Scoping Study on Water Use of Crops/Trees for Biofuels in South Africa

Report to the

WATER RESEARCH COMMISSION

by

GPW Jewitt, HW Wen, RP Kunz and AM Van Rooyen

School of Bioresources Engineering and Environmental Hydrology

University of KwaZulu-Natal

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Executive Summary

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Worldwide, the demand for energy has grown rapidly over the past decade, resulting in the highest oil prices ever seen during 2008. Utilising the potential for the production of fuels from alternative sources has been a priority for many countries, particularly the developed countries of Europe and America. The production of ethanol and diesel from vegetable biomass and oils (i.e. biofuels), has been promoted as an environmentally friendly alternative to oil-based fuels. In line with many countries across the world, South Africa has developed its own biofuels strategy [i.e. The Biofuels Industrial Strategy of South Africa NBIS DME, 2007]. The South African strategy is generally considered to be conservative, tempering the international drive towards large-scale biofuel production with a pragmatic approach towards a goal of 2% biofuel penetration within five years.

Impacts on water resources are a major concern in the production of biofuels with several international studies highlighting that water use in the feedstock production phase is the biggest unknown factor when quantifying the water used in biofuel production. Such uncertainties are exacerbated in the case of dryland crop production, where water use by a crop is even more difficult to measure or estimate. In South Africa, the impacts of land use and land use change on the hydrological cycle and their potential impact on water resources are well known. Thus, in 2007 the Water Research Commission instigated a study to assess both the potential growing areas and water use of potential biofuel feedstocks in South Africa. This scoping study has been undertaken by the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, using tools and databases developed over many years. In particular, the project draws upon information from the South African Atlas of Hydrology and Agrohydrology (Schulze, 2006).

The objectives of this WRC solicited project were to:

1. Identify all crops/trees grown in South Africa that can be used as a biofuel feedstock, for both bioethanol and biodiesel.
2. Assess the available knowledge on water use of crops/trees identified under specific objective 1.
3. Estimate the water requirements of selected crops/trees where information on water use is lacking but crop parameters are available by applying appropriate models.
4. Determine existing gaps in knowledge regarding water use and crop parameters, and recommend priorities for future research.

Objectives 1 and 2 were met through a comprehensive analysis of available literature. Through this process 20 crops were identified with the potential to produce biofuel in South Africa. Information regarding their growing requirements and potential water use, particularly regarding the extent to which this information could be used to derive model parameters, are summarised through Sections 2.1 to 2.20 of the main report. Based on discussions with key stakeholders and guided by the South African National Biofuels Industrial Strategy, (DME, 2007), a sub-set of these were investigated in more detail and summary table appears next.

TABLE 1 *Climatic thresholds for potential SA Biofuel crops derived from available literature*

Crops	MAP (mm)	MMR (mm)	MAT (^{o}C)	T ave (^{o}C)	T min (^{o}C)	T max (^{o}C)	Planting date	Growth days
Canola	500-1000	-	-	-	> 5	< 25	01 Jun	140
Cassava	> 1000	-	20-29	-	-	-	-	-
Jatropha	500-1500	-	11-28	-	Frost free areas		-	-
Sorghum	-	450-650	-	20-25 (Jan T >21)	-	-	01 Nov	115
Soybean	-	550-700	-	20-30	-	-	01 Nov	150
Sugarbeet	550-750	-	15-25	-	> -1	-	01 Aug	200
Sugarcane	850-1500	-	> 18	-	Jun-Jul > 5	-	-	-
Sunflower	-	400-600	-	18-25 (Jan T >19)	-	-	01 Dec	125

Note. MAP – mean annual precipitation; MMR – mean monthly rainfall totals over growing season; MAT – mean annual temperature; T ave – daily mean air temperatures over growing season; T min – daily minimum air temperature over growing season; T max – daily maximum air temperature over growing season; Jan T – mean daily temperature in January.

Objective 3 was completed using information from various sources to identify potential growing areas of the crops listed in Table 1, with the use of a commercial GIS package. The study showed that based on climatological drivers only, canola, sugarbeet, Jatropha and possibly sweet sorghum have the potential to expand production areas. The *ACRU* Agrohydrological modelling system was then used to estimate the water use of these crops. Water use is estimated relative to that of a reference land use, in this case the Acocks Veld Types (Adcocks, 1953) for the point of interest, following the approach established for the quantification of Stream Flow Reductions Activities according to Section 36 of South Africa's National Water Act. Output from this analysis is presented in a series of maps which show that under dryland conditions, only sweet sorghum and sugarcane may have the potential to use substantially more water than the reference natural vegetation.

Finally, an analysis of the areas of uncertainty complemented by a review of national and international literature provides a summary of key research needs regarding the water use of biofuel feedstock crops in South Africa. The most significant of these are:

- A need for better knowledge of optimal growing conditions and water use for each crop.
- Which are the optimal crops for biofuel production in South Africa (with high uncertainties around sweet sorghum, sugarbeet and other emerging crops).
- More detailed mapping/input of biophysical conditions if benefits and impacts are to be adequately assessed at local scales.
- A need for detailed water use efficiency assessments.
- The potential impact of emerging cellulosic feedstock and potential water use impacts of woody vegetation used as a biofuel feedstock.
- The potential for climate change to result in shifting cropping patterns, regions and water use.

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The members of the Steering Committee:

Dr AJ Sanewe	Water Research Commission (Chairman)
Dr GR Backeberg	Water Research Commission
Mr J Potgieter	Department of Agriculture
Ms MM Nthai	Department of Agriculture
Mr PS van Heerden	PICWAT
Prof ES du Toit	University of Pretoria
Mr AT van Coller	Department of Agriculture: AES
Prof CS Everson	CSIR
Ms MJ Gabriel	Department of Agriculture: WUID
Mr L Nndangi	Department of Water Affairs and Forestry
Ms N Fourie	Department of Water Affairs and Forestry
Dr JM Steyn	University of Pretoria

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1. Introduction

Worldwide, the demand for energy has grown rapidly over the past decade, resulting in the highest oil prices ever seen during 2008. Utilising the potential for the production of fuels from alternative sources has been a priority for many countries, particularly the developed countries of Europe and America. The production of ethanol and diesel from vegetable biomass and oils, (i.e. biofuels has been promoted as an environmentally friendly alternative to oil based fuels). However, many have warned against the rush to plant large areas of cropland for biofuel production, warning against, *inter alia,* potential consequences for loss of food production, questions about the susceptibility of many initiatives and queries about the water use of biofuel production, from the crop growth to the final synthesis of the liquid fuel.

In line with many countries across the world, South Africa has developed its own biofuels strategy [i.e. The Biofuels Industrial Strategy of South Africa NBIS (DME, 2008)]. The South African strategy is generally considered to be conservative, tempering the international drive towards large-scale biofuel production with a pragmatic approach towards a goal of 2% biofuel penetration within five years. The focus is on the production of bioethanol from sugarcane and sugarbeet and biodiesel from sunflower, canola and soya beans. Citing food security concerns, it specifically excludes both maize and Jatropha, two feedstocks which have received much attention both locally and internationally.

As highlighted in the NBIS, impacts on water resources are a major concern in the production of biofuels. Several international studies (e.g. Uhlenbrook, 2007) have highlighted that water use in the feedstock production phase is the biggest unknown when quantifying the water used in biofuel production. Such uncertainties are exacerbated in the case of dryland crop production, where water use by a crop is extremely difficult to measure or estimate. In South Africa, the impacts of land use and land use change on the hydrological cycle and their potential impact on water resources are well known. Principle 18 in the preamble to the National Water Act of South Africa (DWAF, 1998) states:
"Since many land uses have a significant impact upon the water cycle, the regulation of land use shall, where appropriate, be used as an instrument to manage water resources within the broader integrated framework of land use management".

This principle has been given effect in legislation by Section 36(2) of the National Water Act of 1998 through the concept of a "stream flow reduction activity", or SFRA, defined as:
"… any activity (including the cultivation of any particular crop or other vegetation) … [that] … is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly"

Thus, in terms of the NWA, it is necessary to assess the potential water use of potential biofuel feedstocks in South Africa. In this context, WRC solicited project K4/1772, a scoping study on water use of crops/trees for biofuels, aims to:

- Identify all crops/trees grown in South Africa that can be used as a biofuel feedstock, for both bioethanol and biodiesel.
- Determine the available knowledge on water use of crops/trees identified above.
- Estimate the water requirements of crops/trees where information on water use is lacking but crop parameters are available by applying appropriate models.
- Determine existing gaps in knowledge regarding water use and crop parameters, and recommend priorities for future research.

1.1. The Biofuels Context

Growing impetus in the production of biofuel has been highlighted in both the United States of America and the European Union (Demirbas, 2007) particularly after the initiation of the Bioenergy Agreement in 1978 by the International Energy Agency (IEA). In parallel and often in response to the demand created by the European Union and American markets, many energy crop-based (crops of lignocellulose nature) projects have since been initiated in those countries, as well as in other, often developing, parts of the world where the climate is more favourable for their production. Brazil and countries in the European Union (EU) together with the USA are the current leading countries for biofuel production (both bioethanol and biodiesel) from food crops (Wright, 2006). The major feedstock in Brazil is sugarcane, while the US uses maize grain. Asia, however, is considered, the largest potential producer of bioethanol from crop residues and wasted crops, using large quantities of rice straw, wheat straw, and maize stover as bioethanol feedstock (Kim and Dale, 2004; Reijnders and Huijbregts, 2006). In addition, many parts of Africa are being considered as potential biofuel feedstock producers by international investors. In southern Africa, Tanzania, Mozambique and Malawi have already instigated biofuel projects using a wide range of feedstocks.

Renewable energy resources (such as biomass energy) are more evenly distributed across the globe than fossil and nuclear resources. Biomass energy includes both traditional uses (e.g. firing for cooking and heating), which is "low-tech", relatively inefficient and extensively applied in developing countries, as well as modern uses (e.g. electricity and steam production, and liquid biofuels). The use of fossil fuels in the present energy system is considered by many to be unsustainable because of equity issues as well as environmental, economic, and geopolitical concerns that have far reaching implications into the future (Foidl et al*.,* 1996; Kim and Dale, 2004; Demirbas, 2007). The encouragement of biofuel production over the past decade is primarily due to its potential in achieving sustainable development, reduction of greenhouse gas emissions, increasing regional development, improving social structure and agricultural economy, and securing energy supply (Hamelink and Faaij, 2006; Kondili and Kaldellis, 2006; Reijnders and Huijbregts, 2006; Demirbas, 2007).

Biomass of various origins is recognised as a major renewable energy source in the production of biofuels (methanol, ethanol, hydrogen, and synthetic diesel) and replacement of fossil fuels (Hamelink and Faaij, 2006; Demirbas, 2007). Biomass appears to be an attractive feedstock for biofuel production for three main reasons:

- It is a renewable resource that could be sustainably grown in the future through appropriate management practices.
- It is perceived that the use of biomass results in no net releases of carbon dioxide into the atmosphere owing to the photosynthetic processes.
- Its use could have significant economic potential provided that fossil fuel prices increase in the future.

However, several authors have cautioned against the implementation of commercial biofuel production because of potential environmental impacts (McLaughlin and Walsh, 1998; Kim and Dale, 2004; Wright, 2006; Demirbas, 2007) In assessing environmental tradeoffs between biofuel technologies and the fossil fuel technologies, there are three important considerations most often raised:

- The agronomic attributes of the bioenergy cropping system, including its use of water for growth and its effect on soil and water quality.
- The net effect of any differences between these and the land use system it replaces.
- The quality and quantity of energy that is produced from the feedstock per unit of energy expended, and per unit of environmental cost of the fossil energy it replaces (Bastianoni and Marchettini, 1996; McLaughlin and Walsh, 1998).

Biofuel feedstocks can be defined as those annual and perennial crops that are cultivated to produce three types of bioenergy (i.e. solid, liquid or gas) through conversion processes (Fig. 1). Food crops can be used to produce biofuel (Tuck et al*.,* 2006), although lignocellulosic biomass such as crop residues and sugarcane bagasse are often argued to be more favourable due to better economic prospects (Hamelink and Faaij, 2006), and also to avoid conflicts between human and industrial use (Kim and Dale, 2004). The full utilisation of crop residues should, however, accompany careful farm management practices to maintain soil organic carbon levels (Reijnders and Huijbregts, 2006) and to avoid increased soil erosion and decreased soil organic matter (Kim and Dale, 2004).

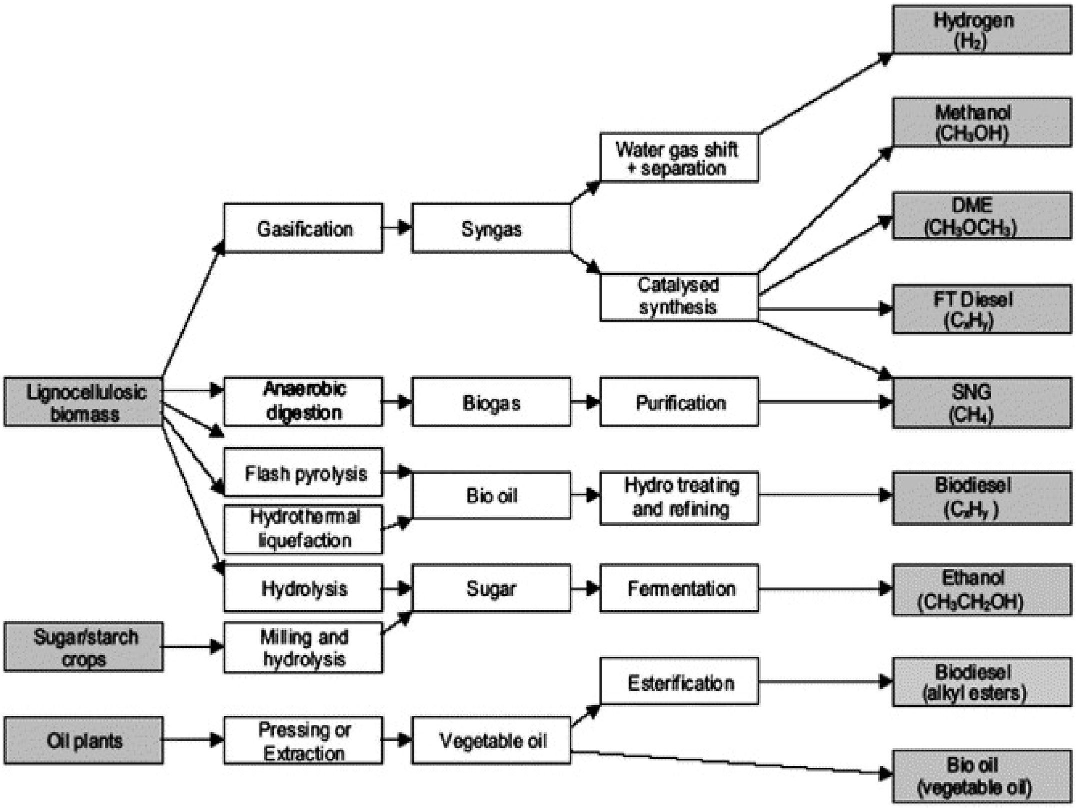

FIGURE 1 *Overview of conversion routes from crops to biofuels (Hamelink and Faaij, 2006).*

Tuck et al. (2006) have divided biofuel crops into four major groups:

- *Oil crops* (e.g. sunflower, soya beans, sunflower, ground nut and palm);
- *Cereals* (e.g. wheat, oat and rye);
- *Starch and sugar crops* (e.g. potato, maize, sugarcane, sugarbeet and cassava) and
- *Solid biofuel crops* (e.g. sorghum, whole crop maize.).

The oil crops are commonly the raw material for production of biodiesel while starch and sugar crops are most often used for the production of bioethanol (Figure 2).

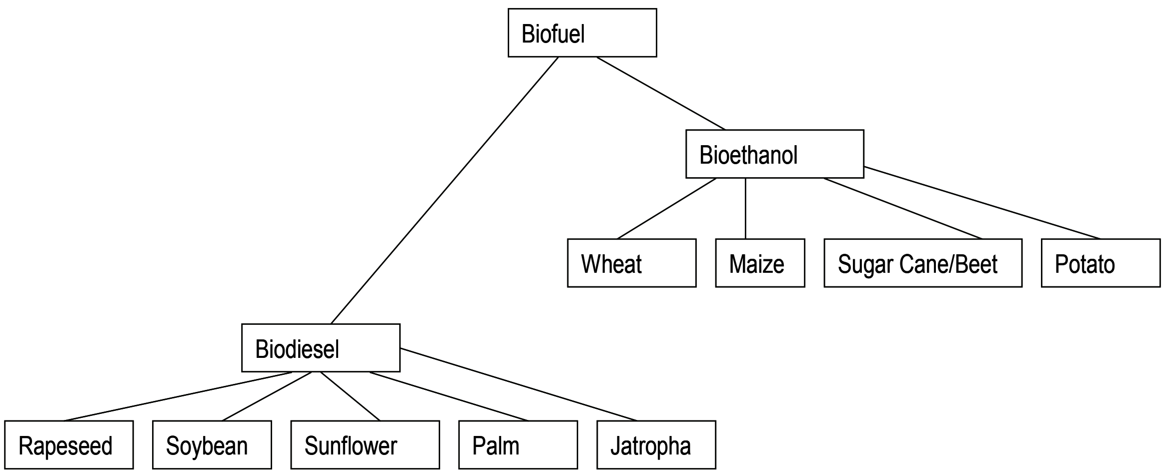

FIGURE 2 *Common sources of liquid biofuel for automotive use.*

1.1.1. Bioethanol

Ethanol is the most widely used liquid biofuel and continues to be of interest because of the renewable nature of the raw materials, and its low combustion by products and greenhouse gasses. Bioethanol generally has a high octane value and is suitable for use in lead free petrol (Nguyen and Prince, 1996). It is an alcohol and is produced from fermented sugars, starches or from cellulosic biomass, i.e. herbaceous and woody plants (Kim and Dale, 2004; Demirbas, 2007). Carbohydrates in plant materials can be converted to sugars by hydrolysis processes and then fermented to produce alcohol by the action of microorganisms usually yeast. The resulting alcohol is ethanol. Ethanol from grains is produced by the dry milling process, in which starch in grain is converted to dextrose (sugar) and then fermented and separated by distillation to produce ethanol (Fig. 2). The estimated yield of ethanol from the grain is based on its starch content (Kim and Dale, 2004; Demirbas, 2007).

The value of any biomass feedstock for fermentation also depends on the ease with which it can be converted to sugars. In the case of carbohydrates, hemicellulose is more readily convertible than cellulosic materials, (Demirbas, 2007). Most commercial bioethanol production use fermented sugars from sugarcane and sugarbeet, as starches and cellulosic biomass usually requires expensive pre-treatment (via mechanical and physical actions e.g. steam) to destroy the cell structure for further chemical and biological treatment (Hamelink and Faaij, 2006; Demirbas, 2007). As a result, the cost of producing ethanol is often higher than for petrol (Nguyen and Prince, 1996). According to Nguyen and Prince (1996), the cost of producing any commercial product, such as ethanol, decreases with increased production plant size. However, as the areas of crop plantation increases, the average crop transport distance and hence the transport cost can also increase. It is, however, possible to reduce ethanol costs by using mixed crops to extend the processing season and by optimising plant capacity – balancing crop transport costs (which increases with plant size) against the decreasing production costs through model applications (Nguyen and Prince, 1996).

1.1.2. Biodiesel

Biodiesel is considered by many to be an environmentally-friendly alternative to petroleum-based diesel fuel because of its potential for reducing CO_2 and sulphur levels in exhaust emissions (Kim and Dale, 2004; Canoira et al*.,* 2005; Demirbas, 2007). It is composed of a mixture of mono-alkyl esters (methyl and ethyl) and fatty acids obtained from vegetable oil, algae, animal fats or used cooking oil (DME, 2003; Cardone et al*.,* 2003; Bouaid et al*.,* 2005; Reijnders and Huijbregts, 2006; Talens et al*.,* 2006; Demirbas, 2007; Biodiesel SA). The reaction between glycerides and short chain alcohols, such as methanol and ethanol, yields glycerol and fatty acids methyl esters, which is known as biodiesel (Foidl et al*.,* 1996; Talens et al*.,* 2006). Both the methyl and ethyl esters are well suited as fuel substitutes in terms of engine performance.

Conversion of vegetable oils and animal fats into biodiesel has progressed rapidly over the past few years. The vegetable oils can be converted to their (m)ethyl esters via the transesterification process to lower the viscosity of the oil, in the presence of a catalyst (usually potassium and/or sodium alkoxides), except when oils are transesterified using supercritical methanol. The transesterification process is potentially a less expensive way of transforming complex vegetable oil molecules into simpler molecule strands required by regular diesel combustion engines (Demirbas, 2007).

The cost of biodiesel production varies depending on many factors, including the cost of the feedstock, geographic area, variability of crop production from season to season, and the price of crude petroleum. To offset the high cost of biodiesel production, by-products such as high-quality glycerol (used in soap production) produced when cooking oils are used as raw material can also be marketed. Demirbas (2007) suggest that there are large amounts of low-cost oils and fats such as restaurant wastes and animal fats to be used as biodiesel feedstock. However, low quality biodiesel would result due to high fatty acid contents that cannot be transesterified using alkaline catalysts.

1.2. Biofuel Production in South Africa

Energy, like water, affects all aspects of development (socially, economically, environmentally and growth of industries). Energy plays a critical role in the development process, particularly in developing countries, where modern and traditional forms of energy are used intensively in both domestic and production arena (Amigun et al*.,* 2008). South Africa relies heavily on its substantial coal resources to meet its energy needs. However, South Africa recognises the emission of greenhouse gases from fossil fuels, such as coal, causes great environmental damage and its consequential climate change. These concerns were articulated during the Johannesburg World

Summit on Sustainable Development in 2002 and commitments were made in the Johannesburg Declaration to promote renewable energy as a means of achieving sustainable development (DEAT, 2002).

South Africa, like other countries abroad, is awakening to the pressing energy demands and increasing oil prices, as well as the demand for biofuel feedstock from the northern hemisphere. A major portion of the nation's expenditure is on imported fuels, and diversification of energy supply would greatly relieve this economic burden.

The SA Government identified essential elements for Renewable Energy Implementation in a White Paper on Renewable Energy (2003) as follows:

- *Sustainable Development* – renewable energy produced from sustainable natural resources contribute to sustainable development, and is not subject to disruption by international crisis or limited energy supplies.
- *Enabling Environment* – the abundant renewable energy resources needs to be made cost competitive against the fossil-based energy (coal) supply industry through fiscal and financial support mechanisms within an appropriate legal and regulatory framework.
- *Institutional Arrangements (Liquid Fuels and Gas Sector)* – the Central Energy Fund Act (Act 38 of 1977) provides legislation to which levies can be imposed on liquid fuels products for collection into the Central Energy Fund and/or the Equalisation Fund. These funds can then be used for renewable energy purposes. The Gas Act (Act 48 of 2001) and amended Petroleum Products Act provide a basis for integration of renewable energy – derived liquid fuels such as biodiesel and ethanol and landfill gas into the gas and petroleum industry regulatory framework.
- *Renewable Energy Technologies* – for short-term objectives, technologies that are currently available in South Africa are to be used for renewable energy production. It is emphasised that local contents should be maximised in order to minimise production and operation costs, as well as the promotion of employment opportunities.

The South African government's long-term goal is the establishment of a renewable energy industry that provides in the future a sustainable, fully subsidised alternative to fossil fuels; while the medium-term (10-year) target is:

"10 000 GWh (0.8 mtoe) renewable energy contribution to final energy consumption by 2013, to be produced mainly from biomass, wind, solar and small-scale hydro. The renewable energy is to be utilised for power generation and non-electric technologies such as solar water heating and biofuels. This is approximately 4% (1667 MW) of the projected electricity demand for 2013 (41539 MW)."

To achieve this target, a phased and flexible strategy is required. The Department of Minerals and Energy has proposed such a strategy in the NBIS (DME, 2007) of the Republic of South Africa (2007), the key aspects of which have been reported above.

1.3 Approach to Project and Structure of this Report

This project is considered a pilot scoping project. As such, it has been a desktop study drawing heavily on information available from a wide range of published and unpublished information sources. A review of the information regarding growing conditions and water use of several of the crops that could be grown in South Africa is presented in Chapter 2. Maps of the potential growing areas and likely water use for some of these crops are shown in Chapter 3. Based on the literature review and results obtained in Chapter 3, recommendations for further research are made in Chapter 4.

2. Characteristics of Potential Biofuel Crops for South Africa

2.1 Canola/Rapeseed (*Brassica napus* L.)

Rape or canola is an annual, cruciferous herb that produces tuber-like rutabagas below ground and vegetation similar to kale above ground (Duke, 1983; Poteet, 2006; FAO, 2006). Flowering takes place from late spring to autumn, while fruit development occurs in early summer to autumn (Duke, 1983). According to Oplinger et al. (1989a), the spring varieties of *B. napus* mature 74 to 140 days after seeding. Canola has been proposed as a feedstock for a major biofuel project in the Eastern Cape.

FIGURE 3 *The canola (rapeseed plant) in flower (a) and the seed produced (b).*

2.1.1 Utilisation of Canola

Oil extracted from canola is used in the food industry, in lubricants, illuminants and soap manufacturing; and more recently has received much attention as a biodiesel feedstock, while the residual seed cake is used as livestock feed (Duke, 1983; Oplinger et al*.*, 1989a). In many eastern countries, the residual cake is used as fertiliser for other field crops (Downey and Röbbelen, 1989). Canola oil is the principle commercial source of erucic acid, which is used in the production of other chemical products such as emulsifying agents, polyamide fibres and resins. As a medicine, canola oil is used in massages and oil baths; the seed powder is further used as a folk remedy for cancer (Duke, 1983). The use of canola cake in livestock feed, however, should be limited due to its toxicity. According to Duke (1983), canola contains goitrogenic L-5-vinyl-2-thiooxazolidone, which induces goitre growth in animals consuming large quantities. The consumption of canola has also been related to several poisoning syndromes in animals, affecting respiratory, digestive, nervous, and urinary systems (Duke, 1983). Due to the presence of glucosinolates, canola meal is also used as a natural pesticide in peanut cultivation (Bhardwaj et al*.*, 1996). With regard to farming practices, canola can be grown in rotation with grains, flax, maize, sugarbeet or a fallow period, however it should not be grown in sequence with itself, mustard, or sunflowers (Duke, 1983).

TABLE 2 *Utilisation of* canola *(FAO, 2006).*

Main use	Detailed use	Used part
Food and beverage	Protein	Seeds
Food and beverage	Vitamins	Seeds
Food and beverage	Minerals	Seeds
Animal food (feed)	Protein	Entire plant
Animal food (feed)	Vitamins	Entire plant
Animal food (feed)	Minerals	Entire plant
Material	Lipids/oil and fats	Seeds
Fuels	Petroleum substitutes/alcohol	Seeds

2.1.2 Present distribution and extent of plantings and yield

Canola is one of the earliest domesticated plants with a primary centre near the Himalayan region (Downey and Röbbelen, 1989). It is commonly produced in Canada, China and many parts of western Europe (Poteet, 2006). The distribution of canola is limited to temperate and sub-temperate regions, due to its vulnerability to contracting fungi, [a total of 33 listed by Duke (1983)]; bacterial and virus-causing diseases, [a total of 11 listed by Duke (1983)]; 14 insect pests (Duke, 1983); and nematodes, which seriously reduce crop yields (Poteet, 2006). In South Africa, major slug damage has been reported in recent (2007) crops ((De Villiers et al., 2006).

The oil content for canola is high, averaging between 37 to 50% per seed (Poteet, 2006). Seed yields can vary from 0.9 to 3.0 tonne/ha, with North Africa only obtaining 0.3 to 0.4 tonne/ha (Duke, 1983). Yields of 1.5 tonne/ha would yield approximately 50.5 tonnes of oil and 11 tonnes of a high protein meal after extraction (Poteet, 2006). However, the drying of the seed to obtain optimal oil production is reported to be highly problematic.

According to Oplinger et al. (1989a), canola should be planted 6 to 8 plants per square foot (~929 cm^2) to produce optimal yields.

2.1.3 Biophysical requirements

Brassica napus L. needs "loose", medium textured and well-drained soils (Duke, 1983a; Oplinger et al*.,* 1989; FAO, 2006) – refer to **TABLE 3**. It also requires sunny days and cool nights for germination. Canola is more adapted to cooler climates, and is best suited to regions receiving winter rainfall (such as the Western Cape region) or high elevations (Poteet, 2006). The plant is reported to tolerate an annual precipitation of 300 to 2800 mm (mean of 90 cases = 830 mm), annual temperature of 5 to 27°C (mean of 90 cases = 11.6°C), and soil pH of 4.2 to 8.2 (mean of 86 cases = 6.2) (Duke, 1978; 1979 in Duke, 1983). According to Oplinger et al. (1989a), it requires approximately 400 to 500 mm of rain during the growing season, with 200 to 210 mm of rain near the flower and pod fill stages of growth. Minimum air temperature for growth is approximately 0^oC; and an optimum soil temperature of 10^oC is needed for seed germination (Oplinger et al*.,* 1989a). According to FAO (2006), the fatal temperature during plant rest is -15^oC, and -6^oC during early growth. Dry weather conditions are essential during canola harvest to avoid the seed moulding (Duke, 1983; Poteet, 2006). In South Africa, the crop is reported to be highly susceptible to pests and diseases.

The Köppen Climate Zones most suitable for canola production are reported to be steppe or semiarid (Bs), warm temperate humid (Cf), warm temperate dry summer (Cs), warm temperate dry winter (Cw), temperate oceanic (Do), temperate continental (Dc), temperate with humid winters (Df), temperate with dry winters (Dw) (FAO, 2006). The photoperiod required is equivalent to a neutral day (12-14 hours) or a long day (>14 hours) [FAO, 2006].

TABLE 3 *Climatic and soil attributes for the production of canola (FAO, 2006).*

Canola Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	medium (50-150 cm)	medium (50-150 cm)
Daily Temp. Requirement (^oC)	15	25	5	41	**Soil texture**	medium, light	heavy, medium, light
Annual Rainfall (mm)	500	1000	400	2800	**Soil fertility**	high	moderate
Latitude	0	0	0	0	**Soil salinity**	low (<4 dS/m)	medium (4-10 dS/m)
Altitude (masl)			0	2000	**Soil drainage**	well (dry spells)	well (dry spells)
Soil pH	6.5	7.6	5.5	8			
Light intensity	very bright	clear skies	Very bright	cloudy skies			

2.1.4 Water use characteristics

Water use of canola is influenced by humidity, temperature, wind and light. It therefore varies from season to season, and location to location (Canola Canada, 2005). Crop evapotranspiration is primarily influenced by the stage of growth and amount of ground cover and root system, increasing gradually until after flowering and then tapering off until harvest. In most parts of the Northern hemisphere, the crop is planted in May and grows through the summer until August (*Brassica rapa*) and slightly later (*Brassica napus*). In South Africa, it is usually a winter crop with the bulk of production found in the western Cape. Peak soil water use during dry, hot weather can be 8 mm per day or more (Canola Canada, 2005), with total water use for the growing season reaching 400 to 450 mm for *Brassica rapa* and 450 to 550 mm for *Brassica napus* under the same growing conditions. Canola plants require a threshold amount of water before any yield is obtained. Once reached, increasing amounts of water lead to higher yields. In a study in Victoria, Australia (Grey, 1998), Canola was grown across 18 sites from 1993 to 1995 to establish the relationship between nitrogen application, growing season rainfall (GSR) and yield. The growing season was from April to October. Results showed that the threshold water requirement for economically viable yield is 112 mm with the water use efficiency being 18 $kg.mm^{-1}/ha$.

According to Canola Canada (2005), 25 mm of water will result in about 0.15 to 0.2 tonne/ha under fair growing conditions, but up to 3.9 t/ha has been achieved under ideal conditions. With irrigation however, yield improves dramatically to 2.6 t/ha if irrigated through the growing season until pod ripening. The oil content and seed weight of canola also increase with adequate water. Under waterlimiting conditions, the best results can be obtained with irrigation just prior to, or at, flowering (Canola Canada, 2005). However, Grey (1998) reports that waterlogging is likely to decrease crop yield. For crop coefficients as determined for the FAO 56 model, see Appendix I.

2.1.5 Potential environmental impact

Environmentalists have claimed that canola cultivation in the fields results in an overall increase in nitrous oxide (N_2O), a greenhouse gas, (AGRICE, 2007). A study conducted by Makareviciene and Janulis (2003) has shown that when considering emissions of nitrogen oxides (NO_x), carbon monoxide (CO) and smoke density, canola ethyl ester had fewer negative effects on the environment in comparison with that of canola oil methyl ester.

