SPATIAL ASSESSMENT OF OPTIMUM AND SUB-OPTIMUM GROWING AREAS FOR SELECTED BIOFUEL FEEDSTOCKS IN SOUTH AFRICA

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ABSTRACT

Energy production using fossil-based fuels (coal, oil and natural gas) has environmental and health effects that have the potential to endanger human welfare. Escalating oil prices and the contribution of carbon dioxide resulting from fossil fuel combustion to global climate change have focused attention on potential substitutes for current energy sources. Renewable energy is argued to improve access to clean energy, limit the use of fossil fuels and thus reduce air pollution.

Biofuel is a liquid transport fuel and its production from biomass containing sugar, starch or vegetable oil is termed a first generation biofuel. The aim of these studies was to delineate areas potentially suitable for the cultivation of three first generation feedstocks (i.e. soybean, grain sorghum and sugarcane) in South Africa. Currently, these feedstocks exhibit the highest potential for biofuel production in this country. In previous studies, climatic factors were the main criteria used to map optimum growing areas for such feedstocks. However, such studies recommended that a more detailed assessment was required to provide a more realistic estimate of biofuel production potential. Thus, other mapping criteria related to edaphic, biotic and topographic factors were also considered. The approach followed is similar to other mapping methods developed by, amongst others, the Food and Agricultural Organisation.

Land suitability assessment was based on crop growth requirements related to rainfall, temperature, relative humidity, soil depth and slope, which were gleaned from the available literature. These factors were then ranked and weighted according to expert opinion. A suitability score ranging from zero (unsuitable for plant growth) to one (most suitable) was derived and used to map areas optimally and sub-optimally suited to feedstock production. Relative to previous studies the inclusion of additional growth criteria decreased the land area deemed suitable for biofuel feedstock production.

The results were further refined by considering current land use. For example, all areas which are deemed unsuitable for feedstock production (e.g. forest plantations and protected areas) were eliminated. The results showed that the provinces of KwaZulu-Natal, Mpumalanga, Limpopo and Free State are most suitable for soybean and grain sorghum cultivation, whilst the Eastern Cape and North-West provinces are least suitable. Similarly, KwaZulu-Natal is most suitable for sugarcane cultivation, whereas Mpumalanga, the Eastern Cape and Limpopo are least suitable. However, there are some limitations in the approach used, due mainly to the scale and accuracy of spatial datasets currently available.

DECLARATION

The work described in this dissertation was carried out in the Centre for Water Resources Research, University of KwaZulu-Natal, Pietermaritzburg, from March 2012 to November 2014, under the supervision of Mr RP Kunz and co-supervision of Professor GPW Jewitt.

This study represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any other university. Where use has been made of the work of others, it is duly acknowledged in the text.

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1. INTRODUCTION

1.1 The Need for Biofuel Production

The world is faced with an energy crisis, which was seen in 2008 by rapid increasing energy prices (Jewitt *et al.*, 2009a). According to Koh and Ghazoul (2008), fossil based fuels such as oil, natural gas and coal account for 80 % of the world's energy supply, of which 58 % is used in the transport sector alone (Nigam and Singh, 2011). The increased emission of greenhouse gases (GHGs) such as CO_2, CH_4 and N_2O from fossil fuel use is implicated in climate change, a rise in sea levels and the loss of biodiversity (IPCC, 2007; İçöz *et al.*, 2009). These concerns have raised interest worldwide towards the production of energy from alternative sources such as biofuels (Demirbas, 2007). Climate change awareness has served as an important additional driver for the promotion of biofuels (Timilsina and Shrestha, 2011).

Biofuels represent an alternative to fossil fuels with a high pro-environment potential related to greenhouse gas (GHG) emission reductions in the transport sector (Costantini *et al.,* 2015). Biofuels can assist climate change mitigation efforts by contributing to the reduction of CO_2 emissions from the transport sector (Timilsina and Shrestha, 2011). Biofuels are seen as a solution for reducing reliance on imported oil and lowering the emission of GHGs, both in developed (e.g. US) and developing (e.g. China) countries (Koh and Ghazoul, 2008). Compared to fossil fuels, biofuels are deemed as cost-effective, sustainable, efficient, possibly reduced GHG emissions and are renewable (Nigam and Singh, 2011). According to Nigam and Singh (2011), biofuels are the most environmentally-friendly alternative fuel source, due to their renewability.

1.2 The Importance of Biofuel in South Africa

In 2007, the South African government introduced the National Biofuels Industrial Strategy (NBIS) (DME, 2007). The aim of this strategy was to achieve a 2 % biofuel penetration of transport fuel by 2013, which represented the production of about 400 million litres. The strategy aimed to replace 240 million litres of petrol with ethanol made from sugarcane and sugarbeet (Mbohwa and Myaka, 2011), as well as the production of 160 million litres of biodiesel from sunflower, canola and soybean.

