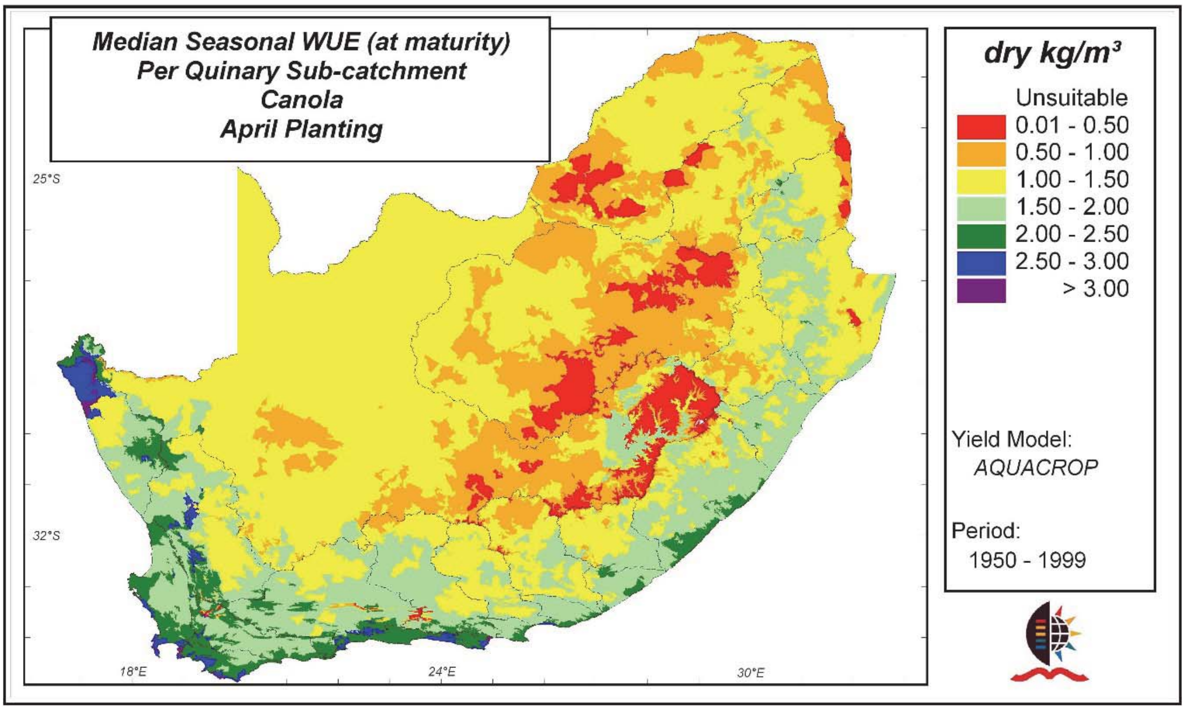

Median Seasonal WUE (at maturity)
Per Quinary Sub-catchment
Sugarbeet
June Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

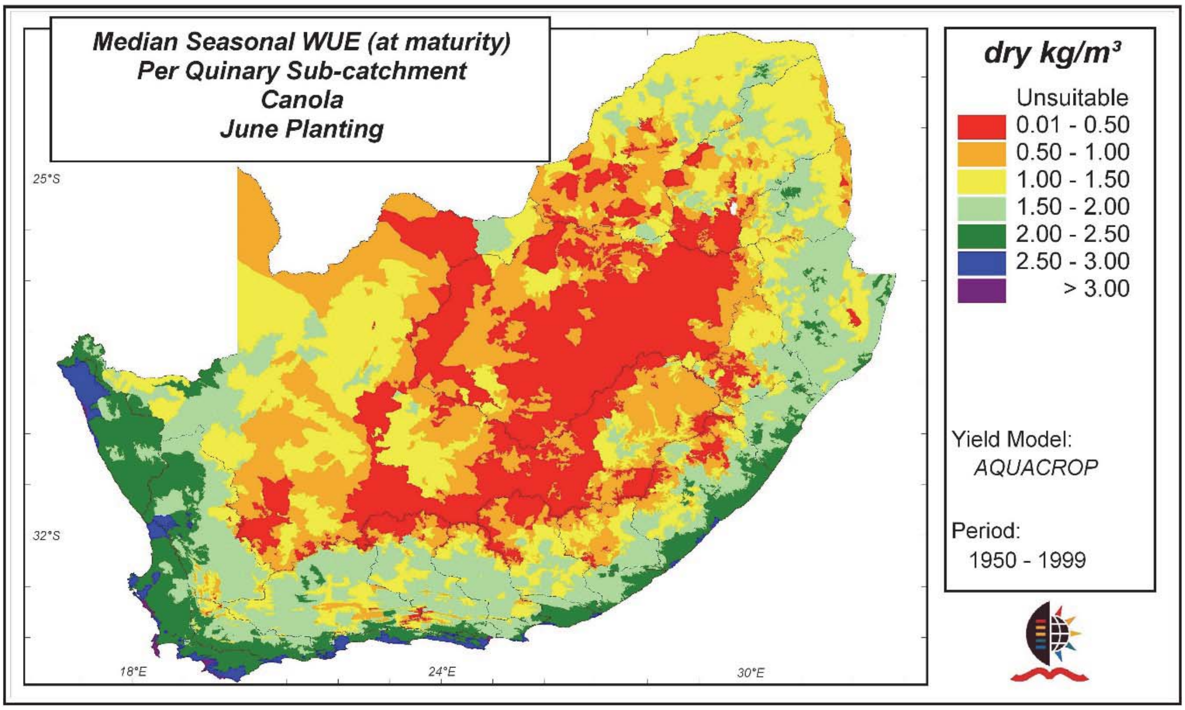


(e)

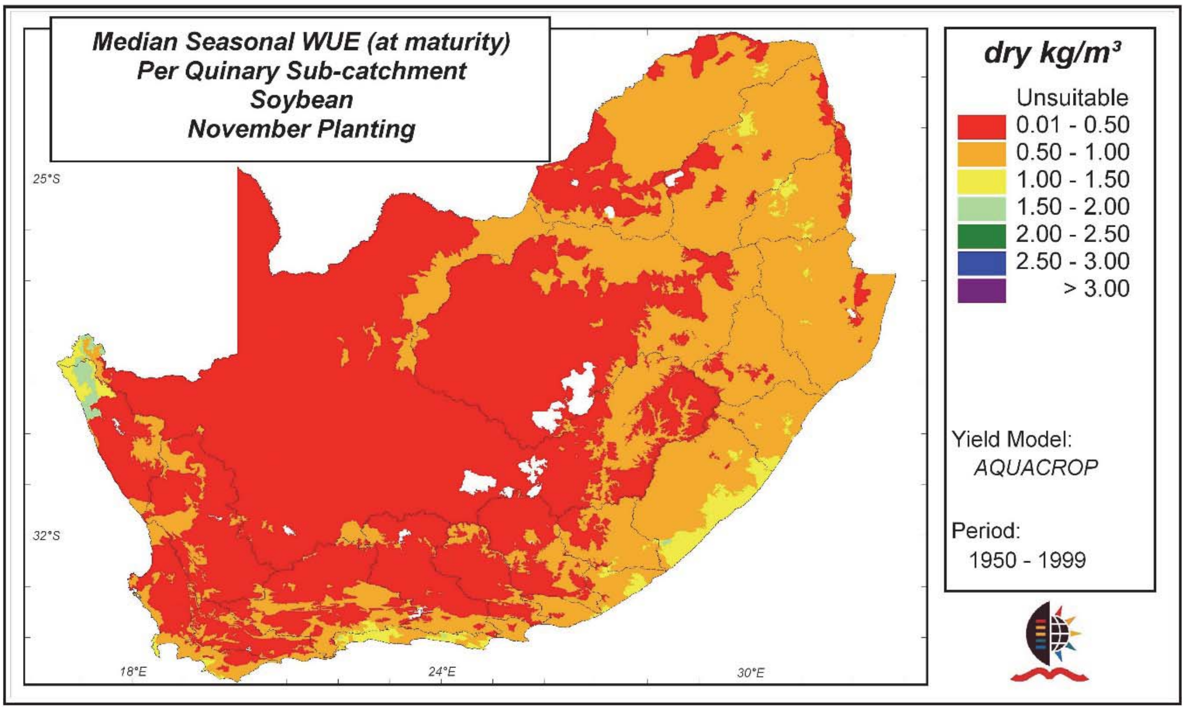
Figure 77 Median seasonal WUE (dry kg m^{-3}) calculated at maturity for selected bioethanol feedstocks (a-e) planted on different dates



(a)



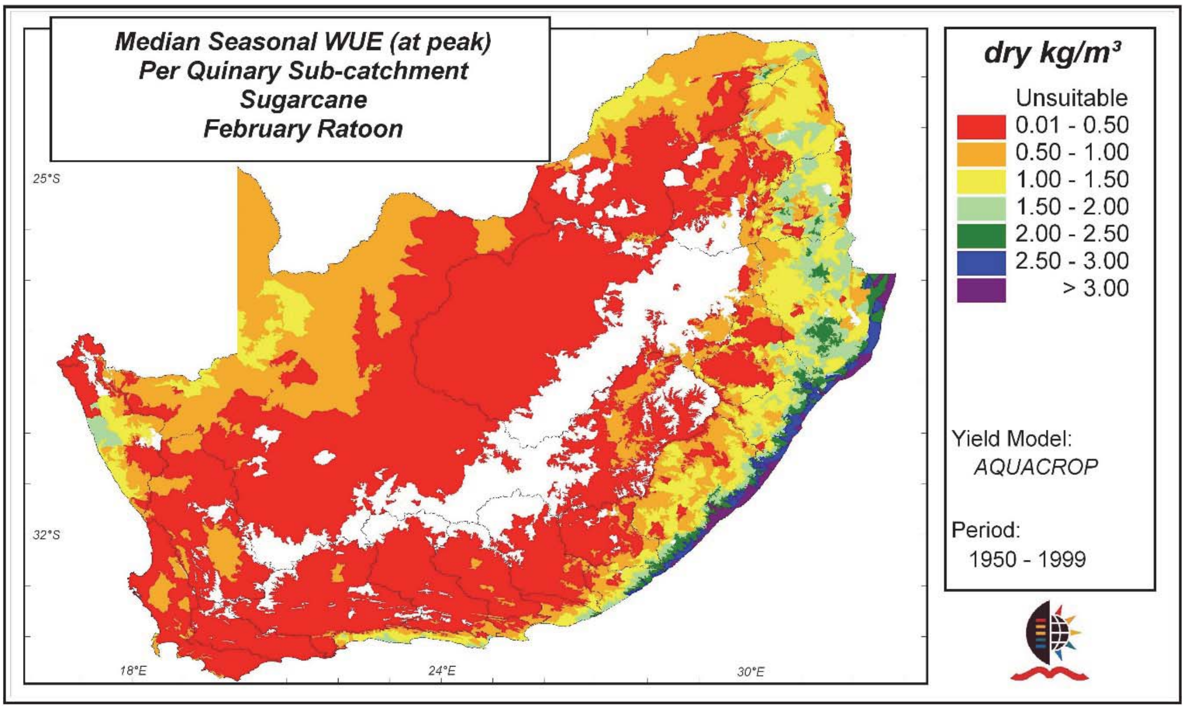
(b)



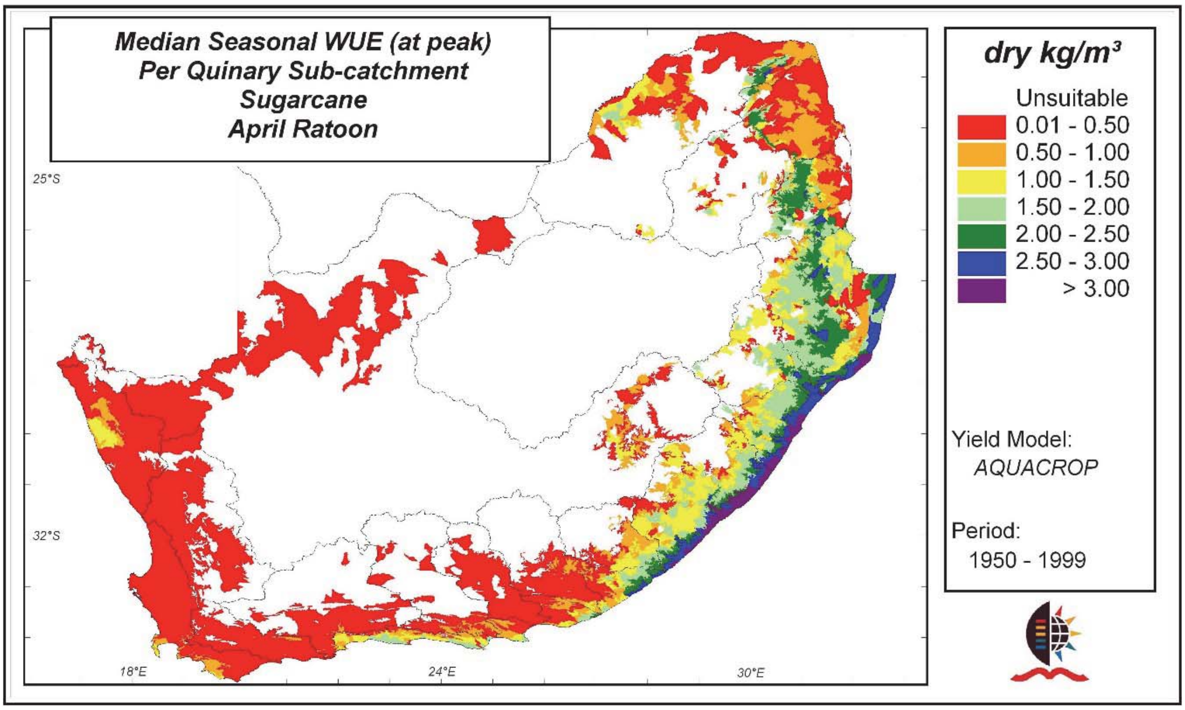
(c)

Figure 78 Median seasonal WUE (dry kg m^{-3}) calculated at maturity for selected biodiesel feedstocks (a-c) planted on different dates

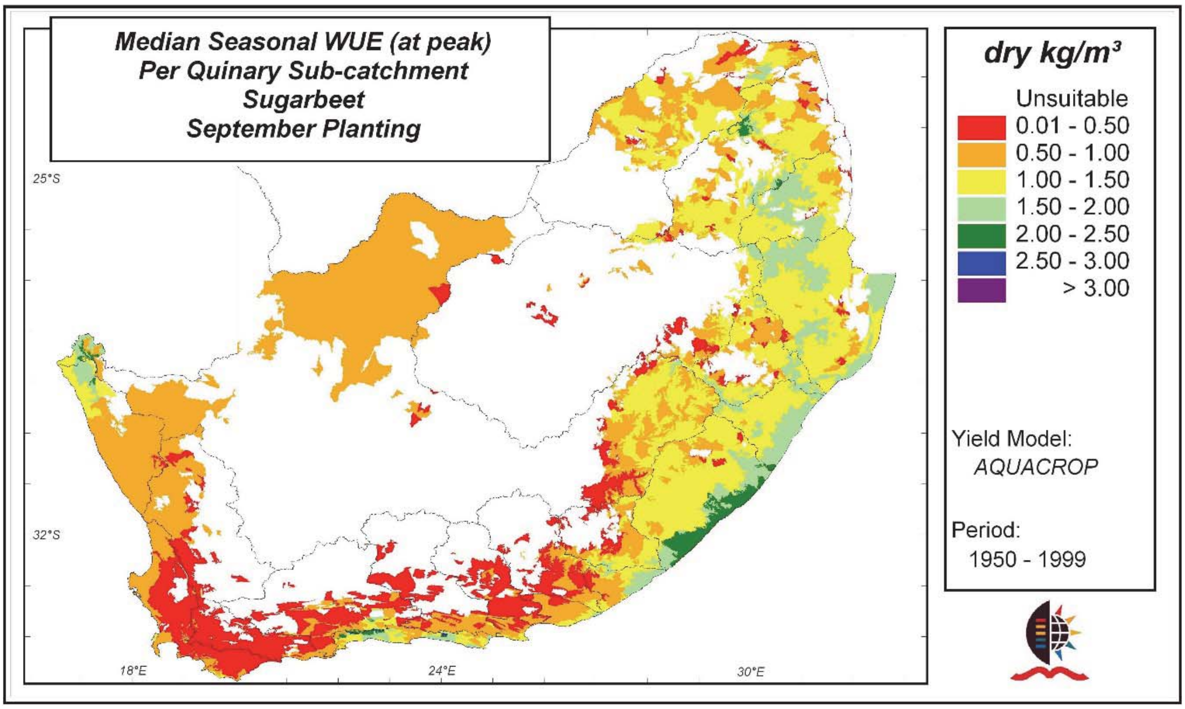
12 APPENDIX E



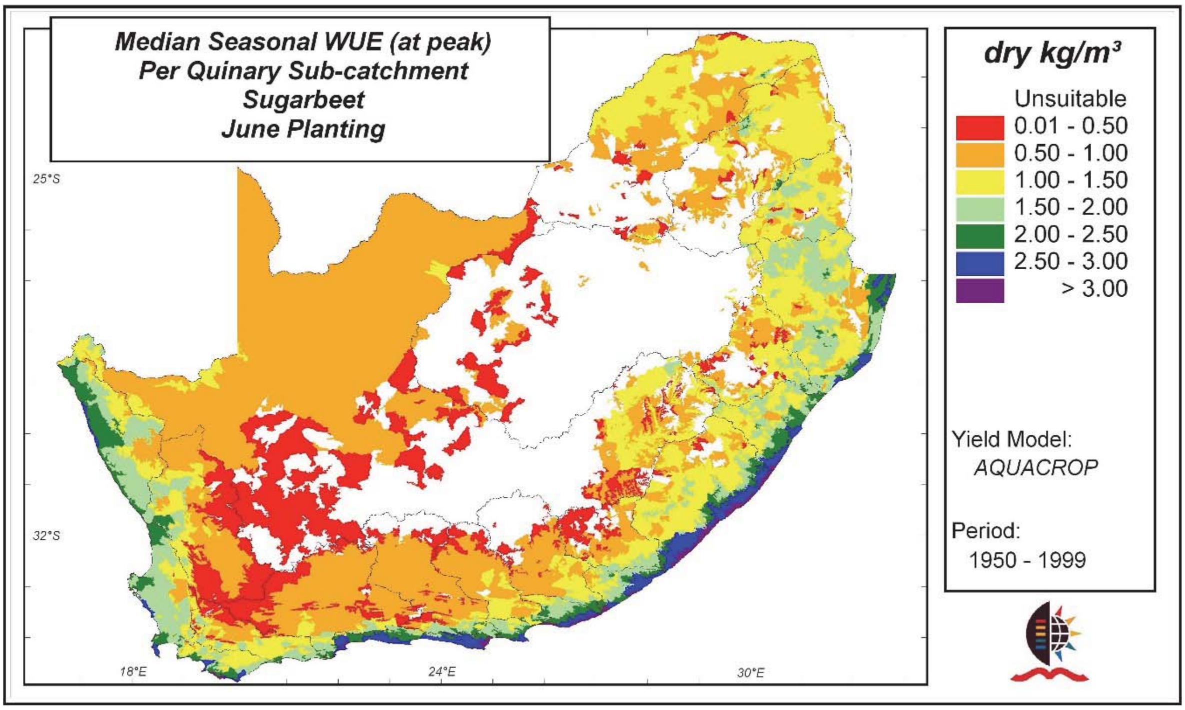
(a)