In a study by Younesabadi (undated), it was shown that the growth of two dominant weeds of canola, i.e. *Amaranthus retroflexus* and *Abutilon theophrasti Medic*., were inhibited by allelochemicals, while no effects were observed for cotton growth in adjacent fields.

2.2 African Oil Palm (*Elaeis guineensis*)

African Oil Palm is a perennial, evergreen tree from the *Palmae* family (Gascon et al*.,* 1989; FAO, 2006). It can grow up to 20 metres in height and 30 cm in diameter; its trunk is ringed and the foliage is in the form of pinnate blades. Male and female flowers appear on separate clusters, but on the same tree; the female flowers consequently produce plum-sized fruits in large clusters ranging from 200 to 300 per cluster. The fruits are ovoid-oblong and appear black when ripe. Palm oil is extracted from the fleshy mesocarp of the fruit varying from light yellow to orange red, and melts from 25-50^{o}C; the palm kernel oil is extracted from the kernel of the endosperm (Duke, 1983).

FIGURE 4 *The Palm oil tree (a) and the fruit produced (b).*

2.2.1 Utilisation of African Oil Palm

Palm oil is commonly used as an ingredient in margarines, vegetable oils, candles, lubricants, soaps, making ice cream and mayonnaise, and recently in biodiesel production (Poteet, 2006). After oil extraction, the oil cake is used as livestock feed because of its rich protein content (Poteet, 2006; FAO, 2006). Palm wine is produced from the sap of the tree, which contains about 4.3 g/100 ml of sucrose and 3.4 g/100 ml of glucose, and is obtained by tapping the male inflorescence (Duke, 1983). The sap is therefore a potential feedstock source for bioethanol production (refer to **TABLE 4**). The central shoot or “cabbage” is edible; leaves are often used for thatching; petioles and branches for fencing, after which the refuse are used for mulching and manuring (Duke, 1983). In addition, the Oil Palm is also used as a folk remedy for cancer, headaches, and rheumatism (Duke, 1983). African Oil Palm can be intercropped with maize, yams, millet, cassava, cowpea, cocoyams, groundnuts, bananas (FAO, 2006).

TABLE 4 *Utilisation of African Oil Palm (FAO, 2006).*

Main use	Detailed use	Used part
Food and beverage	Lipids and vitamins	Fruits
Food and beverage	Lipids and vitamins	Seeds
Food and beverage	Vitamins	Flowers
Food additive	Sweetener	Flowers
Animal food (feed)	Lipids and vitamins	Fruits
Animal food (feed)	Protein	Unspecified part
Material	Lipids/oil and fats	Fruits
Material	Cosmetics and perfumery	Fruits
Material	Waxes	Fruits
Material	Lipids/oil and fats	Seeds
Material	Cosmetics and perfumery	Seeds
Environmental	Shade and shelter	Entire plant
Environmental	Soil improvers	Leaves
Environmental	Agroforestry	Entire plant
Fuels	Petroleum substitutes/alcohol	Fruits
Fuels	Petroleum substitutes/alcohol	Seeds

2.2.2 Present distribution, extent of plantings and yield

Originating along the western coast of Africa, *Elaeis guineensis* is now found in most tropical regions between 16^{o} north and south of the equator (Duke, 1983; Gascon et al., 1989, Poteet, 2006). Major palm oil producing countries include Nigeria, DRC Sierra Leone, Ghana, Indonesia, South America, and Malaysia (Duke, 1983; Gascon et al., 1989, Poteet, 2006).

The oil content extracted from the fleshy endosperm ranges from 40 to 70% while palm kernel has 50% oil content (Poteet, 2006). For commercial production of African palm, the tree spacing is usually 9 m by 9 m, thus a 50 000 tree plantation would require over 400 hectares of land (Poteet, 2006). One hectare of trees may produce almost 6000 litres of palm oil, which has the potential to produce approximately 4 800 litres of biodiesel (Poteet, 2006). In West Africa, the forest is often cleared to allow 75 to 150 plants per hectare, and this yields about 2.5 tonnes of fruit bunches per hectare per annum. According to Duke (1983), 1000 kg of fruit bunches yields 80 kg of oil using "local soft oil extraction" or 180 kg by hydraulic hand press. The African Oil Palm plant is, however, affected by many fungi, nematodes, and pests as listed by Duke (1983).

Although high in oil production compared to other oilseed crops, African Oil Palm has not always been considered economically suitable for biodiesel production, due to the high levels of fatty acids which require extra methanol transesterification it its oil (Crabbe et al., 2001; in Poteet, 2006). In addition, the costs for plantation establishment and harvesting are also high compared to other crops that can be harvested via machinery (Poteet, 2006). Furthermore, the period before the harvest of palm fruit takes place is long (about 3 to 4 years for the initial fruit bunches of poor quality), making African Oil Palm an unlikely potential for short term biodiesel production (Duke, 1983; Poteet, 2006). However, because African Oil Palm is a tree crop, it is possible for farmers to earn an alternate income through intercropping with other crops (Poteet, 2006).

2.2.3 Biophysical requirements

According to Poteet (2006), the African Oil Palm grows wild in freshwater swamps and in forests with braided river channels. Being tolerant of periodical water-logging, it can also occur along riverbeds (Duke, 1983). The African Oil Palm requires adequate light and soil moisture; it does not tolerate high levels of salinity and requires flat topography for cultivation to allow ease in harvesting (refer to **TABLE 5**). According to the Malaysian Palm Oil Board, solar radiation and soil moisture are two critical factors in palm development, therefore a photoperiod of at least five hours per day is necessary to maximise bunch production (Hartley, 1967; Poteet, 2006).

Waterlogged, extremely sandy, stoney or peaty, and laterite soils should be avoided (Duke, 1983).

The Köppen Climate Zones where African Oil Palm growth occurs are Equatorial wet and dry (As and Aw), as well as Tropical wet (Ar) regions. The palm can be grown in areas with short (<12 hours), neutral (12-14 hours), and long (>14 hours) days [FAO, 2006].

TABLE 5 *Climatic and soil attributes for the production of African Oil Palm (FAO, 2006).*

	Optimal		**Absolute**			**Optimal**	**Absolute**
African Palm Attributes	Min	Max	Min	Max	**Soil depth**	deep (>150 cm)	medium (50-150 cm)
Daily Temp. Requirement (^oC)	20	35	12	38	**Soil texture**	heavy, medium	heavy, medium, light
Annual Rainfall (mm)	1500	3000	1000	8000	**Soil fertility**	high	moderate
Latitude	0	10	0	20	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Altitude (masl)			0	1300	**Soil drainage**	well (dry spells)	well (dry spells)
Soil pH	4.5	6	3.2	8			
Light intensity	very bright	very bright	very bright	cloudy skies			

In areas receiving 1780 to 2280 mm of annual rainfall distributed throughout the growing season, African palm can be grown without irrigation, although it is only able to tolerate a short drought period of approximately 2-4 months (Duke, 1983). However, it has been reported that African Oil Palm can tolerate 640 to 4260 mm of annual rainfall (mean of 27 cases = 2270 mm), and annual temperatures of 18.7 to 27.4^oC (mean of 27 cases = 24.8^oC); while soil pH of 4.0 to 8.0 (mean of 22 cases = 5.7) is required for growth (Duke, 1983). According to Duke (1983), air temperature of 35^oC is needed to stimulate germination in thin shelled varieties (such as the *tenera* palms), while thick-walled varieties (such as *dura* palms) require higher temperatures. Fatal temperature during rest and early growth stages is 0^oC (FAO, 2006).

2.2.4 Water use characteristics

Despite its reported sensitivity to soil moisture, no literature on direct water use by Palm oil trees was found, with most water-related reports focusing on secondary impacts, such as pollution from fertilizers and processing plants.

2.2.5 Potential environmental impact

It has been recorded that the palm oil industry is a serious polluter in Malaysia (Duke, 1983). Soil erosion can be severe if trees are cultivated on steep slopes (FAO, 2006) and intercropping of ground cover crops is not practiced. Despite the negative environmental impacts discussed above, Aisueni (1987) found that Oil Palm fields showed increases in total N and total algae and concluded that Oil Palm ecosystems can maintain soil fertility with potential for N_2-fixation properties.

2.3 Jatropha (*Jatropha curcas*)

Jatropha belongs to the *Euphorbiaceae* family. It is a perennial, shrubby, deciduous tree with one fruiting cycle per year when grown as a dryland crop, but up to three fruiting cycles may occur if it is well irrigated (FAO, 2006; Poteet, 2006; Gush and Hallowes, 2007). It grows to a height of 5 to 8 meters and sheds its leaves during the dry season (Poteet, 2006). The fruit bearing seeds are dried upon maturation, splitting into 3 valves exposing the seeds (Gush and Hallowes, 2007). Jatropha trees grown from seed can produce harvestable seed crops within two years, while trees grown from cuttings produce seed in the first year after sowing (Poteet, 2006). However, trees grown from cuttings are more vulnerable to soil water stress (Holl et al., 2007).

FIGURE 5 *Jatropha tree (a) and its fruit and seeds (b).*

2.3.1 Utilisation of Jatropha

Jatropha is commonly used as a natural hedge or fence-row (refer to **TABLE 6**), due to its toxicity to most animals. Jatropha oil is also used in the production of soap, cosmetics and biodiesel (Poteet, 2006). Various parts of the plant have medicinal value, while its flowers attract bees for honey production (Poteet, 2006). The leftover seedcake, although not suitable as a livestock feed, can be used as an organic fertiliser with N, P, and K contents similar to that of chicken manure (Openshaw, 2000; in Poteet 2006). Furthermore, the seedcake may have nematicidal or pest control properties due to its toxic properties (Poteet, 2006). Biogas production from the remaining seed cake is also possible (Gübitz et al., 1999; Poteet, 2006).

TABLE 6 *Utilisation of Jatropha (FAO, 2006).*

Main use	Detailed use	Used part
Environmental	Erosion control	Entire plant
Environmental	Living fence	Entire plant
Medicinal	Digestive system applications	Bark
Material	Lipids/oil and fats	Seeds
Environmental	Soil improvers	Seeds
Fuels	Petroleum substitutes/alcohol	Fruits
Medicinal	Digestive system applications	Leaves
Medicinal	Digestive system applications	Fruits

2.3.2 Present distribution, extent of plantings and yield

Jatropha is indigenous to the Caribbean, but it is now widely distributed to countries including those in Central and South America, India, Africa, and Southeast Asia (Poteet, 2006). Each Jatropha seed contains 43 to 59% oil (Gubitz et al., 1999; in Poteet, 2006), and it has been estimated that one hectare of Jatropha trees could produce between 1 600 to 2 000 litres of oil (Poteet, 2006).

2.3.3 Biophysical requirements

Jatropha is able to withstand high temperatures, drought, slope and varied soil pH levels (Poteet, 2006; Gush and Hallowes, 2007). Its rooting system consist of three or four primary lateral roots near the soil surface, while a vertical taproot is reported to extend down to more than five meters deep (Poteet, 2006). Jatropha has been shown to require high levels of nitrogen and phosphorous, although it is efficient at absorbing nutrients from marginal soils. Therefore, it has been suggested that it requires highly productive land, such as that used for sugarcane or pineapple plantations (Poteet, 2006). In terms of radiation requirements, the species is reported to prefer full sunshine, although there have been observations of the tree thriving under partly shaded growing conditions (Gush and Hallowes, 2007). Jatropha grows best on well-drained soils with good aeration; and have been found on coarse, sandy, stoney, and saline soils (Gush and Hallowes, 2007).

TABLE 7 *Climatic and soil attributes for the production of Jatropha (FAO, 2006).*

Jatropha Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	deep (>150 cm)	deep (>150 cm)
Daily Temp. Requirement (^oC)	11	28	7	36	**Soil texture**	medium	medium, light
Annual Rainfall (mm)	500	1500	300	2000	**Soil fertility**	moderate	low
Latitude	0	28	0	30	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Altitude (masl)			0	1600	**Soil drainage**	well (dry spells)	well (dry spells), excessive (dry/moderate dry)
Soil pH	5.5	7.5	5	8			
Light intensity	very bright	very bright	clear skies	very bright			

An optimal annual precipitation of 500-1200 mm is required, although they are able to grow in regions experiencing annual rainfall of 250 mm (Gush and Hallowes, 2007). Jatropha trees respond well to rainfall or irrigation (Poteet, 2006). The trees tolerate mean annual temperature between 11.0 to 28.5^oC, although the optimal growing temperature is 20-28^oC. Temperatures of -1^oC are fatal when the tree is grown, but during early growth, temperatures of 0^oC are fatal (FAO, 2006). The optimal altitude for tree growth is 0 to 500 m above sea level, but altitudes varying from 7 to 1600 m have been recorded (Gush and Hallowes, 2007). FAO (2006) have similar parameter values listed below (***TABLE*** *7*).

The Köppen Climate Zones associated with Jatropha growth are: Tropical wet (Ar), steppe or semiarid (Bs), warm temperate dry summer (Cs). Jatropha is not sensitive to photoperiod length (FAO, 2006).

2.3.4 Water use characteristics

In a study conducted by Holl et al. (2007), water use of *Jatropha curcas* (*J. curcas*) in northern KwaZulu-Natal, South Africa was measured and assessed. According to the authors of this report, there has been no previous assessment of the water use of *J. curcas* anywhere in the world. Water use was measured in 4 year old trees and 12 year old trees at two different sites by heat pulse velocity techniques (for a description of this method, see Holl et al., 2007). Soil water content was also measured and compared to those measured at a grassland site as a control.

Results from transpiration measurements for the 4 year old trees showed that there is a clear diurnal trend to the data, and that sap flow (transpiration) ceased in mid June until the onset of the first rains in mid to late October. Transpiration rates are therefore season dependent. Tree spacing was 3 m within the row and 4.5 m between rows which translated to approximately 740 tonnes/ha. The transpiration amounts per individual tree were scaled up to a hectare and converted to mm equivalent with the average annual transpiration total for a 4 year old plantation being 144 mm for the site under study. The 12 year old trees were found to be more sensitive to soil water fluctuations with clear periods of water stress in March and April. Sap flow therefore appeared to be strongly influenced by fluctuations in water availability whereas the 4 year old trees appeared only to be influenced by season. The reason for this, besides the difference in ages of the trees, may have been due to the sandy soils at the "12 year" site which have a lower capacity to retain water near the surface where the majority of the roots are. After scaling up in a similar manner to the 4 year old trees, annual transpiration totals were calculated to be 361.8 mm and 298.9 mm for the two trees measured. This higher transpiration value can be attributed to the increased leaf area of the more mature trees. The likely maximum transpiration under ideal conditions was calculated to be 300 mm and 500 mm for the 4 and 12 year old trees respectively. Water use of *J. curcas* was therefore concluded to be generally low. **TABLE 8** below shows the monthly crop coefficients that were generated for the monitoring period.

TABLE 8 *Monthly basal crop coefficient (K_{cb}) values for 4-year old and 12-year old J. curcas trees (after Holl* et al.*, 2007).*

K_{cb}	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4yr	0.11	0.18	0.26	0.21	0.14	0.06	0.00	0.00	0.00	0.04	0.14	0.15
12yr	0.5	0.76	0.56	0.47	0.46	0.15	0.00	0.00	0.00	0.00	0.50	0.37

2.3.5 Potential environmental impact

Jatropha is one of the species listed in the Kyoto Protocol as eligible to trade carbon credits (Openshaw, 2000; in Poteet, 2006). It is also commonly used for erosion control (Poteet, 2006). Its toxicity is well-noted, but no other environmental impacts have been described in the available literature.

2.4 Diesel Tree (*Copaifera langsdorfii*)

The Diesel Tree belongs to the *caesalpiniaceae* family; it is a tropical, evergreen tree that grows to 35 meters tall and 1 meter in diameter (Duke, 1983). It has par pinnate glabrous leaves that are 5 to 10 cm long with numerous whitish flowers grown in compound panicles (Duke, 1983).

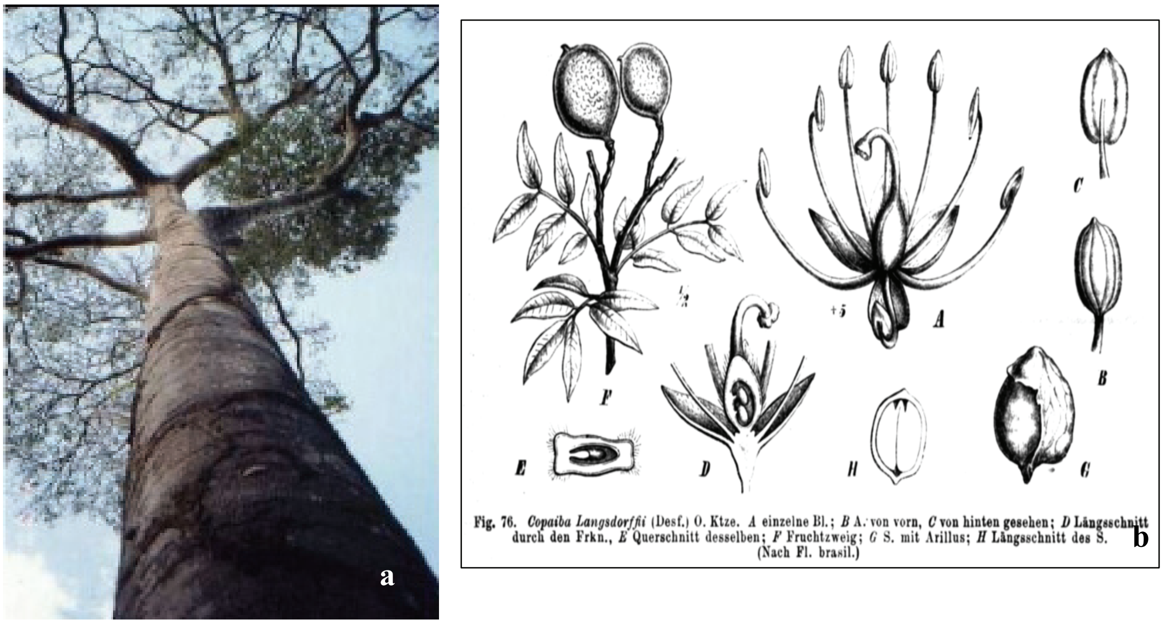

FIGURE 6 *Standing Diesel Tree (a) and schematic diagrams of its flower and seed (b).*

2.4.1 Utilisation of the Diesel Tree

The tree sap, which contains a high content of diesel-like hydrocarbons, is used as a natural fuel. The tree is also a source of folk medicine by native Americans (Duke, 1983). The hydrocarbons collect in thin capillaries that extend to the height of the tree, and it is harvested by drilling into the tree (Duke, 1983). The extracted sap is also used as a moisturising rub, an expectorant and a cure for skin diseases (Duke, 1983; in Poteet, 2006). The Diesel Tree's extracted fuel is said to be usable when injected directly into a standard diesel engine and the copal (brittle yellow and reddish resin from tropical trees) is used in lacquers, massage preparations, medicines, and paints; while the wood and resin can be used for fuel (Duke, 1983). The balsam of the Diesel Tree has been described as a stimulant, diuretic, carminative, laxative; and in large doses it is purgative, causing nausea, vomiting, "strangury", bloody urine, and fever (Duke, 1983).

2.4.2 Present distribution, extent of plantings and yield

According to Duke (1983), the Diesel Tree originated in Brazil and its natural distribution is Central and South America. The Diesel Tree is reported to yield as much as 53 litres of oil per tree, and 40.5 hectares of mature trees could produce 5 300 litres per year.

2.4.3 Biophysical requirements

The Diesel Tree is productive in dry to moist climates with temperatures ranging from 20-27^{o}C, where no frost can occur. The tree is probably tolerant of an annual rainfall from 1000 to 4000 mm and soil pH of 4.5 to 7.5. According to Duke (1983), the Diesel Tree is tolerant to some waterlogging, while the seedlings germinate well under dense shade. Some United States Department of Agriculture publications reported that most of the tree grows in regions with annual precipitation of 3500 mm or more, and a fatal mean annual temperature of at 27^{o}C or more.

2.4.4 Potential environmental impact

None noted in the available literature.

2.5 Ben-oil Tree (*Moringa oleifera* Lam.)

The Ben-oil Tree belongs to the *Moringaceae* family. It is a slender, deciduous, perennial tree that grows to 10 meters tall (FAO, 2006); its branches droop with feathery, pale green leaves that grow 30 to 60 cm long (Magness et al*.,* 1971; Duke, 1983). Its creamy-white flowers are 2.5 cm in diameter, and its brown pods are 30 to 120 cm long, are triangular, containing around 20 seeds (Magness et al*.,* 1971; Duke, 1983). The plant starts bearing pods 6 to 8 months after planting, but regular bearing will commence after the second year. The tree is also reported to tolerate bacteria, fungus, laterite, mycobacteria, drought, and sand (Duke, 1978 in Duke, 1983).

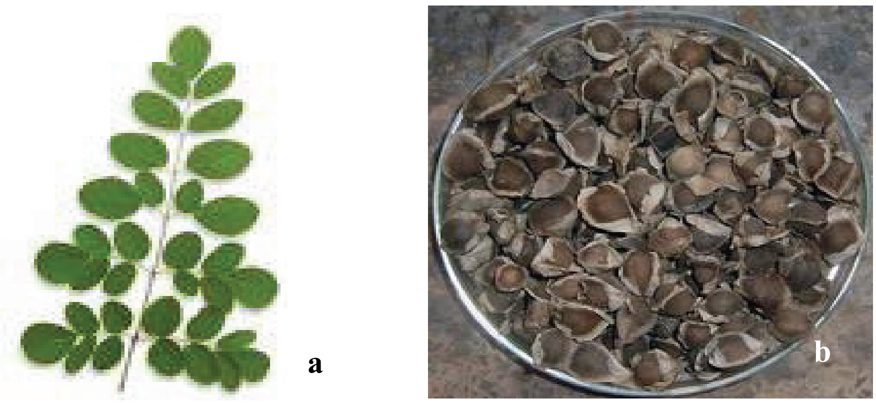

FIGURE 7 Ben-oil Tree *leaf (a) and a collected bowl of its seeds (b).*

2.5.1 Utilisation of the Ben-oil Tree

Moringa oleifera is a well know source of human food (**TABLE 9**). The seeds are eaten like a peanut; roots used as a substitute for horseradish; foliage used in salads, vegetable curries, pickles and for seasoning. The seed oil has non-drying properties and is used in arts, lubricating watches, manufacturing of cosmetics, perfumes and hairdressing. The wood yields blue dye, while the leaves and young branches can be fed to livestock. In Africa, the Ben-oil Tree is often planted as a living fence, and branches are used as charms against witchcraft (Duke, 1983). According to Hartwell (1971, in Duke, 1983) the roots are used in folk remedies as a stimulant in paralytic afflictions, epilepsy, hysteria, and for tumours; the seed for abdominal tumours; while the oil can be applied externally for skin diseases.

TABLE 9 *Utilisation of the* Ben-oil Tree

Main use	**Detailed use**	**Used part**
Food and beverage	Vitamins and minerals	Leaves
Food and beverage	Vitamins and minerals	Fruits
Food and beverage	Vitamins and minerals and lipids	Seeds
Food and beverage	Vitamins and minerals	Roots
Animal food (feed)	Vitamins and minerals	Leaves
Animal food (feed)	Vitamins and minerals	Shoots
Material	Timber wood	Stems
Material	Lipids/oil and fats	Seeds
Material	Cosmetics and perfumery	Seeds
Material	Dye/tannin	Stems
Material	Dye/tannin and fibres	Bark
Fuels	Fuelwood	Stems
Fuels	Petroleum substitutes/alcohol	Seeds
Medicinal	Skin applications	Seeds
Medicinal	Immune system applications	Flowers
Medicinal	Genitourinary system applications	Exudates
Medicinal	Blood system applications	Exudates
Medicinal	Genitourinary system applications	Seeds
Medicinal	Nutritional applications	Seeds
Medicinal	Blood system applications	Roots
Medicinal	Digestive system applications	Bark
Environmental	Windbreak	Entire plant
Environmental	Shade and shelter	Entire plant
Environmental	Pollution control	Entire plant

2.5.2 Present distribution, extent of plantings and yield

According to Duke (1983), the Ben-oil Tree is native to India, Arabia, and possibly Africa and the Malay Archipelago; it has been cultivated and naturalised in tropical Africa, tropical America, Sri Lanka, Mexico, Malabar, Malaysia and the Philippine Islands.

Magnes et al. (1971), report that the seeds contain 25 to 35% of the non-drying oil. Ben-oil seeds yield 38 to 40% of oil, and from personal observation, Duke (1983) suggests a target yield of about 10 metric tonnes pods per hectare. The yield, however, is affected by fruitflies (*Gitona* spp.), weevils, a parasite (*Dendrophthoe flacata*) and various fungi.

2.5.3 Biophysical requirements

Moringa oleifera can be grown in tropical wet and dry (Aw), steppe or semiarid (Bs), subtropical dry summer (Cs) under the Köppen Climate Zone classification system (FAO, 2006); and according to Duke (1983) it tolerates annual precipitation of 480 to 4030 mm (mean of 53 cases = 1410 mm). Annual air temperature of 18.7 to 28.5^{o}C (mean of 48 cases = 25.4^{o}C) and soil pH of 4.5 to 8.0 (mean of 12 cases = 6.5) is required to grow the tree (Duke, 1983). Fatality occurs at 0^{o}C during the rest and early growth periods (FAO, 2006). The plant is drought resistant and grows best on dry sandy soil (Duke, 1983). The FAO (2006) database provides similar parameter values given below (**TABLE 10**). The photoperiod of Ben-oil Tree ranges from short day (<12 hours) to long day (>14 hours) lengths (FAO, 2006).

TABLE 10 *Climatic and soil attributes for the production of* Ben-oil Tree *(FAO, 2006).*

Ben-oil Tree *Attributes*	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	deep (>150 cm)	medium (50-150 cm)
Daily Temp. Requirement (^{o}C)	20	35	7	48	**Soil texture**	medium, light	heavy, medium, light
Annual Rainfall (mm)	700	2200	400	2600	**Soil fertility**	moderate	low
Latitude	10	20	10	30	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Altitude (masl)			0	1000	**Soil drainage**	well (dry spells)	well (dry spells), excessive (dry/moderately dry)
Soil pH	5.5	7	5	8.5			
Light intensity	very bright	clear skies	very bright	cloudy skies			

The Ben-oil Tree can be grown in similar sites to the Jojoba Tree and, therefore yields can be easily compared to those of Jojoba in field experiments (Duke, 1983).

2.5.4 Potential environmental impact

A study by Kumari et al. (2006) found that the shelled Moringa seeds can be used to decontaminate arsenic from water bodies, which can be highly detrimental to human beings and animals by causing several neurological, dermatological, gastrointestinal and cardiorenal diseases.

2.6 Pongam Tree (*Pongamia pinnata* L.)

Belonging to the *Fabaceae* family, the Pongam Tree is a perennial, fast growing, deciduous tree (FAO, 2006) that grows to a height of 25 m with drooping branches. Trunk diameter can reach 60 cm with smooth grey barks. The leaves are shiny; the young leaves appear pinkish-red; mature leaves are glossy and deep green in colour. The flowers vary from white to pink, and are fragrant. The pods are short, oblique-oblong, flat, smooth, thickly leathery, with one seed in each pod which has high triglyceride content. The tree only starts to bear seed pods after 4 to 7 years (Duke, 1983). According to FAO (2006), Pongam Trees have the potential to become a noxious weed in some places.

FIGURE 8 *The* Pongam Tree *(a) and its pods containing seeds (b).*

2.6.1 Utilisation of Pongam Tree

The Pongam Tree is commonly grown as an ornamental tree in gardens and along avenues, particularly in coastal India and Polynesia. Besides ornamental purposes, the Pongam Tree is also cultivated as a host plant for lac (the scarlet resinous secretion of the insects, which is later harvested to manufacture wax and varnish products), and its well-decomposed flowers and leaves are used as nutrient-rich compost. In the Philippines, the bark is used for making strings and ropes as well as a medicine used to treat wounds caused by poisonous fish (Duke, 1983). The crushed seeds and leaves also have medicinal value due to their antiseptic properties; the seed oil is used to treat scabies, herpes, and rheumatism, as well as for illuminating and lubricating purposes. Both the seed oil and the pressed oil cake is toxic, therefore it is unsuitable for human and animal consumption. The wood, although reported as beautifully grained, is not durable and its use is limited to cabinet-making, cart wheels, posts, and firewood; the ash of the wood is often used as a dye (Duke, 1983). In studies conducted by the Indian Council for Scientific and Industrial Research in New Delhi during 1948 to 1976, Pongam oil has been used as fuel in diesel engines and was shown to have good thermal efficiency (Duke, 1983). FAO (2006) has also listed some uses of the Pongam Tree (**TABLE 11**).

2.6.2 Present distribution, extent of plantings and yield

According to Duke (1983), the Pongam Tree has Indo-Malaysian origin, distributed along the alluvial plains of India to Fiji. It was spread to Australia, Florida, Hawaii, Malaysia, Oceania, Philippines and Seychelles.

A single tree could yield 9 to 90 kg seed per tree, and assuming 100 trees/ha, it has a potential yield of 900 to 9000 kg seed/ha, 25% of which can be rendered as oil. The production of the oil is labour intensive, requiring manual removal and shelling of the pods. The Pongam Tree is subjected to many fungi and viruses which are listed in Duke (1983).

TABLE 11 *Utilisation of the* Pongam Tree *(FAO, 2006).*

Main use	Detailed use	Used part
Material	Honey	Flowers
Material	Fibres	Bark
Material	Timber wood	Stems
Material	Dye/tannin	Roots
Material	Lipids/oil and fats	Seeds
Fuels	Petroleum substitutes/alcohol	Seeds
Fuels	Fuelwood	Stems
Medicinal	Skin applications	Seeds

2.6.3 Biophysical requirements

The Pongam Tree is reported to tolerate drought, frost, heat, limestone, salinity, sand, and shade (Duke, 1983). It is a "short day" plant, with a photoperiod requirement of less than 12 hours (FAO, 2006). Globally, its growth region ranges from tropical wet (Ar) and dry (Aw), tropical wet (Ar), steppe or semiarid (Bs) under the Köppen Climate Zone classification system (FAO, 2006); it tolerates annual temperatures ranging slightly below 0^oC to 50^oC, and annual rainfall of 500 to 2500 mm (Duke, 1983). Similar environmental attributes were given by FAO (2006) in ***TABLE 12***. Fatality during plant rest occurs at -1^oC, and 0^oC for the early growth (FAO, 2006).

TABLE 12 *Climatic and soil attributes for the production of Pongam (FAO, 2006).*

Pongam Tree *Attributes*	Optimal Min	Optimal Max	Absolute Min	Absolute Max		Optimal	Absolute
					Soil depth	deep (>150 cm)	medium (50-150 cm)
Daily Temp. Requirement (^oC)	16	40	10	50	**Soil texture**	medium	heavy, medium, light
Annual Rainfall (mm)	500	2000	400	2500	**Soil fertility**	high	moderate
Latitude	10	30	0	40	**Soil salinity**	low (<4 dS/m)	medium (4-10 dS/m)
Altitude (masl)			0	1200	**Soil drainage**	well (dry spells)	poorly (saturated >50% of year), well (dry spells)
Soil pH	6.5	8.5	6	9			
Light intensity	clear skies	very bright	light shade	very bright			

2.6.4 Potential environmental impact

A study by Latha et al. (2001), found that the leachates from Pongamia leaves contain allelochemicals which inhibited the performance of both rice and wheat, while no effects were observed on weeds *Cassia tora* and *C. occidentalis*. The allelochemicals were identified as vanillic acid, syringic acid, melilotic acid and derivatives of quercetin and kaempferol (Latha et al., 2001).

2.7 Camelina (*Camelina sativa* L. Crantz.)

Camelina sativa is also known as “gold of pleasure” or “false flax” and belongs to the family *Brassicaceae.* It is native to Northern Europe and the Central Asian areas. It is an annual or winter-annual that attains a height of 300 to 900 mm tall and has branched smooth or hairy stems that become woody at maturity (Putnam et al., 1993).

FIGURE 9 *Camelina flowers (a) and its seeds (b).*

2.7.1 Utilisation of camelina

Camelina has been traditionally cultivated as an oilseed crop to produce vegetable oil and animal feed. It is short-seasoned (85 to 100 days) and could therefore be incorporated into double cropping systems where conditions allow. In a three year study by Robinson(1987 cited in Putnam, 1993) a winter-sown crop yielded 9% more when seeded with an autumn sown cover crop than without. Subsequent studies have confirmed this (Putnam et al., 1993), indicating the compatibility of camelina with cover crops used for autumn and early spring erosion control. Camelina meal contains 45 to 47% crude protein and 10 to 11% fibre (Korsrud et al*.,* 1978 cited in Putnam et al., 1993), and has been used as a birdfeed an ornamental cover crop and in dried flower arrangements.