About 14 % of arable land, mainly in the former homelands,[1] was estimated as under-utilised of which only 1.4 % is needed to meet this 2 % biofuels target (DME, 2007). About 300 000 ha of land is required for feedstock production (DME, 2007), but the suitability of land in former homelands is unknown. The biofuels industry will support a variety of national priorities, including job creation, poverty alleviation and sustainable development (DME, 2007). According to DME (2007), biofuel production can also contribute to the objectives of the Land Reform and Restitution programmes by providing market access for farmers who benefit from these programmes.

1.3 The Impact of Biofuel Production

There are two arguments that have been put forward concerning the relationship between biofuel production and food security. The first argument is against biofuels, stating that the cultivation of energy crops will lead to the diversion of agricultural resources (land, labour, water, capital, etc.), away from food production and towards biofuel production, thus contributing to food insecurity (Takavarasha *et al.*, 2005). The second argument is in favour of energy crops, with biofuel feedstock production attracting additional resources and investment in agriculture, thus stimulating overall production as well as the economy. This could have positive effects on food security and generate more employment opportunities in agriculture (Takavarasha *et al.*, 2005).

1.4 The Problem Statement

In order to avoid food security issues, there is a need to grow feedstocks on land not currently under food production. Thus, a need exists to identify land for agricultural expansion and re-allocation of under-utilised land that is suitable for biofuel feedstocks. However, the availability of land suited to biofuel feedstocks is largely unknown. A detailed assessment of land suited to feedstock production is required to determine if such areas exist, particularly in the former homelands.

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[1] Land set aside (mainly in the current provinces of KwaZulu-Natal, Eastern Cape, Limpopo and North West) for black South Africans under the apartheid regime, which was then integrated with the rest of South Africa in 1994.

The amount of land realistically available for feedstock cultivation is needed to assess the country's biofuel production potential. The scoping study on biofuel production and water use undertaken by Jewitt *et al*. (2009a) only used climatic factors to map areas suited to feedstock cultivation. The study did not identify land realistically available for cultivation (i.e. it over-estimated the potential for biofuel production). Thus, there is a need to re-assess the production potential of biofuel feedstocks in South Africa. The scoping study also highlighted that a more detailed mapping/input of biophysical conditions was needed if the benefit and impact of biofuels is to be adequately assessed at local scales (Jewitt *et al*., 2009a).

1.5 Research Questions

The main research question addressed in this study is: Which areas of South Africa are optimally and sub-optimally suited to the production (i.e. cultivation) of soybean, grain sorghum and sugarcane?

1.6 Purpose of the Study

In light of the above research question, the main aim of this study was to map areas suitable for soybean, grain sorghum and sugarcane cultivation and to improve the approach used in previous mapping studies. This may help decision-makers and government to make better and more informed decisions regarding biofuels in South Africa.

The specific objectives of this study were to:

(a) Undertake a detailed literature review of factors affecting feedstock production.
(b) Identify climatic factors affecting feedstock production.
(c) Identify edaphic factors affecting feedstock production.
(d) Identify biotic factors affecting feedstock production.
(e) Identify topographical factors affecting feedstock production.
(f) Eliminate areas deemed unsuitable for feedstock production based on current land use.
(g) Map areas optimum and sub-optimally suited to soybean, grain sorghum and sugarcane production.

1.7 Assumptions/Limitations

The approach used in this study is limited by availability of spatial data and thus cannot be applied at the farm level due to the coarse scale of the data used. Only South Africa is considered (not Lesotho and Swaziland) due to lack of land use data in neighbouring countries. Only three feedstocks were considered, as these are strategic feedstocks highlighted in the draft biofuel pricing framework document (DoE, 2014).

1.8 Chapter Overview

This dissertation contains six chapters and is structured as follows:
Chapter two and chapter three present a literature review. This includes a review of different types of biofuels, an overview of key strategic feedstocks and, the emerging biofuels industry in South Africa. Various approaches to assess land availability including case studies are also presented.

The fourth chapter presents the methodology used in this study, which covers various data sources and the steps followed to map areas suited to feedstock production. Chapter five presents the results emanating from this study and a discussion of these results. Conclusions drawn from this study and recommendations for future studies are provided in chapter six.

2. PRODUCTION OF BIOFUELS

The literature review focussed on extending the work undertaken for the scoping study by Jewitt *et al.* (2009a). Thus, literature sources post 2008 were sought. The chapter is divided into several sections. The first section introduces the different types of biofuels and how they are classified. The second and third sections provide an overview of key biofuel feedstocks.