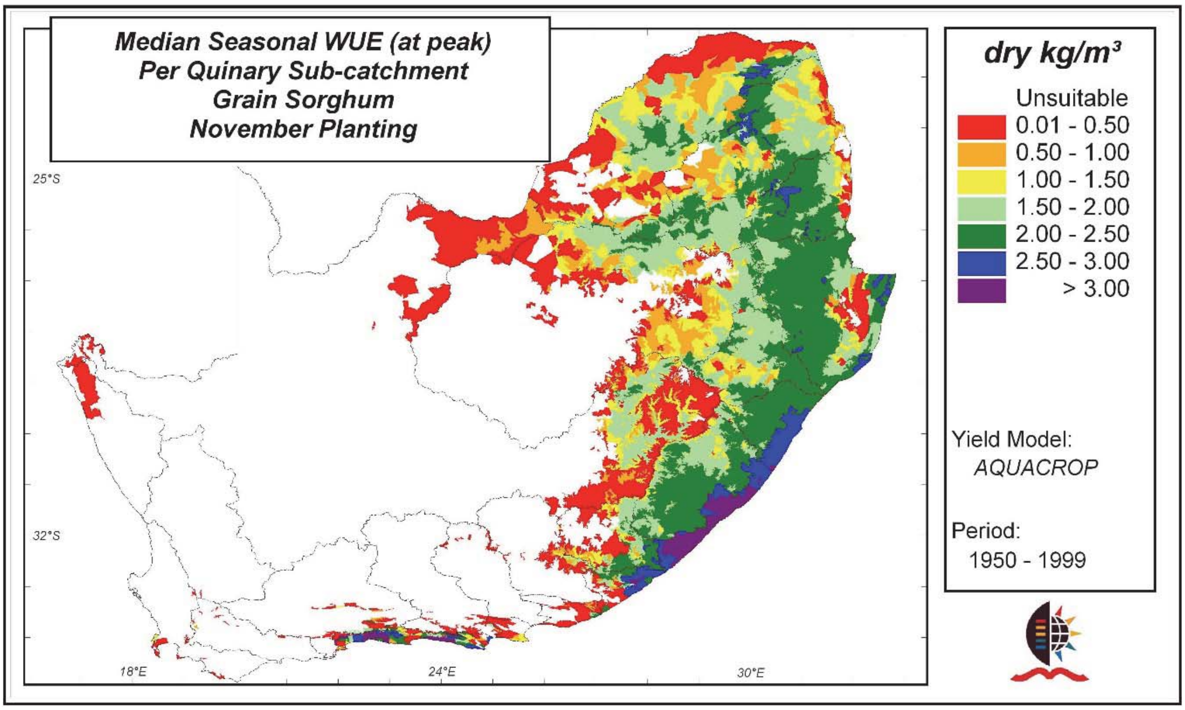
(b)


Median Seasonal WUE (at peak)
Per Quinary Sub-catchment
Sugarbeet
September Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)

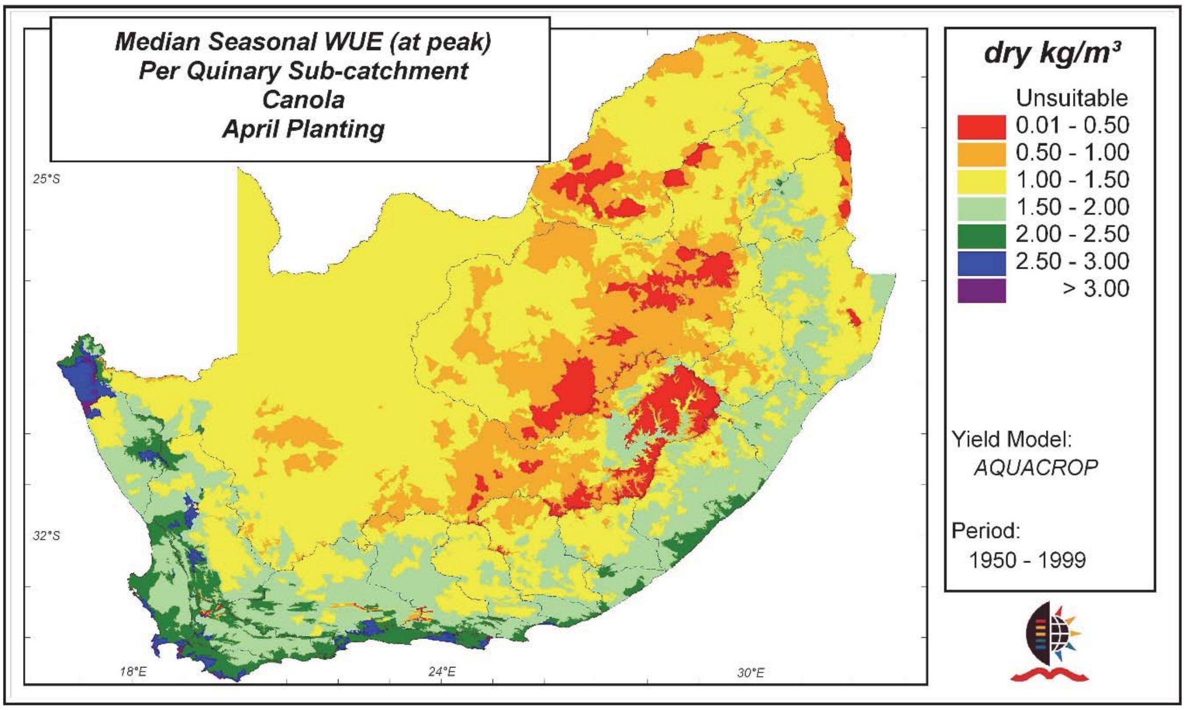

Median Seasonal WUE (at peak)
Per Quinary Sub-catchment
Sugarbeet
June Planting
dry kg/m³
Unsuitable
0.01 - 0.50
0.50 - 1.00
1.00 - 1.50
1.50 - 2.00
2.00 - 2.50
2.50 - 3.00
> 3.00
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

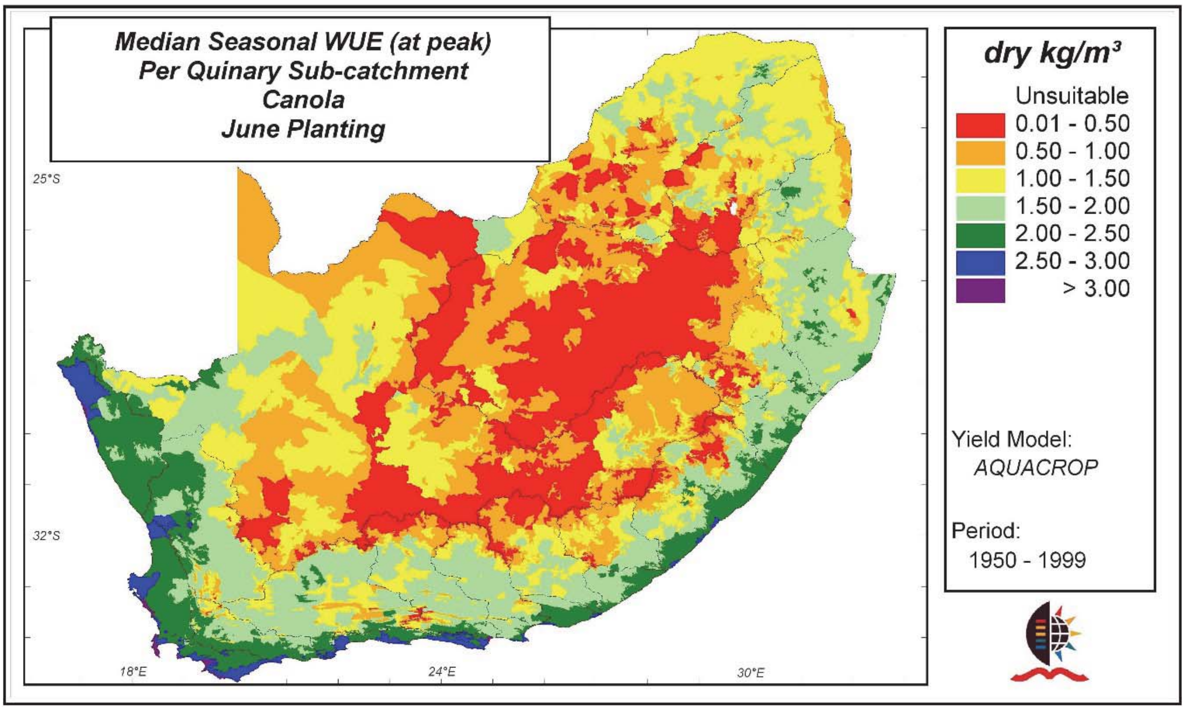


(e)

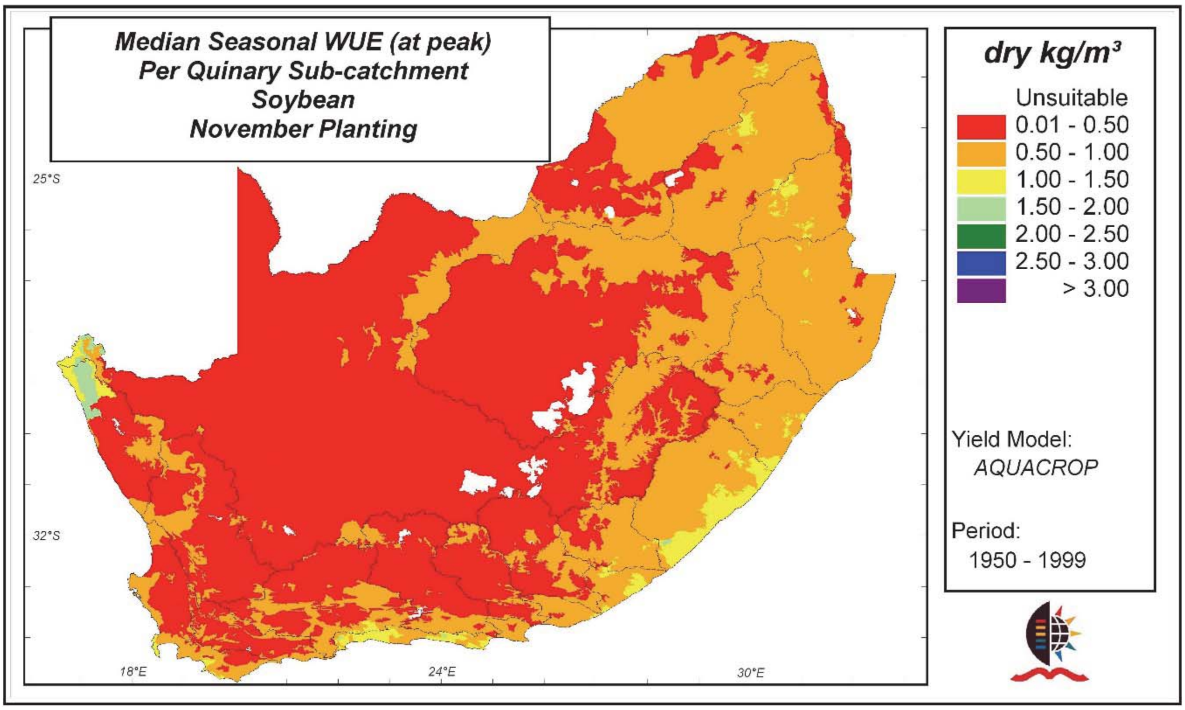
Figure 79 Median seasonal WUE (dry kg m^{-3}) calculated by *AQUACROP* (peak) for selected bioethanol feedstocks (a-e) planted on different dates



(a)



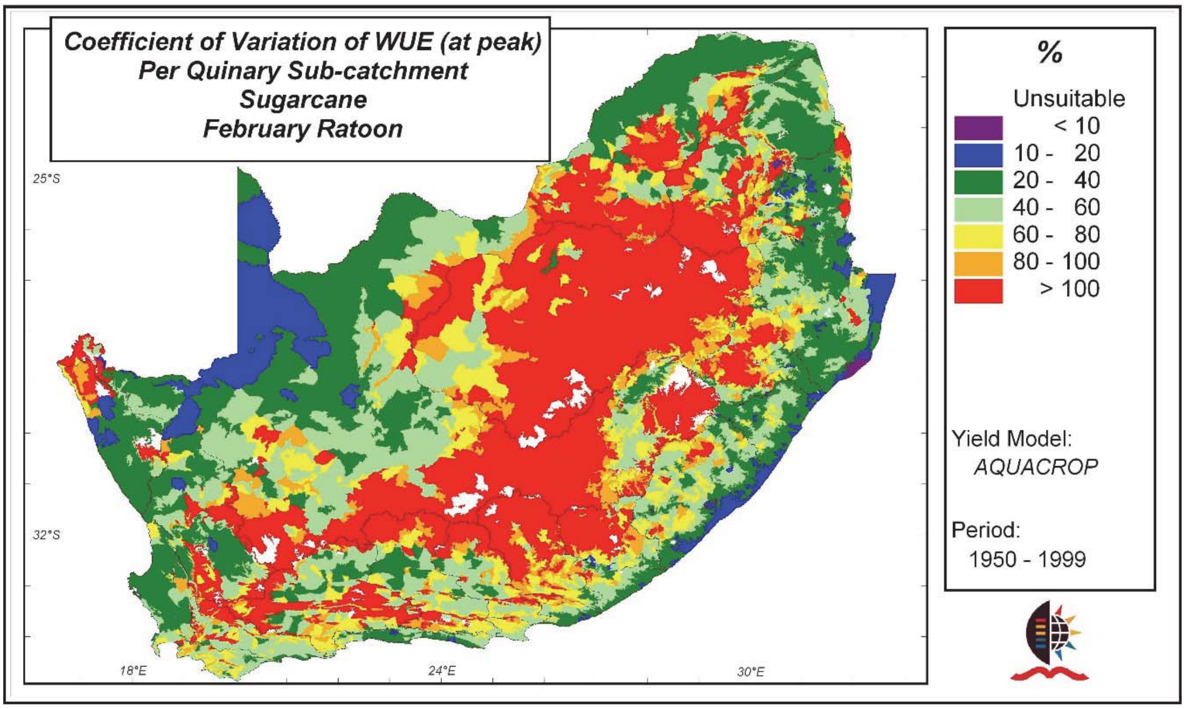
(b)



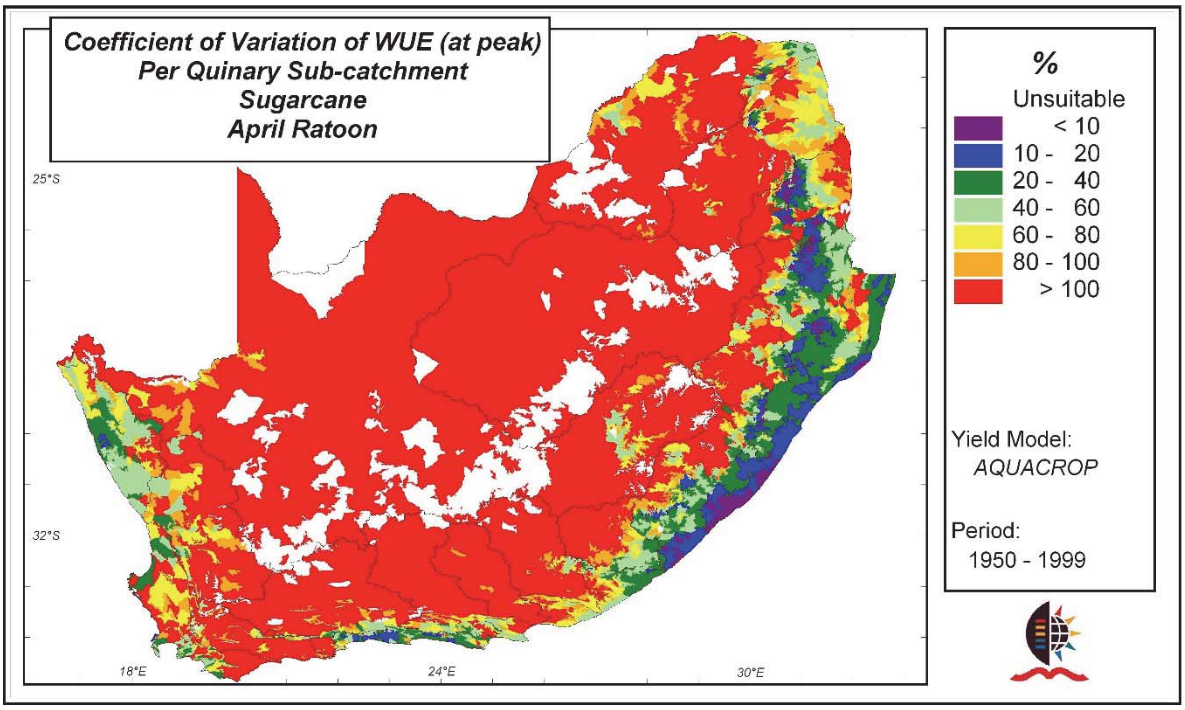
(c)

Figure 80 Median seasonal WUE (dry kg m^{-3}) calculated by *AQUACROP* (peak) for selected biodiesel feedstocks (a-c) planted on different dates

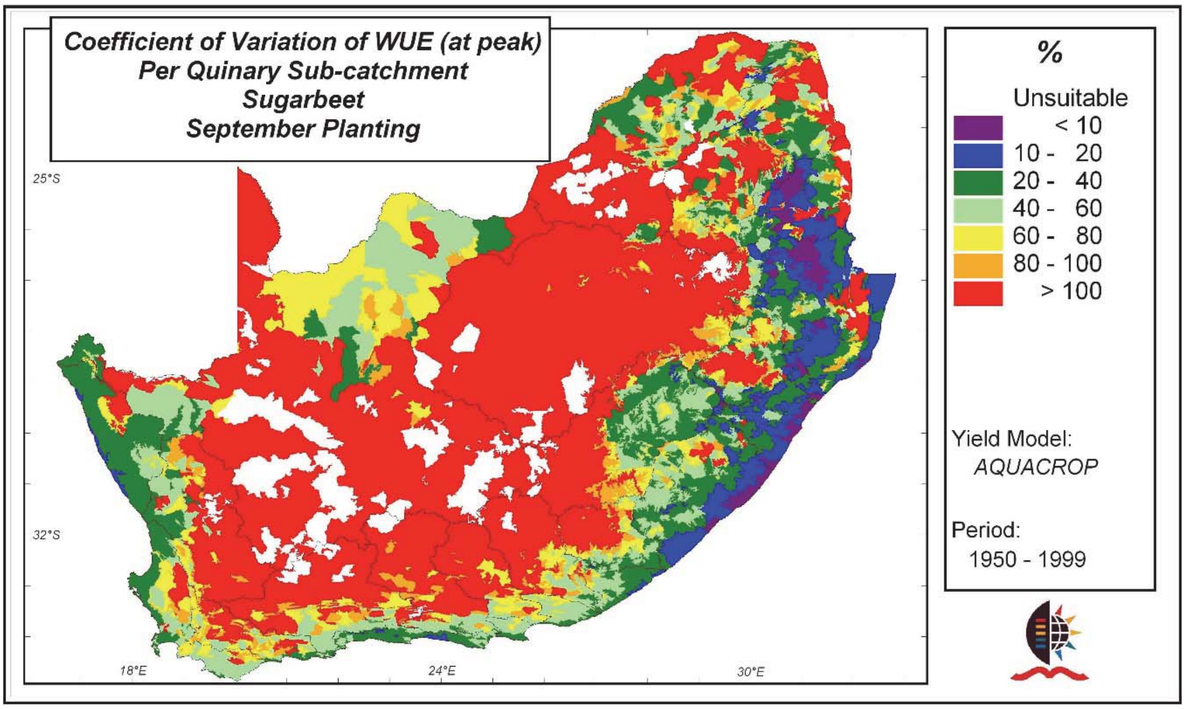
13 APPENDIX F



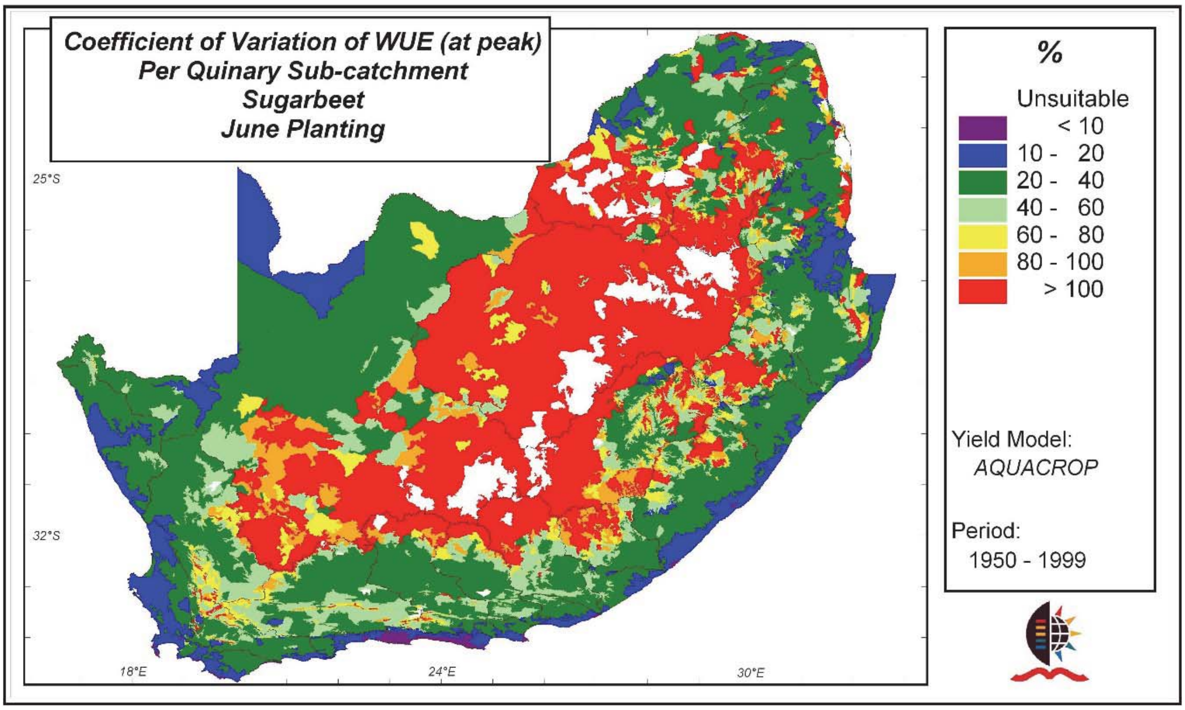
(a)