2.7.2 Present distribution, extent of plantings and yield

Camelina is not widely grown, but has been known to be cultivated in Germany, Poland, the USSR and Canada, with a wide ranging study having been carried out in Minnesota, USA (Putnam et al., 1993). Yields have varied from 0.6 to 1.7 tonne/ha, averaging at about 1.1 to 1.2 tonne/ha over a number of years of trials at Rosemount, Minnesota (Robinson, 1987 cited in Putnam et al., 1993). Seed oil content has ranged from 29 to 39% and seed protein content from 23 to 30% (Marquard and Kuhlmann, 1986 cited in Putnam et al., 1993).

2.7.3 Biophysical requirements

Camelina’s adaptation as a crop has not been widely explored (Putnam et al., 1993) but is thought to be adapted to cooler climates where excessive heat during flowering is not problematic. It is possible that camelina could be grown as a winter crop in areas with very mild winters as it is able to cope with early water deficits (Bramm et al*.,* 1990) cited in Putnam et al., 1993) indicating that camelina may be better suited to drier regions than other oilseeds. Frost tolerance has been observed (Robinson, 1987 cited in Putnam et al., 1993) and camelina has been shown to be hardier than other oil crops (mustard, canola and flax) to frost.

2.7.4 Potential environmental impact

In a study by Lovette and Sagar (1978), and later Lovett and Duffield (cited in Putman et al.,1993), they found that in the presence of nitrogen-fixing bacteria in *Camelina phyllosphere*, the aqueous washings of the foliage of camelina contain allelochemicals; one of the chemicals is identified as benzylamine, which stimulated the growth in length of radicles of germinating seeds of *Linum usitatissimum*.

Camelina is known primarily as a weed in North America (Putnam et al., 1993). An extract from Putnam et al. (1993) clarifies the potential for future research:
"Lack of clear utilisation patterns currently limit the crop, and further work on oil, meal, and seed use is required. The possibilities of using camelina as human food, as birdseed, as edible or industrial oil, a fuel, or other applications remains largely unexplored. Further utilisation and breeding research is required to more fully make use of the unique agronomic qualities that this crop possesses."

2.8 Chinese Tallow Tree (*Sapium sebiferum* L. Roxb.)

Belonging to the *Euphorbiaceae* family, Chinese tallow is an oval-open canopy, and fast-growing deciduous perennial tree (FAO, 2006) that grows 10 to 13 m tall within 30 years. Its trunk is gnarled with vertical cracks appearing in the grey barks (Duke, 1983; Gilman and Watson, 1994). The stem exudes milk-like poisonous sap; the leaves are alternate, shaped rhombic to ovate turning orange to scarlet in autumn (Duke, 1983). The greenish-yellow flowers are monoecious; the fruit is in the form of a 3-valved capsule containing 3 seeds (Duke, 1983) which burst and fall off, leaving behind wax-coated seeds (Gilman and Watson, 1994). In China, it flowers from April to June, and the fruit ripens from September to October (Duke, 1983). The pea-sized fruits and seeds are threshed from the tree and harvest by hand after the leaves have fallen. Plants require 3 to 8 years to bear, and then continue to bear for many years averaging 70 to 100 years (Duke, 1983). According to FAO (2006), Chinese tallow has the potential to be a noxious weed.

FIGURE 10 *Standing* Chinese Tallow Tree *(a) and its circular pods (b)*

2.8.1 Utilisation of the Chinese Tallow Tree

The Chinese Tallow Tree is often cultivated for its seeds as a source of vegetable tallow, drying oil, and protein food. It is also cultivated as an ornamental tree (Duke, 1983). The outer wax covering of seeds is used to produce tallow for manufacturing of candles, soap, cloth dressing, and fuel (Duke, 1983; Gilman and Watson, 1994). The kernel oil is used to make varnishes, paints, and used as machine oil due to its quick-drying properties; and is also used as lamp oil (Duke, 1983). It can also be used in producing emulsifiers, cocoa butter, confections, detergents, and bioactive extracts (Glumac and Cowles, 1990). The residual cake is used as manure (Duke, 1983). The wood is used for furniture making and manufacturing of incense, while the leaves are used to make black dye (Duke, 1983; FAO, 2006). In Chinese medicine, the plant is used to treat skin diseases and the oil is used for its purgative properties. It is toxic for human consumption since an overdose of the oil would cause serious illness and perhaps death (Duke, 1983).

TABLE 13 *Utilisation of the* Chinese Tallow Tree *(FAO, 2006).*

Main use	Detailed use	Used part
Material	Dye/tannin	Leaves
Material	Waxes	Seed
Material	Honey	Flowers
Environmental	Erosion control	Entire plant
Environmental	Soil improvers	Leaves
Environmental	Agroforestry	Entire plant
Poison	Mammals	Exudates
Fuels	Petroleum substitutes/alcohol	Seeds

2.8.2 Present distribution, extent of plantings and yield

The Chinese Tallow Tree is native to central China and Japan, although it is also widely cultivated on Hainan Island, Hong Kong, Taiwan, and Korea. It has been distributed to Sri Lanka, India, Bengal, Sudan, Martinique, southern United States, southern France and Algeria (Duke, 1983).

According to Duke (1983), the seed contains about 20% oil. Glumac and Cowles (1990) reported that the tallow tree bears seed after 3 years with annual yields of up to 12 tonnes/ha per annum from mature wild trees. In plantations, 400 trees should be planted in one hectare, and if trimmed to a convenient size for hand-harvesting, the tree would yield 14 tonnes seed/ha which contains 2.6 tonnes/ha of oil, 2.8 tonnes/ha tallow, 1.5 tonne/ha protein concentrate, 1.1 tonne/ha fibrous coat, and 4.5 tonnes/ha shell. The seed yield increases with age – a tree of five years will yield an average of 0.453 kg/tree, 3.379 kg at 10 years, 11.989 kg at 20 years and thereafter, yield decreases (Duke, 1983).

The flowers of Chinese tallow are favoured by honey bees, and its fruits are readily eaten by birds. However, the tree is remarkable free of insect pests, although it is susceptible to nematode and fungi (Duke, 1983; Gilman and Watson, 1994).

2.8.3 Biophysical requirements

Chinese tallow is a subtropical to warm temperate plant; it grows best in well-drained clayey soils, and tolerates alkaline, saline or acid soils. It grows on canal banks, steep mountain slopes, granite hills, and sandy beaches, at elevations of 100 to 800 masl. Favourable climate conditions are mean air temperatures of 12.5 to 30.1^{o}C, and annual rainfall from 1300 to 3700 mm (Duke, 1983). However, FAO (2006) report markedly different environmental requirements with respect to optimal rainfall and temperature (**TABLE 14**). The tree is drought tolerant (Gilman and Watson, 1994); is also able to withstand frost, but unripened twigs are susceptible to frost injury (Duke, 1983). Temperatures of -10^{o}C are fatal during the dormant phase and -1^{o}C during the growth phase (FAO, 2006).

Chinese tallow is a short day plant with photoperiod of less than 12 hours a day; it is found in tropical wet and dry (Aw), steppe or semiarid (Bs), subtropical humid (Cf), subtropical dry summer (Cs), subtropical dry winter (Cw), temperate oceanic (Do), temperate continental (Dc), temperate with humid winters (Df), temperate with dry winters (Dw) Köppen Climate Zones (FAO, 2006).

2.8.4 Potential environmental impact

The tree is cultivated as a soil binder along roads and canals, thereby reducing soil erosion (Duke, 1983).

TABLE 14 Climatic and soil attributes for the production of the Chinese Tallow Tree *(FAO, 2006).*

Chinese Tallow Tree *Attributes*	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	deep (>150 cm)	medium (50-150 cm)
Daily Temp. Requirement (^oC)	20	28	10	32	**Soil texture**	heavy, medium, light	heavy, medium, light
Annual Rainfall (mm)	700	1500	500	2500	**Soil fertility**	moderate	low
Latitude	25	32	10	50	**Soil salinity**	low (<4 dS/m)	medium (4-10 dS/m)
Altitude (masl)			0	0	**Soil drainage**	Poor (saturated >50% of year), well (dry spells)	Poor (saturated >50% of year), well (dry spells)
Soil pH	6	7	5.5	7.5			
Light intensity	very bright	cloudy skies	very bright	light shade			

2.9 Cassava (*Manihot esculenta* Crantz)

Cassava belongs to the *Euphorbiaceae* family, and is a shrubby, tropical, perennial plant with a fibrous root system (Grace, 1977; Cock, 1985; Adetan et al*.,* 2003; FAO, 2006). According to Allemann and Coertze (1996), cassava can grow to a height of about 5 meters and has large, palmate leaves that vary between green or dark red. The roots or tubers radiate from the stem just below the surface of the ground while the storage roots sometimes penetrate the soil to a depth of 50 to 100 cm (Grace, 1977). The number of tuberous roots and their dimensions vary greatly among the different cassava varieties (Grace, 1977). In South Africa, cassava usually produces between five and ten cylindrical tubers, which vary from 10 to 100 cm in length and up to 15 cm in diameter (Allemann and Coertze, 1996). According to Edwards et al. (1990), the photosynthetic mechanisms of cassava are typical of a C_3 plant although some studies had shown that both C_3 and C_4 enzymatic systems function in cassava, and that the dominant photosynthetic pathway varies between C_3 and C_4 depending on environmental temperature. At lower temperatures, photosynthesis follows a C_3path, and at higher temperatures, a C_4 path (Oyetunde, 2007).

Cassava plants contain glucoside, linamarin and lotaustralin, which releases hydrocyanic acid when the plant tissues are damaged leaving a bitter taste. The glucoside content is considerably lower in the "sweet" cassava variety than the "bitter" variety (Grace, 1977; Cock, 1985; O'Hair, 1995; Allemann and Coertze, 1996; IFAD and FAO, 2000), which according to Grace (1977), also varies depending on soil and rainfall conditions. Cassava grown on poor soils and dry conditions has a higher glucoside content than the same plant that's grown under favourable conditions (Grace, 1977).

According to Allemann and Coertze (1996), good cassava yields are only obtained after 9 to 12 months of planting, although a few quick growing cultivars can be harvested after only seven months. Cassava tubers can be left or "stored" in the soil for up to 60 months, which is the reason why it is recognised as a good famine-reserve crop (Allemann and Coertze, 1996; Nweke et al*.,* 2002). In South Africa, root bulking effectively ceases during the period from May to September and the best time for harvesting appears to be from 18 to 24 months after planting (Allemann and Coertze, 1996). Once the perishable tubers are harvested, however, it deteriorates rapidly and can only be stored up to 48 hours before rotting (Allemann and Coertze, 1996).

A detailed report on cassava has been prepared by Wen (2007) and much of the information below is sourced from that document.

FIGURE 11 *Whole plant cassava (a) and its dense leaves (b).*

2.9.1 Utilisation of cassava

Cassava is frequently cultivated as a famine-reserve crop and temporary shade plant (Grace, 1977; FAO, 2006). In Thailand, however, cassava is grown mostly as the sole commercial crop for the starch industry (Grace, 1977; IFAD and FAO, 2000). The utilisation of cassava is divided into three categories: human food consumption, animal feed and industrial uses (refer to **TABLE 15**). Both cassava leaves and tubers can be utilised, although the starchy root tubers are the main economically useful parts of the cassava plant (Adetan et al., 2003). While the tubers are used for industrial purposes, cassava leaves and stems are used mostly as human food or animal feed (Cock, 1985; IFAD and FAO, 2000; Nweke et al*.,* 2002; Adetan et al., 2003). As human food cassava is considered a low-protein, starchy staple. The starch from the root is used to make flour, which can be processed to make bread, cakes, soups and pancakes (IFAD and FAO, 2000). As animal feed, both cassava leaves and tubers are utilised. Tubers are often made into chips and pellets as a supplementary feed to pigs, poultry, and dairy cattle (Cock, 1985; IFAD and FAO, 2000; Nweke et al*.,* 2002). As part of the industrial uses, starch from cassava tubers is used as a raw material for a wide range of industrial goods, including paper, cardboard, textile, plywood, glue, alcohol (Cock, 1985; IFAD and FAO, 2000) and the manufacture of biodegradable polythenes or plastics (Makina, 1991).

TABLE 15 *Utilisation of cassava (FAO, 2006).*

Main use	**Detailed use**	**Used part**
Food and beverage	Starch	Roots
Food and beverage	Minerals	Roots
Food and beverage	Protein	Leaves
Food and beverage	Minerals	Leaves
Animal food (feed)	Starch	Roots
Animal food (feed)	Minerals	Roots
Fuels	Alcohol	Roots
Fuels	Petroleum substitutes/alcohol	Roots

Besides food consumption and industrial uses, cassava can also be used in the generation of energy in the form of heat, electricity and liquid automotive fuels (**TABLE 16**). The ethanol produced from fermentation of cassava starch can be used as a fuel by itself, or be converted to ethyl tetra-butyl ether (ETBE) for octane boosting in unleaded gasoline.

TABLE 16 *Biomass (cassava) conversion processors and applications (Makina, 1991).*

Part of the plant and conversion process	**Result of the conversion process and further processing**	**Application of the final energy resource**
Leaves biomethenation	Biogas for electricity generation	Rural electrification
Wood direct air combustion	Open fire and boiler	Cooking and heating industrial and electrification application
Wood pyrolysis	Wood gas for methane for: Power generation and methanol	Rural electrification
Wood fermentation	Acetone, butanol and ethanol for blending with diesel	Automotive fuel/transport
Root extract starch and fermentation	Ethanol and butanol for: Lighting, blending with gasoline, blending with diesel, convert to ETBE for petrol upgrading, convert to plastics	Mainly low income groups; transport fuel
Root extract starch residue for biomethenation	Biogas for heat or electricity generation	Rural electrification

2.9.2 Present distribution, extent of plantings and yield

Cassava is native to Central America and north-eastern Brazil (Allemann and Coertze, 1996; FAO, 2006). Cassavas were introduced to Africa by early Portuguese traders during the 16th century (FAO, 2006) and was distributed southwards to South Africa from Mozambique during the 19th century (Allemann and Coertze, 1996). Cassava is still utilised in the rural parts of South Africa, although it has been more widely utilised in the past. Some possible reasons for low domestic cassava production include the loss of plant materials to diseases, or the elderly who knew how to produce and process cassava for food, have died (Allemann and Coertze, 1996). In South Africa, cassava was found in the Limpopo, Mpumalanga, KwaZulu-Natal Provinces, as well as in Swaziland (Allemann and Coertze, 1996).

According to Allemann and Coertze (1996), cassava yield could potentially achieve as much as 90 tonnes of fresh roots per hectare under favourable experimental conditions, but under marginal soil and unfavourable climate conditions, root yields are reduced to 10 tonnes/ha. In South Africa, the best root yields of 50 tonnes/ha have been achieved (Allemann and Coertze, 1996).

Although cassava can be more readily cultivated under harsh climatic and soil conditions compared to other crops, it is subjected to a wide variety of pests, viral and bacterial diseases. The African Cassava Mosaic Disease, caused by Cassava Bacterial Blight remains one of the biggest threats to cassava farmers in South Africa (llemann and Coertze, 1996). Cassava Mealybug, Cassava Green Spidermite, termites and variegated grasshoppers are some of the listed pests that damage cassava crops (Allemann and Coertze, 1996; USAID and ICS-Nigeria, undated). Mammals such as wild pigs, baboons and rodents may damage the tubers, while nematodes attack the roots, potentially causing reductions in tuber yield (Allemann and Coertze, 1996).

2.9.3 Biophysical requirements

Cassava grows best when rainfall is fairly abundant, but it can be grown where annual rainfall is as low as 500 mm (Grace, 1977). In South Africa, a well distributed rainfall of 1000 to 1500 mm is considered optimum, but it can also be grown in regions experiencing 500 to more than 3000 mm/annum (Allemann and Coertze, 1996). Parameter values provided by FAO (2006) are summarised in **TABLE 17.** All literature reviewed has shown that cassava can withstand prolonged periods of drought during the growing season in which most other food crops would perish This makes it a valuable crop in regions where annual rainfall is low or where seasonal rainfall distribution is irregular (Grace, 1977; Cock, 1985; Allemann and Coertze, 1996; IFAD and FAO, 2000; Nweke et al*.,* 2002; FAO, 2006). Cassava is therefore suited to dryland cultivation and irrigation is rarely necessary, although occasional irrigation during very dry periods will help to maintain regular growth (Allemann and Coertze, 1996).

Cassava requires a warm humid climate and is best grown in frost-free areas (Grace, 1977; FAO, 2006), although the plant can tolerate a very light frost as long as the area is free of frost for at least 300 days (Allemann and Coertze, 1996). IFAD and FAO (2000) proposed the annual temperature range of 10 to 40^{o}C for cassava growth. In South Africa, optimum growth temperatures for cassava range from 25 to 35^{o}C, although temperatures above 29^{o}C adversely affect growth. The minimum temperature for cassava growth is 10^{o}C (Grace, 1977; Allemann and Coertze, 1996; IFAD and FAO, 2000); however, during the dormant phase, the crop dies at 7^{o}C and during the early growth stage, temperatures below 0^{o}C are fatal (FAO, 2006).

Cassava is suited to moist, fertile, well-drained, deep, sandy-loam or loamy soils. Where such soils cannot be found, cassava also grows on sandy and clayey soils of low fertility, as long as the soil is not subject to waterlogging (Grace, 1977; Allemann and Coertze, 1996; USAID and ICS-Nigeria, undated). Cassava has been found growing in various soil types in Asia and Latin America; however, according to Howeler (2004), no similar soil data, are yet available for African soils. The optimum planting depth of cassava is 30 mm and it is also tolerant of a wide range of soil pH, from 5.0 to 8.0, and will also grow and produce well in soils with a high aluminium content (Allemann and Coertze (1996).

According to FAO (2006), cassava is grown in tropical wet and dry (Aw), tropical wet (Ar), steppe or semiarid (Bs) Köppen Climate Zones, and it is a short (<12 hours) to neutral (12-14 hours) day plant.

TABLE 17 *Climatic and soil attributes for the production of* cassava *(FAO, 2006).*

Cassava Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	medium (50-150 cm)	medium (50-150 cm)
Daily Temp. Requirement (^{o}C)	20	29	10	35	**Soil texture**	medium, light	heavy, medium, light, organic
Annual Rainfall (mm)	1000	1500	500	5000	**Soil fertility**	moderate	low
Latitude	0	25	0	30	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Altitude (masl)			0	2000	**Soil drainage**	well (dry spells)	well (dry spells), excessive (dry/moderately dry)
Soil pH	5.5	8	4	9			
Light intensity	very bright	very bright	very bright	cloudy skies			

2.9.4 Water use characteristics

In a study by Watanabe et al. (2004), seasonal changes in evapotranspiration, soil water content, and crop coefficients were determined for cassava, sugarcane and maize. The study was performed in Northeast Thailand which is characterised by a semi-arid tropical climate. Mean annual air temperature is 26^o C with solar radiation of between 15 and 20 MJ. m^{-2} and the minimum solar radiation occurring in the dry season. Due to an absence of reliable solar radiation, humidity and windspeed data, evapotranspiration was calculated using the Hargreaves ET equation (Hargreaves and Samani, 1982 cited in Watanabe et al., 2004). Cassava was planted for one year from November 1998 to November 1999 at a density of 25000 plants/ha. ET measurements were performed using the Bowen ratio energy balance technique. Time domain reflectometry (TDR) was used to measure changes in soil water content. Crop coefficients were determined using the relation Kc = ET/ET^0, where ET^0 is the FAO reference total evaporation (Allen et al., 1998 cited in Watanabe, 2004).

Results are as follows: Soil water content (SWC) for cassava was found to be similar to sugarcane, with soil water content beginning at 0.214 $m^3.m^{-3}$ in 1999 and gradually decreasing toward the end of the dry season. At the end of the dry season, SWC reached 0.140 $m^3.m^{-3}$. SWC for maize was consistently less than that for cassava and sugarcane. Crop coefficients for sugarcane and cassava reached peaks of approximately 1.10 and 1.20 respectively, at the mid season stage after which values decreased gradually. For a more detailed description of the study, refer to Watanabe et al. (2004).

In another study by Oguntunde and Alatise (2007), sap flow density in cassava was measured for 10 days in Ghana during December 2002. Whole plant transpiration ranged from 0.8 to 1.2 mm/day and daily canopy conductance varied between 0.7 and 2.1 mm/s.

2.9.5 Potential environmental impact

Cassava has been claimed to be an environmentally-unfriendly crop that has high nutrient demands and exhausts the soil very rapidly, and furthermore causes soil erosion (Grace, 1977). A different view was held by Nweke et al. (2002), who argued that cassava is an environmentally-friendly crop; the myth of cassava being a nutrient-depleting crop is based on the fact that cassava has been widely grown in high rainfall regions, and on sandy or forest soils that are already nutrient-deprived. In a strategic environmental assessment for cassava prepared by FAO and IFAD (2001), the impact of cassava production and processing on the environment, and on biodiversity was outlined. It suggested that cassava, at high yields, removes less nitrogen and phosphorous compared to other crops. At lower yields, cassava removes much less nitrogen, phosphorous, and potassium than most other crops. This is because most nutrients are stored in the stems and leaves of the plant, and they are returned to the soil once leaves and stems have fallen (FAO and IFAD, 2001). There is no documented evidence relating cassava production and biodiversity, although much of biodiversity issues result from human agricultural practices such as monocropping and deforestation (FAO and IFAD, 2001).

With regards to soil erosion, the soil is exposed to the direct impact of rainfall during 3 to 4 months after planting, since cassava needs to be planted at a relatively wide spacing of 1 m by 1 m (O'Hair, 1995; FAO and IAFD, 2001). However, according to Nweke et al. (2002), cassava cultivation involves minimal soil disturbance, especially in sandy soils which are prone to water erosion. Furthermore, the plant being a perennial crop, provides soil cover and does not shed all its leaves with senescence thereby reducing the risk of soil erosion (Nweke et al., 2002). Intercropping of cassava with ground cover crops with initial planting is often encouraged.

The impact of cassava processing on the environment is mostly negative since large amounts of wastes are produced, although the type and composition of those wastes are mostly governed by the processing method and sophistication of the technology used (FAO and IFAD, 2001). The wastes have strong and unpleasant odour, and large volumes of water are required for starch extraction which could produce large amounts of waste water (rich in nutrient), leading to potential eutrophication of rivers (FAO and IFAD, 2001).

With regards to the impact of cassava as a bioethanol product in automobiles, a study conducted by Hu et al. (2004) on the life cycle economics, environmental impacts, and energy consumptions of cassava-based bioethanol blend using Life Cycle Analysis (LCA) techniques have shown that while the cost of cassava-based ethanol is higher than that of gasoline fuelled car in 2004, it has lower life-cycle emissions of carbon dioxide, carbon monoxide, hydrocarbon, particulate matter pollutants, and an overall higher environmental indicator value, despite higher nitrogen oxide emissions.

2.10 Tung-oil Tree (*Aleurites fordii* Hemsl.)

Belonging to the *Euphorbiaceae* family, the perennial, deciduous, soft wood Tung-oil Tree can grow to the height of 12 m (FAO, 2006); its heart-shaped leaves are dark green; white, monoecious flowers gather in clusters; its fruits are spherical or pear-shaped which turn from green to purple at maturity; fruits usually contain 4 to 5 seeds, but may vary from 1 to 15; seeds consist of a hard outer shell and a kernel (Duke, 1983). Tung-oil Trees usually begin to bear fruit in their third year after planting, attaining maximum production in 10-12 years; the average life of the trees is 30 years in the USA.

2.10.1 Utilisation of the Tung-oil Tree

Tung trees are cultivated for their seed-oil which has quick-drying properties. The oil has been utilised in the manufacture of lacquers, varnishes, paints, linoleum, oil cloth, resins, artificial leather, brake-linings, as well as in clearing and polishing compounds. It is also used to insulate wires and other metallic surfaces e.g. in radios, radar, telephone and telegraph instruments. According to Duke (1983), the Chinese used Tung oil for motor fuel during World War II, and have developed techniques to process the oil to make it compatible with gasoline. It has been reported that the tree has tannins, phytosterols, and a poisonous saponin. No medicinal value has been recorded.

FIGURE 12 Tung-oil Tree *with blossoming flowers (a) and its pod containing seeds (b).*

TABLE 18 *Utilisation of the* Tung-oil Tree *(FAO, 2006).*

Main use	**Detailed use**	**Used part**
Material	Lipids/oil and fats	Seeds
Environmental	Manure/fertilizer	Seeds
Fuels	Petroleum substitutes/alcohol	Seeds

2.10.2 Present distribution, extent of plantings and yield

The Tung tree is native to central and western China but major producing countries are mainland China, Argentina, and Paraguay. Duke (1983) reports that the fruit contains 14 to 20% oil, the kernel 53 to 60%, and the nut 30 to 40%. When fruits mature, they are dropped onto the ground and do not deteriorate even after four weeks. In fact, the fruits should be left on the ground to be dried, since wet fruits contain less oil percentage-wise. The fruits are usually picked by hand, sacked, and placed in the crotch of the tree to be dried to 15% moisture. The trees may be planted 125 to 750 trees/ha, while in contour-planting, the rows may be spaced 10 to 12 m apart with trees spaced 3.3 to 4.0 m apart in rows, typically reaching 250 to 350 trees/ha. The trees could yield 4.5 to 5 tonnes of fruits/ha, and may be gathered throughout winter when other crops do not require care.

Tung trees are relatively free of insects and pests, since the fruit and leaves are toxic to most animal life. It is, however, susceptible to bacteria, fungi, and nematodes as listed by Duke (1983).

2.10.3 Biophysical requirements

The tree can tolerate annual rainfall of 640 to 1730 mm (mean of 8 cases = 1230 mm), annual temperature of 18.7 to 26.2^{o}C (mean of 8 cases = 22.5^{o}C), soil pH of 5.4-7.1 (mean of 4 cases = 6.4) with optimum pH at 6.0 to 6.5 (Duke, 1983). Globally it is found in the subtropical dry summer (Cs) regions under the Köppen Climate Zone classification (FAO, 2006). Tung trees require long, hot summers with abundant moisture, with at least 1120 mm of rainfall evenly distributed through the year. However, the trees also require 350 to 400 hours of temperatures 7.2^{o}C or lower in winter, because without this cold treatment, the trees tend to produce suckers from the main branches (Duke, 1983), According to FAO (2006), fatality occurs at 0^{o}C during dormant and early growth stages. Thus, the tree is best grown in frost-free areas, since the trees are susceptible to cold injury during the active growth period. The Tung-oil Tree also requires regions that have relatively uniform diurnal temperatures and are best planted on hilltops or slopes and are suitable for contour-ploughing. Virgin lands with good soil fertility are likely to produce good Tung-oil yields; as the soils need to be well-drained, deep, aerated, and have a high moisture-holding capacity (Duke, 1983). The Tung-oil Tree is a short day plant with a photoperiod of less than 12 hours a day (FAO, 2006).

TABLE 19 *Climatic and soil attributes for the production of* Tung-oil Tree *(FAO, 2006).*

Tung-oil Tree ***Attributes***	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	medium (50-150 cm)	shallow (20-50 cm)
Daily Temp. Requirement (^{o}C)	17	22	10	28	**Soil texture**	medium	Medium
Annual Rainfall (mm)	1000	1200	750	1400	**Soil fertility**	high	Moderate
Latitude	29	32	29	32	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Altitude (masl)			600	1000	**Soil drainage**	well (dry spells)	well (dry spells)
Soil pH	6	7	5.3	7.5			
Light intensity	very bright	clear skies	very bright	cloudy skies			

2.10.4 Potential environmental impact

None was noted in available literature.

2.11 Flax (*Linum usitatissimum*)

Also known as linseed, flax belongs to the *Linaceae* family and was originally used for fibre (linen) and oil (Poteet, 2006). It is a self pollinating annual plant growing up to 1 metre tall. The life cycle of the flax plant consists of a 45 to 60 day vegetative period, a 15 to 25 day flowering period and a maturation period of 30 to 40 days. Water stress, high temperature and disease can shorten any of these growth periods (ARC, 2007).

FIGURE 13 *A field of flax flowers (a) and its seeds (b).*

2.11.1 Utilisation and by-products of flax

Flax is used most commonly for its seed oil which is suitable for paints and varnishes, as well as for nutritional benefits (Poteet, 2006). Linseed oil has been used as a drying agent for paints, varnishes, lacquer and printing ink (Oplinger et al., 1989b). A by-product of flax is its fibre which is used to make linen (ARC, 2007). Straw from seed flax has been used in the manufacture of upholstery cushioning, rugs and paper (Duke, 1983). After oil production, the remaining seedcake provides a high-value livestock feed as well as a dietary supplement for humans. It works well as an intercrop with rice, sugarcane and peanut (in India) as it has a low nitrogen requirement (Poteet, 2006).**TABLE 20** gives a summary of uses according to the FAO (2006).

TABLE 20 *Utilisation of flax (FAO, 2006).*

Main Use	Detailed use	Used part
Material	Fibres	Stems
Material	Lipids/oil and fats	Stems
Material	Fibres	Stems
Animal food (feed)	Minerals	Stems
Animal food (feed)	Protein	Seeds
Medicinal	Skin applications	Seeds
Medicinal	Digestive system applications	Seeds
Fuels	Petroleum substitutes/alcohol	Seeds

2.11.2 Present distribution, extent of plantings and yield

According to Casa et al. (1999), Canada, Argentina and India are the world's largest producers of flax, with it also being produced in Russia and the USA (Poteet, 2006). The United Kingdom produces the majority of Linseed in the European Community (Freer, 1992). The average yield for the UK is approximately 1.8 tonne/ha (Freer, 1992). According to the Agricultural Research Council of South Africa (ARC, 2007), yields can approach 6 to7 tonnes/ha and it is grown largely for fibre with the oil being a by-product.

2.11.3 Biophysical requirements

Flax is a broadleaf plant preferring cooler growing seasons and has similar growth requirements to oats and wheat (Poteet, 2006). It grows in cool temperate regions, but can grow in subtropical climates with evenly spread precipitation throughout the growing season and has a low nitrogen requirement. Flax plants are tolerant to drought, grazing, high pH, herbicides, viruses and weeds (Poteet, 2006) but are susceptible to water stress at the seedling stage, at flowering and during early seed development (Casa et al., 1999). In hot dry climates, irrigation may be necessary (ARC, 2007) as flax grows best in cool, moist climates, suggesting that it should be intercropped with another oilseed crop to maximise land productivity. Slightly acidic to neutral soils, or even slightly alkaline, are best suited to flax production in South Africa (ARC, 2007). ***TABLE 21*** provides a summary of biophysical requirements according to FAO (2006).

TABLE 21 *Climatic and soil attributes for the production of flax (FAO, 2006).*

Flax Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	Shallow (20-50 cm)	Shallow (20-50 cm)
Daily Temp. Requirement (^oC)	16	24	5	30	**Soil texture**	heavy, medium	heavy, medium
Annual Rainfall (mm)	500	800	250	1300	**Soil fertility**	high	high
Latitude	49	53	0	60	**Soil salinity**		
Altitude (masl)			0	3000	**Soil drainage**	well (dry spells)	well (dry spells)
Soil pH	6	6.5	5.5	7			
Light intensity	clear skies	cloudy skies					

2.11.4 Water use characteristics

Flax is reported to grow best on soils with a high water holding capacity and good fertility. Poorly drained, sandy soils are not suitable. (Flax council of Canada, 2007). Flax crop water use can be as high as 410 mm over the growing season ranging from 1 to 3 mm/day up to 7 mm/day during the flowering stage (Flax council of Canada, 2007). The critical water requirement period is from flowering to just prior to seed ripening. Therefore, adequate soil moisture must be maintained during that period. In a study by Lafond et al. (2006), the effect of tillage systems and crop rotations on crop production was assessed. In this study it was found that water use efficiency was improved for flax in wheat by intercropping as follows: spring wheat-spring wheat-flax-winter wheat and spring wheat-flax-winter wheat-field pea. Water use efficiency values were 5.37, 5.35 and 4.86 $kg.mm^{-1}/ha$ for zero, minimum and conventional tillage respectively. For a first crop, water use efficiency was 5.35 and for the second crop, water use efficiency was 5.04 $kg.mm^{-1}/ha$.

2.11.5 Potential environmental impact

None was noted in available literature

2.11.6 Other Information

No specialised farm machinery is needed to plant or harvest its seeds. It is primarily a crop for temperate regions (Casa et al., 1999).

2.12 Jojoba (*Simmondsia chinensis*)

Belonging to the *Simmondsiaceae* family and pronounced "hohoba", Jojoba is has been cultivated to provide a renewable source of unique high-quality oil in the United States and Mexico (Undersander et al., 1990). Their seeds contain wax, not oil and are reported to contain over 50% wax. The oil is extracted from the wax by solvents. The oil is highly-stable, and relatively easy to work with once extracted as it needs little refining (Poteet, 2006). The Jojoba plant can live for up to 200 years (Poteet, 2006; Undersander et al. 1990); it is evergreen and grows to heights of 1 to 5 meters.

