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

<table>
<thead>
<tr>
<th>Crop</th>
<th>Location</th>
<th>Country</th>
<th>Year</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarbeet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain sorghum</td>
<td>Bushland Texas</td>
<td>USA</td>
<td>05/1993</td>
<td><em>AQUACROP</em></td>
</tr>
<tr>
<td>Canola</td>
<td>Pincher Creek Alberta</td>
<td>Canada</td>
<td>Unknown</td>
<td>Kienzle (2015)</td>
</tr>
<tr>
<td>Canola</td>
<td>Swift Current Saskatchewan</td>
<td>Canada</td>
<td>Unknown</td>
<td>Kienzle (2015)</td>
</tr>
</tbody>
</table>

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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 ($E_{To}$) 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

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Planting date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarcane - summer</td>
<td>1st February</td>
</tr>
<tr>
<td>Sugarcane - winter</td>
<td>1st April</td>
</tr>
<tr>
<td>Sugarbeet - summer</td>
<td>1st September</td>
</tr>
<tr>
<td>Sugarbeet - winter</td>
<td>1st June</td>
</tr>
<tr>
<td>Grain sorghum</td>
<td>1st November</td>
</tr>
<tr>
<td>Soybean</td>
<td>1st November</td>
</tr>
<tr>
<td>Canola - winter</td>
<td>1st April</td>
</tr>
<tr>
<td>Canola - summer</td>
<td>1st June</td>
</tr>
</tbody>
</table>

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](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 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.

**Seasonal yield**

*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 24c* 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).
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).
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.
**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 1\textsuperscript{st} 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 31\textsuperscript{st} December 1999.

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.

**Risk of crop failure**
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.
Crop season length (GRO)
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.
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.

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.

**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 11 to 121 days (< 4 months) as shown in Figure 32a (red areas), with only 69 quinaries exhibiting average values below 100 days.

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.
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.
Figure 34  Differences in seasonal yield derived using the AQUACROP (a) and SWB (b) models for 113 quinaries in the Western Cape region
Figure 35  Differences in yield variability derived using the AQUACROP (a) and SWB (b) models for 113 quinaries in the Western Cape region
Figure 36  Differences in water use efficiency derived using the AQUACROP (a) and SWB (b) models for 113 quinaries in the Western Cape region
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).

![Western Cape Canola Potential](image)

**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 5838 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 (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.
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>
<thead>
<tr>
<th>Minimum</th>
<th>Median</th>
<th>Mean</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.05</td>
<td>0.10</td>
</tr>
</tbody>
</table>

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:

$$YLD_A = \frac{365 \cdot YLD}{GRO}$$

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.
(b) Mean Seasonal WUE (at maturity) Per Quinary Sub-catchment Sugarcane April Ratoon

(dry kg/m³)

Yield Model: AQUACROP
Period: 1950 - 1999

(c) Mean Seasonal WUE (at maturity) Per Quinary Sub-catchment Sugarbeet September Planting

(dry kg/m³)

Yield Model: AQUACROP
Period: 1950 - 1999
Figure 41  Mean seasonal WUE (dry kg m$^{-3}$) calculated at maturity for selected bioethanol feedstocks (a-e) 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).
Figure 43  Mean seasonal WUE (dry kg m⁻³) calculated by AQUACROP (peak) for selected bioethanol feedstocks (a-e) planted on different dates
4.2.3.8 Yield variability

The inter-seasonal variation in yield for the selected bioethanol and biodiesel crops is 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.

Figure 44  Mean seasonal WUE (dry kg m\(^{-3}\)) calculated by AQUACROP (peak) for selected biodiesel feedstocks (a-c) planted on different dates
Figure 45  Variability of inter-seasonal yield (%) for selected bioethanol feedstocks (a-e) planted on different dates
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 is 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.
Figure 47  Variability of inter-seasonal WUE (%) calculated at maturity for selected bioethanol feedstocks (a-e) 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 31\textsuperscript{st} 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.
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.
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.
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
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 as 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.
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.
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.
Figure 55  Average length of the growing season (from planting to maturity date) for selected bioethanol 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.
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.
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

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

\(^{a}\) 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 produce 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 m³ of bioethanol (similar to the figure given in the above table).

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

<table>
<thead>
<tr>
<th>Crop</th>
<th>Extraction yield (L t⁻¹)</th>
<th>Crop mass (t)</th>
<th>Feedstock yield (t ha⁻¹)</th>
<th>Harvest area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sugarbeet</td>
<td>75⁺</td>
<td>13 333</td>
<td>95.00⁺</td>
<td>140</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>80⁺</td>
<td>12 500</td>
<td>63.88⁺</td>
<td>196</td>
</tr>
<tr>
<td>Yellow maize</td>
<td>402⁺</td>
<td>2 488</td>
<td>4.63⁺</td>
<td>537</td>
</tr>
<tr>
<td>Grain sorghum</td>
<td>417⁺</td>
<td>2 398</td>
<td>2.66⁺</td>
<td>902</td>
</tr>
<tr>
<td>Canola</td>
<td>413⁺</td>
<td>2 421</td>
<td>2.00⁺</td>
<td>1 211</td>
</tr>
<tr>
<td>Sunflower</td>
<td>398⁺</td>
<td>2 513</td>
<td>1.27⁺</td>
<td>1 979</td>
</tr>
<tr>
<td>Soybean</td>
<td>185⁺</td>
<td>5 405</td>
<td>1.70⁺</td>
<td>3 179</td>
</tr>
</tbody>
</table>

⁺ multiply by crop yield in fresh (i.e. wet) tons  
⁺⁺ multiply by crop yield in dry tons  
⁺⁺⁺ Maclachlan (2012)  
⁺⁺⁺⁺⁺ Lemmer and Schoeman (2011)  
⁺⁺⁺⁺⁺⁺ 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 m³ 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

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

<table>
<thead>
<tr>
<th>Province</th>
<th>Arable land in South Africa (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Potential</td>
</tr>
<tr>
<td>Free State</td>
<td>4 221 423</td>
</tr>
<tr>
<td>North West</td>
<td>3 360 459</td>
</tr>
<tr>
<td>Western Cape</td>
<td>2 454 788</td>
</tr>
<tr>
<td>Eastern Cape</td>
<td>1 172 901</td>
</tr>
<tr>
<td>Limpopo</td>
<td>1 700 442</td>
</tr>
<tr>
<td>Mpumalanga</td>
<td>1 734 896</td>
</tr>
<tr>
<td>KwaZulu-Natal</td>
<td>1 199 675</td>
</tr>
<tr>
<td>Gauteng</td>
<td>438 623</td>
</tr>
<tr>
<td>Northern Cape</td>
<td>454 465</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16 737 672</strong></td>
</tr>
</tbody>
</table>

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 & CO₂ 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.