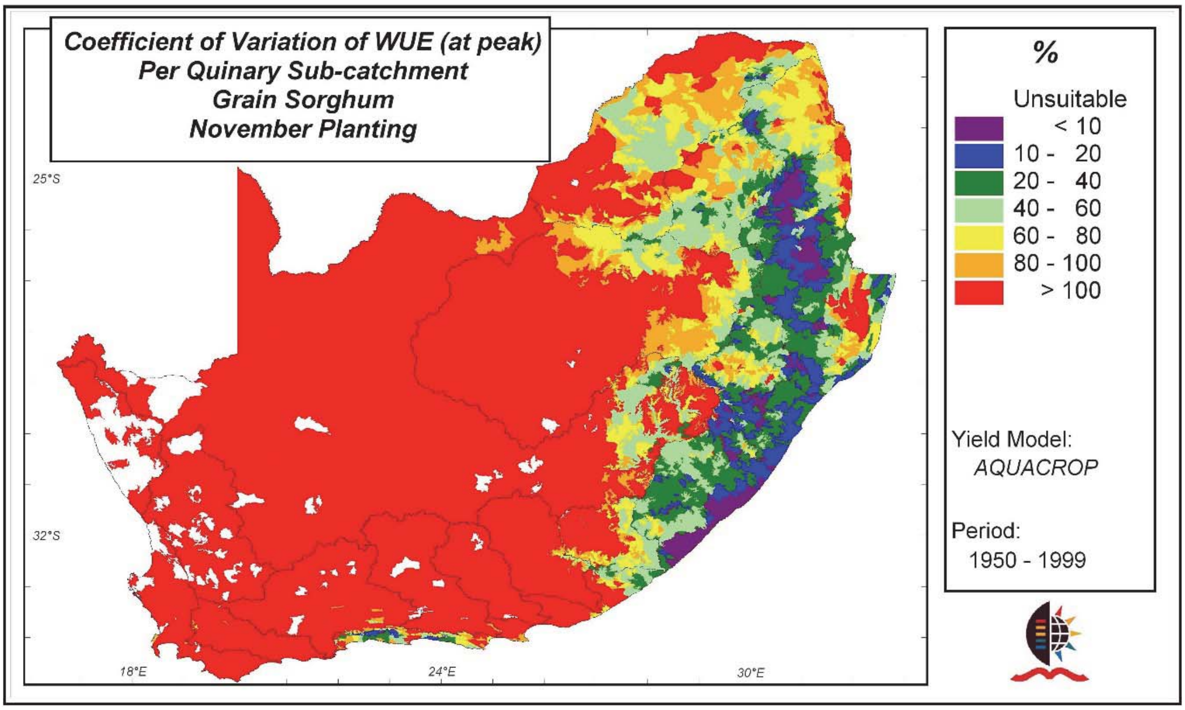
(b)


Coefficient of Variation of WUE (at peak)
Per Quinary Sub-catchment
Sugarbeet
September Planting
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999

(c)

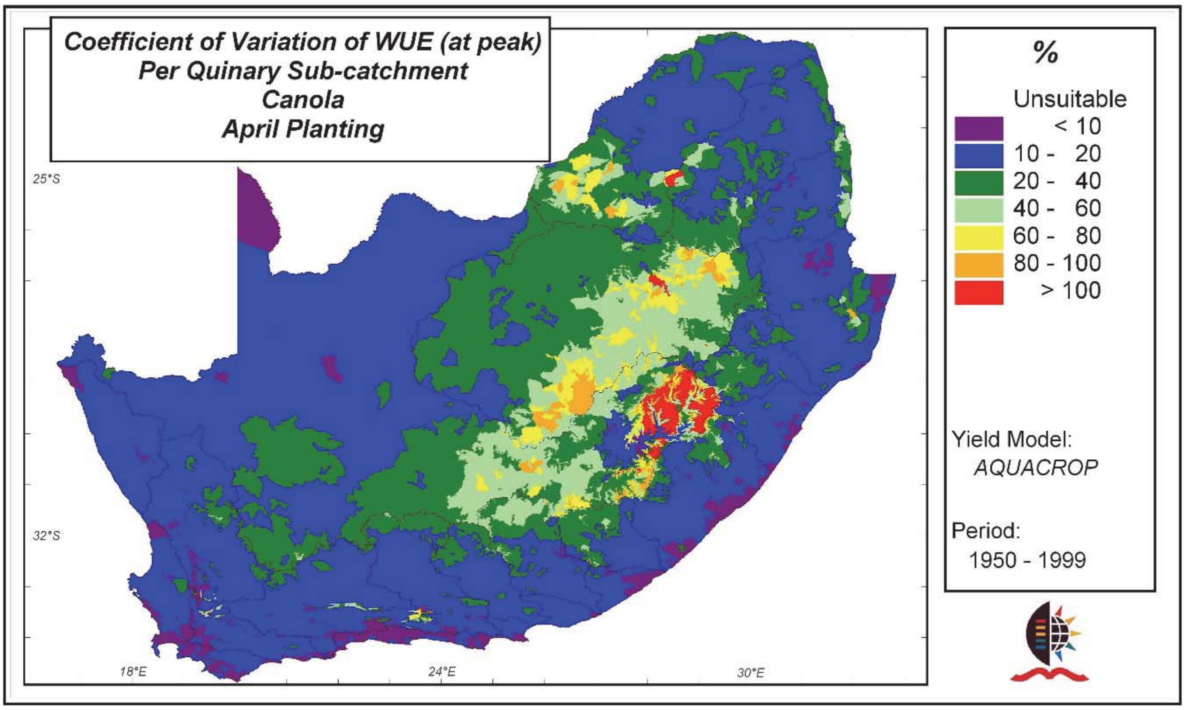

Coefficient of Variation of WUE (at peak)
Per Quinary Sub-catchment
Sugarbeet
June Planting
25°S
32°S
18°E
24°E
30°E
%
Unsuitable
< 10
10 - 20
20 - 40
40 - 60
60 - 80
80 - 100
> 100
Yield Model:
AQUACROP
Period:
1950 - 1999

(d)

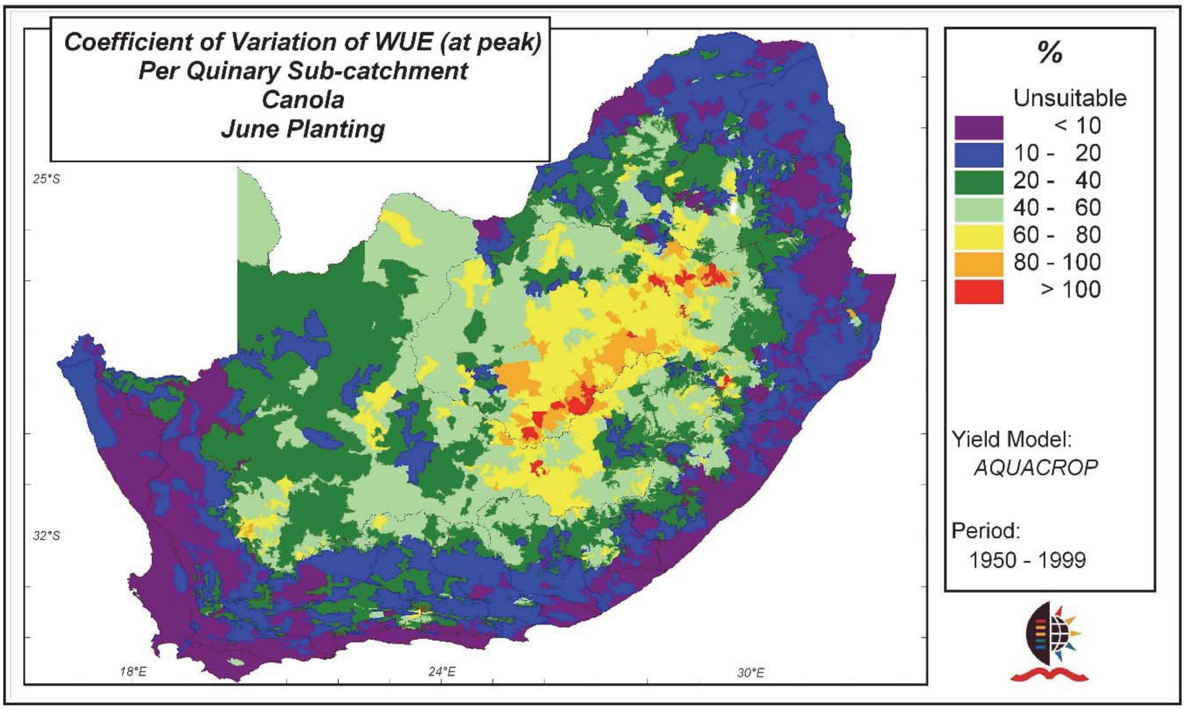


(e)

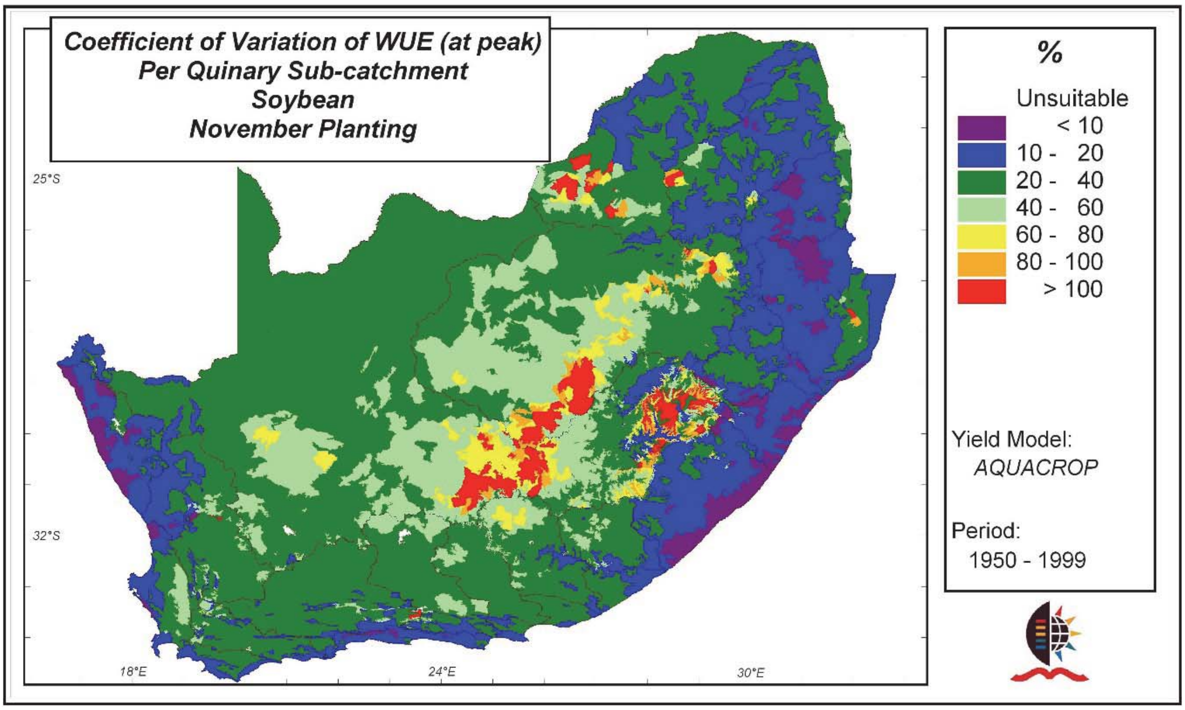
Figure 81 Variability of inter-seasonal WUE (%) calculated by *AQUACROP* (peak) for selected bioethanol feedstocks (a-e) planted on different dates



(a)



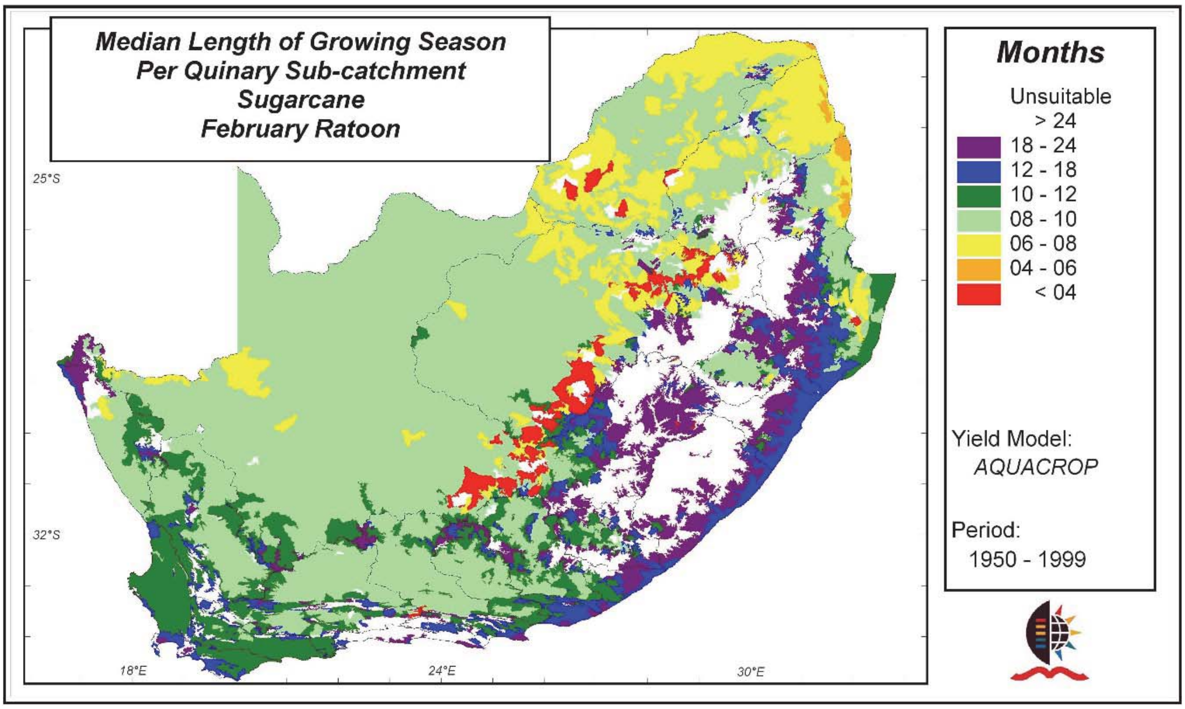
(b)



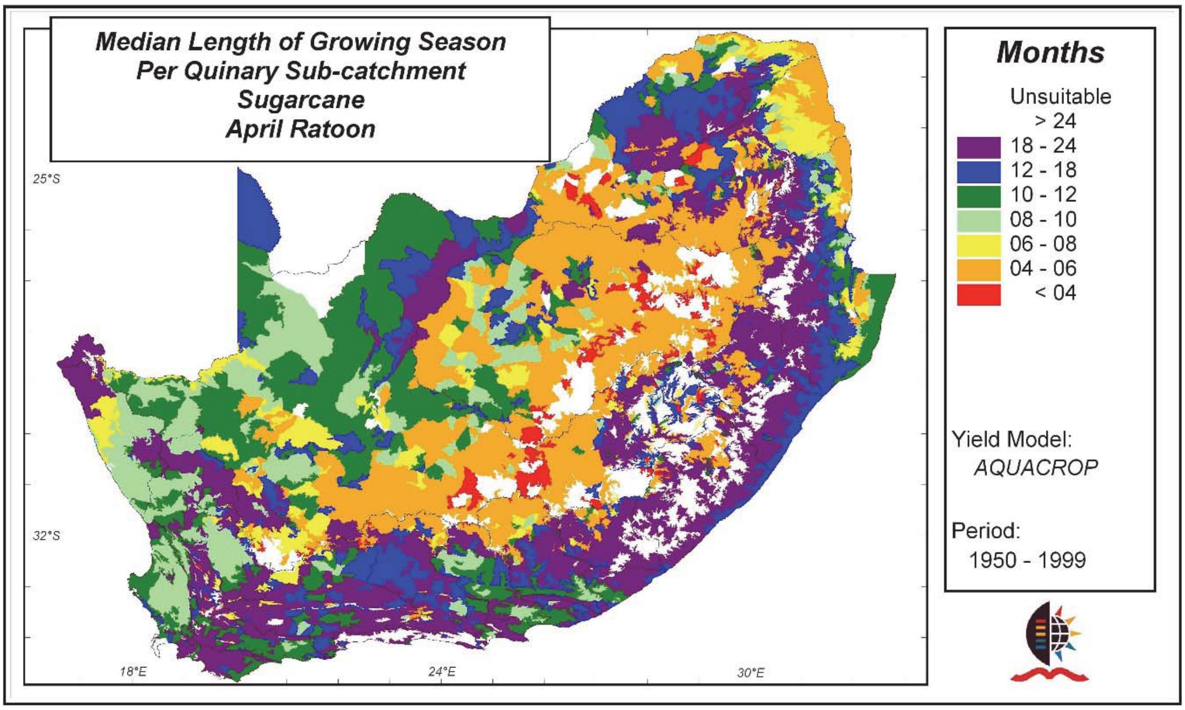
(c)

Figure 82 Variability of inter-seasonal WUE (%) calculated by *AQUACROP* (peak) for selected biodiesel feedstocks (a-c) planted on different dates

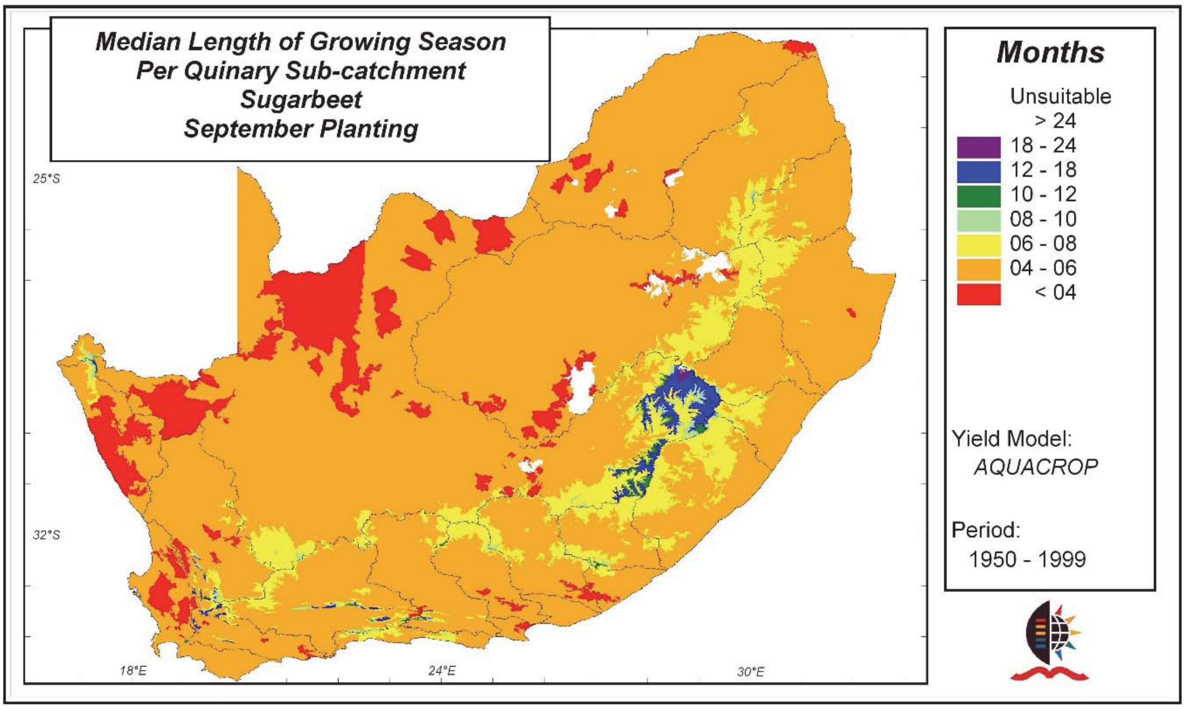
14 APPENDIX G



(a)