FIGURE 14 *Jojoba plant with blossoming flowers (a) and its seed (b).*

2.12.1 Utilisation and by-products of Jojoba

Jojoba is used as replacement for petroleum, cosmetics, hair care products. (Undersander et al., 1990). After wax processing from the seeds, the remaining cake has a protein content of over 30%, making it suitable as an animal feed according to Poteet (2006). However Undersander et al. (1990) noted that toxic compounds are present in the meal, making it potentially hazardous as an animal feed. **TABLE 22** gives a summary of uses according to the FAO (2006).

2.12.2 Present distribution, extent of plantings and yield

Yield of 660 to 2200 seeds/kg has been reported (Undersander et al., 1990). Jojoba is native to southern Arizona, southern California, north-western Mexico, and is now also cultivated in Argentina, Chile, Israel, Australia and India (Benzioni, 1997). Plants do not begin to fruit until five years after establishment and full potential is reached 8 to 10 years after planting (Duke, 1983 cited in Poteet, 2006). Jojoba can be planted tightly into hedgerows for plantation style cultivation. Oil yields can be 1.1 to 2.2 tonnes/ha (Poteet, 2006).

TABLE 22 *Utilisation of Jojoba (FAO, 2006).*

Main Use	**Detailed use**	**Part of Plant used**
Food and beverage	Protein	Seeds
Food and beverage	Vitamins	Seeds
Food and beverage	Minerals	Seeds
Animal food (feed)	Protein	Seeds
Animal food (feed)	Vitamins	Seeds
Animal food (feed)	Minerals	Seeds
Animal food (feed)	Vitamins	Leaves
Animal food (feed)	Minerals	Leaves
Material	Lipids/oil and fats	Seeds
Material	Waxes	Seeds
Material	Cosmetics and perfumery	Seeds
Environmental	Erosion control	Entire plant
Environmental	Living fence	Entire plant
Environmental	Windbreak	Entire plant
Environmental	Agroforestry	Entire plant
Fuels	Petroleum substitutes/alcohol	Seeds

2.12.3 Biophysical requirements

Being native to the desert areas of the south-western North American continent, Jojoba grows best in warm temperate to tropical desert conditions. Loose drained, alkaline soils are best suited for cultivation (Poteet, 2006). Jojoba is found in areas with an annual precipitation of 80 to 450 mm and with a temperature range to 50°C (Gentry, 1958; cited in Benzioni, 1997). It can thus survive in a harsh desert environment. It is drought and to some extent salt resistant and is best suited to frost free environments. In the wild, Jojoba grows on course, light or medium textured soils with good drainage and good water infiltration (Undersander, 1990). **TABLE 23** gives a summary of biophysical requirements according to FAO (2006).

TABLE 23 *Environmental attributes of Jojoba (FAO, 2006).*

Jojoba Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	Deep (>150cm)	Shallow (20-50cm)
Daily Temp. Requirement (^{o}C)	21	36	10	50	**Soil texture**	medium light	heavy, medium light
Annual Rainfall (mm)	250	800	100	2000	**Soil fertility**	moderate	low
Latitude	25	31	23	35	**Soil salinity**	low (<4 dS/m)	high (> dS/m)
Altitude (masl)			0	1500	**Soil drainage**	well (dry spells)	well (dry spells), excessive (dry/moderately dry)
Soil pH	605	705	5	8.2			
Light intensity	very bright	very bright	very bright	very bright			

2.12.4 Potential environmental impact

The crop contains a group of glycosides in the leaves, stems, roots and meal (after oil extraction) making it hazardous as an animal feed (Undersander et al., 1990)

2.13 Switchgrass (*Panicum virgatum*)

Belonging to the *Paniceae* family and native to the United States, where it is receiving much interest as a potential biofuel feedstock. Switchgrass is a sod forming grass that grows up to 1.5 meters tall (Magness et al., 1971). Growth starts late but continues throughout the summer if moisture is available.

FIGURE 15 *Switchgrass flowers (a) and the whole plant (b).*

2.13.1 Utilisation and by products of switchgrass

Switchgrass has been extensively researched in the United States for use as a bioenergy crop where sugar extracted from the stem is used to produce ethanol (McLaughlin et al., 1999). Switchgrass is an important forage crop for livestock, primarily used for warm season pastures and hay. It provides cover and food for ducks, upland game birds and small mammals and has been used in soil restoration, for revegetation and for wildlife cover along pond margins (Silzer, 2007). It benefits when grown with legumes as the legumes substitute fertilisation.
TABLE 24 gives a summary of uses according to the FAO (2006).

TABLE 24 *Utilisation table for* switchgrass *(FAO, 2006).*

Main Use	**Detailed use**	**Used part**
Environmental	Erosion control	Entire plant
Animal food (feed)	Minerals	Entire plant
Animal food (feed)	Vitamins	Entire plant
Fuels	Non-wood fuel	Stems
Fuels	Petroleum substitutes/alcohol	Stems
Fuels	Alcohol	Stems

2.13.2 Present distribution, extent of plantings and yield

Switchgrass grows naturally south of latitude 55°N throughout most of the United States east of the Rocky mountains (Silzer, 2007). Dry matter yields vary from 3.4 to 9.5 tonnes/ha.

2.13.3 Biophysical requirements

Switchgrass grows in most soil types but thrives best on low, moist areas of good fertility (Magness et al., 1971). Switchgrass is tolerant of moderate soil salinity and acidity, growing in soil pH from 4.5 to 7.6 (Silzer, 2007). Optimum temperature for seed germination is 20 to 30°C. Switchgrass is unharmed by burning because its rhizomes are resistant to the heat of fire. **TABLE 25** gives a summary of biophysical information according to FAO (2006).

TABLE 25 *Environmental attributes of* switchgrass *(FAO, 2006).*

Switchgrass Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	medium (50-150cm)	shallow (20-50cm)
Daily Temp. Requirement (°C)	17	32	6	36	**Soil texture**	light	light
Annual Rainfall (mm)	500	1100	350	2700	**Soil fertility**	moderate	low
Latitude					**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Altitude (masl)					**Soil drainage**	well (dry spells), excessive (dry/moderately dry)	well (dry spells), excessive (dry/moderately dry)
Soil pH	6	7	4.9	8.2			
Light intensity	very bright	very bright	very bright	very bright			

2.13.4 Potential environmental impact

Some *Panicum* species are invasive in cultivated land, especially under fertilisation.

2.14 Sugarbeet (*Beta vulgaris*)

Belonging to the *Chenopodiacae* family, sugarbeet is a deciduous single stem herb with large roots/tubers used in the production of sugar and/or alcohol (FAO, 2006).

FIGURE 16 *Sugarbeet tuber (a) and in profile in the soil (b).*

2.14.1 Utilisation and by products of sugarbeet

Primarily produced for sucrose (Cattanach et al., 1991), in many parts of the world, sugarbeet plays a similar role to that of sugarcane in the South African sugarcane industry. Processing by-products include pulp and molasses as feed supplements for livestock. Sugarbeet can be grown with an autumn sown cover crop such as wheat by a process called direct drilling (Richard et al*.,* 1995). The sugarbeet crop is sown in spring and harvested in summer, and the cover crop is usually chemically destroyed before sugarbeet emergence. **TABLE 26** gives a summary of uses according to the FAO (2006).

TABLE 26 *Utilisation table for sugarbeet (FAO, 2006).*

Main Use	**Detailed use**	**Used part**
Food additive	Sweetener	Roots
Animal food (feed)	Sugar	Roots
Animal food (feed)	Starch	Roots
Animal food (feed)	Minerals	Roots
Animal food (feed)	Minerals	Leaves
Food and beverage	Sugar	Roots
Food and beverage	Starch	Roots
Food and beverage	Minerals	Roots
Fuels	Petroleum substitutes/alcohol	Roots
Fuels	Alcohol	Roots

2.14.2 Present distribution, extent of plantings and yield

Thought to originate in Asia, sugarbeet is grown in many countries. The largest producers include the United States, Canada, Russia, Poland, France, Germany and Turkey. Present world production is about 234 million tonnes of beets from about 5.9 million ha. (FAO, 2007). This provides about 16% of the world's sugar production. Yields vary from 40 to 80 t/ha of fresh beet at 15% sugar content (FAO, 2007). According to FAO (2007), the few comparative studies that have been made between sugarcane and sugarbeet, show that climate is the most important factor in dictating which crop is more suitable in terms of production.

2.14.3 Biophysical requirements

Sugarbeet has adapted to a wide range of climatic conditions, but is mainly a temperate zone crop (Cattanach et al., 1991). When produced in hotter climates crops are of lower quality and problems with insects and disease are common. Seed germination requires cool cycles and is possible at 5^{o}C but optimum is 7 to 10^{o}C. High sugar yields are obtained when night temperatures are between 15 to 20^{o}C and day temperatures are between 20 to 25^{o}C during the latter part of the growing period. During this period, temperatures greater than 30^{o}C greatly reduce sugar yields (FAO, 2007).

Sugarbeet is adapted to a wide range of soil types from coarse textured sandy soils to high organic matter. A medium to slightly heavy textured, well drained soil is preferred. Soil pH less than 5.5 is unfavourable for growth.

For maximum production, water requirements of the crop are related to evapotranspiration. Total water requirements are in the range of 550 to 750 mm per growing period (FAO, 2007).

TABLE 27 *Climatic and soil attributes for the production of sugarbeet (FAO, 2006).*

Sugarbeet Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	deep (>150 cm)	Medium (50-150 cm)
Daily Temp. Requirement (^{o}C)	15	25	7	30	**Soil texture**	medium, organic	Heavy, medium, organic
Annual Rainfall (mm)	400	700	250	1000	**Soil fertility**	high	moderate
Latitude	30	60	30	60	**Soil salinity**	medium (4-10 dS/m)	high (>10 dS/m)
Altitude (masl)			0	2100	**Soil drainage**	Well (dry spells)	
Soil pH	6	6.8	5.5	8.5			
Light intensity	cloudy skies	clear skies	light shade	clear skies			

2.14.4 Potential environmental impact

None was noted in available literature

2.15 Maize (*Zea mays* L.)

Maize belongs to the *Poaceae* family (Duke, 1983) and is an annual, C_4 grass; (Duke, 1983; FAO, 2006). The stems are stout with prop roots from lower nodes, and a papery sheath enclosing a thick central cob (Duke, 1983). The South African Atlas of Climatology and Agrohydrology (Schulze, 2006) provides detail regarding the maize plant and its growth in South Africa. It should be noted that in South Africa, there has been a tendency to develop and grow high protein cultivars of the crop and that these are not optimal for bioethanol production.

FIGURE 17 *Maize plants (a) and maize of different sizes showing three growth stages (b).*

2.15.1 Utilisation of maize

Corn or "maize" is a staple cereal for human food in many countries, including South Africa. It is also used in animal feed as grain or fodder and is converted into various substances which have a wide range of uses (e.g. starch, syrup, dextrin, maize oil, and in the making of whiskey and other alcoholic products). In some cases, products from maize are also used in printing, confectionery, condensed milk, tanning leather, plastics, food, soap, paint, and textile industries. In folk medicines, maize has been used as remedies for tumours and warts. The tea from the seed is said to have diuretic and antiseptic properties (Duke, 1983).

TABLE 28 *Utilisation of maize (FAO, 2006)*

Main use	Detailed use	Used part
Food and beverage	Vitamins	Fruits
Food and beverage	Starch	Seeds
Food and beverage	Protein	Seeds
Food and beverage	Lipids	Seeds
Animal food (feed)	Minerals	Entire plant
Animal food (feed)	Vitamins	Entire plant
Material	Lipids/oil and fats	Seeds
Medicinal	Unspecified	Seeds
Fuels	Petroleum substitutes/alcohol	Seeds
Fuels	Alcohol	Seeds

TABLE 29 *Cropping details of maize (FAO, 2006).*

Cropping system	Subsystem	Crop(s)
Arable irrigated	Rotation cropping	Legumes
Arable irrigated	Inter-cropping	Peanuts, okra, pumpkins, melons
Arable irrigated	Alley cropping	Grain legumes (*Vigna unguiculata*), soya beans (*Glycine max*), *Acacia auriculiformis, Cajanus cajan*
Arable irrigated	Phase planting	Coconut, mango, mung bean, oil-palm, young rubber trees

2.15.2 Present distribution, extent of plantings and yield

Maize is widely domesticated, but is believed to have originated in Mexico in prehistoric times (Duke, 1983). The crop is extensively researched and grown throughout the world. In South Africa, recent crop surpluses have been targeted as a feedstock for biofuel production, despite being excluded from the list of plants specified in the SA biofuels strategy (DME, 2007).

Maize yields in South Africa are relatively low and in the decade 1995/6 to 2004/5 mean national values have fluctuated between 2.16 and 3.04 tonnes/ha (Schulze and Walker, 2006). Yields from the commercial sector are somewhat higher (2.7-3.3 tonnes/ha) with highest dryland yields attained in KwaZulu-Natal (3.93 tonnes/ha) and Mpumalanga (3.42 tonnes/ha). However, in recent years, new seed varieties and enhances in crop management through innovations such as conservation tillage have resulted in crop yields in excess of 7 tonnes/ha being achieved quite commonly. In the developing sector yields are approximately 0.8 tonne/ha for white and 1.4 tonne/ha for yellow maize (Schulze and Walker, 2006). According to Schulze and Walker (2006), yields under irrigation average at 6.05 tonnes/ha, with highest yields in the northern Cape (6.76 tonnes/ha), Free State (6.31 tonnes/ha) and Mpumalanga (6.27 tonnes/ha).

2.15.3 Biophysical requirements

Maize in South Africa is generally planted from October to December, depending on regional and seasonal rainfall and temperature patterns. Being a warm weather crop, daily mean temperatures greater than 22°C are required with a January mean temperature between 19°C and 24°C being ideal. The critical upper temperature affecting yield reductions is 32°C. Frost can damage maize at all growth stages and generally a frost-free period of 120 to 140 days is required to prevent damage. While maize can be produced when the mean annual precipitation is around 350 mm, ideally 450 to 600 mm is needed during the growing season. Maize prefers a relatively deep (greater than 750 mm) well drained soil, with both light and heavy textured soils reducing yields, particularly in drier areas (NDA, 2005).

TABLE 30 *Environmental attributes of maize (FAO, 2006).*

Maize Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	medium (50-150 cm)	shallow (20-50 cm)
Daily Temp. Requirement (^{o}C)	18	33	10	47	**Soil texture**	medium, organic	wide
Annual Rainfall (mm)	600	1200	400	1800	**Soil fertility**	high	low
Latitude	0	40	0	48	**Soil salinity**	low (<4 dS/m)	medium (4-10 dS/m)
Altitude (masl)			0	4000	**Soil drainage**	well (dry spells)	well (dry spells), excessive (dry/moderately dry)
Soil pH	5	7	4.5	8.5			
Light intensity	very bright	very bright	clear skies	very bright			

Köppen Climate Zone requirements are reported as tropical wet and dry (Aw), tropical wet (Ar), steppe or semiarid (Bs), subtropical humid (Cf), subtropical dry summer (Cs), subtropical dry winter (Cw), temperate oceanic (Do), temperate continental (Dc), temperate with humid winters (Df), temperate with dry winters (Dw) (FAO, 2006). Maize growing areas and potential yield under different conditions have been produced for South Africa by Schulze (2006), as illustrated in **FIGURE 18**.

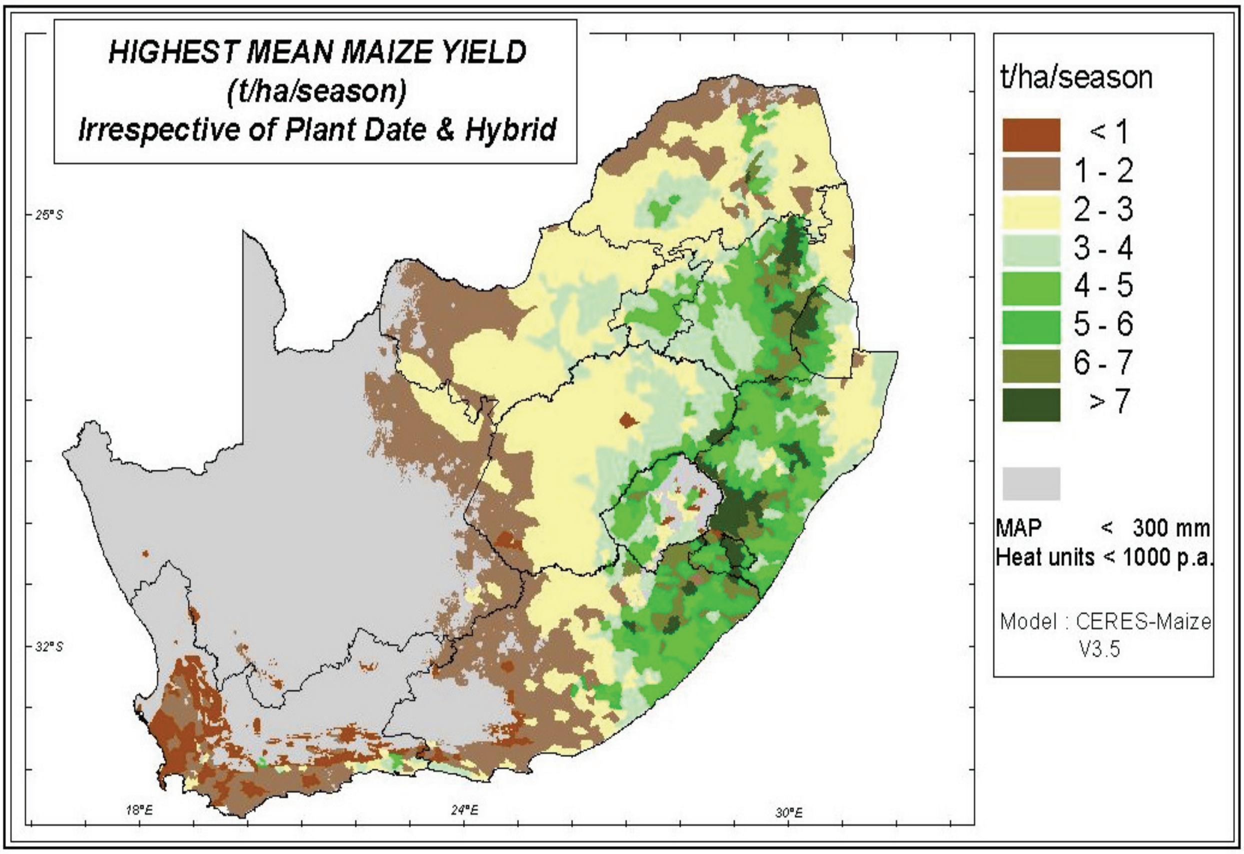

FIGURE 18 *Highest potential maize yields in South Africa (Schulze, 2006).*

2.15.4 Water use characteristics

Maize is an efficient user of water in terms of total dry matter production and is potentially the highest yielding grain crop among cereals (FAO, 2002). While maize can be produced when MAP exceeds 350 mm, ideally 450 to 600 mm is needed during the growing season (NDA, 2005) and for maximum production, a medium maturity crop requires between 500 to 800 mm water depending on climate (FAO, 2002). Sustained production is dependent on an even distribution of rainfall throughout the growing season, but is critical particularly during the flowering season when soil water stress reduces yields more during other growth phases.

According to FAO (2002), the crop factor (Kc) relating water requirements (ETm) to reference evapotranspiration (ETo) for different crop growth stages of grain maize is 0.3 to 0.5 for the initial stage (15 to 30 days), 0.7 to 0.85 for the development stage (30 to 45 days), 1.05 to 1.2 for the mid-season stage (30 to 45 days), 0.8 to 0.9 for the late season stage (10 to 30 days) and 0.55 to 0.6 at pre-harvest. Maize is relatively tolerant to water deficits during the vegetative and ripening periods but most sensitive during the flowering period (where the greatest decrease in grain yields has been reported). South African values are well established through the work of Schulze (2006). Water use efficiency of harvested yield for grain varies between 0.8 and 1.6 $kg.m^{-3}$ (FAO, 2002).

2.15.5 Potential environmental impact

Extensively cultivated areas can lead to soil erosion.

2.16 Sugarcane (*Saccharum officinarum* L.)

Sugarcane belongs to the *Poaceae* family (Duke, 1983); it is a perennial grass (FAO, 2006) with stalks 3 to 5 m tall, 2 to 3cm thick. Sheaths overlap, and blades are elongated (Duke, 1983). The South African Atlas of Climatology and Agrohydrology (Schulze 2006) provide details for South Africa. Sugarcane is used as an external feedstock, though not extensively. South Africa has a well established sugarcane industry and investigations into cane varieties for "energy" production, rather than sugar are ongoing.

FIGURE 19 *Sugarcane plantation (a) and sugarcane (b).*

2.16.1 Utilisation of sugarcane

Sugarcane produces cane sugar, cane syrup, molasses, wax and rum. Molasses is further used in sweeteners, industrial alcohol, explosives, synthetic rubber and combustions engines. Sugarcane bagasse is used in the manufacturing of paper, cardboard and fuel. The reeds are made into pens, mats, screens and thatch. A mixture of bagasse and molasses (Molascuit) is used as cattle feed; the dried cane is excellent mulch and can be baled and shipped economically due to its light weight (Duke, 1983). Sugarcane is suited to mono-cropping (FAO, 2006).

TABLE 31 *Utilisation of sugarcane (FAO, 2006).*

Main use	**Detailed use**	**Used part**
Food additive	Sweetener	Stems
Food additive	Condiment/seasoning	Stems
Food and beverage	Minerals	Stems
Food and beverage	Minerals	Flowers
Material	Paper	Stems
Material	Fibres	Stems
Animal food (feed)	Minerals	Stems
Fuels	Petroleum substitutes/alcohol	Stems
Fuels	Alcohol	Stems

2.16.2 Present distribution, extent of plantings and yield

Sugarcane originated in the South Pacific Islands and New Guinea (Duke, 1983). It is now found throughout the tropics and subtropics, cultivated as far North as 36.7^{o} N (Spain) and as far south as 31^{o}S (South Africa).

According to SASA (2005), approximately 432 000 ha in South Africa is under sugarcane, of which approximately 325 000 ha are harvested annually. Of the area cultivated, approximately 72% is rainfed and 28% is under irrigation (Schulze et al., 2006). In South Africa, dryland sugarcane is grown mainly in KwaZulu-Natal (97%) with smaller pockets in the Eastern Cape and Mpumalanga. Average sucrose content of the South African crop is approximately 13.5%, varying from 11.9 to 13.8% and inversely related to the year's rainfall. It takes approximately 8.5 tonnes of sugarcane to produce one tonne of sugar (Schulze et al., 2006).

2.16.3 Biophysical requirements

Sugarcane requires a summer growing season which is warm to hot, with daily mean temperatures optimally between 22°C and 32°C. Conditions should be moist, with a minimum mean annual precipitation of 850 mm. Optimally, 1 300 mm of rainfall should fall per year, with 120 mm per month (Smith, 1998). Hot summers should be followed by a dry, but sunny and frost-free (only very light frosts tolerated) winter ripening and harvesting period during which relative humidity should be less than 70%. For ripening, 10-20°C is necessary to reduce vegetative growth and increase sucrose content (Smith, 1998). Minimum growth takes place at daily temperatures below 20°C and greater than 34°C. In KwaZulu-Natal, production areas are limited by the July minimum temperature isotherm of 5°C (Smith, 1998). Fatal temperature during rest is -2°C; and during early growth is 0°C (FAO, 2006).

The crop does well under a range of soils, but prefers well structured and aerated loams and sandy loam more than 1 m deep with plant available water greater than 150 mm. The crop can withstand short spells of waterlogging, but generally the water table should be below 1.5-2.0 m (Schulze et al., 2006). Photoperiod for sugarcane is short day (<12 hours), and neutral day (12-14 hours), with annual sunshine hours of greater than 1200 hours. According to FAO (2006), the Köppen Climate Zones for sugarcane growth are: tropical wet and dry (Aw), tropical wet (Ar), subtropical humid (Cf).

TABLE 32 *Environmental attributes of sugarcane (FAO, 2006).*

Sugarcane Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	deep (>150 cm)	medium (50-150 cm)
Daily Temp. Requirement (°C)	18	33	10	47	**Soil texture**	heavy, medium	heavy, medium, light
Annual Rainfall (mm)	600	1200	400	1800	**Soil fertility**	high	moderate
Latitude	0	40	0	48	**Soil salinity**	low (<4 dS/m)	medium (4-10 dS/m)
Altitude (masl)			0	1600	**Soil drainage**	well (dry spells)	poorly (saturated >50% of year), well (dry spells)
Soil pH	5	8	4.5	9			
Light intensity	very bright	very bright	very bright	clear skies			

2.16.4 Water use characteristics

Adequate available moisture throughout the growing season is important for obtaining maximum sugarcane yields because the vegetative growth including cane growth is directly proportional to the water transpired (FAO, 2002). Depending on climate, water requirements (ETc) of sugarcane are 1500 to 2500 mm evenly distributed over the growing season. The crop coefficient values for the different growth stages are provided in **TABLE 33** below.

The water use efficiency for harvested yield for sugarcane containing about 80% moisture is 5 to 8 $kg.m^{-3}$, and for sucrose containing no moisture 0.6 to 1.0 $kg.m^{-3}$. In the recent past, there have been a number of studies undertaken to assess the water use by sugarcane and the potential impacts of sugarcane on water resources. These range from practical field experimentation to theoretical assumptive work.

Van Antwerpen et al. (1996) discussed the complexity in estimating root water use in sugarcane. Van Antwerpen et al. (1996) after Philip (1966), described the uptake of water through roots as a dynamic physical continuum which can be divided into a demand and supply component. Philip (1966) also stated that the rate of non-limiting soil water depletion by plants is primarily controlled by the atmospheric demand in combination with characteristic plant and soil properties. However, under limited water conditions, supply to the soil-plant-atmosphere continuum is controlled by the soil-root characteristic (Hillel, 1982).

TABLE 33 Crop coefficient (Kc) values, relating to reference evapotranspiration (ETo) for the different growth stages of sugarcane (FAO, 2002).

Development stages	Days	Crop Coefficients
Planting to 0.25 full canopy	30-60	0.45-0.6
0.25 to 0.5 full canopy	30-40	0.75-0.85
0.5 to 0.75 full canopy	15-25	0.90-1.00
0.75 to full canopy	45-55	1.00-1.20
Peak use	180-330	1.05-1.30
Early senescence	30-150	0.80-1.05
Ripening	30-60	0.60-0.75

Smithers et al. (1997) investigated the impacts of grassland, forestry and sugarcane on runoff at the Umzinto research catchments in KwaZulu-Natal using a modelling approach. According to Smithers et al. (1997), there is a lack of accurate data and knowledge of the influence of sugarcane production on the water resources of a catchment. Smithers et al. (1997) also stated that a cost effective and efficient method of assessing the impact of a crop on water resources is to develop credible simulation models. These models should be able to simulate the runoff response from a catchment as well as be sensitive to catchment characteristics such as land cover, management practices and soil characteristics.

Schmidt (1997) noted that the impact of sugarcane on streamflow depends on its location within the river catchment as well as the soil and slope conditions, stage of crop growth, management practices and the local climate. Approximately 70% of the land under sugarcane production is along the coastal belt of KwaZulu-Natal near the outlet of catchments and within 30 kilometres of the sea. Therefore, most of the runoff entering streams in these areas enters the Indian Ocean. However, the hydrological impact of different land uses has to be quantified for decisions to be made with regard to land use impacts on water resources, especially in sensitive catchments where there are many competing water users (Schmidt, 1997).

Bezuidenhout et al. (2006), estimated the water use of commercial sugarcane in South Africa. According to this study water use of rainfed sugarcane has come under the spotlight in South Africa largely as a result of changes in legislation and a focus on SFRAs as highlighted previously. The concern raised by Bezuidenhout et al. (2006) is that an influential study undertaken by Kruger et al. (2000), adopted a methodology whereby candidate SFRAs were determined based upon comparing potential evapotranspiration rates from the identified crops to corresponding Acocks Veld Types. Kruger et al. (2000) reported that potential evapotranspiration for sugarcane was approximately 1400 mm per annum and was compared to a country wide average of potential evaporation for Acocks Veld Types (Adcocks, 1953) of approximately 1100 mm per annum. Bezuidenhout et al. (2006) noted that the potential evapotranspiration of a crop assumes ideal growing conditions with no soil water limitations. In reality, this rarely occurs. For example, they argue that if 700 mm of water was available in the soil profile for a year, both sugarcane and Acocks Veld Types would consume close to 700 mm as their annual potential evapotranspiration, are 1400 mm and 1100 mm respectively. Bezuidenhout et al. (2006) therefore concluded that actual water use and potential hydrological impacts of different crops is complex and largely dependent on the specific environmental limitations imposed. Thus, to base a crops effect on water resources on potential evapotranspiration of a crop and comparing it to the potential evapotranspiration from the original vegetation, is concluded by Bezuidenhout et al. (2006), as not realistic and fundamentally flawed. Rather, the key question should be to qualify the actual evapotranspiration from sugarcane for the regions in which the crop is grown relative to what it replaces or will be replaced by.

Bezuidenhout et al. (2006) undertook an investigation whereby historical regional sugarcane production records for South Africa were used in conjunction with a robust relationship between sugarcane yield and actual evapotranspiration, developed by Thompson (1976). They concluded that the mean water use of sugarcane at an industry scale was 598 mm per annum which amounts to approximately 40% of the mean annual potential evapotranspiration for a full vegetative canopy calculated with the Penman-Monteith equation (McGlinchey and Inman-Bamber, 1996) and included irrigated areas. Water use by rainfed sugarcane amounted to approximately 36% of the mean annual potential evapotranspiration. Clearly, the difference between actual and potential evapotranspiration for sugarcane is a critical issue in assessing water use of sugarcane.

Burger (1999) compared evaporation measurements above commercial forestry and sugarcane canopies in the

KwaZulu-Natal midlands using the Bowen ratio method. She concluded that during the winter of 1997, mature sugarcane consumed 2.8 mm/day whilst young *Acacia* and *Eucalyptus* canopies over this same period consumed 2.4 mm/day and 1.8 mm/day respectively. According to Burger (1999), these differences resulted from changes in the leaf area indices and canopy reflection coefficients. The increase in canopy height of the *Acacia* and *Eucalyptus* tree species over the next year (measured in winter 1998), resulted in increased evaporation rates of 4.9 mm/day and 5.4 mm/day for *Acacia* and *Eucalyptus* respectively.

According to Burger (1999), physiological maturity and high canopy resistance of the sugarcane during the summer of 1997 and winter of 1998 contributed to the lower evaporation rate measured to be 2.1 mm/day and 3.7 mm/day respectively. Over this same period, no stress conditions were visible for *Acacia* (3.7 mm/day and 4.9 mm/day respectively) and *Eucalyptus* (4.3 mm/day and 5.6 mm/day respectively) for summer 1997 and winter 1998. This was assumed to be a result of the ability of deep rooted trees to reach water supplies not available to the sugarcane.

2.16.5 Potential environmental impact

Dryland sugarcane is considered a candidate Streamflow Reduction Activity in South Africa. As with any mono-culture biodiversity is low in areas of extensive production. In some places, degradation, in particular excessive sedimentation of riparian areas and downstream water systems, has been reported.

2.17 Sunflower (*Helianthus annuus* L.)

Sunflower belongs to the *Asteraceae* family (Duke, 1983). It is a fast-growing, annual, C_3 herb (FAO, 2006); stems 0.7 to 3.5 m tall with alternate, ovate leaves. Flowers rotate to face the sun, neuter with yellow ligulate corolla (Duke, 1983). Refer to the South African Atlas of Climatology and Agrohydrology (Schulze, 2006) for more details.

FIGURE 20 *Sunflower plantation (a) and its seeds (b).*

2.17.1 Utilisation of sunflower

Sunflower oil is generally considered a premium oil because of its light colour, high level of unsaturated fatty acids and lack of linoleic acid, and high smoke points (Putman et al*.,* 1990). The primary fatty acids in the oil are oleic and linoleic, with minor portions of palmitic and stearic saturated fatty acids (Duke, 1983; Putman et al*.,* 1990).