2.1 Definition of Biofuels

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

2.1.1 Classification of biofuels

Biofuels are classified into primary and secondary biofuels. Primary biofuels are used in an unprocessed manner for cooking and heating (Nigam and Singh, 2011). Secondary biofuels comprise of bioethanol and biodiesel made from biomass, which can be used mainly for transportation. Hence biodiesel and bioethanol are the two most common biofuels aimed at reducing petrol and diesel produced from crude oil (Nigam and Singh, 2011). This study only considered liquid biofuels, produced from first generation feedstocks.

2.1.2 First and second generation feedstocks

Sugar, starch and oilseed yields from feedstocks are converted into biofuels using first generation technologies. Such feedstocks are expected to dominate biofuel production for many years, since the conversion technologies are well-established and large production programmes currently exist which are deemed economically viable (Ravindranath *et al*., 2011). Second generation feedstocks include woody biomass, tall grass, agricultural residues and forest plantation residues. They comprise of ligno-cellulosic biomass, harvested mainly for bioenergy production via biological or thermo-chemical processing (Nigam and Singh, 2011). These advanced conversion technologies are still under development and not considered economically viable at present (Ravindranath *et al*., 2011).

2.1.2.1 Bioethanol

Ethanol can be produced from a variety of carbohydrates stored in plant material, which are first converted to sugars by hydrolysis and then fermented using microorganisms to produce alcohol (Demirbas, 2008). Ethanol from grain is produced by first dry milling the grain, then converting the starch stored in the grain to dextrose and finally, by fermenting and distilling it into ethanol (Demirbas, 2008).

Ethanol is a biofuel that is expected to be produced mostly around the world because of its production from potential supplies which include sugar, starch and cellulosic biomass (John *et al.,* 2011). Bioethanol production can reduce the levels of GHG emissions, since the feedstocks utilise atmospheric CO_2 during their growth phase. In addition, emissions of CO_2 and SO_2 using bioethanol combustion are lower than those using fossil fuels from internal combustion engines (John *et al.*, 2011). Since bioethanol has a high octane value, it therefore can be employed to replace octane enhancers, thereby increasing the efficiency of combustion engines (John *et al.*, 2011).

2.1.2.2 Biodiesel

Biodiesel is a clean burning, alternative fuel produced from renewable resources. It is manufactured from vegetable oils and considered a suitable candidate for alternative diesel fuel (Demirbas, 2008). Biodiesel is produced using the process of trans-esterification, where vegetable oil is mixed with methanol to produce biodiesel and glycerine as a by-product (McDowell Bomani *et al.*, 2009). Biodiesel can be used in most modern diesel engines in pure form, or blended with petroleum diesel at any concentration (UNDESA, 2007).

2.2 Overview of the Emerging Biofuels Industry in South Africa

The biofuels industry in South Africa has not become well-established since the release of the NBIS in 2007. The main reasons that have the potential to render the biofuel industry inactive include mandatory blending, farmer participation, targeted arable land use and government support (DoE, 2014).

2.2.1 The national biofuels strategy

The aim of the NBIS (DME, 2007) was to achieve social and economic upliftment in rural areas through agricultural expansion in the former homelands. The specific objectives were to improve the country's fuel security and to add to the renewable energy pool (DME, 2007). The key components of the strategy are job creation and to address the imbalance between small-scale and commercial farming. The suggested crops for ethanol production were sugarcane and sugarbeet as well as soybean, canola and sunflower for biodiesel. There were no mandatory blending rates proposed in the NBIS (DME, 2007), which was one of the main reasons why the biofuels industry remained stagnant.

The strategy stated that the use of under-utilised arable land in the former homelands is preferred and thus alleviates concerns regarding the impacts of biofuel production on food security. This land is owned by the state but under control by local tribes (DME, 2007).

2.2.2 Mandatory blending rates

The mandatory blending regulations require a minimum blend level of B5 (5 % of biodiesel mixed with fossil-based diesel) for biodiesel and a blend between E2 (2 % of ethanol mixed with fossil-based petrol) and E10 (10 % ethanol mix) for ethanol published under Government Notice R.671 (DoE, 2012). According to the notice published in the *Government Gazette* on 30 September 2013, the mandatory blending for biofuel will come into operation from 1st October 2015 (DoE, 2014). This effective date should allow time for the installation of the required infrastructure required to blend and supply biofuels.

2.2.3 Proposed biofuel plants

Table 2.1 provides an update on the licensing of biofuel manufacturing facilities from the Department of Energy. Two processing plants for sorghum-based bioethanol have been licensed, one granted (Arengo 316) and the other issued (Mabele Fuels). A “granted” license status indicates that not all the requirements have been met by the applicant (DoE, 2014). An “issued” license means the applicant has met all the requirements and that the company is in possession of a manufacturing licence (DoE, 2014). A sorghum-based bioethanol plant should be constructed at Cradock in the Eastern Cape and the other at Bothaville in the Free State province. Sugarcane to ethanol plant will be constructed in Jozini in KwaZulu-Natal. A biodiesel plant from canola and soybean will be built in Port Elizabeth in the Eastern Cape. It is interesting to note that the soybean plant will produce oil cake for animal feed as a primary product and the oil for biodiesel as a by-product (Payne, 2013).