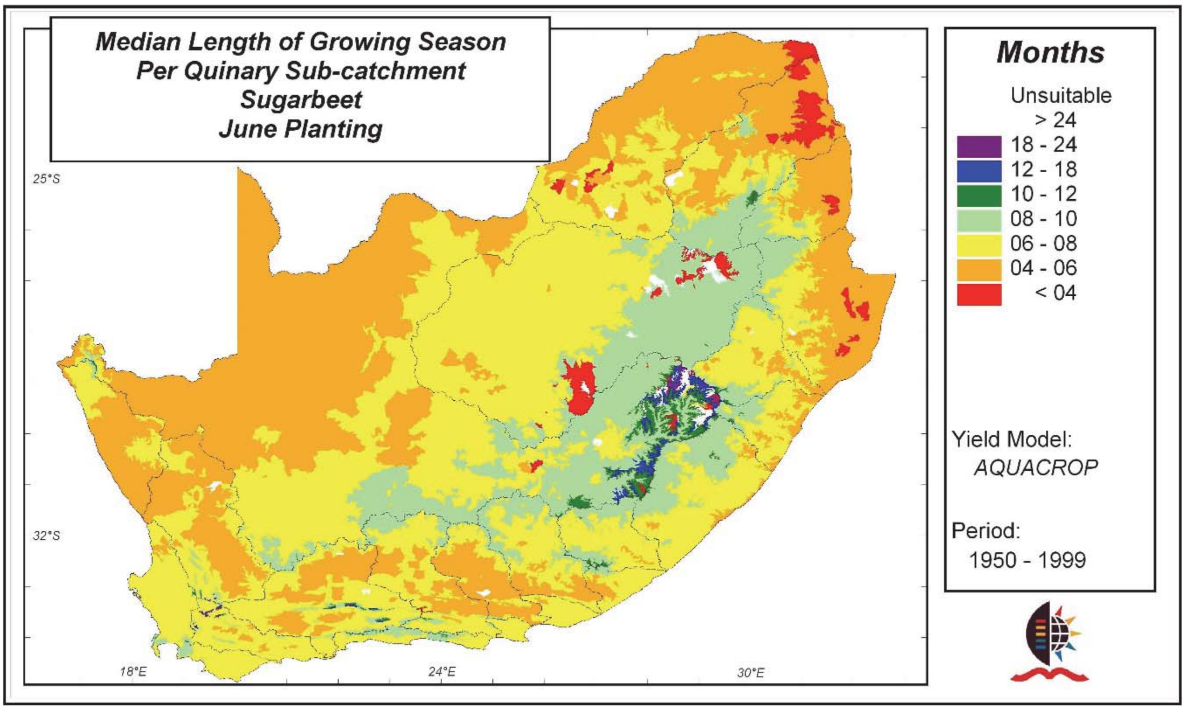


(b)



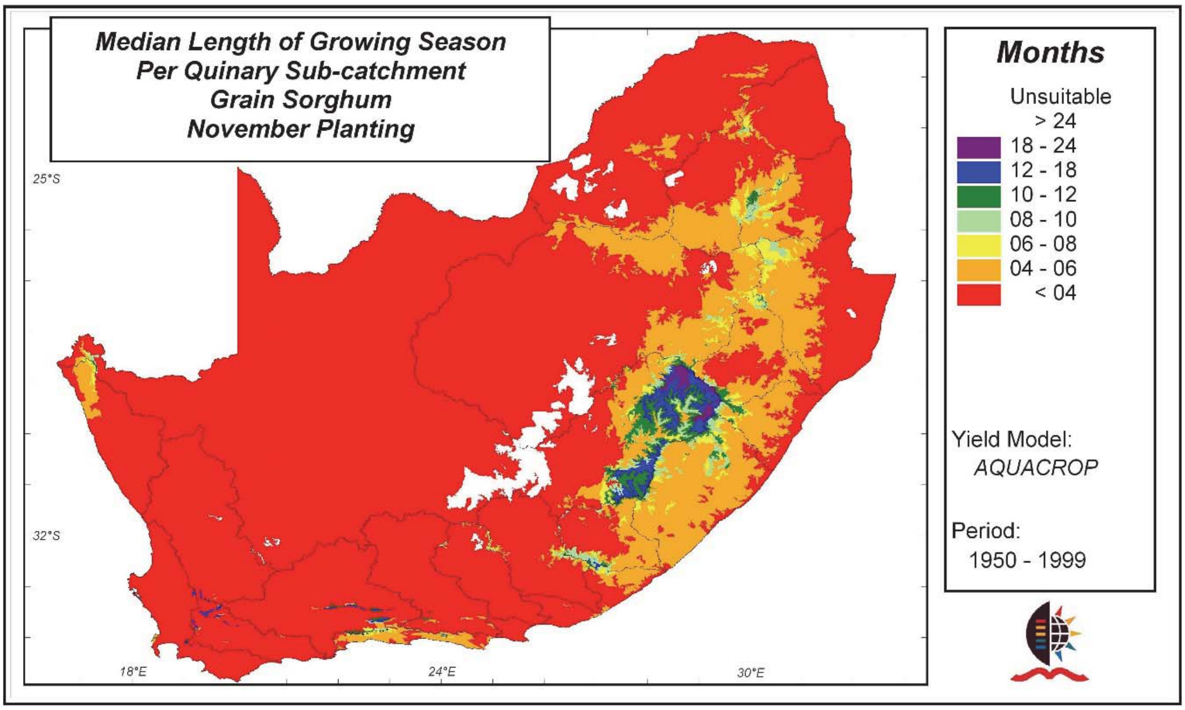
Median Length of Growing Season
Per Quinary Sub-catchment
Sugarbeet
September Planting
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)



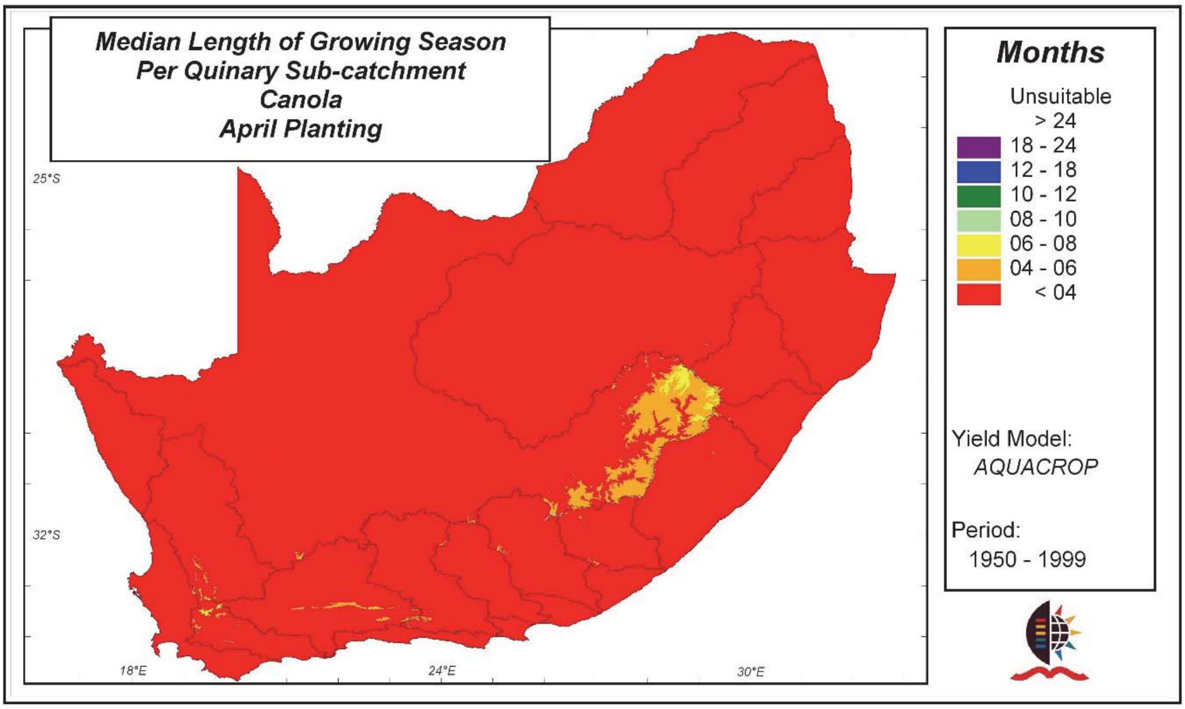
Median Length of Growing Season
Per Quinary Sub-catchment
Sugarbeet
June Planting
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

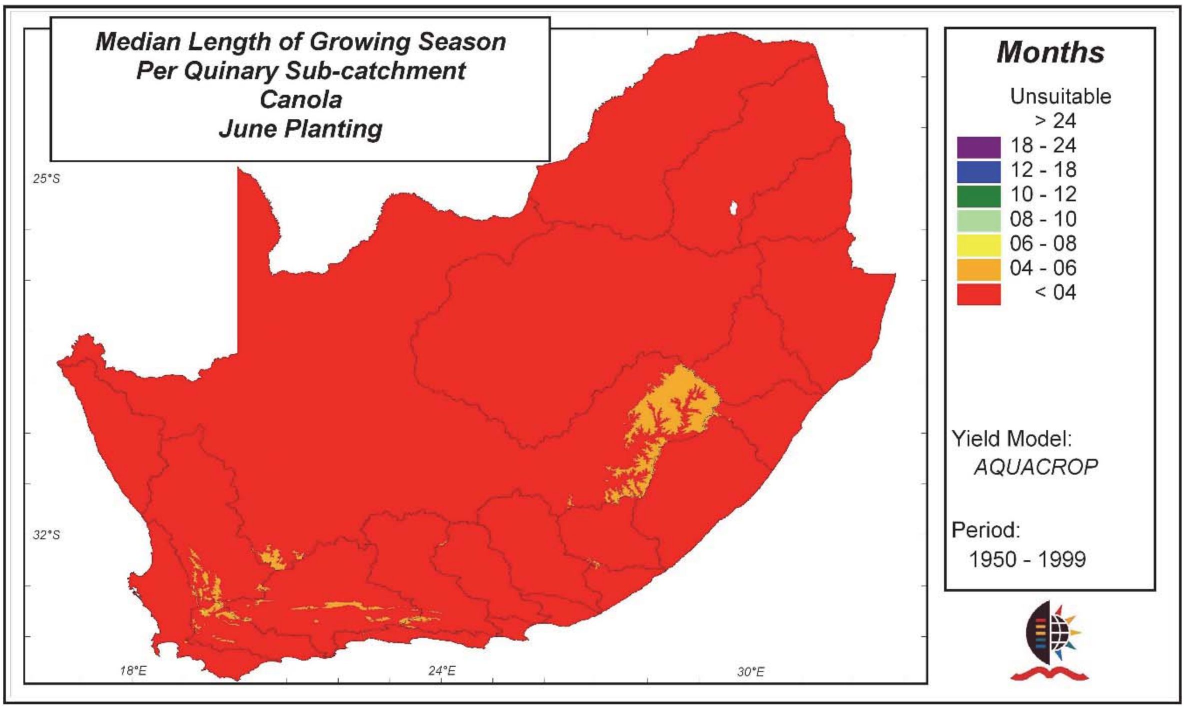


(e)

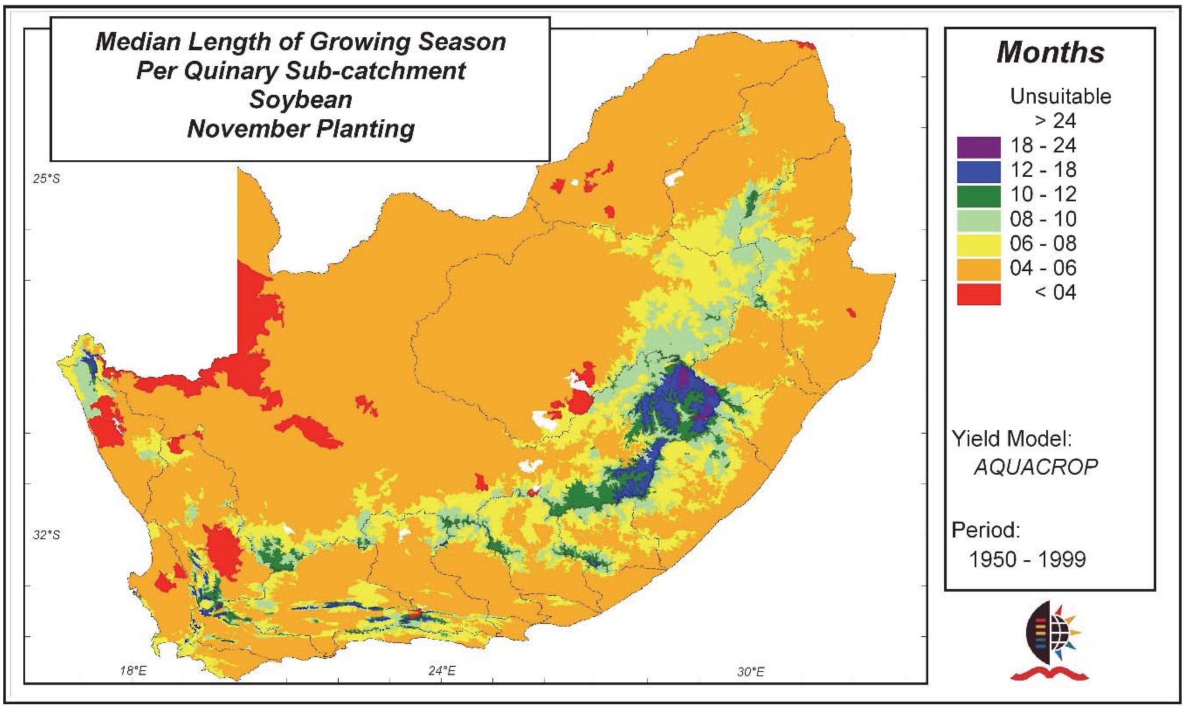
Figure 83 Median length of the growing season (from germination to peak yield) as determined by *AQUACROP* for selected bioethanol feedstocks (a-e) planted on different dates



(a)



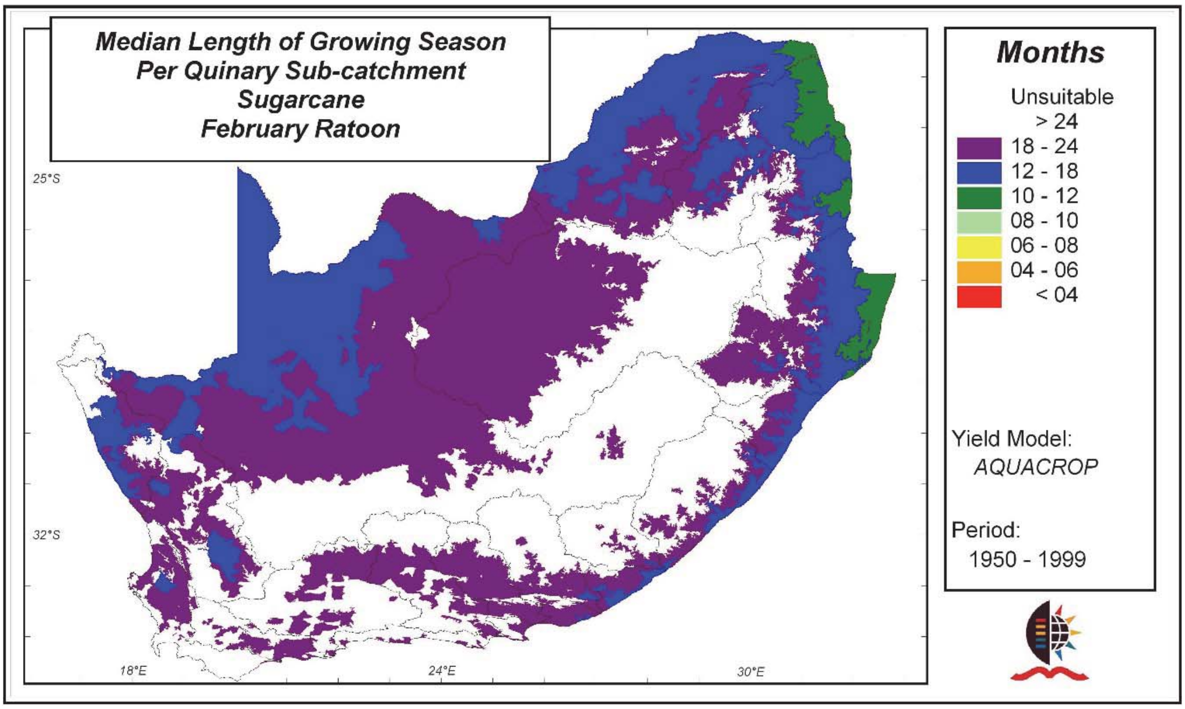
(b)



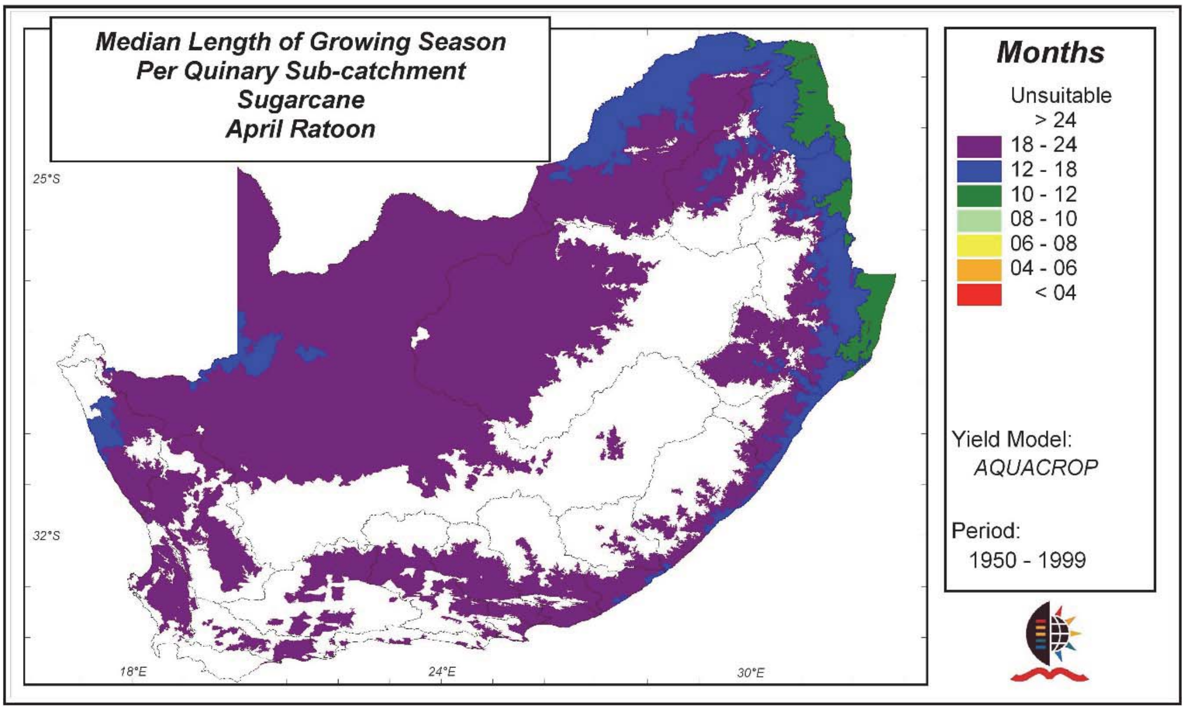
(c)

Figure 84 Median length of the growing season (from germination to peak yield) as determined by *AQUACROP* for selected biodiesel feedstocks (a-c) planted on different dates

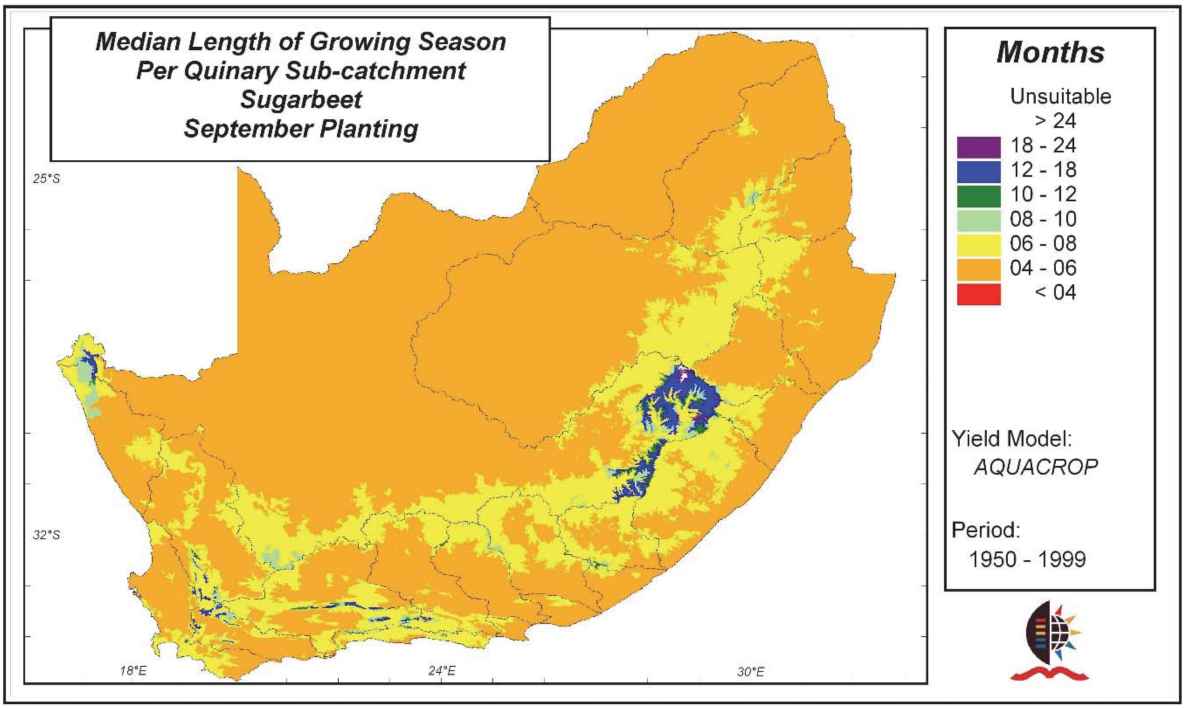
15 APPENDIX H



(a)