TABLE 34 *Utilisation of sunflower (FAO, 2006).*

Main use	Detailed use	Used part
Material	Essential oils	Seeds
Material	Fibres	Seeds
Animal food (feed)	Minerals	Seeds
Animal food (feed)	Vitamins	Seeds
Environmental	Ornamental/turf	Entire plant
Material	Lipids/oil and fats	Seeds
Medicinal	Digestive system applications	Flowers
Medicinal	Digestive system applications	Seeds
Fuels	Petroleum substitutes/alcohol	Seeds

Sunflower oil is used for cooking, margarine, salad dressings, lubrication, soaps, and illumination (Duke, 1983; Putman et al., 1990). Together with linseed oil and other drying oils, sunflower oil is also used in paints and varnishes (Duke, 1983). The flowers yield a yellow dye, hulls provide filler in livestock feeds and bedding, while the pressed seed cake is a high protein food for livestock (Duke, 1983). Sunflowers are commonly cultivated under a mono-cropping system (FAO, 2006).

2.17.2 Present distribution, extent of plantings and yield

Sunflowers are native to western North America (Duke, 1983; Putman et al., 1990) and were initially introduced to Europe. Thereafter, they have been cultivated in both tropical and temperate regions around the world (Duke, 1983).

In South Africa, around 600 000 ha is used to cultivate sunflowers. Of the total area, 46% is in the Free State and 39% in the North West province (NDA, 2005). Of this total area, 98% is under dryland production and only 2% is irrigated (Schulze and Maharaj, 2006a). Average yields range from 0.9 to 1.6 tonne/ha of seed; yield from seeds typically made up of an oil content of 40%, 35% protein meal, and 20 to 25% hulls (Duke, 1983).

2.17.3 Biophysical requirements

Sunflowers are planted from November to December in the eastern parts and up to mid-January in the drier western parts of South Africa. Good yields require an evenly distributed 400-600 mm rainfall during their growing season of about 120 days (Smith, 1998). Although sunflower tolerates short periods of severe soil moisture stress, the water use efficiency of sunflower is reported to be low (720 g water/g dry matter vs. 400:1 for maize or 300:1 for sorghum). Optimum growing temperatures are 18-25°C; sub-optimally the range is 13-30°C. Mean January temperatures should exceed 19°C (Smith, 1998). To complete its growth cycle, sunflowers need 1 500 heat units with a base of 7°C and an upper limit of 30°C (Schulze and Maharaj, 2006a). Sunflowers are, however, very sensitive to high soil temperatures during emergence, especially in the sandy soils of the western Free State and North West province (NDA, 2007).Sunflowers are frost and high humidity susceptible and thrive best at mean monthly temperature around 22°C. Each 1°C increase decreases oil content by 1.5% (Schulze and Maharaj, 2006a). The fatal temperature during dormancy is at -10°C, while temperatures of 0°C during the early growth stage are fatal (FAO, 2006).

While grown on a range of soils, sunflowers prefer sandy clay loam to clay textures with clay percentages in the range 15 to 55%. The plants, which extract most of their soil water from the top 0.75 to 1.50 m of soil but have maximum rooting depths to 3 m, are intolerant to waterlogging and to wind (Smith, 1998). Sunflowers are short day plants, requiring less than 12 hours of photoperiod (FAO, 2006).

The Köppen Climate Zones for sunflower production regions (FAO, 2006) are reported to be tropical wet and dry (Aw), steppe or semiarid (Bs), subtropical humid (Cf), subtropical dry summer (Cs), subtropical dry winter (Cw), temperate oceanic (Do), temperate continental (Dc), temperate with humid winters (Df), temperate with dry winters (Dw).

TABLE 35 *Climatic and soil attributes for the production of sunflower (FAO, 2006).*

Sunflower Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	medium (50-150 cm)	medium (50-150 cm)
Daily Temp. Requirement (^{o}C)	17	34	5	45	**Soil texture**	medium, light	heavy, medium, light
Annual Rainfall (mm)	600	1000	300	1600	**Soil fertility**	high	low
Latitude	20	50	0	55	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Altitude (masl)			0	2600	**Soil drainage**	well (dry spells)	well (dry spells)
Soil pH	6	7.5	5.5	8			
Light intensity	very bright	very bright	very bright	clear skies			

2.17.4 Water use characteristics

Comparatively speaking, sunflowers (*Helianthus annus*) perform well under drought conditions and they are therefore popular in the climatically more marginal areas of South Africa (Schulze and Maharaj, 2006a). They are however, relatively high water users when compared to most crops in respect of total yield produced (FAO, 2002). Water requirements of sunflower vary from 600 to 1000 mm per annum, depending on climate and length of total growing period (FAO, 2002). Evapotranspiration increases from establishment to flowering and according to the FAO can be as high as 12 to 15 mm/day (FAO, 2002) but this seems unlikely under most conditions. Water use over the different growth periods is about 20% during the vegetative growth period, 55% during the flowering period and the remaining 25% during the yield formation and ripening periods. The internally accepted crop coefficient (Kc) is 0.3 to 0.4 during the initial stage (20 to 25 days), 0.7 to 0.8 during the crop establishment stage (35 to 40 days), 1.05 to 1.2 during the mid-season stage (40 to 50 days), 0.7 to 0.8 during the late-season stage (25 to 30 days) and 0.4 at maturity or harvest (FAO, 2002).

In deep soils the root system of sunflower may extend up to 2 to 3 m but normally when the crop is full grown, all water is extracted from the top 0.8 to 1.5 m soil. Under conditions when maximum evapotranspiration is 5 to 6 mm/day, the water uptake is affected when about 45% of the total available soil water is depleted (FAO, 2002). The water use efficiency for harvested yield for seeds containing 6 to 10% moisture is 0.3 to 0.5 $kg.m^{-3}$.

2.18 Groundnut (*Arachis hypogaea*)

Groundnut belongs to the *Fabaceae* family (Duke, 1983); it is an annual herb and is susceptible to hail (FAO, 2006). Groundnut has a tap root with four series of spirally arranged lateral roots, usually heavily supplied with nodules. The root tip does not have epidermis nor root hairs. Leaves are stipulate, pinnate with two opposite pairs of leaflets, alternately arranged. Flowers are pea-like, with orange, yellow, cream or rarely white petals, and are enclosed between two bracts (Duke, 1983). The South African Atlas of Climatology and Agrohydrology (Schulze 2006) provides more details.

FIGURE 21 *Groundnut plant (a) and its seeds (b).*

2.18.1 Utilisation of groundnut.

Groundnut seeds yield a non-drying, edible oil used in cooking, margarines, salads, canning, and deep-frying; for shortening in pastry and bread as well as for pharmaceuticals, soaps, cold creams, pomades and lubricants, emulsions for insect control, and finally fuel for diesel engines. The oil cake, a high-protein livestock feed, may also be used for human consumption. Other products include dyes, ice cream, massage oil, paints, and peanut milk (Duke, 1983).

TABLE 36 *Utilisation of groundnut (FAO, 2006).*

Main use	Detailed use	Used part
Material	Lipids/oil and fats	Seeds
Food and beverage	Protein	Seeds
Food and beverage	Minerals	Seeds
Food and beverage	Vitamins	Seeds
Food and beverage	Minerals	Leaves
Medicinal	Blood system applications	Seeds
Animal food (feed)	Vitamins	Entire plant
Animal food (feed)	Minerals	Entire plant
Animal food (feed)	Protein	Seeds
Animal food (feed)	Vitamins	Seeds
Environmental	Agroforestry	Entire plant
Fuels	Petroleum substitutes/alcohol	Seeds

This drought resistant crop is a rotational crop, which ideally should be planted in the same soil only once every 4 years (NDA, 2005 cited in Atlas).

2.18.2 Present distribution, extent of plantings and yield

Groundnut is native to South America; but is now widely cultivated in warm countries throughout the world. It was introduced in pre-Columbian times to West Indies and Mexico, and in early post-Columbian times to Africa and eastern Asia and during the colonial period to Atlantic North America (Duke, 1983).

In South Africa, the main areas of groundnut production occur in the North West province, Northern Cape, the Free State, and North West (Schulze and Maharaj, 2006c). Irrigated yields average around 2.2 tonnes/ha (Northern Cape: 2.3 tonnes/ha) while dryland yields are only about half that at 1.1 tonne/ha, with the Free State yielding 1.3 tonne/ha and the Northern Cape only 0.9 tonne/ha (Statistics SA, 2002).

2.18.3 Biophysical requirements

For optimum yields, groundnuts require a mean annual precipitation greater than 700 *mm*, of which more than 500 mm should fall over their 5 to 6 month summer growing season (Smith, 1998) although good yields can be attained with only 300 mm over the growing season (NDA, 2005). Groundnuts are drought resistant at the early stages of growth, but cannot tolerate moisture stress during the seed formation stage. Mean daily temperatures should be in the range of 22 to 28°C for optimum growth, with yield reductions occurring above 33°C and below 18°C, with soil temperatures below 20°C delaying germination (Smith, 1998). The growing season (i.e. October to March) heat units (base 10°C) for groundnuts should exceed 1600 degree days (Schulze and Maharaj, 2006c). Groundnuts are sensitive to frost, requiring at least180 frost free days, as well as being sensitive to daily minimum temperatures. Fatal temperature during rest and early growth is 0^{o}C. The photoperiod for groundnut can range from less than 12 hours to greater than 14 hours (FAO, 2006).

TABLE 37 *Climatic and soil attributes for the production of groundnut (FAO, 2006).*

Groundnut Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	medium (50-150 cm)	medium (50-150 cm)
Daily Temp. Requirement (^{o}C)	22	32	10	45	**Soil texture**	medium	heavy, medium, light, organic
Annual Rainfall (mm)	600	1500	400	4000	**Soil fertility**	high	moderate
Latitude	0	40	0	45	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Altitude (masl)			0	1650	**Soil drainage**	well (dry spells)	well (dry spells)
Soil pH	5.5	6.5	4.5	8.5			
Light intensity	very bright	very bright	very bright	clear skies			

According to FAO (2006), Köppen Climate Zones for groundnuts are: tropical wet and dry (Aw), steppe or semiarid (Bs), and subtropical humid (Cf).

2.18.4 Water use characteristics

Groundnut is a drought resistant, rotational crop, which ideally should be planted in the same soil only once every 4 years (NDA, 2005). Water requirements for groundnut range from 500 to 700 mm for the growing period (FAO, 2002). The crop has a well developed tap root with many laterals which may extend to a depth of 1.5 m but most of the rooting system is found in the first 0.5 to 0.6 m, of soil. All water in mature plants is extracted from the first 0.5 to 1 m of soil. Under an evapotranspiration rate of 5-6 mm/day, the rate of water uptake by the crop starts to reduce when about 50% of the total available soil water has been depleted (FAO, 2002) For the initial stage (15-35 days), the crop coefficient value is 0.4 to 0.5; 0.7 to 0.8 for the development stage (30 to 45 days); 0.95 to 1.1 for the mid-season stage (30 to 50 days); 0.7 to 0.8 for the late-season stage (20 to 30 days) and 0.55 to 0.6 at harvest. The FAO reports water use efficiency values for the harvested yield for unshelled, dried nuts with a moisture content of about 15% is 0.6 to 0.8 $kg.m^{-3}$.

2.18.5 Potential environmental impact

None was noted in available literature.

2.18.6 Potential environmental impact

None was noted in available literature.

2.19 Sweet Sorghum (*Sorghum bicolor* L.)

Sorghum belongs to the *Poaceae* family; it is a C_4, annual, indigenous grass (Schulze and Maharaj, 2006b). Sorghum is reported to be a drought resistant crop, i.e. requiring less than 300 units of water to produce one unit of dry matter, sorghum can tolerate erratic rainfall and will recover even if wilted for up to 14 days (Smith, 1998). It is widely grown in the drier parts of the world as both a food grain and for fodder. Sweet sorghum (*sorghum bicolor L*. var. sweet) was initially developed as a silage crop, but has been the focus of much attention recently as a potential bioethanol feedstock. The South African Atlas of Climatology and Agrohydrology (Schulze 2006) provides more details on the grain variety.

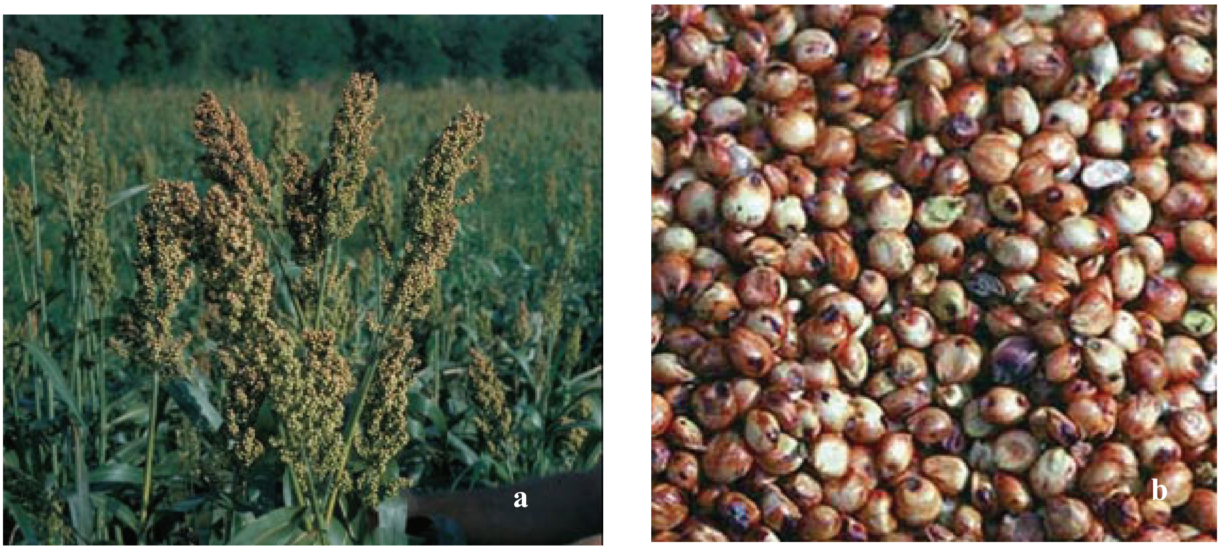

FIGURE 22 *Sorghum plants (a) and its seeds (b).*

2.19.1 Utilisation of sweet sorghum

Sorghum is grown for grain, forage, syrup and sugar, and industrial uses of stems and fibres. It is a staple cereal in hot dry tropics, often grains are ground into flour, while the stalks are used as animal feed (Duke, 1983). Sorghum has large juicy stems, containing as much as 10% sucrose which can be used in the manufacture of syrup. Sugar can also be manufactured from sorghum (Duke, 1983). Sweet sorghum usually fits into most common crop rotation systems with maize or soya bean crop. However, sweet sorghum should not be grown on land following a tobacco crop (Bitzer, 1997).

TABLE 38 *Utilisation of sweet sorghum (FAO, 2006).*

Main use	**Detailed use**	**Used part**
Food and beverage	Starch	Seeds
Food and beverage	Minerals	Seeds
Food additive	Sweetener	Stems
Animal food (feed)	Starch	Seeds
Animal food (feed)	Minerals	Stems
Animal food (feed)	Minerals	Leaves
Material	Dye/tannin	Stems
Material	Fibres	Stems
Material	Canes	Stems
Fuels	Petroleum substitutes/alcohol	Stems
Fuels	Alcohol	Stems

2.19.2 Present distribution, extent of plantings and yield

Worldwide, sorghum is an important grain crop where it is typically grown in areas that are considered too hot or dry to support maize. The area planted to commercially grown sorghum in South Africa in recent years (1995/6-2004/5) is around 120 000 ha, varying from 75 000 ha to 175 000 ha (NDA, 2006). Commercial production is concentrated in the Free State with 54% of the South African area under sorghum, while 26% of the total crop is produced in Mpumalanga, 9% in the North West, 6% in Limpopo and 4% in Gauteng (NDA, 2005).

Nationally the yield averaged 2.9 tonnes/ha for the period 1995/6-2003/4, but this has ranged from 2.2 to 3.5 tonnes/ha (NDA, 2006). The crop is often severely impacted by birds feeding on the seeds prior to harvest.

2.19.3 Biophysical requirements

In South Africa, sorghum is typically planted from mid-October to mid-December, depending on weather patterns of the particular season (NDA, 2005 cited in Schulze and Maharaj, 2006b). Sorghum is cultivated in rainfall regimes ranging from 300 to 1 200 mm in the growing season, its optimal rainfall for this period is around 600 mm per annum (Schulze and Maharaj, 2006b). Fatal temperature during rest and early growth is 0^{o}C (FAO, 2006). Sorghum grows in a range of temperatures with optima around 25°C and a January mean greater than 21°C. When average daily temperatures fall below 20°C, the growing period increases by 10 to 20 days for every 0.5°C decrease in temperature. Since flowering takes place 50 to 70 days after planting, rainfall for the stress-sensitive third month should exceed 100 mm, because severe water stress during flowering causes pollination failure. Periods with temperatures less than 15°C or greater than 35°C at flowering can cause poor seed set (Smith, 1998).

Sorghum grows on a variety of soils, but ideally prefers deep and well drained light to medium textures. However, compared with maize, it is cultivated mainly in lower potential soils, often with high clay content. The crop also tolerates a wide range of drainage conditions, including short periods of waterlogging. (Smith, 1998).

According to FAO (2006), the photoperiod for sorghum is less than 12 hours; the appropriate Köppen Climate Zones range through equatorial wet and dry (Aw), desert or arid (Bw), steppe or semiarid (Bs) and temperate humid (Cf).

TABLE 39 *Climatic and soil attributes for the production of sweet sorghum (FAO, 2006).*

Sweet sorghum Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	medium (50-150 cm)	medium (50-150 cm)
Daily Temp. Requirement (^{o}C)	27	35	8	40	**Soil texture**	heavy, medium	heavy, medium, light
Annual Rainfall (mm)	500	1000	300	3000	**Soil fertility**	moderate	low
Latitude	0	35	0	40	**Soil salinity**	low (<4 dS/m)	medium (4-10 dS/m)
Altitude (masl)			0	2500	**Soil drainage**	well (dry spells)	poorly (saturated >50% of year), well (dry spells), excessive (dry/moderately dry)
Soil pH	6	7	5	8.5			
Light intensity	very bright	very bright	very bright	clear skies			

2.19.4 Water use characteristics

Sorghum is indigenous to Africa (Schulze and Maharaj, 2006[b]). Being a drought resistant crop, (i.e. requiring <less than 300 units of water to produce one unit of dry matter, sorghum can tolerate erratic rainfall and will recover even if wilted for up to 14 days (Smith, 1998; cited in Schulze and Maharaj, 2006[b]). The crop coefficient relating maximum evapotranspiration to reference evapotranspiration is 0.4 during the initial stage (20 to 25 days), 0.7 to 0.75 during the development stage (30 to 40 days), 1.0 to 1.15 during the mid-season stage (40 to 45 days), 0.75 to 0.8 during the late season stage (30 days) and 0.5 to 0.55 at harvest (FAO, 2002). According to FAO (2002), the water use efficiency for harvested yield for grain is between 0.6 and 1.0 $kg.m^{-3}$.

In a study in Spain the effect of the water regime on the productivity of sweet sorghum (var: "Keller") was assessed in order to determine the effect of irrigation on sugar content(Curt et al., 1995). Three experiments were run with differing planting dates and cycle lengths. Water use efficiency (WUE) was calculated as the ratio of the biomass produced in stages 2 and 3 of the crop cycle (stage 2 being the irrigation stage and stage three being from the end of stage 2 until harvest) to the actual water transpired over the same period, and was similar for all irrigation regimes, but varied between sorghum seasons.

2.19.5 Potential environmental impact

It has a risk of being poisonous to man or animals (FAO,2006). Sorghum can contain a cyanogenic glycoside that can produce Hydrogen Cyanide (HCN) during times of stress or if damaged by frost or mastication. However, modern sorghums have been developed for their low HCN potential and are normally safe. Sorghum can also accumulate toxic levels of nitrates. Cattle and occasionally horses have been poisoned (Kingsbury, 1964; Gray et al*.,* 1968; Clay et al*.,* 1976).

2.20 Soya Bean (*Glycine maximum*)

Soya beans belong to the *Fabaceae* family. It grows as a bushy, summer season annual herb (FAO, 2006; Schulze and Maharaj, 2006d) which has three-fold leaves and grows to between 0.6 and 1.2 m. Each plant produces between 3 and 350 pods, depending on cultivar, plant density and prevailing climatic conditions (Schulze and Maharaj, 2006d).

FIGURE 23 *Soya bean pod (a) and soya bean seeds (b).*

2.20.1 Utilisation of soya bean

The soya bean seeds are considered one of the world's most important sources of oil and protein. Unripe seeds are eaten as vegetable and dried seeds eaten whole, split or sprouted (Duke, 1983). When processed they give soy milk, a valuable protein supplement in infant feeding which also provides curds ("tofu") and cheese. Soy sauce is made from the mature fermented beans and roasted seeds are used as a coffee substitute (Duke, 1983). The expressed seed oil is used industrially in manufacture of paints, linoleum, oilcloth, printing inks, soap, insecticides, and disinfectants. The vegetative portions of plant can be used for silage, hay, pasture or fodder, or may be ploughed under as a green manure (Duke, 1983).

TABLE 40 *Utilisation of* soya bean *(FAO, 2006).*

Main use	**Detailed use**	**Used part**
Food and beverage	Protein, vitamins and minerals	Seeds
Food and beverage	Protein, vitamins and minerals	Fruits
Food and beverage	Vitamins and minerals	Seedlings
Food and beverage	Vitamins and minerals	Leaves
Food additive	Condiment/seasoning	Fruits
Food additive	Stabiliser	Seeds
Animal food (feed)	Protein, vitamins and minerals	Fruits
Animal food (feed)	Protein, vitamins and minerals	Entire plant
Material	lipids/oil and fats	Seeds
Material	Cosmetics and perfumery	Seeds
Material	Fibres	Entire plant
Environmental	Soil improvers	Entire plant
Environmental	Agroforestry	Entire plant
Fuels	Petroleum substitutes/alcohol	Seeds

2.20.2 Present distribution, extent of plantings and yield

Soya bean is an annual legume which is indigenous, in its original form, to the Manchurian region of China, where it has been grown in rotation with other crops for over 5 000 years, with the beans used both as a food and in medicines (Schulze and Maharaj, 2006d). It is believed to be a cultigen from *Glycine ussuriensis,* which are reported to grow in China, Japan, Korea, Russia, and Taiwan (Duke, 1983).

While the area planted to soya beans in South Africa fluctuates quite considerably from year to year, it currently (1997/8-2004/5) averages around 120 000 ha. In South Africa, the main areas of production are Mpumalanga at 48%, KwaZulu-Natal at 22%, the Free State at 10%, Limpopo at 8% and North West province at 7% (NDA, 2006). Of the area under soya bean, 15% is irrigated, with the main irrigated areas being in Limpopo (34%), North West province (32%) and KwaZulu-Natal (19%) (Statistics SA, 2002). Overall soya bean yields average around 1.6 to 1.7 tonne/ha in South Africa (Schulze and Maharaj, 2006d).

2.20.3 Biophysical requirements

Soya beans, typically planted in November-December, ideally require a mean annual precipitation greater than 700 mm, with more than 450 mm falling over the growing season. They can survive short periods of drought, mainly because their flowering period extends over 3 to 5 weeks, longer than other crops, such as maize (10 to 14 days) (Smith, 1998). While relatively resistant to very high and low temperatures, optimum growth takes place at temperatures between 20°C and 30°C, with growth rates decreasing when daily maxima are greater than 35°C and below 18°C (Smith, 1994). Soya beans require in excess of 1 500 heat units (base 10°C), and it is highly sensitive to daylength, and especially the interaction between daylength and temperature (Schulze and Maharaj, 2006d).

The plant displays a medium tolerance to frost, and recovers from frost damage if it occurs before flowering (Schulze and Maharaj, 2006d). However, fatal temperature during rest and early growth stages is 0^{o}C according to FAO (2006). This legume can be grown in a wide range of soils, but they should not be too sandy, or too poorly drained. Maximum rooting depth is around 1.2 m, but most soil water extraction is from the top 0.6 m (Smith, 2006).

Köppen Climate Zones for soya beans are (FAO, 2006) equatorial climates (Aw), steppe or semiarid (Bs) and warm temperate dry summer (Cs).

TABLE 41 *Climatic and soil attributes for the production of soya bean (FAO, 2006).*

Soya bean Attributes	**Optimal**		**Absolute**			**Optimal**	**Absolute**
	Min	Max	Min	Max	**Soil depth**	medium (50-150 cm)	shallow (20-50 cm)
Daily Temp. Requirement (^{o}C)	20	33	10	38	**Soil texture**	medium, organic	heavy, medium, light
Annual Rainfall (mm)	600	1500	450	1800	**Soil fertility**	high	low
Latitude	0	47	0	52	**Soil salinity**	low (<4 dS/m)	medium (4-10 dS/m)
Altitude (masl)			0	3000	**Soil drainage**	well (dry spells)	poorly (saturated >50% of year), well (dry spells), excessive (dry/moderately dry)
Soil pH	5.5	6.5	4.5	8.4			
Light intensity	very bright	very bright	very bright	clear skies			

2.20.4 Water use characteristics

Soya bean is grown for oil and protein (FAO, 2002), mainly under rainfed conditions with irrigation (specifically supplemental irrigation) increasingly being used. Water requirements for maximum production vary between 450 to 750 mm per season depending on climate and length of growing period. Water requirements are given as crop coefficients in relation to reference evapotranspiration: crop coefficients are as follows: 0.3 to 0.4 during the initial stage (20 to 25 days), 0.7 to 0.8 during the development stage (25 to 35 days), 1.0 to 1.15 during the mid-season stage (45 to 65 days), 0.7 to 0.8 during the late season stage (20 to 30 days) and 0.4 to 0.5 at harvest. The tap root of soya bean may extend to over 1.5 m and all available soil water can be drawn up to 1.8 m but under normal conditions, all water is drawn from the first 0.6 to 1.3 m of the soil. Soya bean is rarely grown under full irrigation, but supplemental irrigation during critical growth periods will substantially increase yields (FAO, 2002).

2.20.5 Potential environmental impact

None was noted in available literature

2.21 Summary of Water Use Characteristics

A summary of key characteristics for all crops reported is tabulated as Appendix I.

3 Potential Growing Areas and Water Use of Selected Biofuel Feedstocks

The South African National Biofuels Industrial Strategy (NBIS) document published in December 2007 (DME, 2007) provided an opportunity to focus the analysis of potential growing areas and water use on particular crops of interest to biofuels development. As highlighted in Chapter 1, sugarbeet and sugarcane have been highlighted as potential bioethanol feedstocks. Similarly, canola, sunflower and soya bean as potential biodiesel feedstocks. In the South African context, the water use of sugarcane has been studied extensively (See Section 2.16) resulting in a comprehensive national study published in June 2008 (Jewitt et al*.,* 2008). This study provides far more detail than the desktop study undertaken here, and thus sugarcane is excluded from further analysis in this report. All other crops highlighted in the NBIS are included for further analysis, together with four crops which are the focus of biofuel developments in the SADC area, as well as other parts of the developing world, namely cassava, Jatropha and sweet sorghum.

3.1 Mapping of Potential Growing Areas of Selected Biofuel Crops

Mapping of climatically optimum crop distribution was accomplished using the commercial ArcView GIS package. Mapping is based on only two classes (i.e. suitable for optimum growth and unsuitable for optimum growth) for each crop. The classes were determined using climatic thresholds obtained mainly from the literature as described in Chapter 2 (and summarised in Appendix I) and some additional values from other literature (e.g. Hanson, 1990 and Smith, 2006). Mathematical and operational functions were run as scripts within the GIS package to integrate climatic attributes (i.e. mean annual rainfall, mean monthly rainfall total, mean annual temperature, mean monthly temperature, daily maximum temperature and daily minimum temperature). In most cases, where the crops are harvested annually, seasonal rainfall and seasonal temperature were used (if information in this regard was available from the literature). Planting dates and length of growing season were obtained from available literature resources (Appendix I). Values greater than maximum rainfall and temperature thresholds were assumed to negatively affect crop growth, unless otherwise stipulated in available literature.

Soil parameters such as soil depth, soil water drainage and soil texture were not considered. Hence, all assessments assume a sandy clay loam soil. Further work is necessary to refine the potential growing area based on soil characteristics. Similarly, more detailed analysis based on finer spatial and temporal scale climatic data is necessary. In particular, the use of daily temperature estimates, rather than monthly thresholds may provide more accurate estimates of potential growing areas of these potential biofuel crops.

TABLE 42 *Climatic thresholds derived for potential biofuel crops based on information from the available literature*

Crops	MAP (mm)	MMR (mm)	MAT (^oC)	Tave (^oC)	Tmin (^oC)	Tmax (^oC)	Planting date	Growth cycle
Canola	500-1000	-	-	-	> 5 (June to October)	< 25 (June to October)	01 Jun	140
Cassava	> 1000	-	20-29	-	-	-	-	-
Jatropha	500-1500	-	11-28	-	Frost free areas > 0		-	-
Sorghum	-	450-650	-	20-25 (Jan T >21)	-	> 21 in Jan	01 Nov	115
Soya bean	-	550-700	-	20-30	-	-	01 Nov	150
Sugarbeet	550-750	-	15-25	-	> -1 (August to February)	-	01 Aug	200
Sunflower	-	400-600	-	18-25	-	> 19 in Jan	01 Dec	125

Note. MAP – mean annual precipitation; MMRain – mean monthly rainfall totals over growing season; MAT – mean annual temperature; Dmean T – daily mean air temperatures over growing season; Dmin T – daily minimum air temperature over growing season; Dmax T – daily maximum air temperature over growing season.

3.1.1 Potential growing areas of selected biofuel crops

Potential growing areas for each of the aforementioned crops were mapped according to the methodology described in Section 3.1 and are presented in Figures 24 to 30 below.