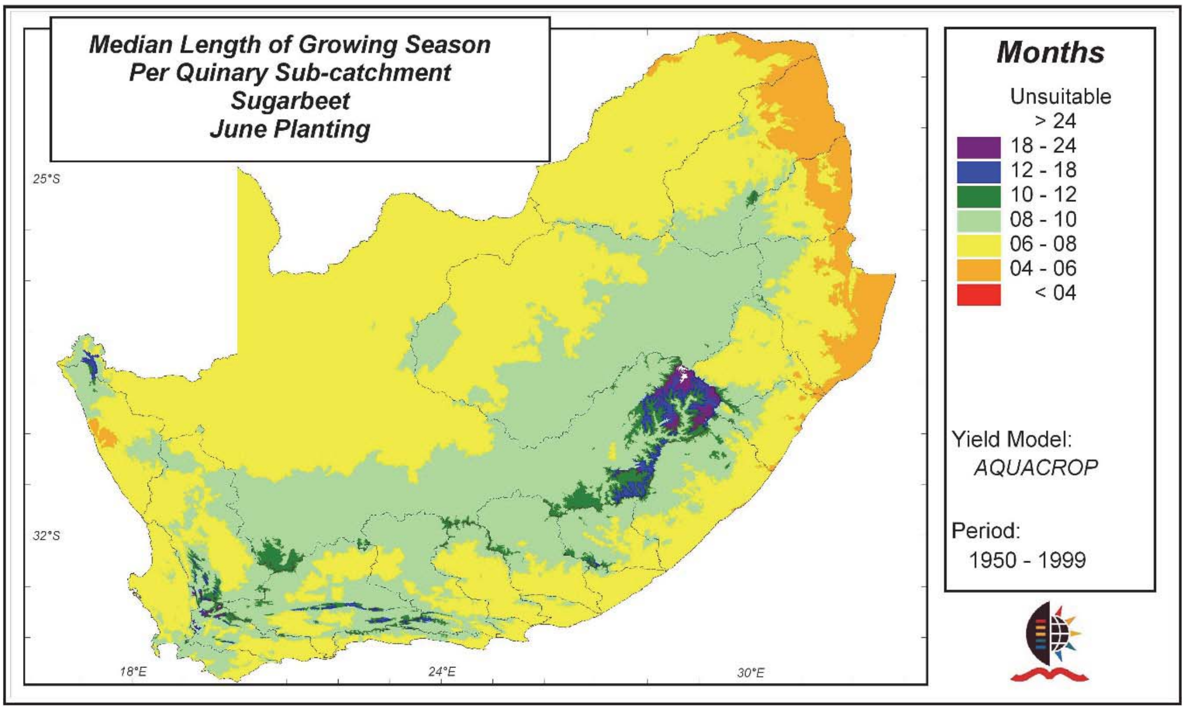


(b)



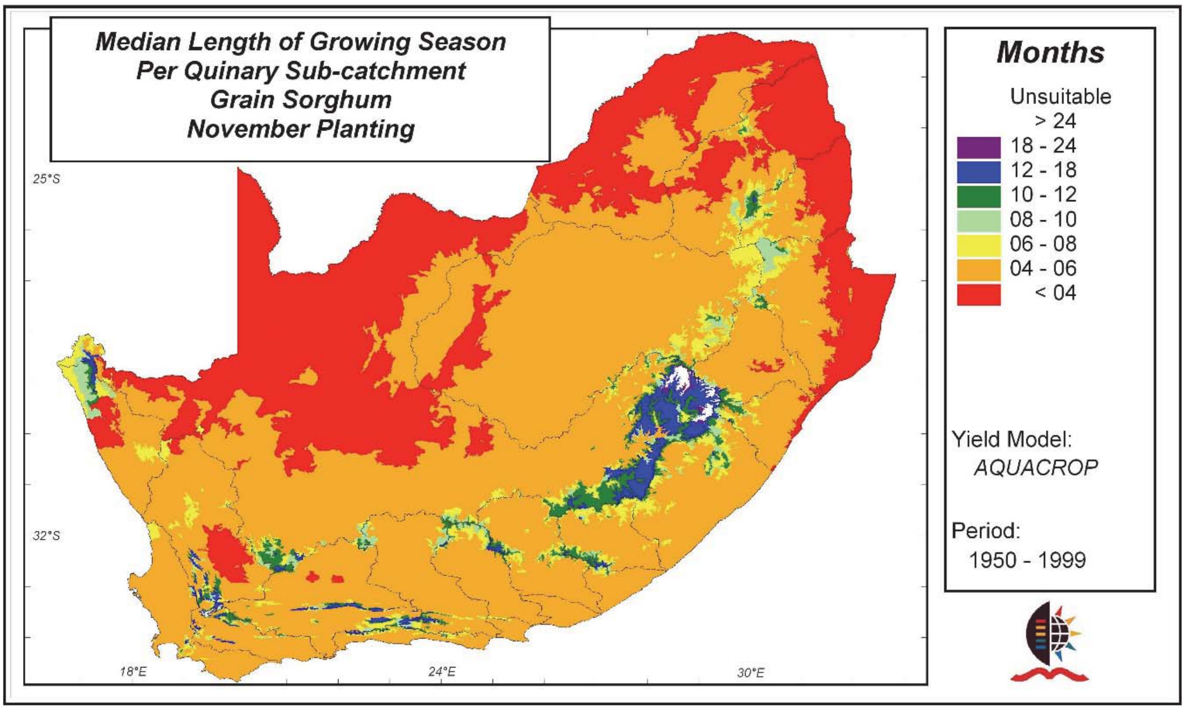
Median Length of Growing Season
Per Quinary Sub-catchment
Sugarbeet
September Planting
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)



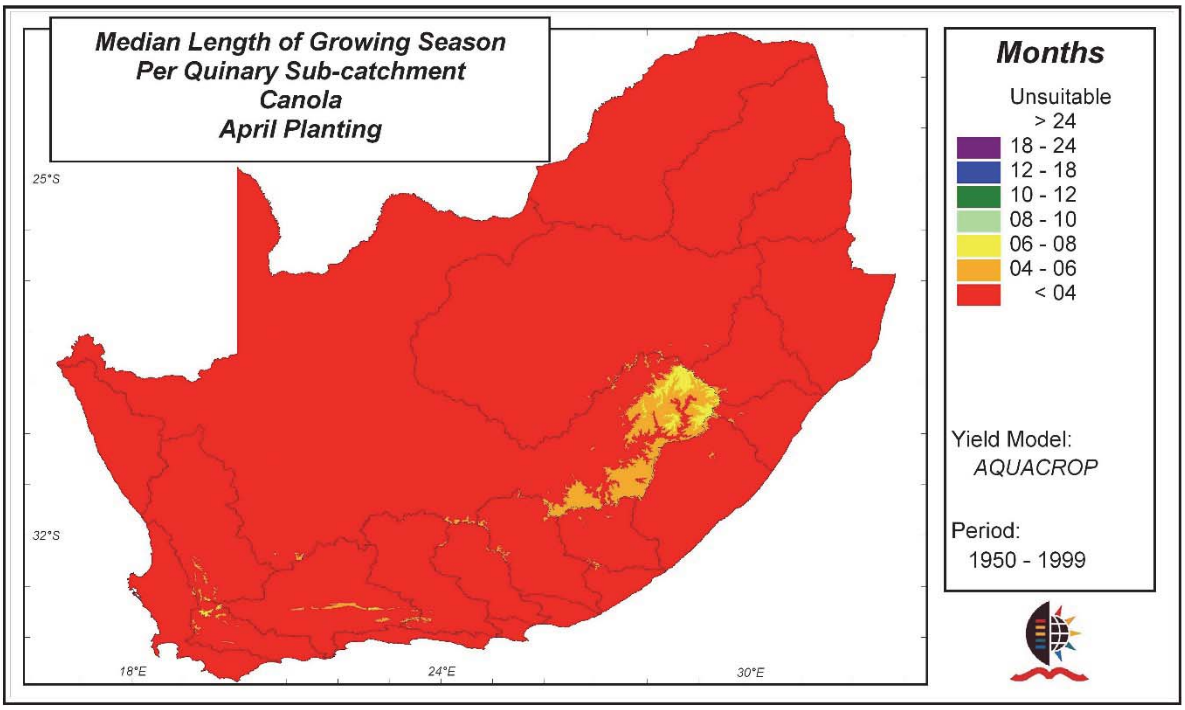
Median Length of Growing Season
Per Quinary Sub-catchment
Sugarbeet
June Planting
Months
Unsuitable
> 24
18 - 24
12 - 18
10 - 12
08 - 10
06 - 08
04 - 06
< 04
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

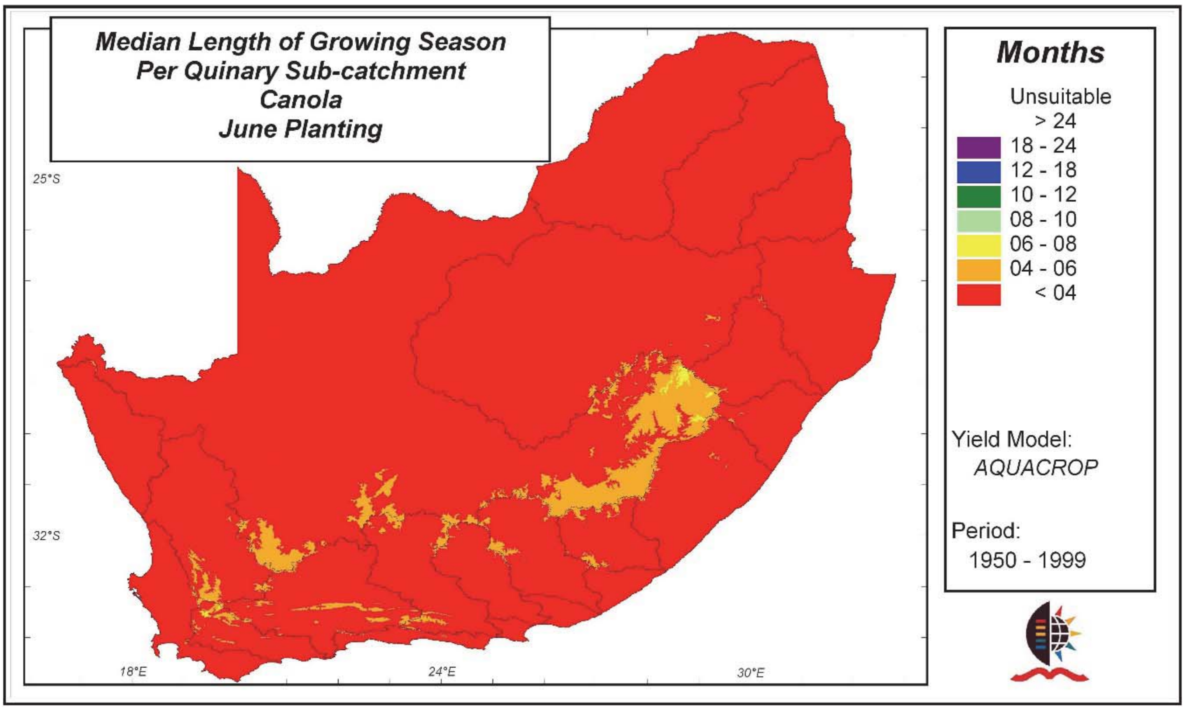


(e)

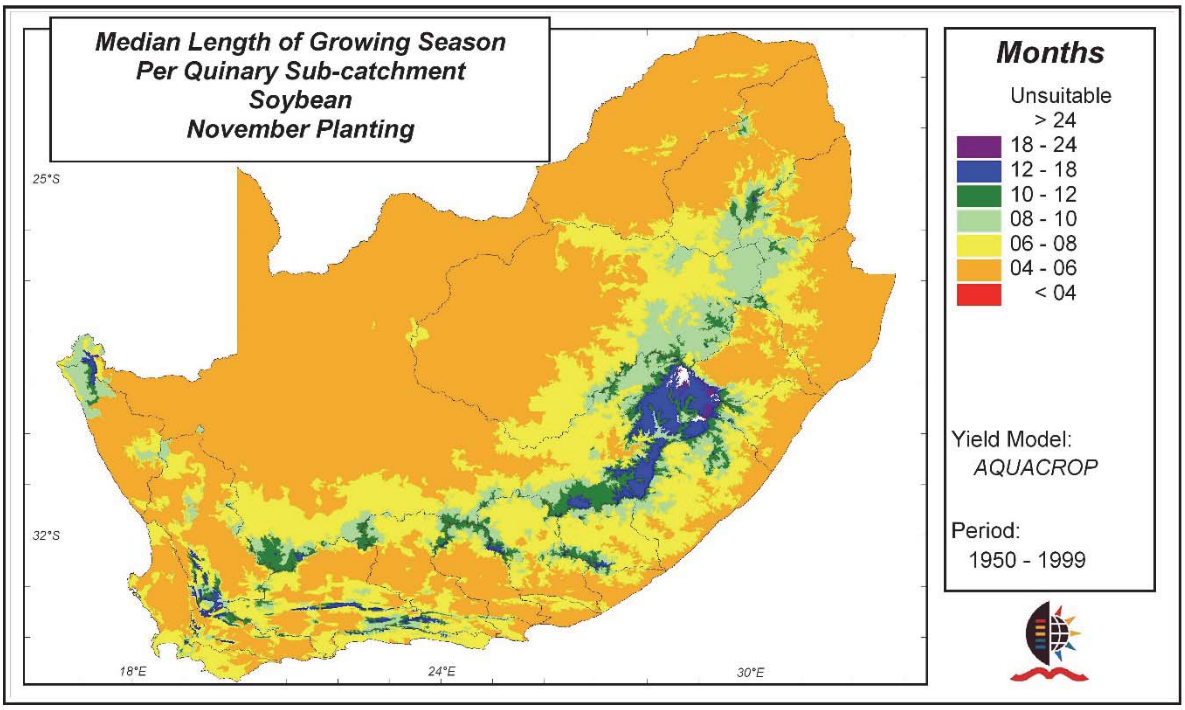
Figure 85 Median length of the growing season (from planting to maturity date) for selected bioethanol feedstocks (a-e) planted on different dates



(a)



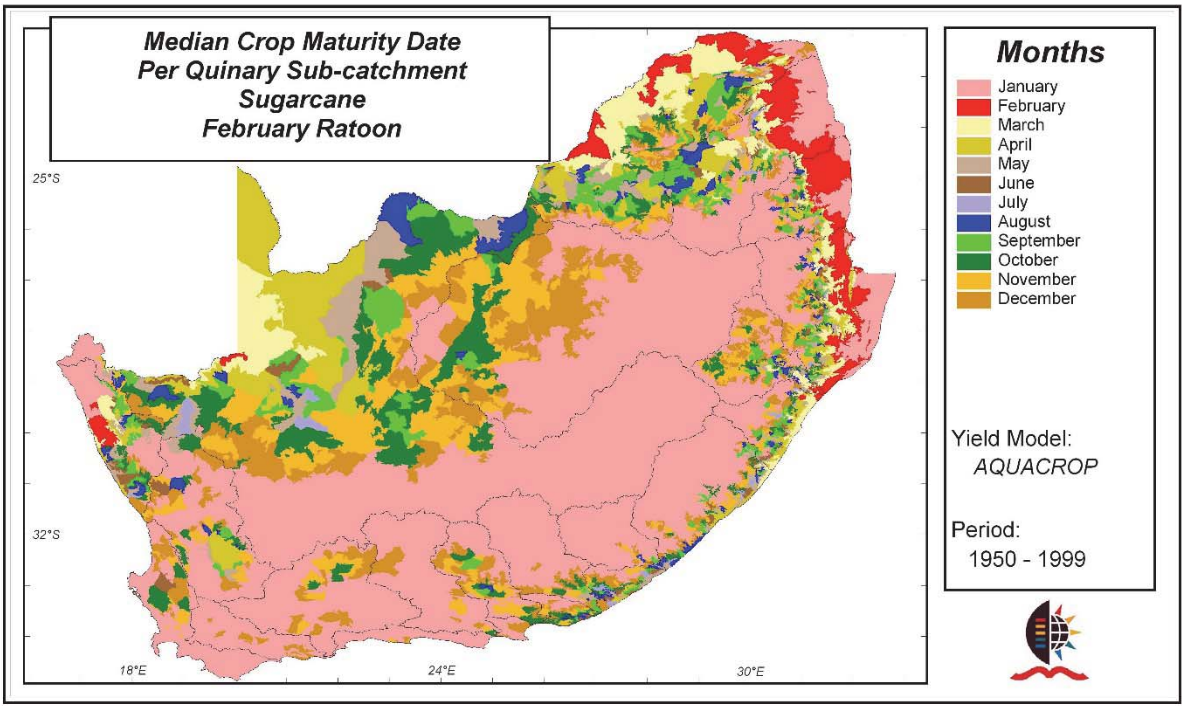
(b)



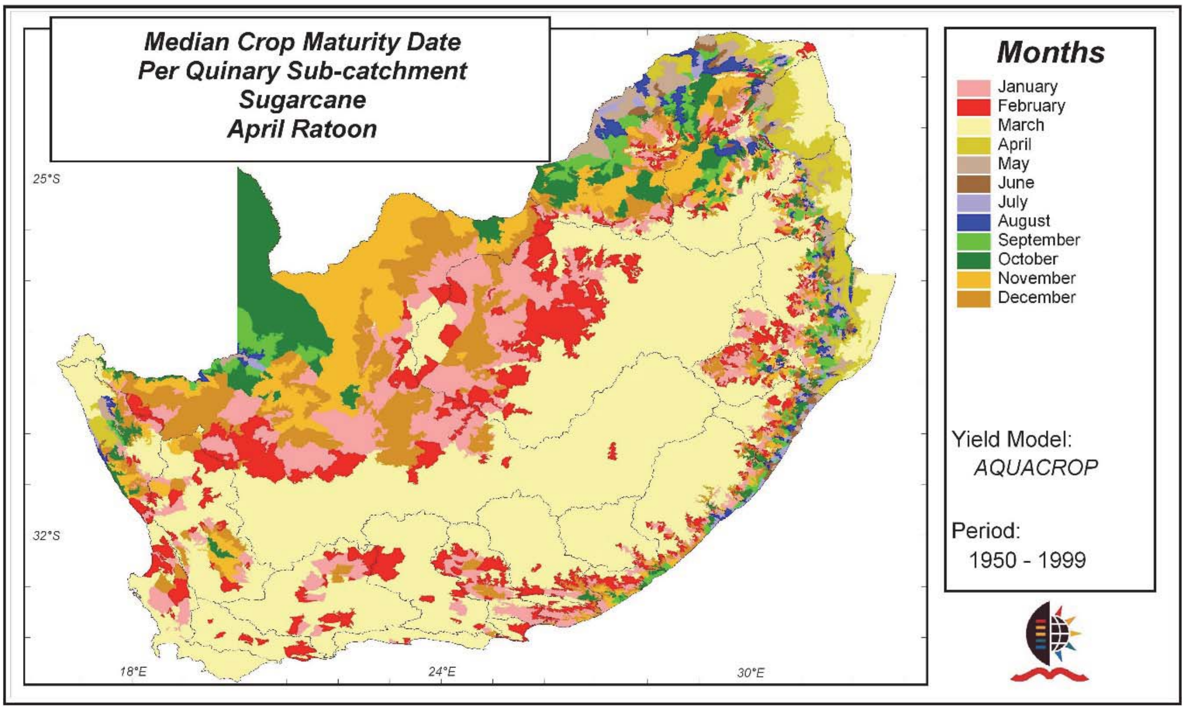
(c)

Figure 86 Median length of the growing season (from planting to maturity date) for selected biodiesel feedstocks (a-c) planted on different dates

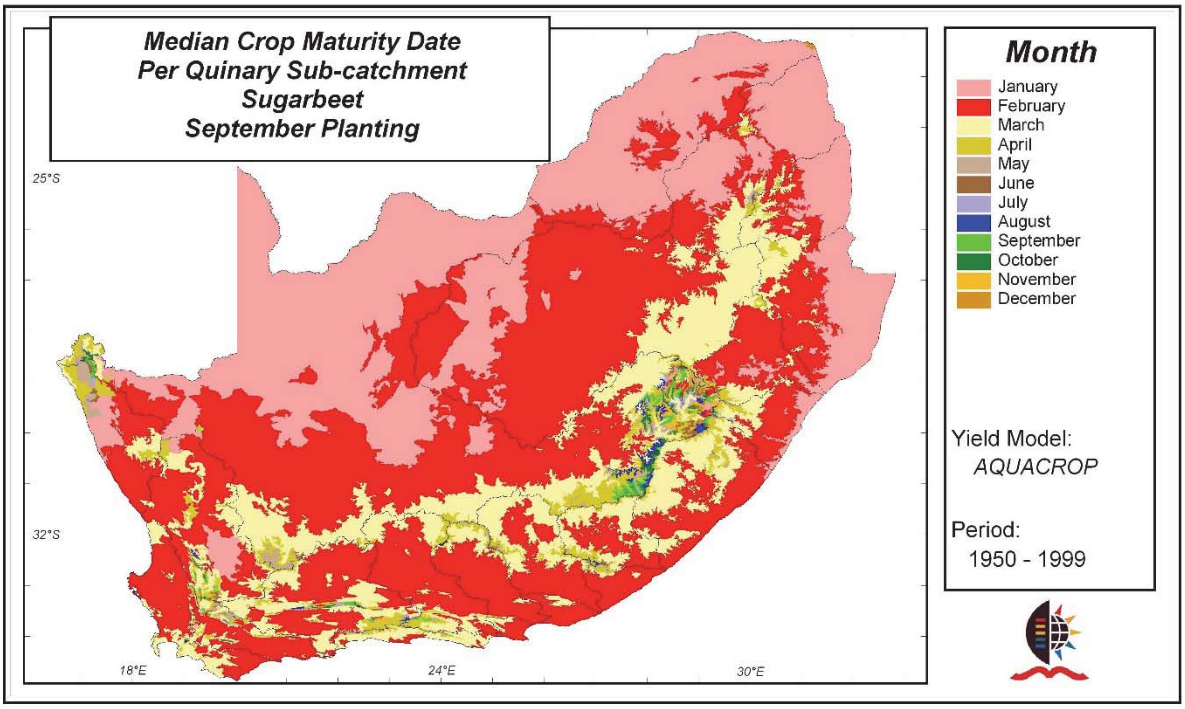
16 APPENDIX I



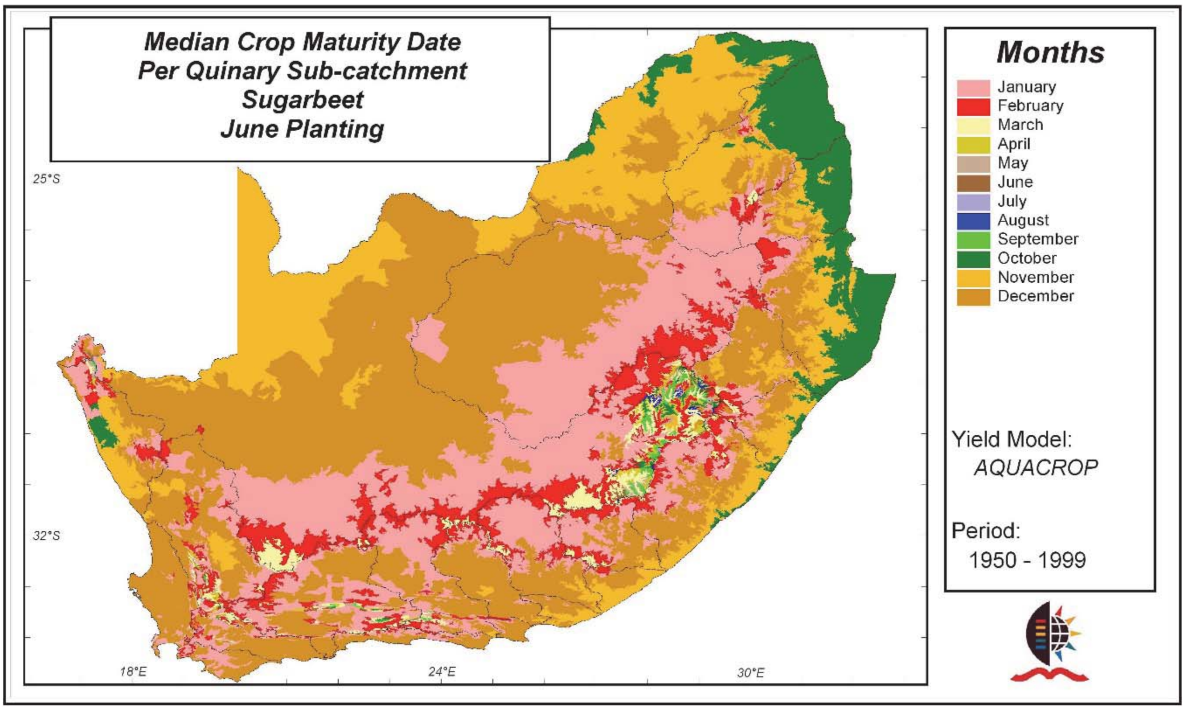
(a)



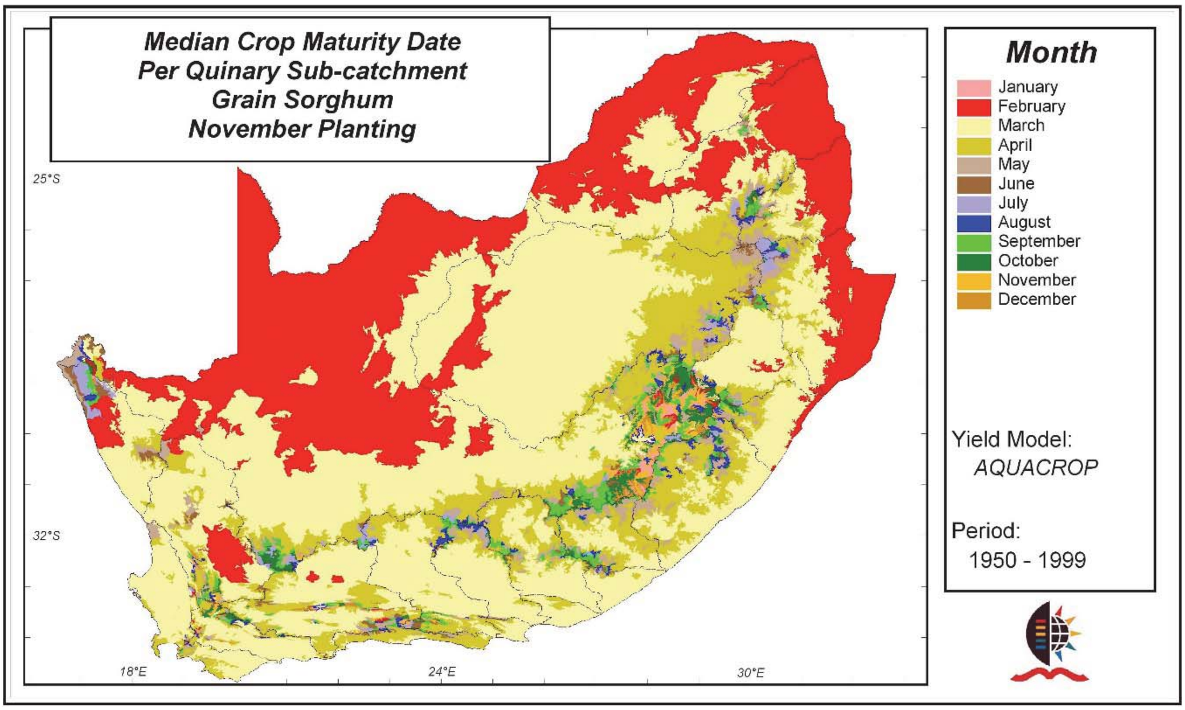
(b)


Median Crop Maturity Date
Per Quinary Sub-catchment
Sugarbeet
September Planting
Month
January
February
March
April
May
June
July
August
September
October
November
December
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(c)

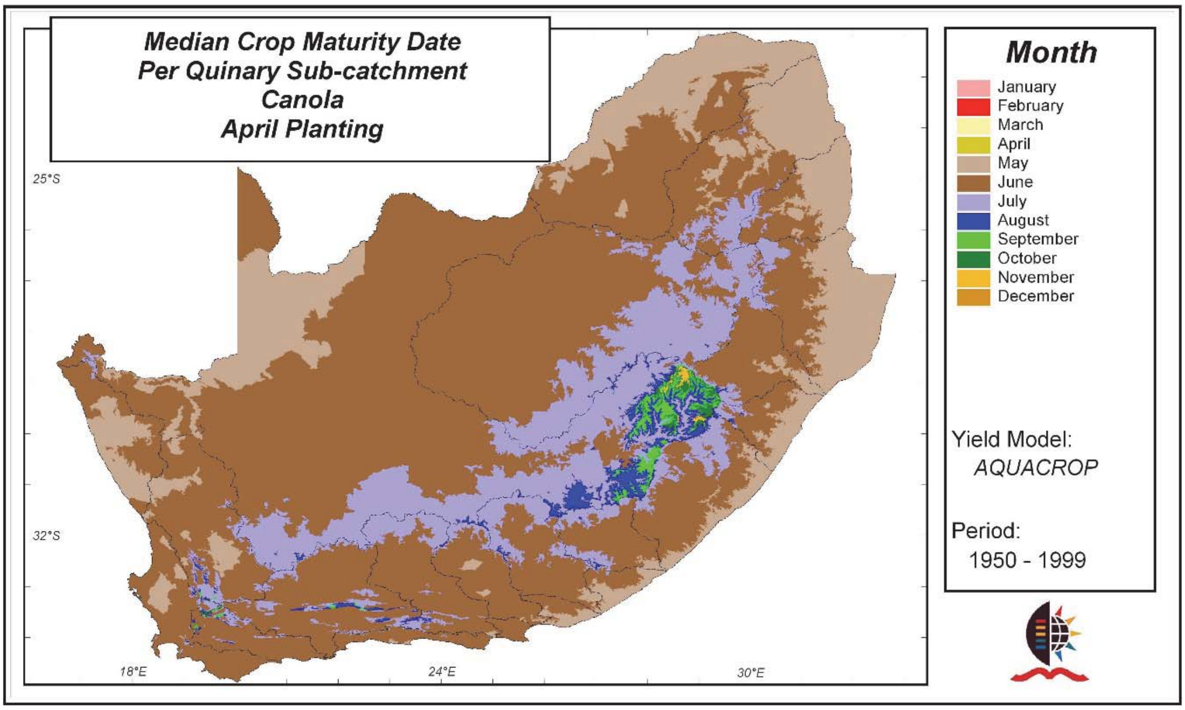

Median Crop Maturity Date
Per Quinary Sub-catchment
Sugarbeet
June Planting
Months
January
February
March
April
May
June
July
August
September
October
November
December
Yield Model:
AQUACROP
Period:
1950 - 1999
25°S
32°S
18°E
24°E
30°E

(d)

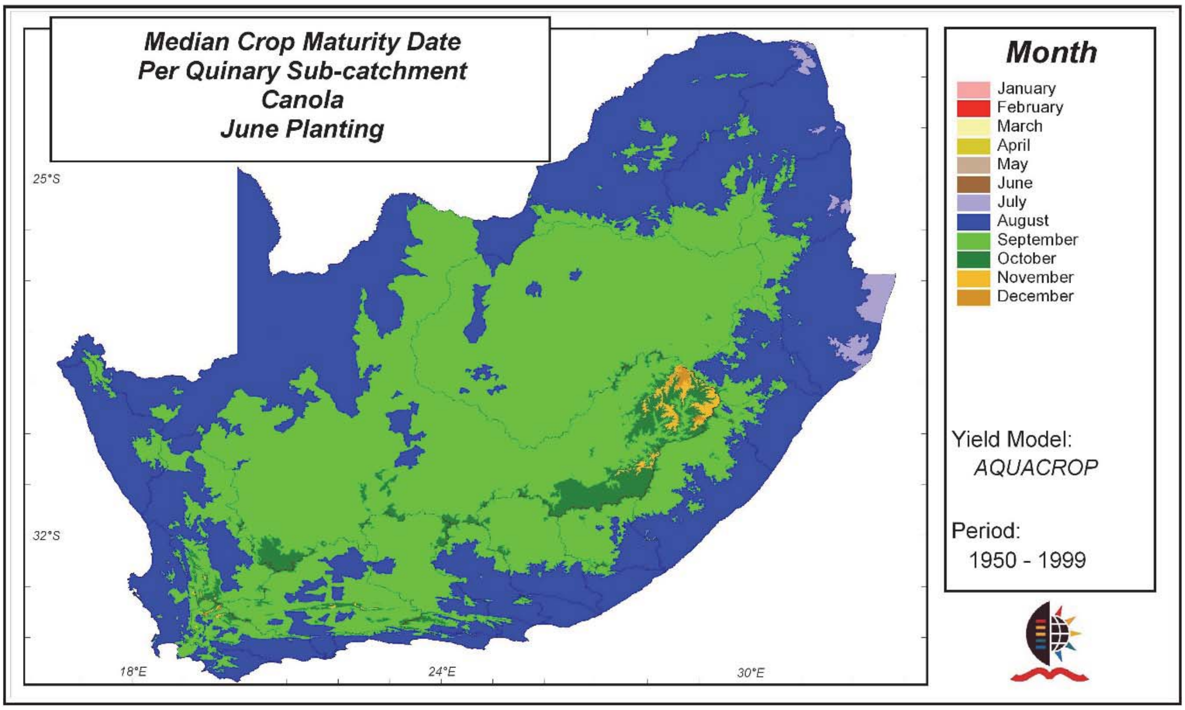


(e)

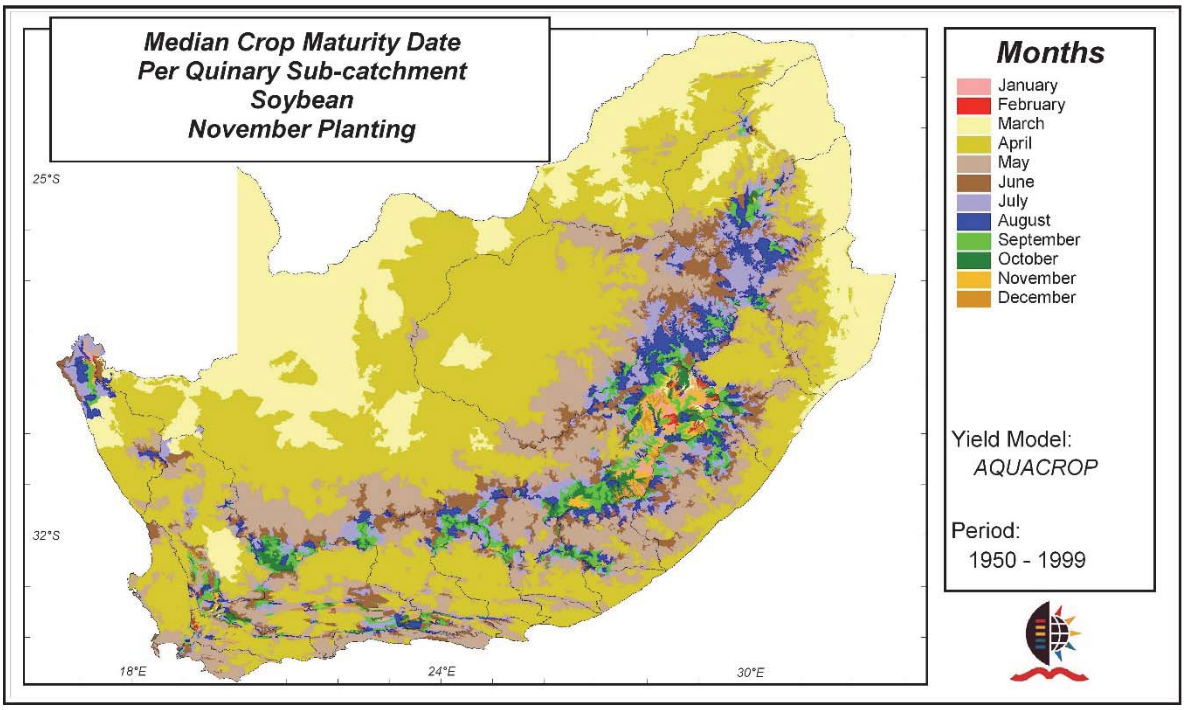
Figure 87 Median month in which the crop matures (i.e. expected harvest date) for selected bioethanol feedstocks (a-e) planted on different dates



(a)



(b)



(c)

Figure 88 Median month in which the crop matures (i.e. expected harvest date) for selected biodiesel feedstocks (a-c) planted on different dates

17 APPENDIX J

17.1 Introduction

17.1.1 Installation

The Biofuels Assessment Utility is made up of four parts:

a) The software utility (Application).

b) The spatial data (GIS coverages).

c) A demo database which contains time series data for only nine quinary sub-catchments (i.e. *ACRU* BIN files) per land use.

d) A complete database which contains time series data for 5 018 quinary sub-catchments (i.e. *ACRU* BIN files) per land use.

To install the Biofuels Assessment Utility (i.e. part a and part b above):

1) Run the **setup.exe** on the DVD.

2) This will install the application and the GIS coverages.

To install the demo time series database for each land use (i.e. part c above):

1) Copy the **demo_data.exe** file (≈40 Mb) from the DVD/Blu-ray to the installation folder which is the following (by default):

   Win XP: C:\Program Files\CWRR\Biofuels Assessment Utility
   Win 7/8 32-bit: C:\Program Files\CWRR\Biofuels Assessment Utility
   Win 7/8 64-bit: C:\Program Files (x86)\CWRR\Biofuels Assessment Utility

2) Run **demo_data.exe** and make sure the destination folder is correct (as shown above). Then select Extract. This will extract time series data for quinary sub-catchments A10A1 to A10C3 (i.e. nine sub-catchments per land use). This allows the user to test that the application is working correctly on the installed computer.

3) This step requires approximately 260 Mb of hard drive space.

4) One the utility has been tested and is working correctly, the user should delete the **demo_data.exe** file which was manually copied to the application's installation folder. This will recover approximately 40 Mb of disk space.

To install the times series database for each land use (i.e. part d above):

1) Copy the **<Land_Use>_db.exe** file (≈2.5 Gb) from the DVD/Blu-ray to the installation folder which is the following (by default):

   Win XP: C:\Program Files\CWRR\Biofuels Assessment Utility
   Win 7/8 32-bit: C:\Program Files\CWRR\Biofuels Assessment Utility
   Win 7/8 64-bit: C:\Program Files (x86)\CWRR\Biofuels Assessment Utility

2) Run **<Land_Use>_db.exe** and make sure the destination folder is correct (as shown above). Then select Extract, followed by Yes to All. This will extract all the time series data files for the selected land use.

3) This step requires approximately 66 GB of hard drive space to complete all 10 land uses.

4) Once the full database has been installed, the user should delete the **<Land_Use>_db.exe** file which was manually copied to the application's installation folder. This will recover approximately 22.72 Gb of disk space.

5) Thus, the total amount of disk space required for the complete time series data files (stored in the Bins folder) is 43.26 Gb.

Note: When installing the land use databases, the demo data does not need to be re-installed (i.e. don't run the **demo_data.exe** file again). The Baseline data (i.e. **Acocks_Veld_Types_db.exe)** is required and must be installed, then the required land use databases can be installed, depending on available disk space and user requirements.

Minimum Requirements

1) PC running Microsoft Windows XP or Windows 7/8 (32- or 64-bit).

2) On Windows XP, Dot Net Framework 2 must be installed for the application to run. These files are included on the installation DVD for the user's convenience.

3) On Windows 7/8, Dot Net Framework 2 is already pre-installed (i.e. no need to install this package).

4) Minimum of 260 Mb of data free hard drive space for testing the application.

5) An additional 66 Gb for installing the full time series database in the "Bins" folder, which decreases to 43.26 Gb once all the **<Land_Use>_db.exe** files have been deleted.

6) Please check the Microsoft® Web site for updates/patches for the Dot Net Framework.

7) The application has been tested on Windows XP (SP3) and Windows 7 (SP1; both the 32- and 64-bit version).

8) The application was installed and tested on Windows 8 Pro (64-bit). The application should also work on Windows 8.1 and Windows 10 (32- and 64-bit versions).

9) Please refer to the guide for Windows 8 installations, which deals with the activation of Dot Net version 2.