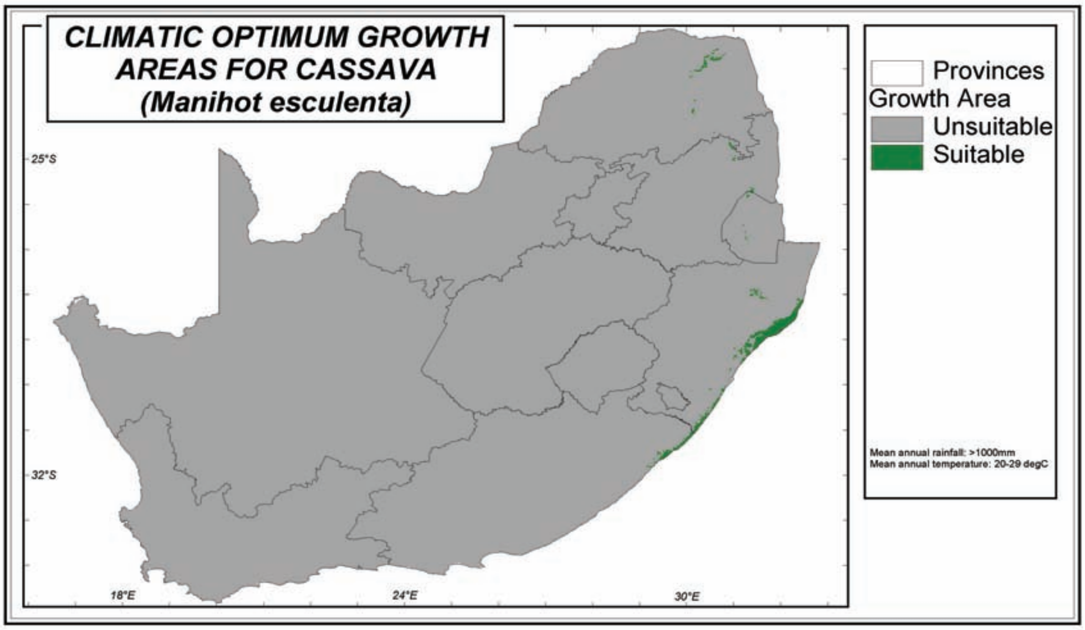

__FIGURE 24__ Potential growing areas of cassava

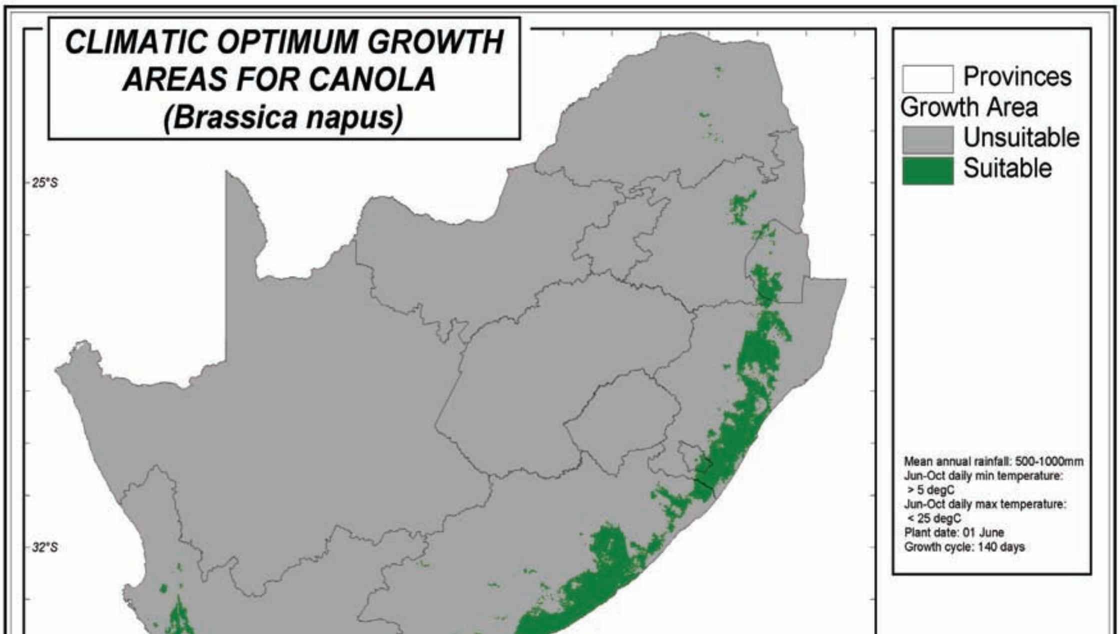

__FIGURE 25__ Potential growing areas of canola

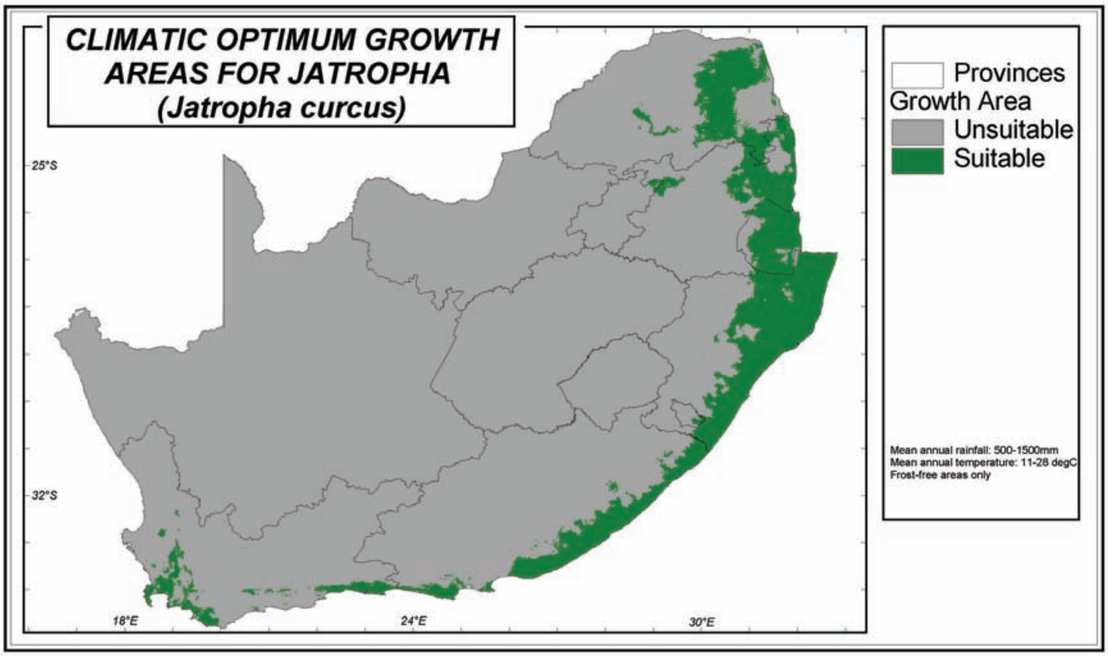

FIGURE 26 *Potential growing areas of Jatropha*

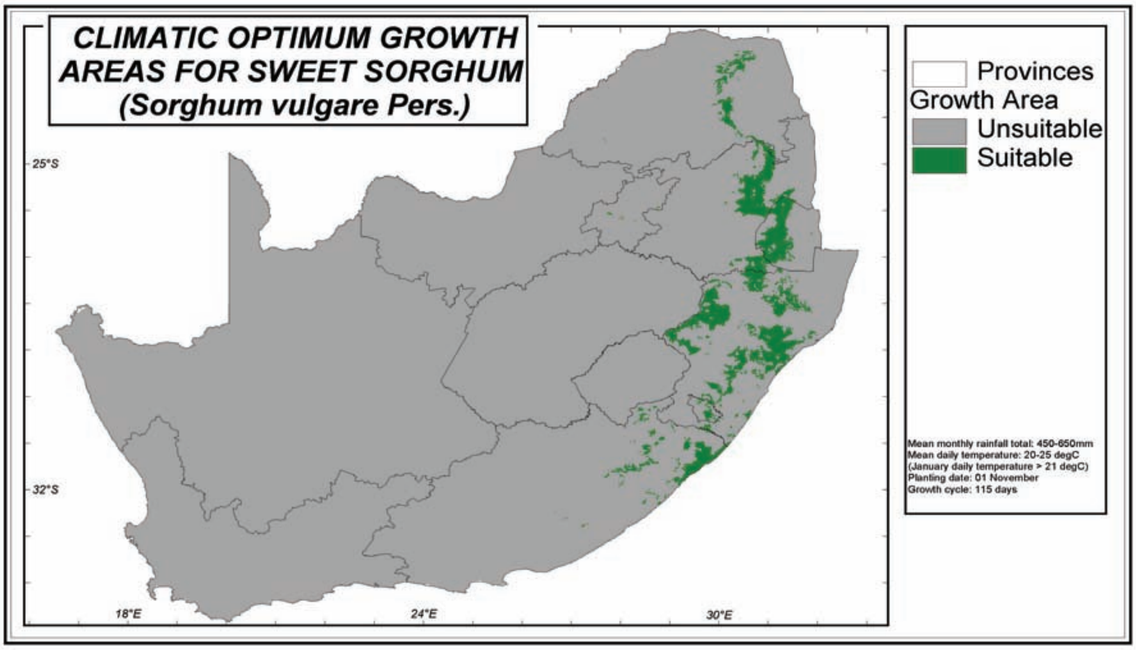

FIGURE 27 *Potential growing areas of sweet sorghum*

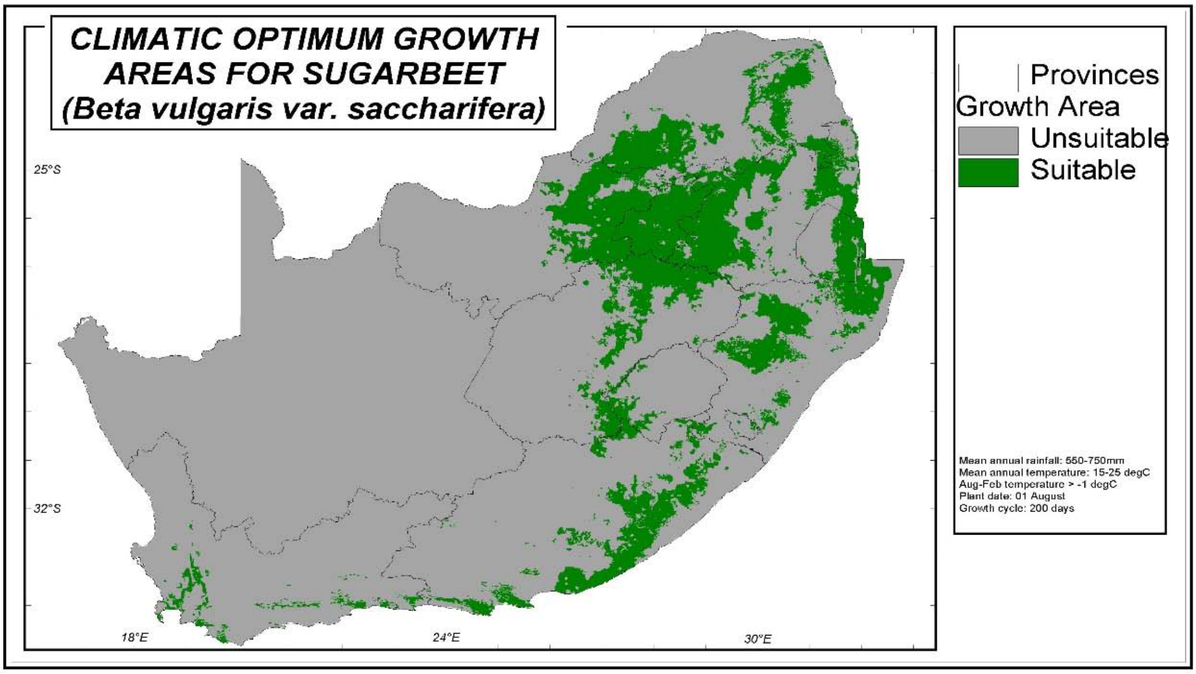

FIGURE 28 *Potential growing areas of sugarbeet*

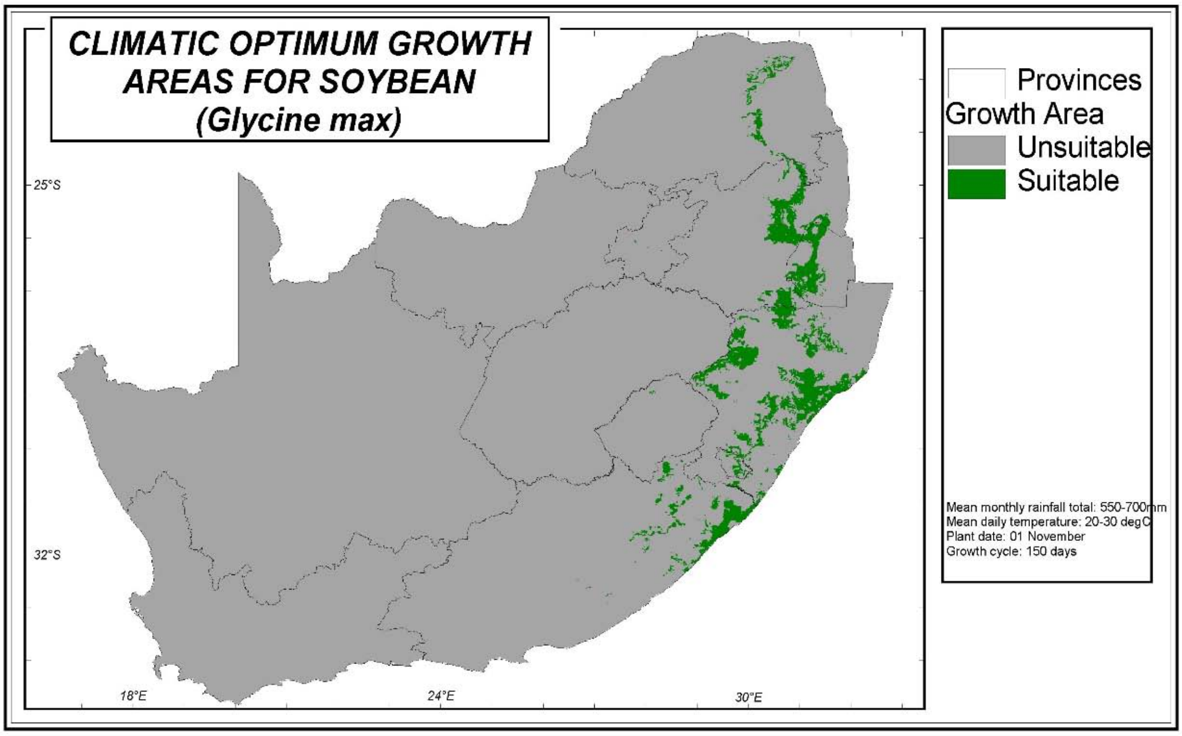

FIGURE 29 *Potential growing areas of soya bean*

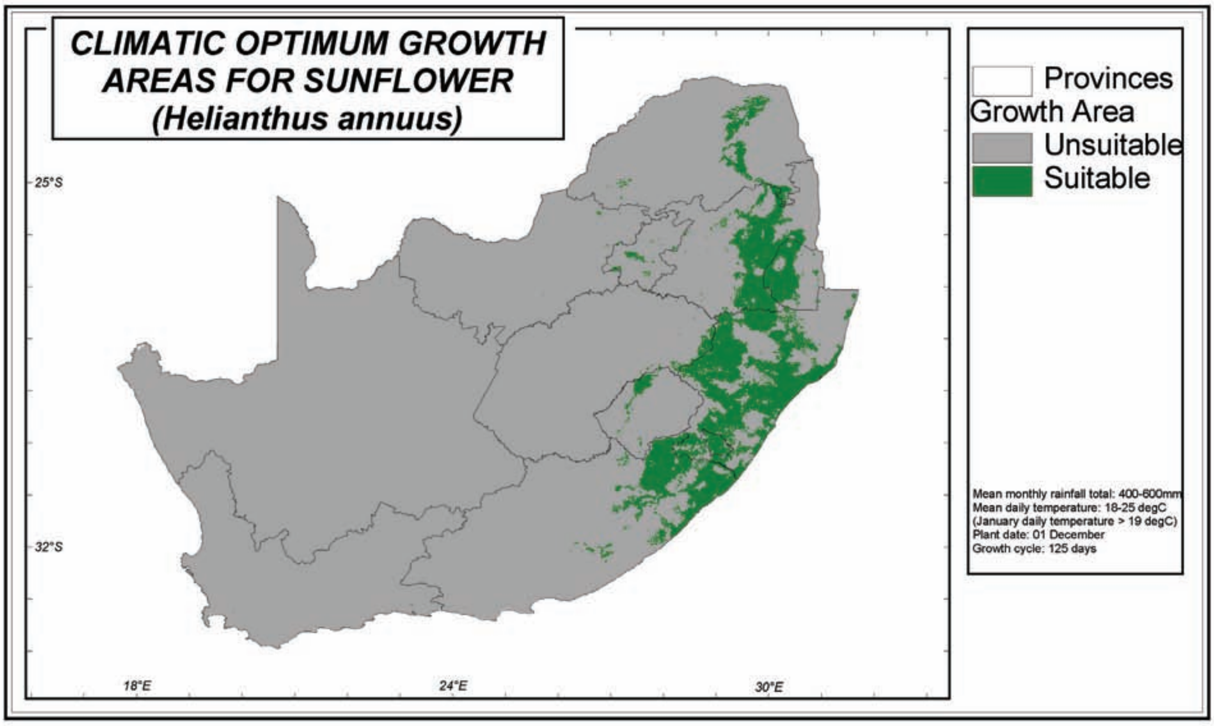

FIGURE 30 *Potential growing areas of sunflower*

Of the crops studied, cassava has the smallest potential growing area, being restricted to the hot regions of the country with adequate rainfall, i.e. coastal regions of KwaZulu-Natal and parts of the northern Limpopo province. The growing areas for canola, soya bean and sunflower largely mirror those where these crops are already grown commercially. The growing areas for sweet sorghum, are similar to the existing summer grain growing areas. Jatropha is restricted to the warm frost free areas of the country, but with a larger potential growing area than sugarcane or cassava because of its lower water requirement. Based on the limited information available for sugarbeet the plant does appear to have the potential to be grown in fairly large areas of the country, and based on this analysis, seems to have potential to be grown in areas which are marginal for many other crops. However, it must be noted that much more detailed analyses are needed to confirm this finding as these maps represent a macro-level analysis and far more detail is required for smaller scale planning.

3.2 Assessment of a Land Use as a Potential SFRA

Section 36 of the National Water Act provides for the declaration of Stream Flow Reduction Activities. Should a land use be shown to have a significant impact on the country's water resources, declaration would require either some knowledge of actual water use (such as is available from measurements made on sugarcane and to a limited extent Jatropha) or based on simulation modelling. Under South African water law, all land uses declared an SFRA require a water use license before being established. Currently (September, 2008), commercial timber plantations are the only declared SFRAs, but dryland sugarcane is considered a "candidate" SFRA and is under investigation as regards to its formal declaration as such. The factors assessed in deciding whether a land use should be declared a SFRA or not, are the extent of stream flow reduction, its duration, and its impact on any relevant water resource and on other water users.

In 2005 the DWAF Stream Flow Reduction Sub-Directorate proposed a new approach, where the processes of declaring and regulating SFRAs are separated. The draft proposal states: "*The declaration process should be an all-encompassing, low cost, and simple process, based on the likelihood of an activity's impact on water resources. The importance of that impact is then dealt with in the process of regulation. The greater and more serious the impact, the stronger the regulation.*" (DWAF, 2003). The 2005 DWAF proposal provides an alternative in that the proposed regulatory approach suggests a much broader basis for **declaration**, but with a more relaxed approach to **regulation**. Essentially, a crop that can be shown to impact on the water resource in any way would automatically fall into the basket of 'SFRAs', but would only need to be regulated in specific areas, or if the spatial extent of the crop became extensive.

A separate WRC project (K5/1428 – Jewitt et al., 2006) has proposed a methodology, considered appropriate in terms of the current state of hydrological understanding and availability of input data, to facilitate both the existing and the proposed DWAF approaches. The approach requires the simulation of water use by a hydrological model. In this study, the *ACRU* Agrohydrological Modelling System was used (Schulze, 1995)

3.2.1 Estimates of water use by biofuel feedstocks

The School of Bioresources Engineering and Environmental Hydrology (BEEH) has recently completed the development of a quinary catchment scale national database. quinary catchments are topographically based sub-divisions of the DWAF delimited national Quaternary catchments. Details of the development of this database are provided by Schulze and Horan (2007). In essence, the use of the BEEH quinary database allows for fairly detailed representation of catchment conditions including soils, dominant Acocks veld type as well as a 50 year record of daily climatic data including precipitation, reference evaporation, maximum and minimum temperature.

In order to estimate water use of each crop, 50 years of daily runoff for each potential biofuel feedstock crop is compared to that from the dominant Acocks veld type in each quinary catchment which has been identified as having the potential to support the growth of the crop in question. A map of the distribution of Acocks Veld Types is shown in Figure 31. A particular advantage of this approach is that water use can be predicted over a long time period through detailed soil water budgeting which includes both dry and wet seasons.

In this study, estimates of water use were obtained using the *ACRU* Agrohydrological Modelling System operated at the quinary catchment scale, in line with the methodology developed for the identification of potential Stream Flow Reduction Activities described earlier. Internally, the option in the *ACRU* model to use the well-known Ritchie evaporation model (Ritchie, 1972) to partition evapotranspiration between soil water evaporation, plant transpiration and interception was invoked.

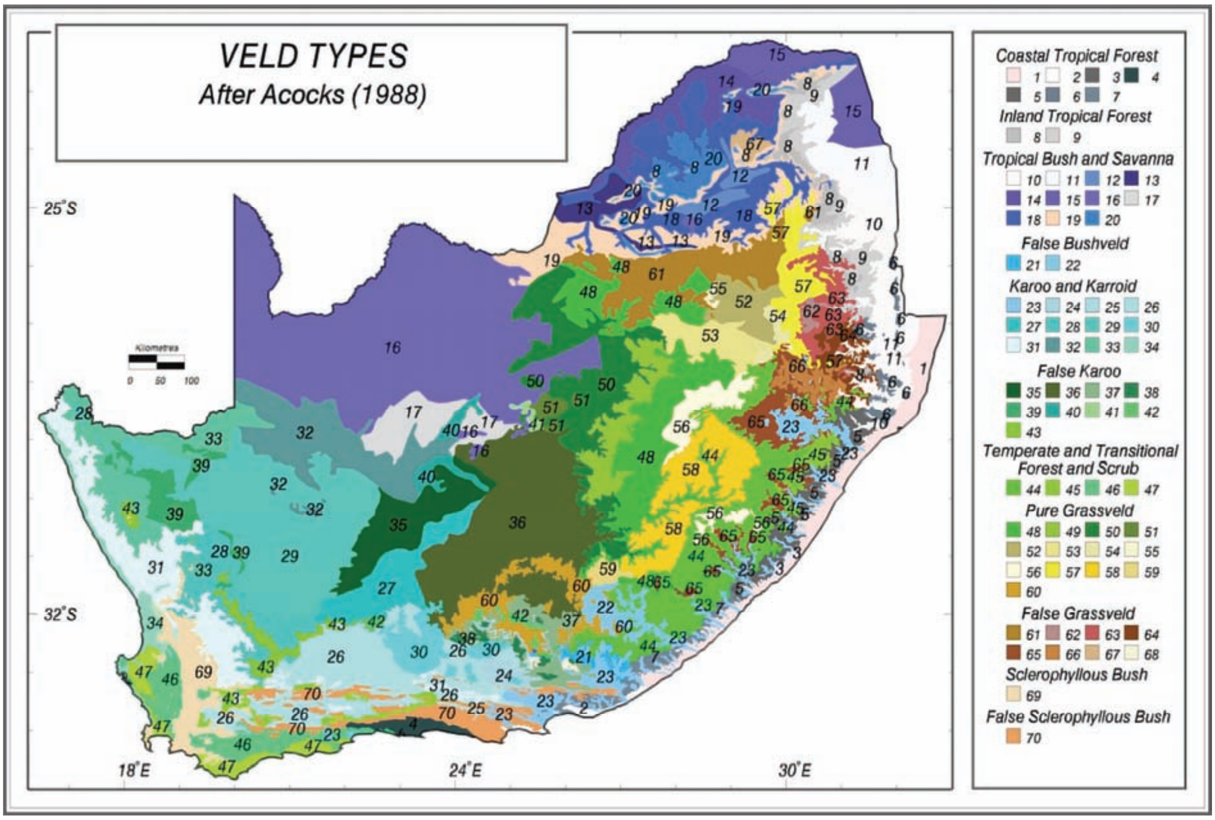

FIGURE 31 *Distribution of Acocks Veld Types*

3.2.2 Input parameters

ACRU requires several input parameters as detailed by Schulze (1995). Most of these are obtained from information acquired from the quinary scale catchments database for South Africa developed by BEEH and do not vary with the crop type. However, those that are most important and which vary according to crop type and used in the estimation of water use by the potential biofuel crops identified are detailed in **TABLE 43**, together with the source of information and assumptions made in estimating these values. A summary of biophysical parameters for all crops considered appears in Appendix I.

TABLE 43 *ACRU parameters which vary between crop types and assumptions made in this study.*

<table>
<tr><th>Parameter</th><th>Description</th><th>Function</th><th>Source</th><th>Assumptions made</th></tr>
<tr><td>CAY</td><td>Crop coefficient</td><td>Governs the rate at which the plant is able to transpire. Secondary functions in model include providing a basis for interception from plant leaves, extent of coverage (shading) of the soil surface, etc.</td><td rowspan="4">FAO-56 Report (Allen et al.,1998).

Various other publications as detailed in Chapter 2.</td><td rowspan="4">Values available from published literature are appropriate and applicable to South African growing conditions.

No variation in crop coefficients between growing regions occurs.</td></tr>
<tr><td>ROOTA</td><td>Proportion of plant roots in the top soil horizon.</td><td>Governs the extent to which water transpired by the plant is proportioned between top and sub-soil horizons.</td></tr>
<tr><td>COLON</td><td>Extent of colonisation of plant roots of the B soil horizon</td><td>Regulates the amount of water that may be extracted by the plant from the subsoil horizon</td></tr>
<tr><td>CONST</td><td></td><td>Regulates the extent to which the plant's physiological characteristics control the onset of stress in response to drier soil conditions.</td></tr>
</table>

3.2.3 Estimates of water use for selected biofuel crops

Based on the output produced by the *ACRU* model, maps of "water use" have been produced. It must be emphasised that these maps are of "water use", based on the simulated difference in runoff relative to that of the dominant Acocks veld type in the quinary catchment under consideration. This methodology is in line with the SFRA approaches used in the consideration of water use by commercial forestry in South Africa. These are not estimates of "consumption" by the plant during its growth cycle, which is the approach followed in the internationally popular "virtual water use" and "water footprint" articles. Thus, these maps provide an indication of whether there would be an increase (i.e. negative reduction) or decrease (positive reduction) in streamflow should any of the potential biofuel crops be established under dryland (i.e. non-irrigated) conditions in "virgin" land represented by the dominant Acocks veld type in the catchment. The potential growing areas of cassava are so small, that it was not considered in this water use analysis.

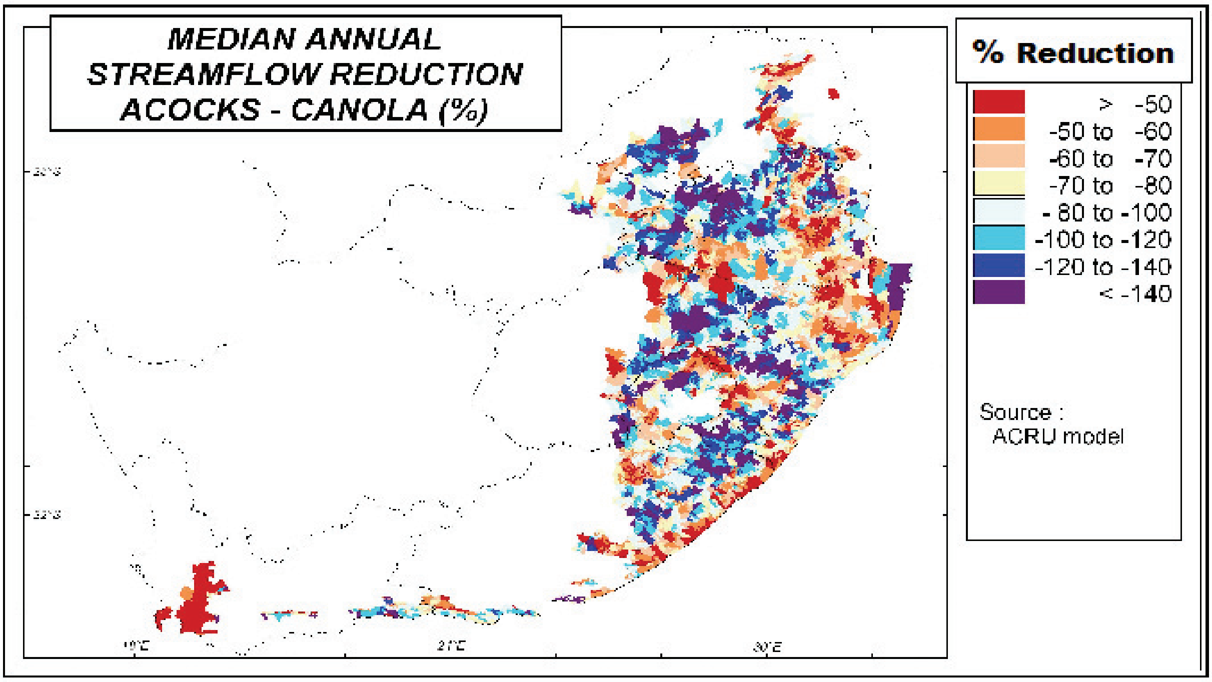

FIGURE 32 Median annual water use of canola relative to that of the dominant Acocks Veld Type.

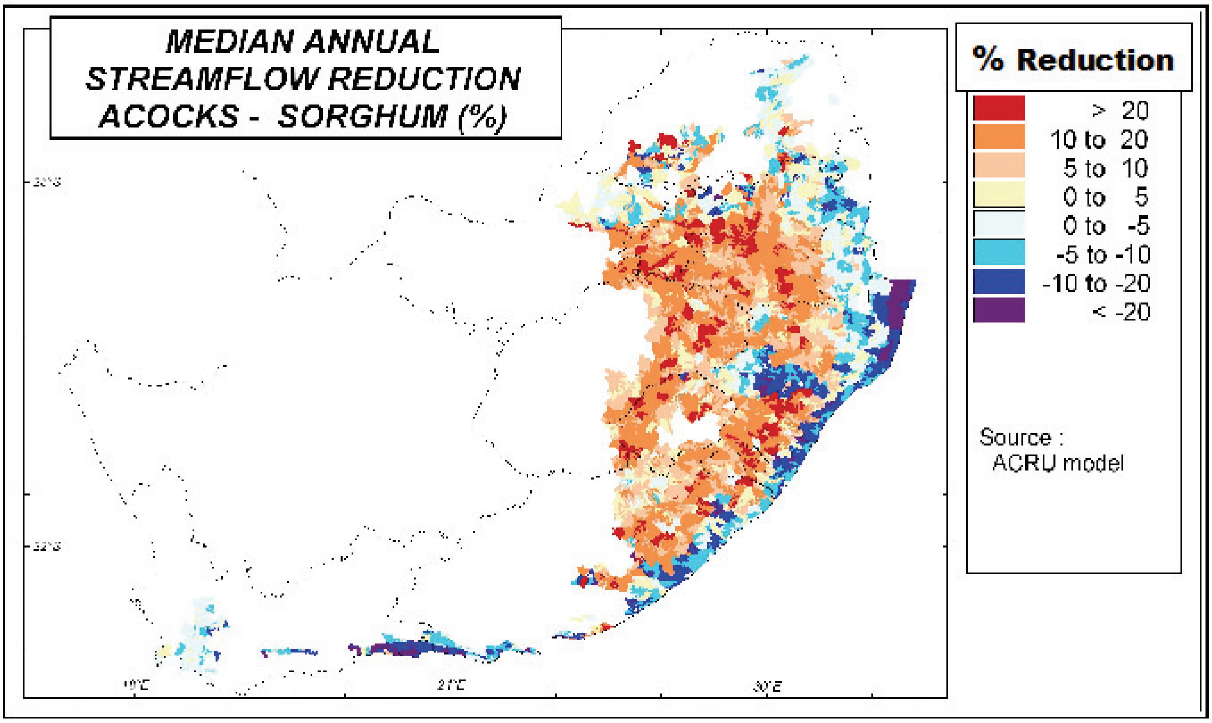

FIGURE 33 Median annual water use of sweet sorghum relative to that of the dominant Acocks Veld Type.

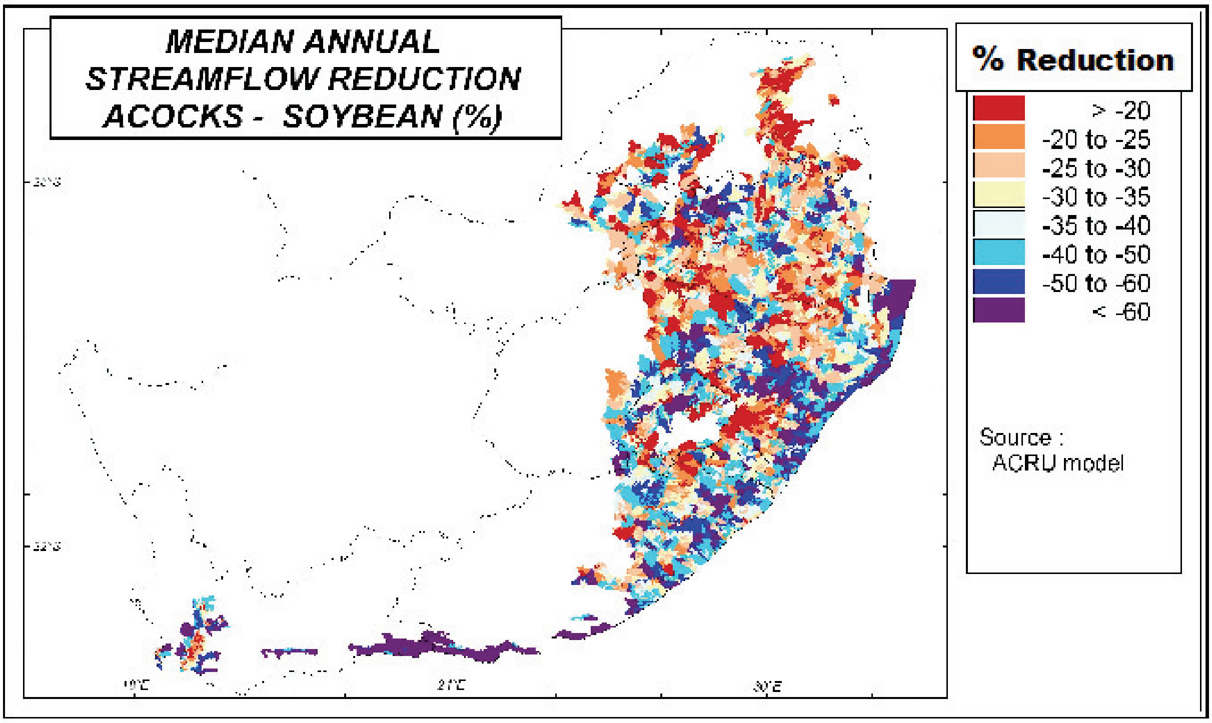

FIGURE 34 Median annual water use of Soya bean relative to that of the dominant Acocks Veld Type.

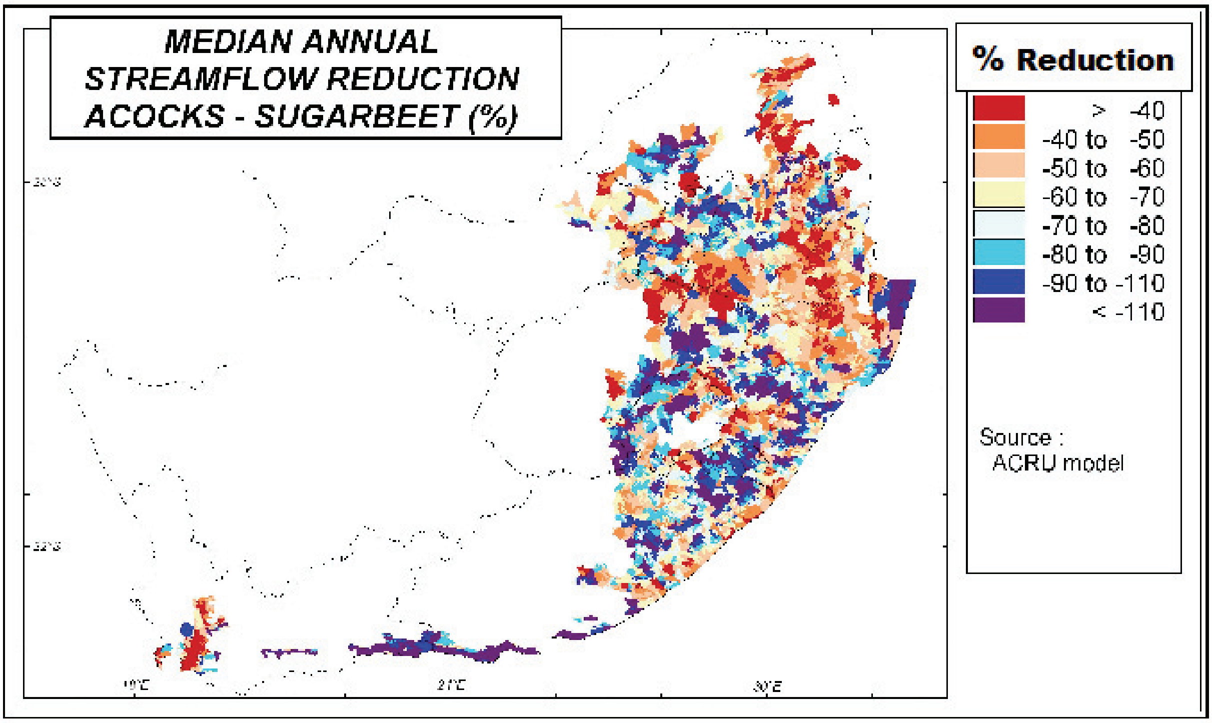

FIGURE 35 Median annual water use of sugarbeet relative to that of the dominant Acocks Veld Type.

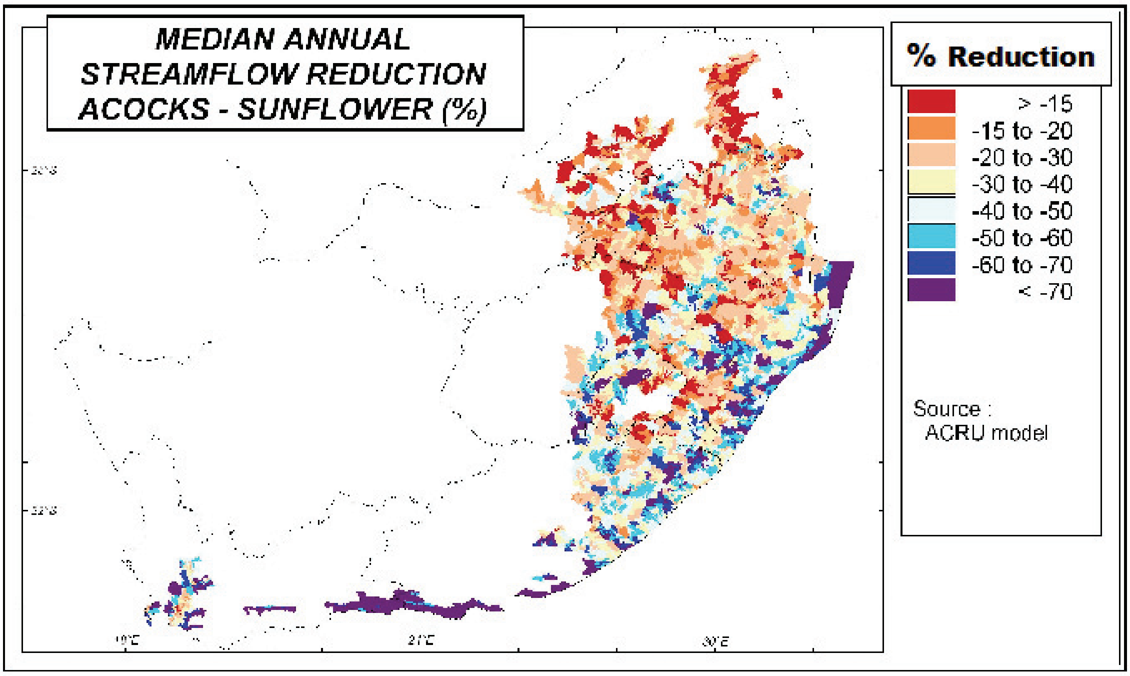

FIGURE 36 Median annual water use of sunflower relative to that of the dominant Acocks Veld Type.

The water use of sugarcane has been assessed as part of separate DWAF funded study. A summary map of estimated water use is shown in Figure 37.

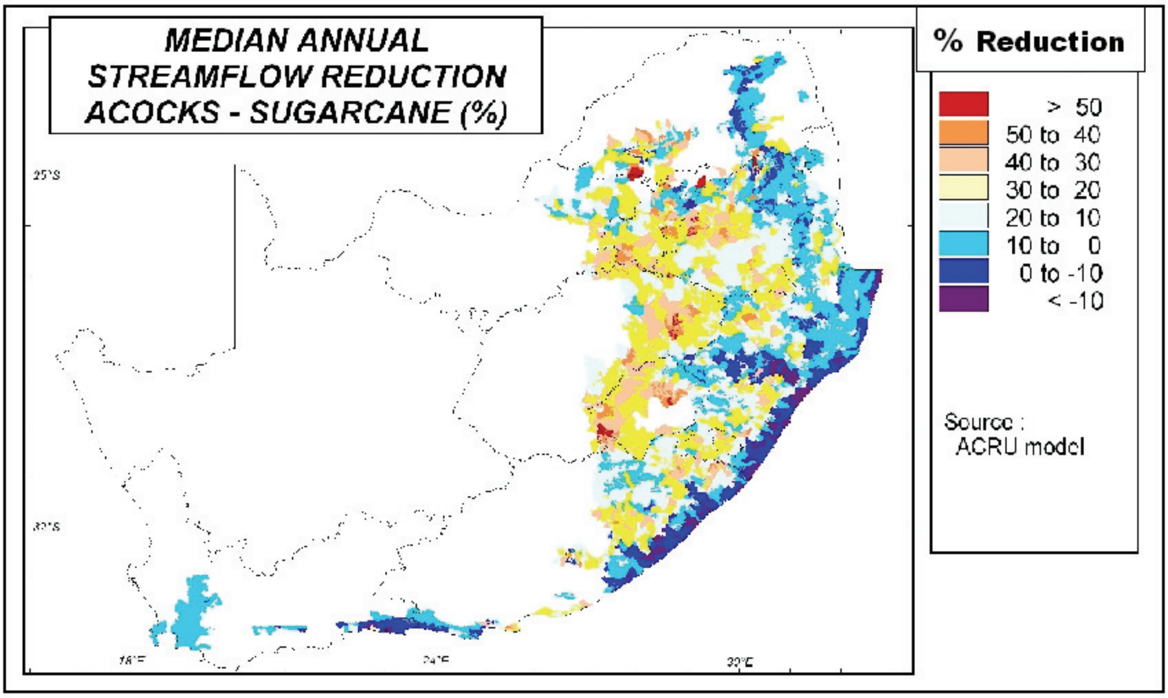

FIGURE 37 Median annual water use of sugarcane relative to that of the dominant Acocks Veld Type (Jewitt et al., 2008).

3.2.4 Discussion: Water use of potential biofuel crops

Based on comparison of median annual runoff from each crop, only sweet sorghum and sugarcane have the potential to utilise more water than the dominant Acocks veld type. All other crops show that on annual basis, water use is likely to be less than that under "natural" conditions if these crops are established under dryland conditions, i.e. under dryland conditions, the analysis suggests that the crop will use less water than the dominant Acocks veld type. However, it should be noted that this outcome may not necessarily be valid during months of the crop growing season when the plant is growing optimally and transpiring. An analysis of the output for the month of January only, showed that sunflower is likely to reduce streamflow in the summer months, but that on an annual basis no impact is shown, i.e. there may be an impact during the crop growing season. It should also be noted that the analyses assume traditional crop management approaches, i.e. conventional tillage with no consideration of, *inter alia,* different seed types, and planting dates. However, as reported by Lumsden et al. (2004), in the case of annual crops, the management of the crops (e.g. no till on contoured land) is likely to have a larger impact on the local water resources than the type of crop grown.

3.3 Conclusions: Potential Growing Areas and Water Use

The crops that have been highlighted in the South African NBIS (with the exception of sugarcane) and some other crops, which are relevant for their regional interest, have been analysed in terms of the potential growing areas and water use. These are based only on climatological drivers, and do not consider other drivers such as soil, pests, and access to markets. Based on this desktop analysis which formed the basis of this scoping study, sugarbeet should be analysed further in terms of its potential as bioethanol feedstock. Of the crops studied, only sweet sorghum has the potential to use more water than the dominant Acocks veld type, although the potential for sugarcane to do so in some parts of the country is well established. These aspects are discussed further in Chapter 4.

4 Priorities for future research

Developments related to biofuels continue to generate much interest, despite the slowdown in world economic markets since the second half of 2008. Much attention is now being focussed on so called second (lignocellulosic based), third (algae and other improved feedstock based) and even fourth (combined genetically optimized feedstocks, with genomically synthesized microbes) generation biofuel technologies. Furthermore, despite the controversy over the "food versus fuel" issue, there is still a large demand for land for biofuel cultivation worldwide, with large areas in Africa being developed. Consequently, there are many calls for a full Life Cycle Analysis of biofuels crops water use. However, despite the importance of water use at the "downstream" phases, most recognise that water use at the production (distillation) phase is negligible relative to the crop growth phase, and that the water used for crop growth is the biggest area of uncertainty in assessing water use and water use efficiency of biofuel crops. According to the Comprehensive Assessment of Water Use for Agriculture (CA, 2007), "The biomass needed to produce one litre of biofuel evaporates between 1000 and 4000 litres". This scoping study has highlighted many aspects which need additional research if we are to be able to estimate the water use and potential growing areas of potential biofuel feedstock crops in South Africa. With good confidence. Many of these research needs reflect the issues identified by other authors who have raised concerns about the rapid expansion of growing areas for biofuel feedstocks (De Fraiture et al*.,* 2007; Uhlenbrook, 2007), whilst others are unique to the South African situation.

4.1 Crop Water Use Parameters

As highlighted in this document, it is a relatively simple task to model the potential growing areas, and water use of various crops at large spatial scales for average conditions. However, the confidence in the output from any such exercise is low. Whilst there are many uncertainties in modelling, including model structure, climatic and soils input data, these are common for all crop types. Relative to this process for other agricultural crops, additional uncertainties arise when input parameters relating to crop water use for biofuel feedstocks are required. These parameters include, *inter alia*, crop growth and transpiration rates, rooting patterns, as well as responses to dry spells. Whilst this information is usually available for the more well known South African crops, including those that have biofuel feedstock potential (e.g. maize, sugarcane), this information is not known for many crops now being considered as biofuel feedstock. Thus, information used in parameterising the models was drawn from the international literature. In order to address this knowledge gap, detailed water balance studies are required in both laboratories (greenhouses) and in representative growing areas for the "new" crops.

4.2 Potential Growing Areas

The SA National Biofuels Industry Strategy has prioritised the production of sugarcane and sugarbeet for bioethanol production and soya bean, canola and sunflower for biodiesel production. The potential growing areas of these have been identified in Chapter 3. However, the predictions made are based purely on the survival criteria shown in Appendix I and the model input parameters provided in the *ACRU* User Manual (Smithers and Schulze, 1997) and in the SA Atlas of Hydrology and Agrohydrology (Schulze, 2007). In order to confirm whether these crops could actually be produced and also be economically viable, requires not only the type of information identified above, but also estimates of crop yield in order that crop water use efficiency (WUE) studies can be undertaken. The WUE aspect is considered a critical research need in terms of developing guidelines for policy and decision makers as well as likely growers, towards the optimal biofuel feedstock production in the potential growing areas. It must be recognised that to be truly informative, such studies must consider the amount and value of fuel generated per unit of water, not merely crop yield or biomass production.

An additional complication arises as potential impacts on water resources, and WUE differ whether converting indigenous vegetation to cropland, particularly to monoculture, whether increasing/intensifying current production practices or shifting crops or whether the existing indigenous vegetation itself is used as a feedstock. In the past two years, there have been several studies which consider the "virtual water use" or "water footprint" of the production of biofuels (e.g. Hoekstra and Chapagain, 2007). However, it can be argued that the approach taken in these studies is flawed, as no consideration is made for a reference or baseline condition. Thus, "water use" is absolute and not considered relative to natural vegetation. It must be recognised that such impacts are typically described at the national or regional level, but that the effects are most severely felt at the local level.

The maps produced showing potential growing areas in Chapter 3, illustrate areas where the crop is predicted to survive. The subtleties of climatic risk assessment, and whether these are optimal or marginal land for crop production still needs further investigation. The better the crops grow, the more water they are likely to use, so whether they are grown on climatically marginal land is an aspect that needs to be considered and the information pertaining to this type of assessment needs to be improved.

4.2.1 Water use efficiency

Typically, it is difficult to calculate crop WUE because of the practical difficulties of separating the water transpired by the crop from other water lost or unused in the soil-plant atmosphere system, and the variable proportion of the crop that is harvested as grain. This is further complicated when considering biofuel crops as the WUE when considering fuel yield rather than biomass or grain, yield introduces further complexity to the analysis. The assessment is essentially one of "fuel per drop" rather than "crop per drop" and the economic analyses associated with these.

4.2.2 The irrigation dilemma

Based on the desktop level analysis undertaken in this study, it seems unlikely that biofuel production produced under rainfed conditions will change the national water "picture", but the impact at smaller spatial scales and in times of drought could be significant at a local scale. However, whilst this study only considered rainfed production and despite policies to the contrary, it is inevitable that biofuel crops will be irrigated. Indeed, there are already plans for substantial production of sugarbeet under irrigation in the Fish River. This introduces an additional source of uncertainty into analyses of the likely impact of biofuels on water resources. Under irrigated conditions, the impact of biofuel production on water resources could be significant, in particular where new irrigation developments are planned which do not support this production. The Biofuels Industrial Strategy notes that "Irrigated cropping for biofuels will have to find its water from existing allocations, or compete for scarce new water", and states that that biofuels feedstock production could take up water made available through the Water Allocation Reform Programme. However, the current DWAF position is that no water will be allocated for irrigation of biofuel crops, hence the statement in the biofuels licensing criteria document (DME, 2008) that "The production of feedstock under irrigation will only be allowed in exceptional circumstances and a detailed motivation will have to be provided". However, it should be noted that in Mozambique, there a several large irrigation developments driven by the biofuels market, and that several of these are planned for river systems that are shared with South Africa (such as the Inkomati and Limpopo Rivers). It should also be noted that because these crops are not intended for human consumption, there are opportunities for irrigation with poor quality water. Further crop water balance studies which are required, and highlighted in Chapter 3, will also be of benefit in assessing the likely water use of irrigated biofuel crops. The experimental design needed to assess crop water parameters for modelling studies should include growing the plants under optimal water supply conditions.

4.2.3 Sweet sorghum and sugarbeet.

Sugarbeet and sweet sorghum have been the foci of research on potential biofuel feedstocks in many parts of the world. Sugarbeet is a relatively new crop for South Africa, and no water use studies pertaining to this country were found in the literature. Simulations reported herein are based on parameters derived from international studies, typically in cool temperate regions. Thus, some focus on sugarbeet and its potential water use requirements are strongly recommended in the near future.

ICRISAT, (2008) in particular, have promoted the use of sweet sorghum as a feedstock that uses little water, but is high yielding and being suitable for developing countries, especially where water resources are a major concern. Sweet sorghum is promoted as a hardy, indigenous crop producing food, fodder and fuel. It is a C_4 crop which implies that it is likely to have a high WUE. Its drought tolerant characteristics are partly due to its deep root development (lateral distribution of 1 m and depth of up to 2 m if no root impediment occurs), waxy leaf and stem coating, the ability of the leaves to roll as well as rapid closure of stomata under soil water stress conditions (Du Plessis, 2008). Based on research produced by Soltani and Almodares (1994), ICRISAT (2007) have claimed that sweet sorghum can produce similar yields to sugarcane using substantially less water at lower cost **(TABLE 44).** However, results from Chapter 3 and published research (Mastrorilli et al*.*, 1999; Makellariou-Makrantonaki et al*.*, 2007) show markedly different water requirements, highlighting a need for a detailed study of this crop.

TABLE 44 Reported Water use and yield of sweet sorghum and sugarcane (after ICRISAT, 2007).

Crop	Cost of Production ($US\$.ha^{-1}$)	Crop Duration	Water Requirement ($m^3.ha^{-1}$)	Ethanol Productivity ($litres.ha^{-1}$)
Sweet sorghum	360	4.5 months	8000 (2 crops)	5600 per year over two crops
Sugarcane	900	12-16 months	36000 (1 crop)	6500

4.3 The Future

The rapid advancement in the technologies to support biofuel production means that there are many risks and uncertainties associated with the future of biofuel production systems. It also creates some uncertainty as to where research efforts should be prioritised.

4.3.1 Second generation production

One development, already in place in some parts of the world, is the use of the entire crop for biofuel production, i.e. not only the "fruit", a development that is likely to be a focus of next generation systems. Depending on the effectiveness, it is probable that perennial crops and natural vegetation will become sources of cellulose for biofuel production. The higher the biomass generated from a site, the greater the impact on water resources is likely to be. This is particularly true should deep rooted, evergreen crops which are able to transpire throughout the year be considered for biofuel production. In this case, the crops would be considered similar to commercial afforestation in terms of current SFRA policies.

4.3.2 Multiple use systems

At present, biodiesel is produced primarily from annual crops such as canola and soya bean. However, there are many oilseed trees that offer great potential for biofuel production. Some argue that biofuel tree crops present a unique approach of producing alternative fuel from a source usually not used as food and, therefore, may not impact negatively on food security if they do not compete with food crops for their growing area. A further advantage of trees is that they are relatively easy to maintain and some suggest that they may have the highest overall energy return of any biofuel. Unlike annual crops, trees are perennial, yielding oil seeds for many years after planting, and can usually be grown without irrigation in marginal conditions where many other potential crops are unlikely to grow. Such initiatives also provide opportunities for multiple-use and inter-cropping systems, such as agroforestry and related production systems.

4.3.3 Climate change and potential shifts in cropping patterns

Climate change related research is well established in water resources and crop production in South Africa. The potential shifts in growing regions and the sensitivity of key crops to climate change are important aspects which must be considered in future biofuel related research in South Africa.

4.4 In Summary

In this document, a desktop analysis of the potential growing areas and water use of a wide range of biofuel feedstocks that could be grown in South Africa are described. Led by the NBIS and the priorities developed for South Africa, research questions regarding the potential water use impacts of these crops have been highlighted. To summarise, these are:

- A need for better knowledge of optimal growing conditions and water use for each crop.
- Which are the optimal crops for biofuel production in SA (with high uncertainties around sweet sorghum, sugarbeet and other emerging crops).
- More detailed mapping/input of biophysical conditions if the benefit and impact is to be adequately assessed at local scales.
- A need for detailed water use efficiency assessments.
- The potential impact of emerging cellulosic feedstock and potential water use impacts of woody vegetation used as a biofuel feedstock.
- The potential for climate change to result in shifting cropping patterns, regions and water use.

5 References

Acocks J.P.H. 1953. Veld Types of South Africa. Memoirs of the Botanical Survey of South Africa 57: 1-146. Government Printer, Pretoria, RSA.

Adetan, D.A., Adekoya, L.O. and Aluko, O.B. 2003. Characterisation of some properties of cassava root tubers. Journal of Food Engineering, 59;: 349-353.

AGRICE. 2007. Rapeseed production in environmentally acceptable conditions. URL: http://www.ademe.fr/partenaires/agrice/fiches_gb/card.asp?nc=4010c0015. Accessed: September, 2007.

Aisueni, N.O. 1987. Impact of Oil Palm (*Elaeis guineensis* Jacq.) cultivation on some chemical and microbiological properties of an ultisol. Biology and Fertility of Soils 4(3): 167-169.

Allemann, J. and Coertze, A.F. 1996. The cultivation of cassava. Vegetable cultivation in South Africa. ARC Vegetable and Ornamental Plant Institute, Roodeplaat.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. 1998. Crop evapotranspiration – Guidelines for computing crop water requirements – FAO Irrigation and drainage paper 56. Chapter 6. Internet site accessed October 2007: http://www.fao.org/ag/agl/aglw/cropwater/docs/method.pdf. Accessed: October, 2007

Amigun, B., Sigamoney, R., and von Blottnitz, H. (in press) Commercialisation of Biofuel Industry in Africa: a review. Article in Press. Renewable Sustainable Energy Reviews. Article in Press.

ARC. 2007. Cultivating flax fibre in South Africa. URL: www.arc.agric.za/home.asp?pid=372andtoolid=63anditemid=1473. Accessed: September, 2007.

Bastianoni, S., Marchettini, N., 1996. Ethanol production from biomass: analysis of process efficiency and sustainability. Biomass and Bioenergy 11(5), 411-418.

Benzioni, A. 1997. New crop fact sheet: Jojoba. URL: www.hort.purdue.edu/newcrop/cropfactsheets/Jojoba.html. Accessed: September, 2007.

Bezuidenhout, C.N, Lecler, N.L, Gers, C. and Lyne, P.W.L. 2006. Regional based estimates of water use for commercial sugarcane in South Africa. *Water SA.* 32: 219-222.

Bhardwaj, H.L., Hamama, A.A., Porter, D.M. and Reese, P.F. (Jr). 1996. Rapeseed meal as a natural pesticide. In: J. Janick (ed.). Progress in new crops. ASHS Press, Arlington. p 615-619.

Bitzer, M.J. 1997. Production of sweet sorghum for syrup in Kentucky. URL: http://www.ca.uky.edu/agc/pubs/agr/agr122/agr122.pdf. Accessed: September, 2007.

Bouaid, A., Diaz, Y., Martinez, M., Aracil, J., 2005. Pilot plant studies of biodiesel production using *Brassica carinata* as raw material. Catalysis Today 106, 193-196.

Bramm, A., M. Dambroth, and S. Schulte-Korne. 1990. Analysis of yield components of linseed, false flax, and poppy. Landbauforschung Volkenrode 40:107-114

Burger, C. 1999. Comparative Evaporation Measurements Above Commercial Forest and Sugarcane Canopies in the KwaZulu-Natal Midlands. Unpublished MSc. Dissertation. School of Applied Environmental Sciences, University of Natal, Pietermaritzburg, South Africa.

Canoira, L., Alcantara, R., Garcia-Martinez, M.J. and Carrasco, J., 2006. Biodiesel from Jojoba oil-wax: transesterification with methanol and properties as a fuel. Biomass and Bioenergy 30, 76-81.

Canola Canada, 2005. Internet site accessed October 2007: www.canola-council.org/wateryield.aspx. Accessed: October, 2007

Cardone, M., Mazzoncini, M., Menini, S., Rocco, V., Senatore, A., Seggiani, M. and Vitolo, S., 2003. *Brassica carinata* as an alternative oil crop for the production of biodiesel in Italy: agronomic evaluation, fuel production by transesterification and characterization. Biomass and Bioenergy 25, 623-636.

Casa R, Russell G, Lo Cascio B, and Rossini F. 1999. Environmental effects on linseed (*Linum usutatissimum* L.) yield and growth of flax at different stand densities. European Journal of Agronomy 11:267-278.

Cattanach, A.W., Dexter, A.G., and Oplinger, E.S. 1991. Alternative field crops manual: Sugarbeets. URL: http://www.hort.purdue.edu/newcrop/afcm/sugarbeet.html. Accessed August 2007.

Clay, B. R., Edwards, W. C., Peterson, D. R. 1976. Toxic nitrate accumulation in the sorghums. Bovine Pract. 11:28-32.

Cock, J.H. 1985. Cassava: new potential for a neglected crop. London, Westview Press.

Comprehensive assessment of water management in agriculture (CA)., 2007 . Earthscan. London and International Water Management Institute, Columbo

Comprehensive Assessment of Water Management in Agriculture. 2007. Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan, and Colombo: International Water Management Institute.

Crabbe, E., Nolasco-Hipolito, C., Kobayashi, G., Sonomoto, K., Ishikazi, A. 2001. Biodiesel production from crude palm oil and evaluation of butanol extraction and fuel properties. Process Biochemistry 37 (1), 65-71.

Curt, M.D., 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) 401-499.
De Fraiture, C., Giordano, M., Liao, Y. 20078. Biofuels and implications for agricultural water use: blue impacts of green energy, Water Policy 10 Supplement 1: 67-81
De Villiers, R.J., Lamprecht, S.C. and Agenbag, G.A., 2006. Effect of chemical seed treatment on the germination and seedling growth of canola under different soil conditions. S. Afr. J. Plant Soil 23: 287 -296.
Demirbas, A., 2007. Progress and recent trends in biofuels. Progress in Energy and Combustion Science, 33, 1-18.
Department of Environmental Affairs and Tourism (DEAT), 2002. A Summary of the World Summit on Sustainable. Development, Johannesburg, Tyrrell Associates, Pretoria.
Department of Mining and Energy (DME), 2003. Integrated Energy Plan for the Republic of South Africa. Department of Minerals and Energy, Pretoria
Department of Mining and Energy (DME), 2007DME, 2007. *The* South African N*ational Biofuels Industrial Strategy. D*epartment of Minerals and Energy, Pretoria South Africa.
Department of Mining and Energy (DME), 2008. Biofuels Licensing Criteria document. http://www.dme.gov.za/pdfs/energy/biofuels licensing criteria.pdf. December 28, 2008.
Downey, R.K. and Röbbelen, G. 1989. *Brassica* species, Chapter 16. In: Oil Crops of the World. G. Röbbelen, Downey, R.K., Ashri, A. (eds). United States of America, McGraw-Hill Inc. p339-430.
Du Plessis, J. 2008. Sorghum Production. National Department of Agriculture. http://www.nda.agric.za/docs/Sorghum/FieldCrops_Sorghum.pdf (Accessed: September 23, 2008).
Duke, J.A. 1983. Handbook of energy crops. Available through Center for New Crops and Plants Products, Purdue University. URL: http://www.hort.purdue.edu/newcrop/Indices/index_ab.html. Accessed: August, 2007.
DWAF, 1998. National Water Act No. 36 of 1998. Department of Water Affairs and Forestry, Pretoria
DWAF, 2003. The Identification and Declaration of Stream Flow Reduction Activities in Terms of the National Water Act. A Discussion Paper Drafted by the Sub directorate: Stream Flow Reduction, Unpublished Draft copy, Department of Water Affairs and Forestry, Pretoria, South Africa.
Edwards, G.E., Sheta, E., De Moore, B., Dai, Z., Franceschi, V.R., Cheng, S.-H., Lin, C.-H. and , Ku, M.S.B. 1990. Photosynthetic characteristics of cassava (*Manihot esculenta* Crantz), a C_3 species with chlorenchymatous bundle sheath cells. Plant Cell Physiology 31(8): 1199-1206.
FAO, 2002. Crop water information. Internet site accessed October 2007:
FAO, 2007. Sugarbeet. URL: http://www.fao.org/ag/agl/aglw/cropwater/sugarbeet.stm. Accessed: August 2007.
FAO. 2006. Ecocrop info. URL: http://ecocrop.fao.org. Accessed: September, 2007.
FAOSTAT. 2007. Crop production data. URL: http://faostat.fao.org/site/567/default.aspx. Accessed: September, 2007.
Flax Council of Canada, 2007. Internet site accessed October 2007: http://www.flaxcouncil.ca/english/index.php?p=growing2andmp=growing
Foidl, N., Foidl, G., Sanchez, M., Mittelbach, M. and, Hackel, S. 1996. Jatropha curcas L. as a source for the production of biofuel in Nicaragua. Bioresource Technology 58, 77-82.
Freer, J.B.S. 1992. Linseed Husbandry: a UK perspective (Abstract). Industrial Crops and Products 1(2-4): 211-217.
Gascon, J.P., Noiret, J.M. and Meunier, J. 1989. Oil palm, Chapter 27. In: Oil Crops of the World. G. Röbbelen, Downey, R.K., Ashri, A. (eds). United States of America, McGraw-Hill Inc. p475-504.
Gentry, H.S. 1958. The natural history of Jojoba (*Simmondsia chinensis*) and its cultural aspects. Econ. Bot. 12:261-291.
Gilman, E.F. and Watson, D.G. 1994. Chinese Tallow Tree. URL: http://hort.ufl.edu/trees/SAPSEBA.pdf. Accessed: September, 2007.
Glumac, E. and Cowles, J. 1990. Chinese tallow: multipurpose tree crop. URL: http://www.hort.purdue.edu/newcrop/proceedings1990/V1-267.html#Glumac. Accessed: September, 2007.
Grace, M.R. 1977. Processing of cassava. URL: http://www.fao.org/docrep/x5032e/x5032E01.htm#Introduction. Accessed: August, 2007.
Gray, E., Rice, J. S., Wattenbarger, D., Benson, J. A., Hester, A. J., Loyd, R. C. and Greene, B. M. 1968. Hydrocyanic acid potential of *Sorghum* plants grown in Tennessee. Tenn. Agric. Exp. Stn. Bull., 445. 48 pp.
Grey, D. 1998. Water-use efficiency of canola in Victoria. Proceedings of the Australian agronomy conference, Australian society of Agronomy. www.regional.org.au/au/asa/1998/5/181grey.html. Accesses October 2007.
Gübitz, G.M., Mittelbach, M. and Trabi, M. 1999. Exploitation of the tropical oil seed plant *Jatropha curcas* L. Bioresource Technology 67, 73-82.
Gush, M.B. and Hallowes, J. 2007. *Jatropha curcas* literature review. In: Holl, M., Gush, M.B., Hallowes J. and Versfeld, D.B. (Eds). 2007. *Jatropha curcas* in South Africa: an assessment of its water use and bio-physical potential. Water Research Commission, Pretoria, RSA, WRC Report 1497/1/07, Chapter 2.