17.2 Using the Biofuels Assessment Utility

The **Biofuels Assessment Utility.exe** is run by selecting the shortcut from Start…Programs…CWRR, or by double-clicking the shortcut on the user's Desktop. The User Interface (UI) is shown in **Figure 89**.

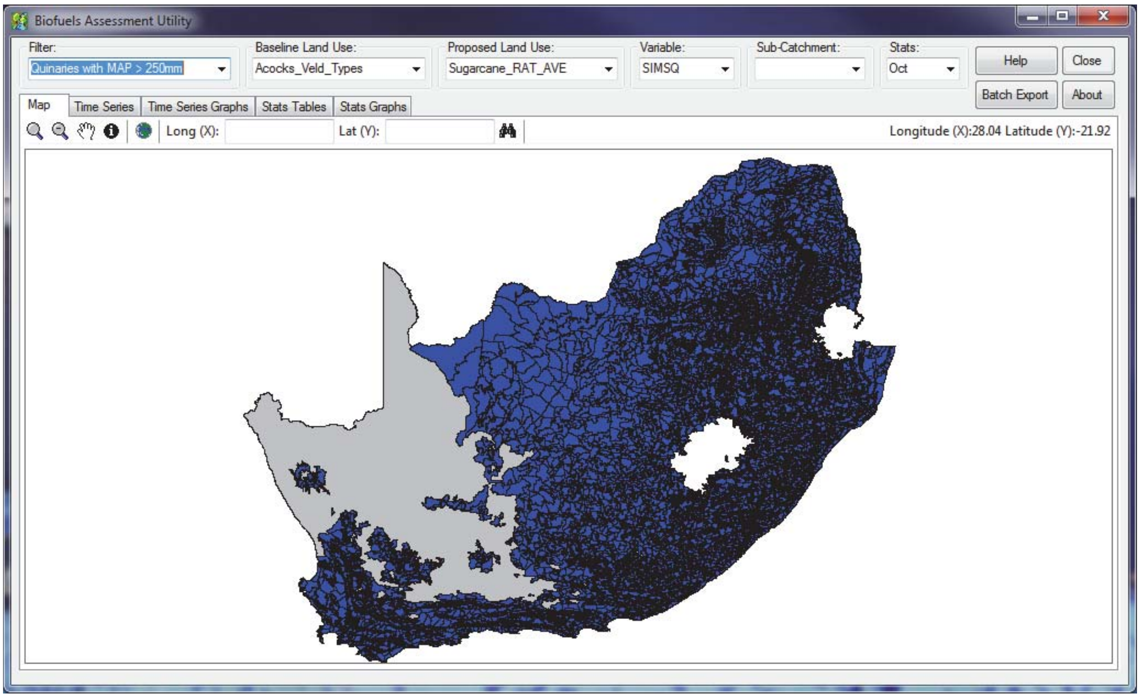


Figure 89 Biofuels Assessment Utility's User Interface

The main user interface comprises of *Combo Boxes*, as displayed in **Figure 90** and described in **Table 30**, and *Display Option Tabs*, as shown in **Figure 91**.

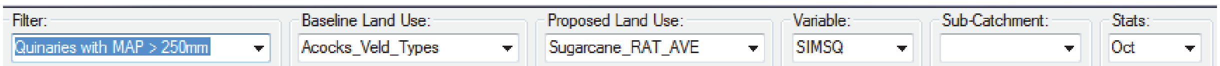


Figure 90 Biofuels Assessment Utility's *Combo Boxes*

Table 30 The *Combo Box* headings and descriptions

Combo Boxes	Description
Filter	The general land use used to filter the map display
Baseline Land Use	Land use to be compared against (usually Acocks Veld Types)
Proposed Land Use	The proposed land use to be analysed
Variable	The output variable to be analysed (as listed in **Table 32**)
Sub-Catchment	The quinary catchment to be analysed
Stats	Select the start month for the annual statistics (October is the default)

Figure 91 Biofuels Assessment Utility's *Display Option Tabs*

Click on the **Down** arrow on the **Filter** *Combo Box* and select the desired land use grouping from the available filter options as shown in **Figure 92**. The default option selected is all the quinary sub-catchments with a Mean Annual Precipitation (MAP) greater than 250 mm. Once the **Filter** has been selected, the corresponding map is shown in the **Map** display tab, which highlights possible growing areas for the selected crop. The **Proposed Land Use** is populated with the corresponding land uses as displayed by an example in **Figure 93**, and the **Sub-Catchment** list is then filtered to match the available regions.

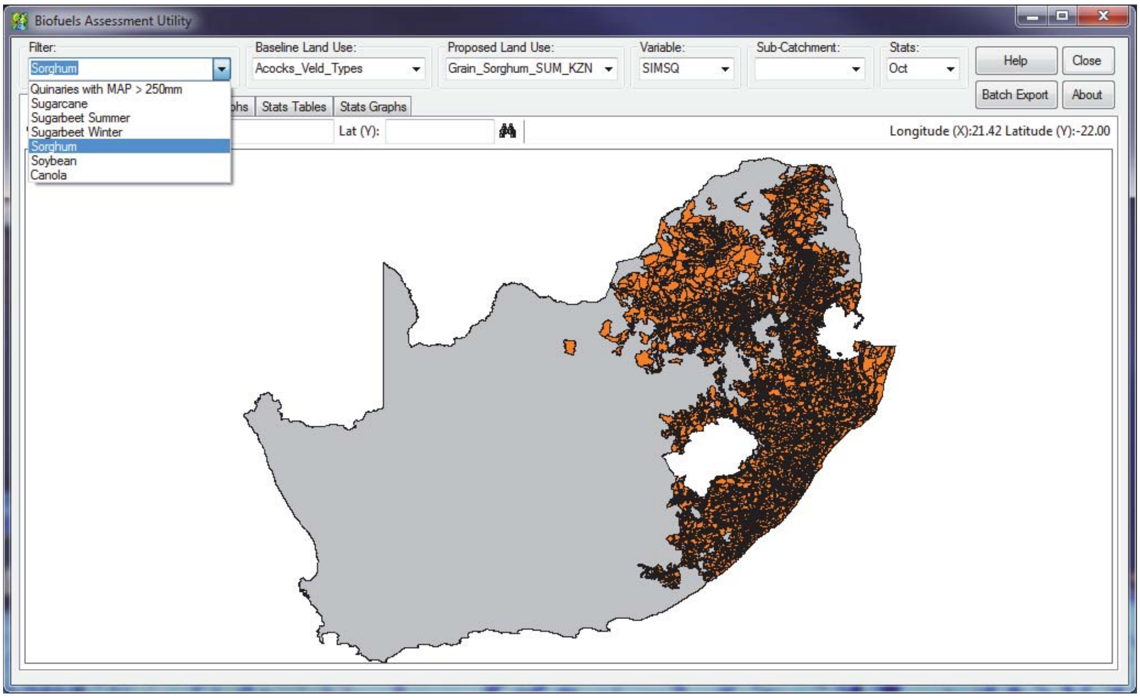


Figure 92 Biofuels Assessment Utility's filter selection

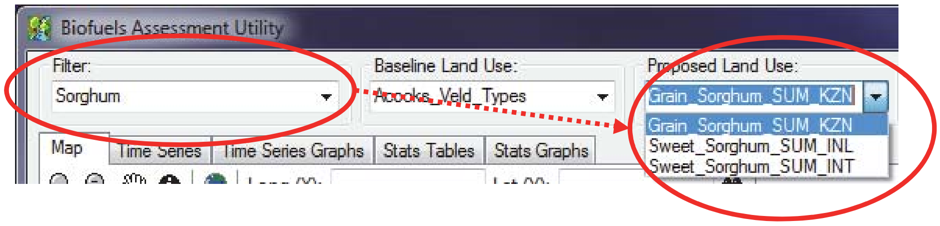


Figure 93 Proposed land use options filtered according to selected filter

Next, the **Baseline Land Use** is selected, which is typically **Acocks_Veld_Types** by default. The **Proposed Land use** is selected, (e.g. sugarcane) from the available options in the **Proposed Land Use** drop-down *Combo Box*. The available options will vary depending on the **Filter** selected as shown in **Figure 93** above. **Table 31** contains more detail on each of the proposed land use options.

Table 31 Proposed land use options, the assumed planting date and the location of the trial, from which the monthly crop coefficients were derived

Land Use	**Planting date**	**Location of trial**
Sugarcane_RAT_AVE	Ratooned	Eston, Umzinto & Kearsney (KwaZulu-Natal)
Sugar_Beet_WIN_KZN	Winter (June)	Ukulinga (KwaZulu-Natal)
Sugar_Beet_SUM_KZN	Summer (September)	Ukulinga (KwaZulu-Natal)
Sweet_Sorghum_SUM_INL	Summer (December)	Ukulinga (KwaZulu-Natal)
Sweet_Sorghum_SUM_INT	Summer (December)	Hatfield (Gauteng)
Grain_Sorghum_SUM_KZN	Summer (November)	Ukulinga (KwaZulu-Natal)
Soya_Bean_SUM_KZN	Summer (November)	Baynesfield (KwaZulu-Natal)
Canola_WIN	Winter (April)	International
Sunflower_SUM	Summer (November)	International

Then, select the desired output variable (See **Table 32**) from the **Variable** drop-down *Combo Box*. The default output variable selected is *SIMSQ, i.e.* simulated runoff (storm flow + base flow) from the sub-catchment selected. *SIMSQ* does not include contributions from upstream sub-catchments.

Table 32 Description (and units) of each *ACRU* output variable

Variable	Description	Aggregation	Units
AET	Total evaporation (i.e. actual evapotranspiration)	Sum	mm
APAN	A-pan equivalent reference evaporation	Sum	mm
ASOEV	Actual evaporation from the soil surface	Sum	mm
ATRAN1	Actual transpiration from the A-horizon	Sum	mm
ATRAN2	Actual transpiration from the B-horizon	Sum	mm
CAYD	Crop coefficient	Average	-
DPE	Maximum evaporation (potential evapotranspiration)	Sum	mm
EFRL	Effective rainfall (rainfall available for plant growth)	Sum	mm
QUICKF	Storm flow leaving catchment outlet on a given day	Sum	mm
RFL	Input rainfall, adjusted by monthly *CORPPT* values	Sum	mm
RUN	Base flow	Sum	mm
SIMSQ	Simulated runoff (storm flow + base flow) from the sub-catchment, excluding upstream contributions	Sum	mm

A quinary sub-catchment can then be selected via the drop-down *Combo Box* called **Sub-Catchment**, as shown in **Figure 94**.

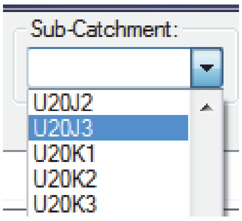


Figure 94 Sub-Catchment drop-down *Combo Box*

Alternatively, the user can input a particular co-ordinate of interest in the **Long** and **Lat** input boxes (See **Figure 95**) and the utility will attempt to locate in which quinary the point of interest resides when the search button is pressed.

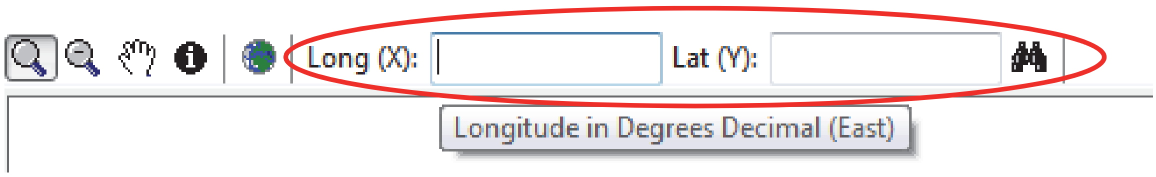


Figure 95 Map search by location controls

Note: Data for each of the first 12 quinaries (comprising of Quaternary's A10A, A21B and A21C) are installed when the demo dataset is installed (i.e. **demo_data.exe**). Alternatively, if the user installed the full database (i.e. the **<Land_Use>_db.exe** files), then data are available for a total of 5 018 quinaries.

The utility then loads the time series data for the selected **Baseline Land Use** as well as the **Proposed Land Use**. This enables the comparison of data for the selected **Sub-catchment** (i.e. quinary) and the statistical analysis to be performed. The utility also calculates the change (i.e. **Baseline Land Use - Proposed Land use**), which is expressed in mm and as a percentage change relative to the Baseline (c.f. **Time Series** below for more information).

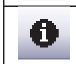
17.2.1 Display option tabs

The *Display Option Tabs* enable simple navigation between the map view, simulated time series (data & graphs) and statistics (data & graphs).

17.2.2 Map

This display tab has various tools to navigate to a particular sub-catchment (as listed in **Table 33**), which allows the user to visualise the quinary boundaries (**Figure 96**).

Table 33 Map navigation tools

Icon	Name	Action
	Zoom	In the map window, left-click and hold, then drag the mouse to select an area of interest to zoom into
	Zoom Out	Left click on the map to zoom out
	Pan	On the map, left click and hold, then drag the mouse to pan around the map view
	Full	Zoom out to full extent of the map
	Identify	Left click on a polygon to identify the sub-catchment
	Find	Find a sub-catchment by inputting the Longitude and Latitude (in decimal degrees, with latitude negative) 

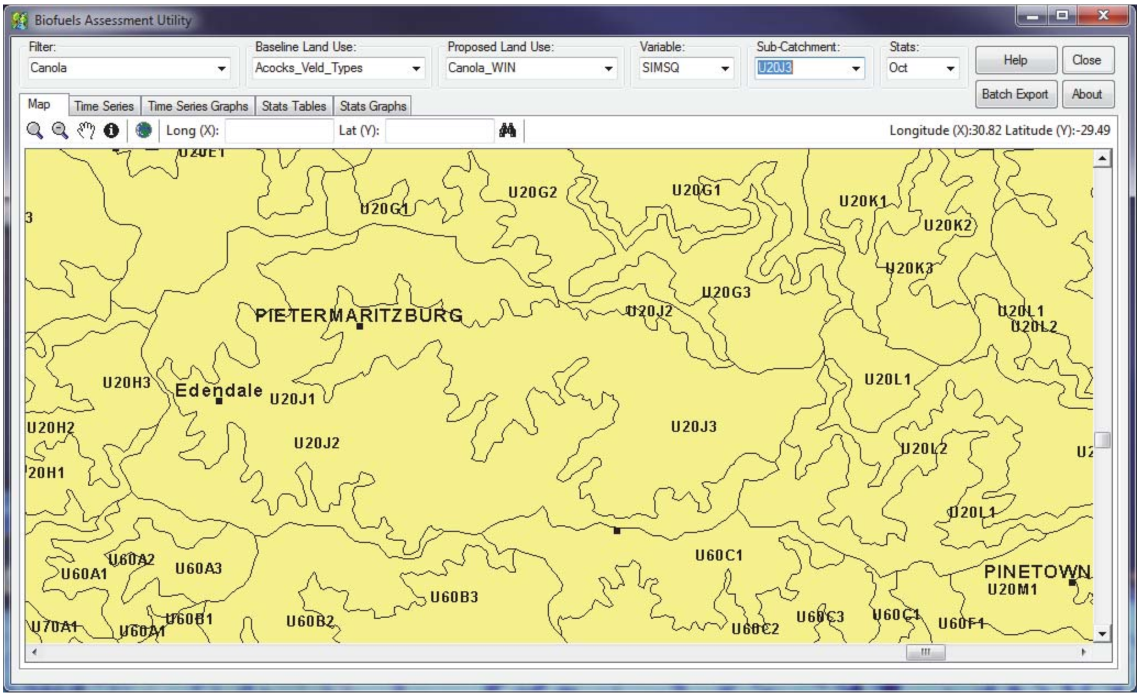


Figure 96 Biofuels Assessment Utility's *Map* tab

17.2.3 Time series

This displays the time series for the selected sub-catchment's **Baseline Land Use** and the **Proposed Land Use** in tabular format (see **Figure 97**), as well as the calculated reduction (i.e. **Baseline Land Use - Proposed Land Use**). The times series can be viewed in either the original daily format, or aggregated to monthly values. However, the calculated reduction table is only available as monthly values. These tables can be exported to comma delimited (.CSV) files by selecting the corresponding **Save To Text File** button.

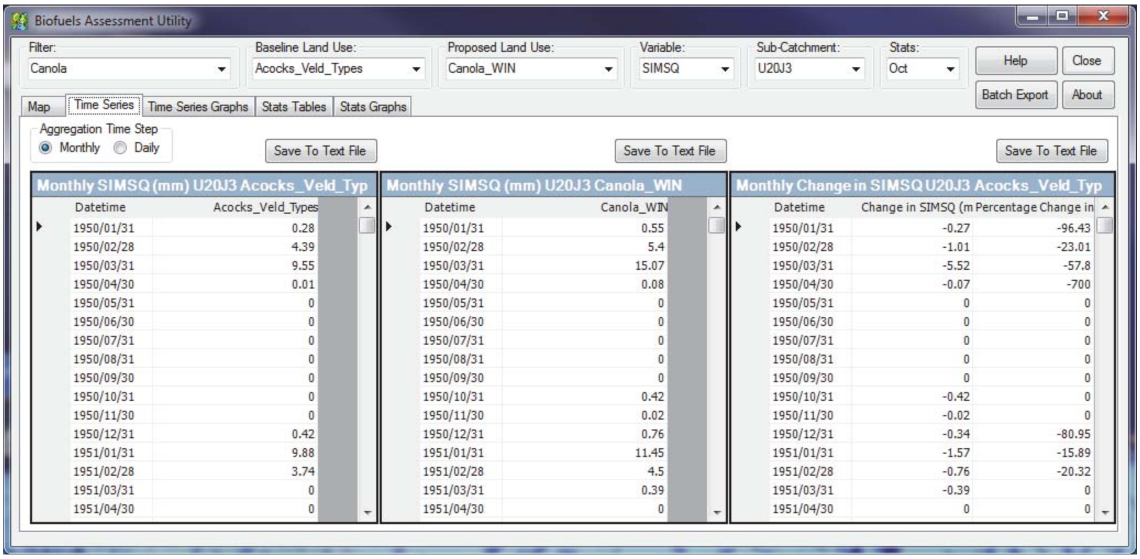
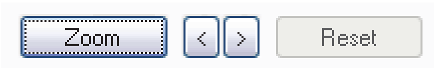


Figure 97 Biofuels Assessment Utility's *Time Series* tab

17.2.4 Time series graphs

This displays the time series for the selected sub-catchment's **Baseline Land Use** and **Proposed Land use** in graphical format (See **Figure 98**). Similarly, the time series can be either viewed in the original daily format or aggregated to monthly values. The graphical view option has various buttons to enable closer inspection of the time series.



The time series graph can also be navigated by various left and right mouse clicks:

Reset graph : Double click (left or right)
Pan graph : Right click, hold and drag mouse
Zoom graph : Left click, hold and drag mouse

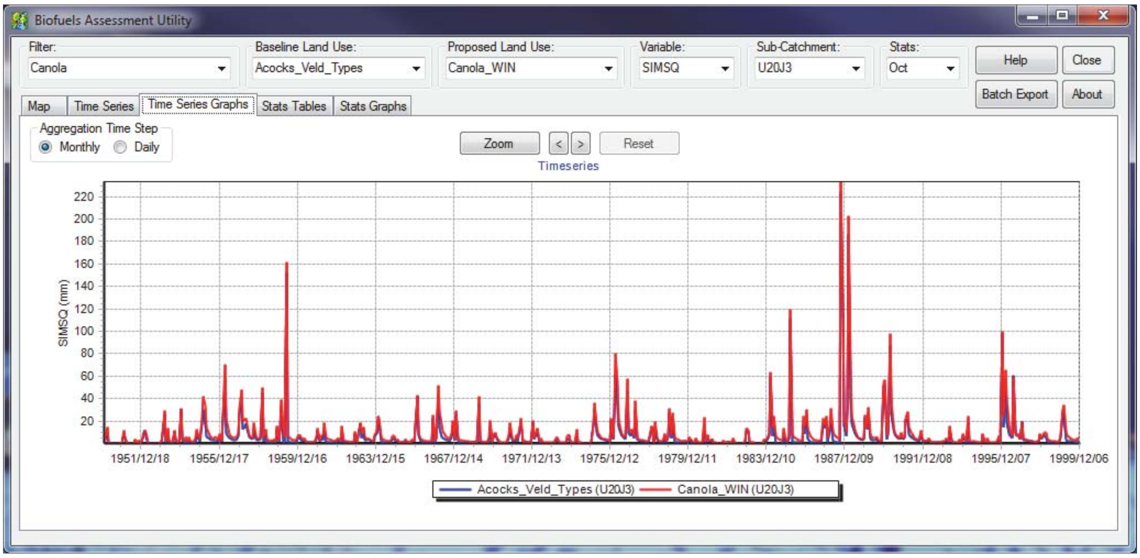
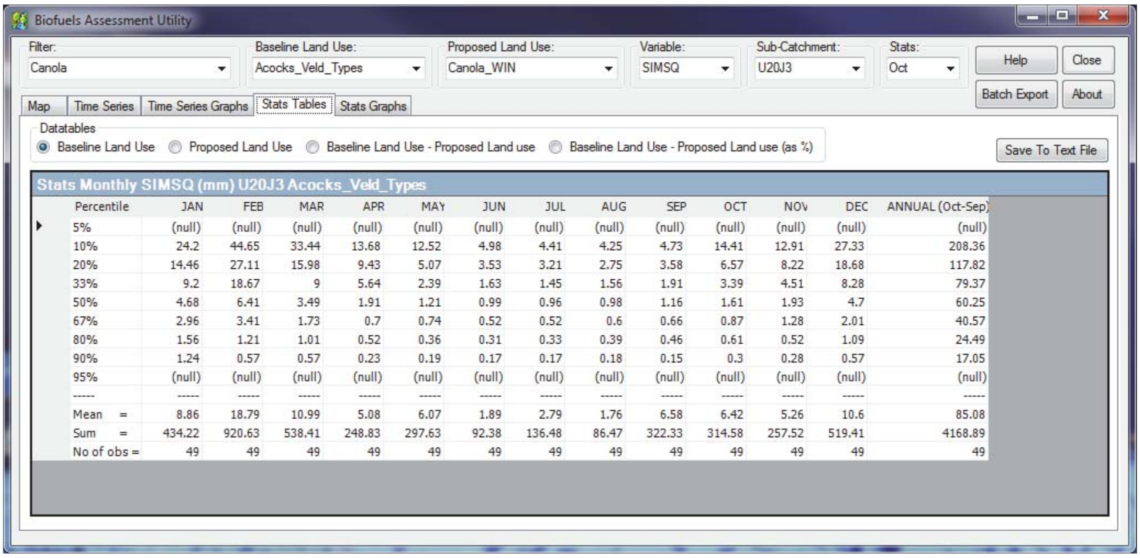


Figure 98 Biofuels Assessment Utility's *Time Series Graphs* tab

17.2.5 Stats tables

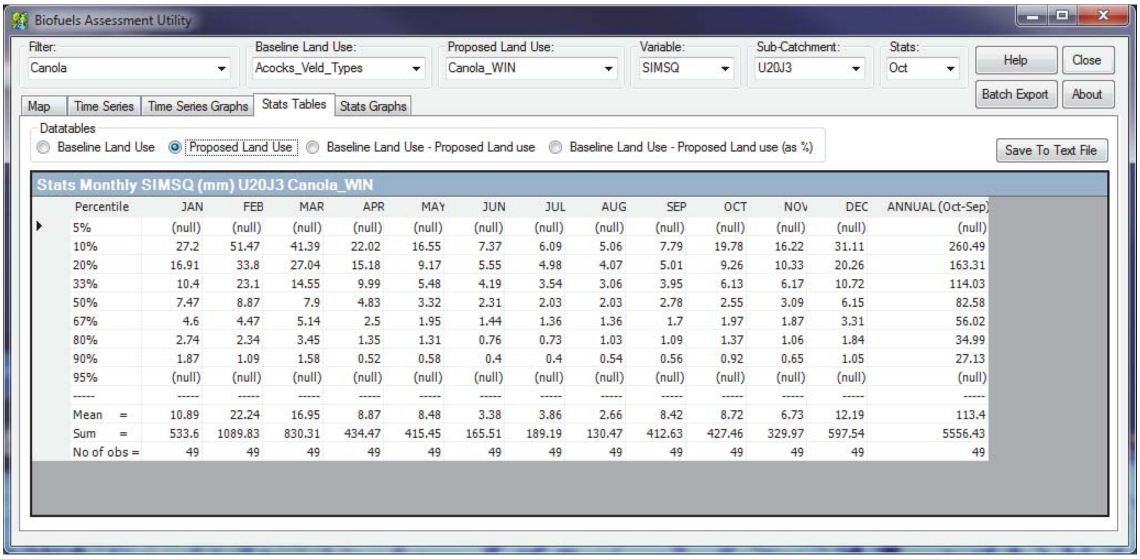
Statistics are only done on the monthly aggregated data. The start month for the calculation of annual statistics can be selected from the **Stats** *drop-down* option. These statistics can also be exported as comma separated (CSV) files. The **Stats Tables** tab displays the calculated statistics in tabular format for the selected sub-catchment's:

- **Baseline Land Use** (**Figure 99**), or
- **Proposed Land Use** (**Figure 100**), or
- the calculated **Change in Streamflow**, i.e. **Baseline Land Use - Proposed Land Use** (**Figure 101**), or
- the calculated change in the Mean represented as a percentage, i.e. **Baseline Land Use - Proposed Land Use as %** (**Figure 102**).



Percentile	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL (Oct-Sep)
5%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
10%	24.2	44.65	33.44	13.68	12.52	4.98	4.41	4.25	4.73	14.41	12.91	27.33	208.36
20%	14.46	27.11	15.98	9.43	5.07	3.53	3.21	2.75	3.58	6.57	8.22	18.68	117.82
33%	9.2	18.67	9	5.64	2.39	1.63	1.45	1.56	1.91	3.39	4.51	8.28	79.37
50%	4.68	6.41	3.49	1.91	1.21	0.99	0.96	0.98	1.16	1.61	1.93	4.7	60.25
67%	2.96	3.41	1.73	0.7	0.74	0.52	0.52	0.6	0.66	0.87	1.28	2.01	40.57
80%	1.56	1.21	1.01	0.52	0.36	0.31	0.33	0.39	0.46	0.61	0.52	1.09	24.49
90%	1.24	0.57	0.57	0.23	0.19	0.17	0.17	0.18	0.15	0.3	0.28	0.57	17.05
95%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean =	8.86	18.79	10.99	5.08	6.07	1.89	2.79	1.76	6.58	6.42	5.26	10.6	85.08
Sum =	434.22	920.63	538.41	248.83	297.63	92.38	136.48	86.47	322.33	314.58	257.52	519.41	4168.89
No of obs =	49	49	49	49	49	49	49	49	49	49	49	49	49

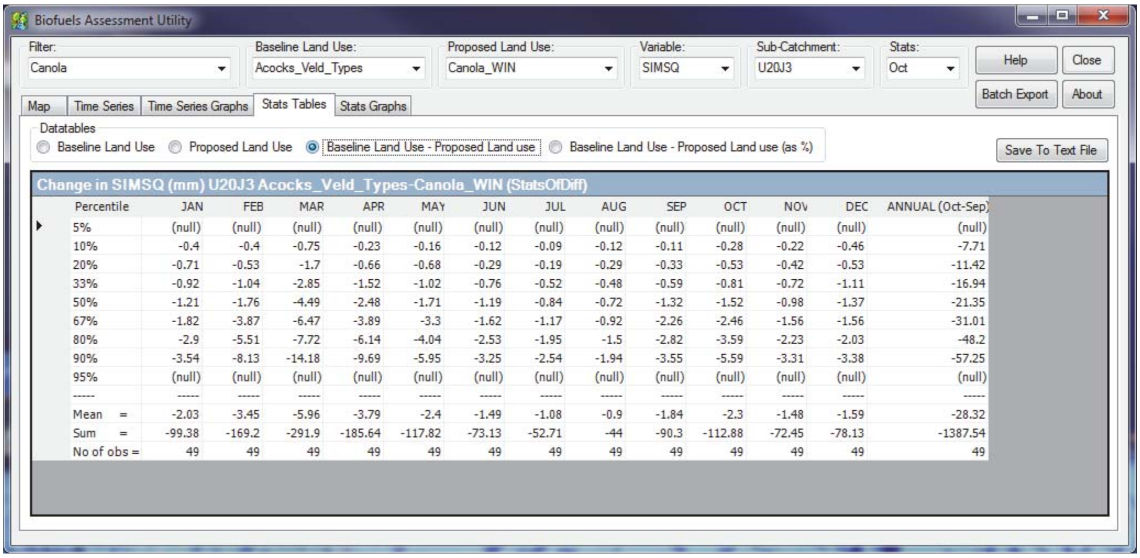
Figure 99 *Stats Tables* tab (Baseline Land Use)



Percentile	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL (Oct-Sep)
5%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
10%	27.2	51.47	41.39	22.02	16.55	7.37	6.09	5.06	7.79	19.78	16.22	31.11	260.49
20%	16.91	33.8	27.04	15.18	9.17	5.55	4.98	4.07	5.01	9.26	10.33	20.26	163.31
33%	10.4	23.1	14.55	9.99	5.48	4.19	3.54	3.06	3.95	6.13	6.17	10.72	114.03
50%	7.47	8.87	7.9	4.83	3.32	2.31	2.03	2.03	2.78	2.55	3.09	6.15	82.58
67%	4.6	4.47	5.14	2.5	1.95	1.44	1.36	1.36	1.7	1.97	1.87	3.31	56.02
80%	2.74	2.34	3.45	1.35	1.31	0.76	0.73	1.03	1.09	1.37	1.06	1.84	34.99
90%	1.87	1.09	1.58	0.52	0.58	0.4	0.4	0.54	0.56	0.92	0.65	1.05	27.13
95%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean =	10.89	22.24	16.95	8.87	8.48	3.38	3.86	2.66	8.42	8.72	6.73	12.19	113.4
Sum =	533.6	1089.83	830.31	434.47	415.45	165.51	189.19	130.47	412.63	427.46	329.97	597.54	5556.43
No of obs =	49	49	49	49	49	49	49	49	49	49	49	49	49

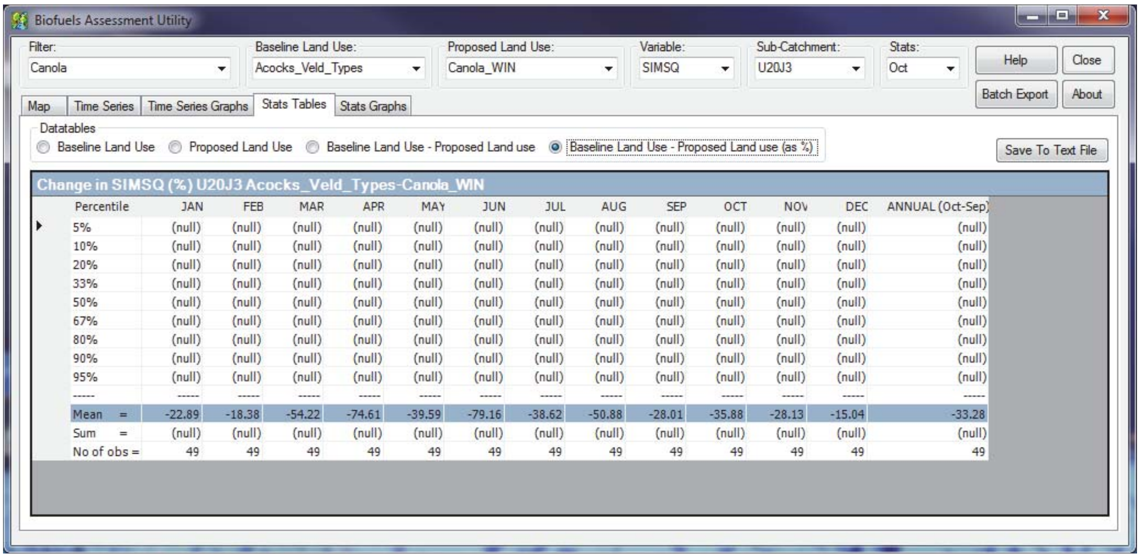
Figure 100 *Stats Tables* tab (Proposed Land Use)

The **Baseline Land Use - Proposed Land Use (as %)** is calculated by first determining the monthly and annual mean values for the respective land uses, and then subtracting the **Proposed Land Use** means from the corresponding **Baseline Land Use** means to determine their differences. The differences are then divided by the corresponding Baseline values and multiplied by 100 to get the monthly and annual changes as percentages. Subtracting the percentiles does not make mathematical sense, thus these are left empty in the table and only the **Mean** row is highlighted as seen in **Figure 102**.



Percentile	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL (Oct-Sep)
5%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
10%	-0.4	-0.4	-0.75	-0.23	-0.16	-0.12	-0.09	-0.12	-0.11	-0.28	-0.22	-0.46	-7.71
20%	-0.71	-0.53	-1.7	-0.66	-0.68	-0.29	-0.19	-0.29	-0.33	-0.53	-0.42	-0.53	-11.42
33%	-0.92	-1.04	-2.85	-1.52	-1.02	-0.76	-0.52	-0.48	-0.59	-0.81	-0.72	-1.11	-16.94
50%	-1.21	-1.76	-4.49	-2.48	-1.71	-1.19	-0.84	-0.72	-1.32	-1.52	-0.98	-1.37	-21.35
67%	-1.82	-3.87	-6.47	-3.89	-3.3	-1.62	-1.17	-0.92	-2.26	-2.46	-1.56	-1.56	-31.01
80%	-2.9	-5.51	-7.72	-6.14	-4.04	-2.53	-1.95	-1.5	-2.82	-3.59	-2.23	-2.03	-48.2
90%	-3.54	-8.13	-14.18	-9.69	-5.95	-3.25	-2.54	-1.94	-3.55	-5.59	-3.31	-3.38	-57.25
95%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean =	-2.03	-3.45	-5.96	-3.79	-2.4	-1.49	-1.08	-0.9	-1.84	-2.3	-1.48	-1.59	-28.32
Sum =	-99.38	-169.2	-291.9	-185.64	-117.82	-73.13	-52.71	-44	-90.3	-112.88	-72.45	-78.13	-1387.54
No of obs =	49	49	49	49	49	49	49	49	49	49	49	49	49

Figure 101 *Stats Tables* tab (Baseline Land Use - Proposed Land Use)



Percentile	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANNUAL (Oct-Sep)
5%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
10%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
20%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
33%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
50%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
67%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
80%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
90%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
95%	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
Mean =	-22.89	-18.38	-54.22	-74.61	-39.59	-79.16	-38.62	-50.88	-28.01	-35.88	-28.13	-15.04	-33.28
Sum =	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
No of obs =	49	49	49	49	49	49	49	49	49	49	49	49	49

Figure 102 *Stats Tables* tab (Baseline Land Use - Proposed Land Use as %)

17.2.6 Stats graphs

This displays the probability of exceedance values in graphical format. The **Graph Options** enables annual or monthly curves to be switched on or off in the display. The graphs corresponding to the selection made on the **Stats Tables** tab will be plotted on this tab with the exception of **Baseline Land Use - Proposed Land use (as %)** as there are no percentiles calculated for this table. For the **Baseline Land Use - Proposed Land use** and **Baseline Land Use** options, the graphs in **Figure 103** and **Figure 104** are displayed respectively.

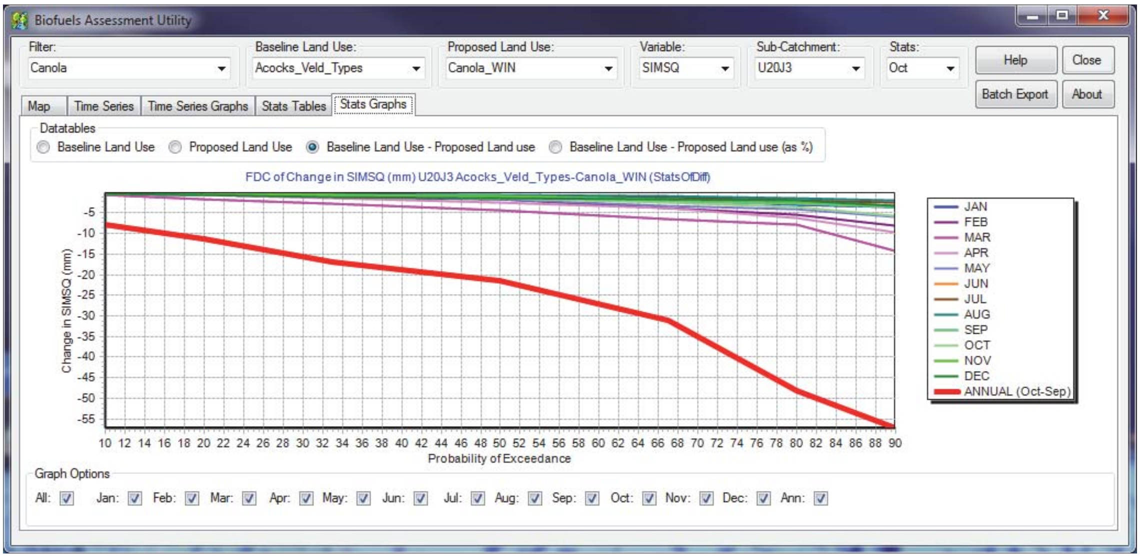


Figure 103 Time Statistics Graphs tab (Baseline Land Use - Proposed Land Use)

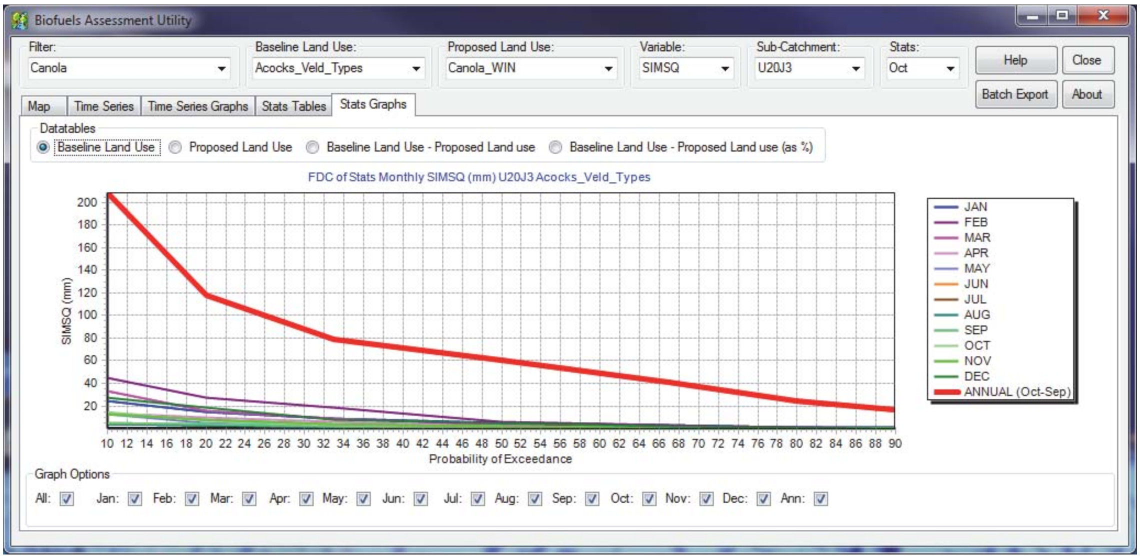
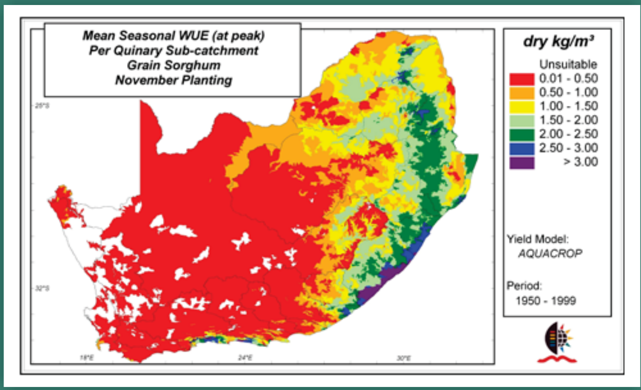
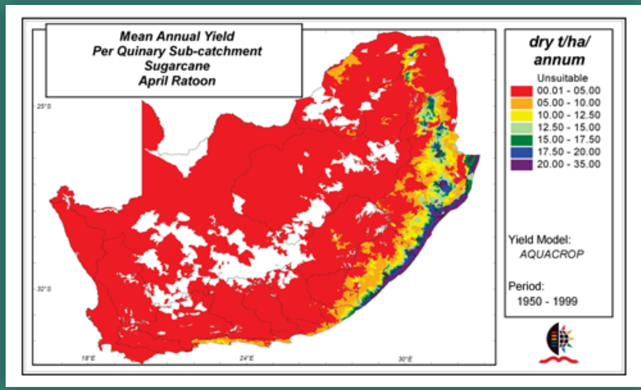


Figure 104 Time Statistics Graphs tab (Baseline Land Use)

17.3 Batch Export

The **Batch Export** button is linked to the options on the **Stats Tables** tab (c.f. **Section 17.2.5** for more information) and will thus export the calculated mean based on the option selected in this tab. The start month for the annual statistics is dependent on the selection from the **Stats** *drop-down* option. The data are exported to a comma delimited file (*.csv) for the catchments listed in an input file. An example file (*"CatchmentList.txt"*) is provided.





9781431207503