Hamelinck, C.N., Faaij, A.P.C. 2006. Outlook for advanced biofuels. Energy Policy 34: 3268-3283.
Hanson, A.A. 1990. Practical handbook of agricultural science. CRC Press Inc.: Boca Raton, Florida.
Hargreaves, G.H. and Samani, Z.A. 1982. Estimating potential evapotranspiration. J. Irrig. and Drain Engr., ASCE, 108(IR3):223-230.
Hartley, C.W.S. 1967. The Oil Palm. Published by Longmans, Green and Co. Ltd. London, England. 706 pgs.
Hartwell, J.L. 1967-1971. Plants used against cancer. A survey. Lloydia, 30-34.
Hillel, D. 1982. *Introduction to Soil Physics*. Academic Press, New York.
Hoekstra, A.Y. and Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern. Water Resources Management, 21, 35-48.
Holl, M., Gush, M.B. and Moodley, M. 2007. Water use assessment of *Jatropha Curcas*. *In*: Holl, M., Gush, M.B., Hallowes, J. and Versveld, D.B. (Eds). 2007. *Jatropha curcas* in South Africa: an assessment of its water use and bio-physical potential. Water Research Commission, Pretoria, RSA, WRC Report 1497/1/07, Chapter 4.
Howeler R.H., W. Watananonta and Ngoan, TT. 2004. Farmers decide. A participatory approach to development and dissemination of improved cassava technologies that improve yield and prevent soil degradation. In: The proceedings of the 13th international Society of tropical Root Crops Held in Aruza Tanzania.
http://www.fao.org/ag/AGL/AGLW/cropwater/cwinform.stm Accessed: October 2007
Hu, Z., Pu, G., Fang, F. and Wang, C. 2004. Economics, environment, and energy life cycle assessment of automobiles fueled by bio-ethanol blends in China. Renewable Energy 29: 2183-2192.
IFAD and FAO. 2000. The world *cassava* economy, facts, trends and outlook. URL: http://www.fao.org/docrep/009/x4007e/x4007e00.htm. Accessed: August, 2007.
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)., 2008. Biofuel Bonanza Should Benefit the Poor. http://www.icrisat.org/SASA/sasaindex.htm Accessed on August 28, 2008.
Jewitt, G.P.W., Gush, M.B. and Versveld, D.B. 2006. Green water flows as a basis for SFRA declaration. Interim report for WRC project K5/1428.
Jewitt, G.P.W., Kunz, R.P., Ernst, S.I. and Schulze, R.E. 2008. Estimates of Water Use by Sugarcane. Report to the Department of Water Affairs and Forestry by School of Bioresources Engineering and Environmental Hydrology
Kar, G., Kumar, A. and Martha., M. 2007. Water use efficiency and crop coefficients of dry season oilseed crops, Agric. Water Manage. 87: 73-82
Kassam, A. and Smith, M. 2001. FAO methodologies on crop water use and crop water productivity. Paper No. CWP-M07. [Internet]. Food and Agricultural Organisation of the United Nations. Available from:
Kim, S. and Dale, B.E., 2004. Global potential bioethanol production from wasted crops and crop residues. Biomass and Bioenergy, 26, 361-375.
Kingsbury, J. M. 1964. Poisonous plants of the United States and Canada. Prentice-Hall Inc., Englewood Cliffs, N.J., USA. 626 pp.
Kondili, E.M., Kaldellis, J.K., 2007. Biofuel implementation in East Europe: current status and future prospects. Renewable and Sustainable Energy Reviews. 11 (9), 2137-2151 doi:10.1016/j.rser.2006.05.001.
Korsrud, G.O., M.O. Keith, and J.M. Bell. 1978. A comparison of the nutritional value of crambe and camelina seed meals with egg and casein. Can. J. Anim. Sci. 58:493-499
Kruger F J, Bosch J M, Everson C and Burger C (2000) Land-Based Activities that may be Declared Stream Flow Reduction Activities in terms of Section 36 of the National Water Act. Report to the Sub-Directorate: Stream Flow Reduction Activities of the Department of Water Affairs and Forestry, South Africa
Kruger, F.J., and Bosch, J.M. 2002. Criteria for identifying activities that qualify as Stream Flow Reduction Activities. Department of Water Affairs and Forestry, Pretoria
Kumari, P., Sharma, P., Srivastava, S. and Srivastava, M.M. 2006. Biosorption studies on shelled *Moringa oleifera* Lamarck seed powder: removal and recovery of arsenic from aqueous system. International Journal of Mineral Processing 78: 131-139.
Lafond, G.P., May, W.E., Stevenson, F.C. and Derksen, D.A. 2006. Effects of tillage systems and rotations on crop production for a thin Black Chernozem in the Canadian Prairies. Soil Tillage and Research, 89 232-245.
Latha, S., Mariamma, J. and Daniel, M. 2001. Studies on the effects of leaf leachates of *Pongamia pinnata* on certain crops and weeds and the soil mycoflora. National Academy Science Letters, 24(5-12): 63-68.
Lovett, J.V. and Duffield, A.M. 1981. Allelochemicals of *Camelina sativa*. Journal of Applied Ecology 18: 283-290.
Lovett, J.V. and Sagar, G.R. 1978. Influence of bacteria in the phyllosphere of *Camelina sativa* (L.) Crantz on germination of *Linum usitatissimum* L. New Phytol 81: 617-625.
Lumsden, T, Jewitt, G.P.W. and Schulze, RE (2004) Modelling the Impacts of Land Cover and Land Management Practices on Streamflow. Water Research Commission, Pretoria
Magnes, J.R., Markle, G.M. and Compton, C.C. 1971. Food and feed crops of the United States: a descriptive list

classified according to potentials for pesticide residues. URL: http://www.hort.purdue.edu/newcrop/CropInfoSources/Magness_info.html. Accessed: September, 2007.
Makareviciene, V. and Janulis, P. 2003. Environmental effect of rapeseed oil ethyl ester. Renewable Energy 28: 2395-2403.
Makellariou-Makrantonaki, M, D. Papalexis, N. Nakos, I.K. and Kalavrouziotis, Z. 2008. Effect 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 .
Makina, H.S. 1991. Energy from cassava. Cassava as a Cash Crop for Food, Fuel, Fodder and Chemicals, Proceedings held in Bulawayo, Zimbabwe, Commonwealth Science Council and Biomass Users Network.
Marquard, R. and H. Kuhlmann. 1986. Investigations of productive capacity and seed quality of linseed dodder (*Camelina sativa* Crtz.), Fette Seifen Anstrichmittel (Germany), 88;:245-249.
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. Eur. J. Agron. 11,. 207-215
McGlinchey, MG and Inman-Bamber, NG. 1996. Predicting Sugarcane water use with the Penman-Monteith equation. *Proceedings of Evapotranspiration and Irrigation Scheduling Am. Soc. Agric. Eng*. San Antonio, USA. 592-597
McLaughlin, S., Bouton, J., Bransby, D., Conger, B., Ocumpaugh, W., Parrish, D., Taliaferro, C., Vogel, K. and Wullschleger, S. 1999. Developing switchgrass as a bioenergy crop. In: J. Janick (ed), Perspectives on new crops and their uses. ASHS Press, Alexandria, VA. URL: www.hort.purdue.edu/newcrop/proceedings1999/v4-282.html. Accessed: September, 2007.
McLaughlin, S.B., Walsh, M.E., 1998. Evaluating environmental consequences of producing herbaceous crops for bioenergy. Biomass and Bioenergy 14 (4), 317-324.
National Department of Agriculture (2005) (NDA). Maize Profile. http://www.nda.agric.za/docs/Maize/maize.htm Accessed on July 7, 2005.
National Department of Agriculture (2005) (NDA). Sunflower Profile. www.nda.agric.za/docs/sunflower.pdf. Accessed on September 7, 2007.
NDA, 2006. Abstract of Agricultural Statistics. Department of Agriculture, Pretoria, RSA. CD-ROM
Nguyen, M.H., Prince, R.G.H., 1996. A simple rule for bioenergy conversion plant size optimisation: bioethanol from sugarcane and sweet sorghum. Biomass and Bioenergy 10 (6), 361-365.
Nweke, F.I., Spencer, D.S.C. and Lynam, J.K. 2002. The *cassava* transformation: Africa's best-kept secret. East Lansing, Michigan State University Press.
O'Hair, S.K. 1995. Cassava. Tropical Research and Education Center. URL: http://www.hort.purdue.edu/newcrop/cropfactsheets/cassava.html. Accessed: September, 2007.
Oguntunde, P.G. and Alatise, M.O., 2007. Environmental regulation and modelling of cassava canopy conductance under drying root-zone soil water. Meteorological Applications. 14(3), 245-252. http://dx.doi.org/10.1002/met.24
Openshaw, K. 2000. A review of *Jatropha curcas*: an oil plant of unfulfilled promise. Biomass and Bioenergy 19, 1-15.
Oplinger, E.S., Hardman, L.L., Gritton, E.T., Doll, J.D. and Kelling, K.A. 1989a. Canola (rapeseed). Alternative field crops manual. URL: http://www.hort.purdue.edu/newcrop/afcm/canola.html. Accessed: August 2007.
Oplinger, E.S., Oelke, E.A., Doll, J.D., Bundy, L.G. and Schuler, R.T. 1989b. Flax. Alternative field crops manual. URL: www.hort.purdue.edu/newcrop/afcm/flax.html. Accessed: August, 2007.
Oyetunde, A. 2007. Physiology of cassava. URL: http://www.iita.org/cms/details/trn_mat/irg55/irg552.html. Accessed: August, 2007.
Philip, J.R. (1966). Plant water relations: some physical aspects. Annu. Rev. Plant Physiol. 17, 245-268.
Poteet, M.D. 2006. Biodiesel Crop Implementation in Hawaii. Hawaii Agriculture Research Center. Aiea. Report number HDOA-2006-2. URL: http://www.hawaiiag.org/hdoa/pdf/biodiesel%20report%20(revised).pdf. Accessed: August, 2007.
Putnam D.H., Budin, J.T., Field, L.A. and Breene, W.M. 1993. Camelina: A promising low-input oilseed. In: J. Janick and J.E. Simon (eds), New Crops. Wiley New York. p314-322.
Putnam, D.H., Oplinger, E.S., Hicks, D.R., Durgan, B.R., Noetzel, D.M., Meronuck, R.A., Doll, J.D. and Schulte, E.E. 1990. Sunflower. URL: http://www.hort.purdue.edu/newcrop/afcm/sunflower.html. Accessed: September, 2007.
Reijnders, L and Huijbregts, M.A., 2006. Life cycle greenhouse gas emissions, fossil fuel demand and solar energy conversion efficiency in European bioethanol production for automotive purposes. Journal of Cleaner Production. doi:10.1016/j.jclepro.2006.05.007. Article in press.
Richard, G., Bioffin, J. and Duval, Y. 1995. Direct drilling of sugarbeet (*Beta vulgaris* L.) into a cover crop: effects on soil physical conditions and crop establishment. Soil and Tillage Research 34:169-185.

Ritchie, J.T. 1972. Model for predicting evaporation from a crop with incomplete cover. Water Resources Research, 8 (5), 1204-1213.

Robinson, R.G. 1987. Camelina: A useful research crop and a potential oilseed crop. Minnesota Agr. Expt. Sta. Bul. 579-1987. (AD-SB-3275).

Schmidt, EJ 1997. Impacts of sugarcane production on water resources. *Proceeding of the South African Sugar Technologists Association* 71: 73-75

Schulze, R.E. 2006. South African atlas of Climatology and Agrohydrology. WRC Report 1489/1/06. Water Research Commission, Pretoria, RSA

Schulze, R.E. and Horan M.J.C. (2007). A quinary scale national catchments database for South Africa. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal.

Schulze, R.E. and Maharaj, M. 2006a. Sunflower seed yield estimation. In: R.E. Schulze (ed). South African Atlas of Climatology and Agrohydrology. Water Research Commission. Pretoria, RSA. WRC Report 1489/1/06.

Schulze, R.E. and Maharaj, M. 2006b. Sorghum yield estimation. In: R.E. Schulze (ed). South African Atlas of Climatology and Agrohydrology. Water Research Commission. Pretoria, RSA. WRC Report 1489/1/06.

Schulze, R.E. and Maharaj, M. 2006c. Groundnut yield estimation. In: R.E. Schulze (ed). South African Atlas of Climatology and Agrohydrology. Water Research Commission. Pretoria, RSA. WRC Report 1489/1/06.

Schulze, R.E. and Maharaj, M. 2006d. Soya bean yield estimation. In: R.E. Schulze (ed). South African Atlas of Climatology and Agrohydrology. Water Research Commission. Pretoria, RSA. WRC Report 1489/1/06.

Schulze, R.E. and Walker, N.J. 2006. Maize yield estimation. In: R.E. Schulze (ed). South African Atlas of Climatology and Agrohydrology. Water Research Commission. Pretoria, RSA. WRC Report 1489/1/06.

Schulze, R.E., Hull, P.J., Maharaj, M. 2006. Sugarcane yield estimation. In: R.E. Schulze (ed). South African Atlas of Climatology and Agrohydrology. Water Research Commission. Pretoria, RSA. WRC Report 1489/1/06.

Schulze, R.E., Maharaj, M. and Moult, N. 2006. Reference crop evaporation by the Penman-Monteith method. In: Schulze, R.E. South African atlas of climatology andagrohydrology. WRC Report 1489/1/06. Water Research Commission, Pretoria, RSA.

Schulze, RE, 1995. Hydrology and Agrohydrology: A Text to Accompany the *ACRU* Agrohydrological Modelling System. Water Research Commission Report Number TT69/95. Pretoria, South Africa.

Silzer, T. 2007. *Panicum virgatum* L. URL: www.usask.ca/agriculture/plantsci/classes/range/panicum.html. Accessed: September, 2007.

Smith, B. 2006. The farming handbook. University of KwaZulu-Natal Press: Pietermaritzburg.

Smith, J.M.B. 1998. Handbook for Agricultural Advisors in KwaZulu-Natal. KwaZulu-Natal Department of Agriculture, Cedara, RSA. Pp 277.

Smithers, J.C and Schulze, R.E, 1995. *ACRU* agrohydrological modelling system: User manual version 3.00. Water Research Commission Report No. TT70/95. Pretoria, South Africa.

Smithers, JC, Schulze, RE and Schmidt, EJ. 1997. Modelling the impacts of grassland, forestry and sugarcane run-off at the Umzinto research catchments. *Proceedings of the South African Sugar Technologists Association* 71: 15-17

Soltani A and Almodares A. 1994. Evaluation of the investments in sugarbeet and sweet sorghum production. National Convention of Sugar Production from Agriculture Products, 13-16 March 1994, Shahid Chamran University, Ahwaz, Iran.

South African Sugar Association (SASA), 2005. The SA Sugar Industry: Fact and Figures. http://www.sasa.org.za Accessed on September 7, 2007.

Statistics SA, 2002. Census of Commercial Agriculture. Statistics South Africa, Pretoria, RSA, Report No. 11-02-01.

Talens, L., Villalba, G. and Gabarrel, X., 2006. Energy analysis applied to biodiesel production. Resources Conserv Recycl, doi:10.1016/j.resconrec.2006.10.008. Article in press.

Thompson G D (1976) Water use by sugarcane. S. Afr. Sugar J. 60 598-600, 629-635.

Tuck, G., Glendining, M.J., Smith, P., House, J.I., Wattenbach, M., 2006. The potential distribution of bioenergy crops in Europe under present and future climate. Biomass and Bioenergy 30, 183-197.

Uhlenbrook, S.: Biofuel and water cycle dynamics: What are the related challenges for hydrological processes research?, Hydrol. Process., 21, 3647-3650

Undersander, D.J., Oelke, E.A., Kaminski, A.R., Doll, J.D., Putnam, D.H., Combs, S.M. and Hanson, C.V. 1990. Jojoba. Alternative field crops manual: Jojoba. URL: www.hort.purdue.edu/newcrop/afcm/Jojoba.html. Accessed: September, 2007.

University of KwaZulu-Natal, Pietermaritzburg, South Africa

Van Antwerpen, R;, McGlinchey, M;, Inman-Bamber, NG, and Bennie, ATP. 1996. Estimating root water use in sugarcane. *Proceedings of the South African Sugar Technologists Association,* 70;: 57-58

Watanabe, K., Yamamoto, T., Yamada, T., Sakuratani, T., Nawata, E., Noichana, C., Sributta, A. and Higuchi, H. 2004. Changes in seasonal evapotranspiration, soil water content, and crop coefficients in sugarcane, cassava and maize fields in Northeast Thailand. Agricultural Water Management 67: 133-143.

Wen, H-W., 2007. Cassava as a biofuel crop in South Africa: Distribution and water use. Honours Project. School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal.

Wright, L. 2006. Worldwide commercial development of bioenergy with a focus on energy crop-based projects. Biomass and Bioenergy 30: 706-714.

Younesabadi, M. undated. Study of allelopathic interference of rapeseed (*Brassica napus var.belinda*) on germination and growth of cotton (*Gossypium hirsutum*) and its dominant weeds. URL: http://www.regional.org.au/au/allelopathy/2005/2/1/2445_younesabadim.htm?print=1. Accessed: September, 2007.

Picture references

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APPENDIX 1

Criteria	Rapeseed / Canola	African Oil Palm	Jatropha	Diesel Tree
Botanical name	*Brassica napus* L.	*Elaeis guineensis*	*Jatropha curcas*	*Copaifera langsdorfii*
Plant family	Cruciferae	Palmae (Arecaceae)	Euphorbiaceae	Caesalpiniaceae
Physical description	Cruciferous plant that produces tuber-like rutabagas below ground and vegetation similar to kale above ground.	Grows up to 20 meters. Fruit is in the size of a plum.	Shrubby, deciduous tree; grows to a height of five meters and sheds its leaves during the dry season.	It is a tropical, evergreen tree that grows to 35 m tall and 1 m in diameter.
Region of origin	Widely domesticated with primary center near Himalyan region; commonly produced in Canada, Western Germany and China.	Africa	The Caribbean	Brazil
*Extreme rainfall range	400-2800 mm	1000-8000 mm	300-2000 mm	1000-4000 mm[1]
*Extreme temperature range	5-41°C	12-38°C	7-36°C	20-27°C
*Optimal rainfall range	500-1000 mm, with 200-210 mm[1] of rain near flower and pod fill.	1500-3000 mm	500-1500 mm	3500 mm and more
*Optimal temperature range	15-25°C	20-35°C	11-28°C	27°C
Bioethanol/diesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Annual/perennial	Annual	Perennial	Perennial	Perennial
Irrigation threshold				
Frost tolerance	No (except some varieties)	No	No	No
C3/C4[#]			C3	C3
Soil depth-water extraction	0-120 cm		3 or 4 lateral root near surface, vertical root reach 5 m	
Threshold for yield	112 mm (Grey, 1998)	Not available	Not available	Not available
Yield	Oil content averaging between 37-50% per seed. Seed yields can vary from 900-3 000 kg ha^{-1}.	Oil content range from 40-70%, while 50% of oil is extracted from the palm kernel. Fruit produced from 200-300 per cluster, about 5 branches per tree.	Seed contains 43-59% oil, and it has been estimated that one hectare of Jatropha trees could produce 1 600-2 000 litres of oil.	Yield as much as 53 litres per tree, and 40.5 hectare of mature trees could produce 5 300 litres per year.
Toxicity	Yes	No	Yes	Yes
Allelopathic?	*Amaranthus retroflexus* and *Abutilon theophrasti Medic*. (weeds) growth			

	was inhibited by allelochemicals from rapeseed.			
Invasiveness	Not yet listed in SA	Not yet listed in SA	Listed (no category)	Not yet listed in SA
Cropping systems	Grown in rotation with grains, flax, corn, sugar beets or fallow, however it should not be grown after itself, mustard, or sunflowers.	African oil palm can be intercropped with maize, yams, millet, cassava, cowpea, cocoyams, groundnuts, bananas.		
By-products	Oil used in food industry (canola), in lubricants, illuminants and soap manufacturing; in western world residual seed cake is used as livestock feed, in the east it is used as an organic fertiliser for field crops.	Oil used to make margarines, vegetable oils, candles, lubricants, soaps. Extracted meal is used as livestock feed. Wine made from male inflorescence sap.	Commonly used as natural hedges and fence-rows; oil used to make soap and cosmetics. Seedcake applied as fertiliser, biogas and pest control.	Used as natural liquid fuel, moisturising rub, an expectorant, and a cure for skin diseases
Water use efficiency information available	Yes	No	No	No

* Annual values taken from FAO (2006).
# All trees are C3 (Morris, 2007, personal communication).
[1] No extreme, optimal rainfall and temperature values available from FAO (2006). Values taken from Duke (1983).

Criteria	**Moringa Tree**	**Pongam Tree**	**Tung-oil Tree**	**Jojoba**
Botanical name	*Moringa oleifera* Lam	*Pongamia pinnata* L.	*Aleurites fordii* Hemsl.	*Simmondsia chinensis*
Plant family	Moringaceae	Fabaceae	Euphorbiaceae	Simmondsiaceae
Physical description	A slender, deciduous tree that grows to 10 meters tall; branches droop with feathery, pale green leaves.	Fast growing, deciduous tree. Flowers are varied from white to pink, and are fragrant. The pods are short, oblique-oblong, flat, and thickly leathery.	grow to the height of 12 m; its heart-shaped leaves are dark green; white, monoecious flowers gather in clusters; its fruits are spherical or pear-shaped which turns from green to purple at maturity; seeds consists of a hard outer shell and a kernel.	Perennial woody shrub. Jojoba plant can live for up to 200 years; it is evergreen and grows to heights of 1 to 5 meters.
Region of origin	India, Arabia, and possibly Africa and the Malay Archipelago	Indo-Malaysia	Central and western China	Deserts of Arizona, California, Mexico
*Extreme rainfall range	400-2600 mm	400-2500 mm	750-1400 mm	100-2000 mm
*Extreme temperature range	7-48^{o}C	10^{o}C-50^{o}C	10-28^{o}C	10-50^{o}C
*Optimal rainfall range	700-2200 mm	500-2000 mm	1000-1200 mm	250-800 mm
*Optimal temperature range	20-35^{o}C	16-40^{o}C	17-22^{o}C	21-36^{o}C
Bioethanol/diesel	Biodiesel	Biodiesel	Biodiesel	Biodiesel
Annual/perennial	Perennial	Perennial	Perennial	Perennial
Irrigation threshold				
Frost tolerance	Yes	Yes	No	No
C3/C4$^{\#}$	C3	C3	C3	C3
Soil depth-water extraction				One or more long tap roots (up to 12 m)
Threshold for yield	Not available	Not available	Not available	
Yield	Pods contain around 20 seeds, each seed yield 38-40% of oil. About 10 metric ton pods per hectare are possible.	A single tree could yield 9-90 kg seed per tree; a hectare of 100 trees yield of 900-9000 kg seed/ha, 25% of which can be rendered as oil	The fruit contains 14-20% of oil, the kernel 53-60%, and the nut 30-40% of oil. The trees could yield 4.5-5 tonnes of fruits per hectare.	Does not produce economically useful yield until 4th or 5th year after planting. Currently yield less than 340 kg/ha.
Toxicity	No	Yes	Yes	Yes

Allelopathic?		Leachates from Pongamia leaves contain allelochemicals which inhibited the performance of both rice and wheat.		
Invasiveness	Not yet listed in SA.	Not yet listed in SA. Potential noxious weed*	Not yet listed in SA.	Not yet listed in SA
Cropping systems				
By-products	Source of human food; oil used for lubricating watches, manufacturing of perfumes and hairdressing. Wood yields blue dye, while the leaves and young branches can be fed to livestock. Tree planted as living fence, as well as used in traditional healing and witchcraft.	Commonly grown as an ornamental tree; also cultivated as a host plant for lac insects, and its well-decomposed flowers and leaves are used as nutrient-rich compost.	Seed oil utilised in the manufacture of lacquers, varnishes, paints, linoleum, oilcloth, resins, artificial leather, brake-linings; used by the Chinese as gasoline blend.	30%protein is found in the seed cake, but toxic compounds make it currently hazardous as an animal feed.
Water use efficiency information available	No	No	No	No

* Annual values taken from FAO (2006).
# All trees are C3 (Morris, 2007, personal communication).

Criteria	Chinese Tallow Tree	Cassava	Sugarbeet	Flax
Botanical name	*Sapium sebiferum* L.	*Manihot Crantz*	*Beta vulgaris*	*Linum usitatissiumum* L.
Plant family	Euphorbiaceae	Euphorbiaceae	Chenopodiacae	Linaceae
Physical description	Deciduous tree that grows to 10-13 m tall (in 30 yrs); have gnarled trunk, grey bark with vertical cracks. Stem exudes milky toxic juice.	Shrubby, tropical plant that has a fibrous root system. Grow to a height of about 5 meters and has large, palmate leaves that vary between green or dark red.	A deciduous single stem herb with large roots/tubers used in the production of sugar and/or alcohol	Grows to height of 300-900 mm. Has distinct main stem with numerous branches at the top that produce flowers.
Region of origin	Central China and Japan	Central America and northeastern Brazil	Asia	Mediterranean region of Europe
*Extreme rainfall range	500-2500 mm	500-5000 mm	250-1000 mm	250-1300 mm
*Extreme temperature range	10-32^{o}C	10-35^{o}C	7^{o-}30^{o}C	5-30^{o}C
*Optimal rainfall range	700-1500 mm	1000-1500 mm	400-700 mm	500-800 mm
*Optimal temperature range	20-28^{o}C	20-29^{o}C	Optimal: 15-20^{o} during night, 20-25^{o} during day.	16-24^{o}C
Bioethanol/diesel	Biodiesel	Bioethanol	Bioethanol	Biodiesel
Annual/perennial	Perennial	Perennial	Biennial	Annual
Irrigation threshold			Both – Dryland: soils with high water holding capacities. Irrigation must stop at least 2-4 weeks prior to harvest.	Both – irrigation necessary under hot, dry climatic conditions
Frost tolerance	No	Yes (< 300 days frost)	No	Not during early growth
C3/C4#	C3	C3-C4 intermediate		
Soil depth-water extraction		50-100 cm (root depth)	Taproot system 1.5-2.4 metres	Branched taproot system. 0.9-1.2 metres deep.
Threshold for yield				
Yield	A hectare of 400 trees may yield 14t seed, 2.6t oil, 2.8t tallow, 1.5t protein concentrate, 1.1t fibrous coat, and 4.5t shell. Seed contain 20% oil.	Between five and ten cylindrical tubers are produced per plant. Root yields of 50 t/ha have been achieved in SA.	30-60 tons/ha (FAO)	6-7 tons/ha under favourable conditions. Yield decreases as rainfall decreases.
Toxicity	Yes	Yes	No	No
Allelopathic?				
Invasiveness	Not listed in SA	Not yet listed in SA	Not yet listed in SA	Not yet listed in SA

	Potential noxious weed*			
Cropping systems		In West Africa, cassava is found to be grown as an intercrop with maize, yam, peanut, or cowpea; while in East Africa, it is grown with banana, maize, cowpea and beans.	Can be grown with an autumn sown cover crop such as wheat, but cover crop must be destroyed before emergence. Rotates well with barley or wheat.	Works well as an intercrop with rice, sugarcane and peanut (in India) as it has a low nitrogen requirement.
By-products	Tallow used to make candles, soap, cloth dressing and lamp oil. Residual cake used as fertiliser, particularly for tobacco fields. Black dye produced from leaves. Used as soil binder along canals.	Cultivated as a famine-reserve crop and temporary shade plant; the plant is used in human food (although low in protein) consumption, animal feed and industrial uses.	Pulp and molasses as feed supplements for livestock.	After oil production, the remaining seedcake provides a high-value livestock feed as well as a dietary supplement for humans.
Water use efficiency information available	No	Yes	Yes	Yes

* Annual values taken from FAO (2006).
# All trees are C3 (Morris, 2007, personal communication).

Criteria	**Camelina**	**Switchgrass**
Botanical name	*Camelina sativa*	*Panicum virgatum* L.
Plant family	Brassicaceae	Poaceae
Physical description	Grows to height of 300-900 cm. Has branced, smooth or hairy stems that become woody at maturity.	An erect, coarse, warm season perennial grass, growing to 1-1.5 m tall.
Region of origin	Northern Europe and central Asia	United States
*Extreme rainfall range		350-2700 mm
*Extreme temperature range		6-36^{o}C
*Optimal rainfall range		500-1100 mm
*Optimal temperature range		17-32^{o}C with optimum germination at 20-30^{o}C.
Bioethanol/diesel	Biodiesel	Bioethanol
Annual/perennial	Annual/Winter annual	Perennial
Irrigation threshold		
Frost tolerance	Yes	Dormant over winter period.
C3/C4[#]		C4
Soil depth-water extraction		Long scaly rhizomes with fibrous roots. Can grow to 3 m in depth.
Threshold for yield		
Yield	Average 1.1 tons/hectare but can be as high as 1.7 tons/ha.	3450-9280 kg/ha/yr
Toxicity	Yes	
Allelopathic?	Benzylamine, which negatively influence *Linum usitatissimum* growth.	
Invasiveness	Not yet listed in SA	Not yet listed in SA

Cropping systems	Performs better when seeded with an autumn sown cover crop than after conventional tillage in the spring or surface seeding on bare ground in the autumn	Switchgrass benefits when grown with legumes as the legumes substitute for fertilisation.
By-products		
Water use Efficiency information available	No	No

* Annual values taken from FAO (2006).
\# All trees are C3 (Morris, 2007, personal communication).

Criteria	**Maize**	**Sugarcane**	**Sunflower**	**Sweet Sorghum**
Botanical name	*Zea mays* L.	*Saccharum officinarum* L.	*Helianthus annuus* L.	*Sorghum bicolor* L.
Plant family	Poaceae	Poaceae	Asteraceae	Poaceae
Physical description	Annual grass; a deciduous plant. Culms stout with prop roots from lower nodes. Papery sheath enclose the thick central cob.	Culms are 3-5 m tall, 2-3 cm thick. Sheaths overlap, and blades are elongated.	Fast-growing annual herb; stems 0.7-3.5 m tall with alternate, ovate leaves. Flowers rotate to face sun; flowers neuter with yellow ligulate corolla.	Indigenous grass; drought resistant crop, i.e. requiring < 300 units of water to produce one unit of dry matter, it can tolerate erratic rainfall and will recover even if wilted for up to 14 days.
Region of origin	Mexico	South Pacific Islands and New Guinea	western North America	Africa
Extreme rainfall range	400-1800 mm	400-1800 mm	300-1600 mm	300-3000 mm
Extreme temperature range	10-47^{o}C	10-47^{o}C	5-45^{o}C	8-40^{o}C
Optimal rainfall range	600-1200 mm	600-1200 mm	600-1000 mm	500-1000 mm
Optimal temperature range	18-33^{o}C	18-33^{o}C	17-34^{o}C	27-35^{o}C
Bioethanol/diesel	Bioethanol	Bioethanol	Biodiesel	Bioethanol
Annual/perennial	Annual	Perennial	Annual	Annual
Irrigation threshold				
Frost tolerance	No	No	No	No
C3/C4	C4		C3	C4
Soil depth-water extraction	Greater than 7.5 cm	Greater than 100 cm	Taproot grow to 3 m	
Threshold for yield				
Yield	Maize yields in South Africa are low. In the decade 1995/6 to 2004/5 they have fluctuated between 2.16 and 3.04 t/ha.	Average sucrose content of the South African crop is approx 13.5%, varying from 11.9-13.8% and inversely related to the year's rainfall. It takes approximately 8.5 tonne	Average yields range from 900-1575 kg/ha of seed; yield from seeds consist oil content of 40%, 35% protein meal, and 20-25% hulls (Duke, 1983j).	In South Africa, sorghum yield has averaged 2.9 t/ha for the period 1995/6-2003/4, but this has ranged from 2.2 to 3.5 t/ha.

		sugarcane to produce 1 t sugar, varying from 8.3-10.0 t		
Toxicity	No	No	No	Yes
Allelopathic?				
Invasiveness	No	No	No	No
Cropping systems	Rotation cropping with legumes; intercropping with peanuts, okra, pumpkins, melons; alley cropping with grain legumes (Vigna unguiculata), soybeans (Glycine max), Acacia auriculiformis, Cajanus cajan; phase planting with coconut, mango, mung bean, oil-palm, young rubber trees.	Monocrop	Monocrop	Sweet sorghum usually fits into most common crop rotation systems with corn or soybean crop. However, sweet sorghum should not be grown on land following a tobacco crop.
By-products	The entire plant can be used as animal feed. Pressed cake could be used as feed for livestock.	The reeds are made into pens, mats, screens, and thatch. A mixture of bagasse and molasses (Molascuit) is used as cattle feed.	Hulls provide filler in livestock feeds and bedding, while the pressed seed cake is a high protein food for livestock.	Stalks are used as animal feed.
Water use efficiency information available	Yes	Yes	Yes	Yes

Criteria	**Groundnut**	**Soybean**		
Botanical name	*Arachis hypogaea*	*Glycine maximum*		
Plant family	Fabaceae	Fabaceae		
Physical description	Leaves are stipulate, pinnate with two opposite pairs of leaflets, alternately arranged. Flowers pea-like, with orange, yellow, cream or rarely white petals, are enclosed between two bracts.	Bushy, summer season annual herb. It has three-fold leaves and grows to between 0.6 and 1.2 m.		
Region of origin	South America	Manchurian region of China		
Extreme rainfall range	400-4000 mm	450-1800 mm		
Extreme temperature range	10-45°C	10-38°C		
Optimal rainfall range	600-1500 mm	600-1500 mm		
Optimal temperature range	22-32°C	20-33°C		
Bioethanol/diesel	Biodiesel	Biodiesel		
Annual/perennial	Annual	Annual		
Irrigation threshold				
Frost tolerance	No	No		
C3/C4				
Soil depth-water extraction				
Threshold for yield				
Yield	In South Africa, the irrigated yields average around 2.2 t/ha (Northern Cape: 2.3 t/ha) while dryland yields are only about half that at 1.1 t/ha, with the Free State yielding 1.3 t/ha and the Northern Cape only 0.9 t/ha.	Each plant produces between 3 and 350 pods. Overall soybean yields now average around 1.6-1.7 t/ha in South Africa.		
Toxicity	No	No		
Allelopathic?				

Invasiveness	No	No		
Cropping systems	Rotational crop, which ideally should be planted in the same soil only once every 4 years	Rotational crop.		
By-products	The oil cake, a high-protein livestock feed, may also be used for human consumption.	The vegetative portions of plant can be used for silage, hay, pasture or fodder, or may be ploughed under as a green manure. Seed cake fed to livestock.		
Water use efficiency information available	Yes	Yes		