Table 2.1: Update on licensing of biofuels manufacturing facilities (DoE, 2014)

Company name	**Plant type and preferred feedstock**	**Capacity (million liters per annum)**	**Location**	**License status**
Arengo 316	Sorghum-based bioethanol	0 90	Cradock (Eastern Cape)	Granted
Mabele Fuels	Sorghum-based bioethanol	158	Bothaville (Free State)	Issued
Ubuhle Renewable Energy	Sugarcane-based bioethanol	0 50	Jozini (KwaZulu-Natal)	Granted
Rainbow Nation Renewable Fuels	Soybean-based biodiesel	0288	Port Elizabeth (Eastern Cape)	Issued
Phyto Energy	Canola-based biodiesel	> 500	Port Elizabeth (Eastern Cape)	Initial stages of license application

Granted means the applicant has not met all the requirements but is in possession of a **conditional** manufacturing license.

Issued means the applicant has met all the requirements and is in possession of a manufacturing license.

2.3 Strategic Biofuel Feedstocks

The preferred feedstocks to be used by the proposed biofuel companies are canola, soybean, grain sorghum, and sugarcane (DoE, 2014). It is believed that Phyto Energy may import canola feedstock and thus, was not considered in this study (van Rooyen, 2013). Hence, this study focused on the other three important feedstocks, namely soybean, grain sorghum and sugarcane.

Soybean emerged as the appropriate feedstocks because large quantities of it are grown locally and experience exists to expand production. Biofuel production may provide an alternative market for grain sorghum farmers. As discussed further in Section 2.4.2 below, grain sorghum profitability is deteriorating, due to improving maize prices. Therefore, the area under grain sorghum is currently declining. According to REEEP (2007), sugarcane should be the initial choice for ethanol production in South Africa because the country is exporting sugar on a regular basis. However, mandatory blending rates place more emphasis on biodiesel production, compared to ethanol production (i.e. minimum E2 *vs*. B5 blending). An overview of each potential feedstock is provided next and considers its present distribution and criteria for growth.

2.3.1 Soybean (*Glycine maximum*)

Soybean belongs to the *Fabaceae* family. It is a bushy, erect, leguminous annual plant that prefers short days and requires warm temperatures (DAFF, 2010a). Plant height is usually 40 to 100 cm with a well-developed root system and each plant produces between 3 and 350 pods (DAFF, 2010a). The stem is round and hairy with many branches. Soybean has two growth stages: the first is from emergence to flowering (vegetative) and the second from flowering (reproductive) to maturation (Kandel, 2012). If the crop is rotated with other crops such as maize and sorghum, it ensures nitrogen fixation for maintaining and replenishing soil fertility (Ngalamu *et al.,* 2012). Soybean can be used for livestock feed, human nutrition, industrial use, as well as a source of biofuel and is thus considered a multi-purpose crop (Chianu *et al.,* 2009). According to DAFF (2010a), in South Africa the crop is planted from November to December and harvested from February to March.

2.3.1.1 Present distribution

Countries growing soybean (top producers) are mainly the USA, Brazil and Argentina, where the annual production is about 77.3, 44.5 and 30.3 million tons per year respectively. Production from these countries is more than twice Africa's average because the legume was only recently introduced to the continent (Ngalamu *et al.,* 2012). The production of soybean in South Africa ranges from 450 000 to 500 000 tons per year, with an average yield of 2.5 to 3 $t.ha^{-1}$ under dryland conditions. Table 2.2 shows the main soybean production areas in South Africa (DAFF, 2010a).

Table 2.2: The main soybean production areas in South Africa (DAFF, 2010a)

Provinces	**Production (%)**
Mpumalanga	42
Free State	22
KwaZulu-Natal	15
Limpopo	08
North West	05
Gauteng	02

2.3.1.2 Optimum growth criteria

Soybean is best adapted to summer rainfall regions with an annual precipitation above 700 mm, where more than 450 mm falls in the growing season (Smith, 1998). The crop can also do well under irrigation in dry and warm regions. Soybean plants can tolerate drought because of their deep rooting system, but moisture is essential during the flowering stage (DAFF, 2010a).

Temperature is an important factor affecting the growth rate of soybeans. Daily average temperatures above 35 °C and below 18 °C can delay plant growth. The optimum daily maximum temperature for soybean is between 20 and 30 °C and differs with growth stage (Smith, 1994). Hot weather conditions can damage the seedlings, whilst very cold and very warm conditions can delay flowering (DAFF, 2010a). Soybean can be influenced by day-length because of its photoperiod sensitivity and requires 1 000 – 2 600 heat units (Schulze and Maharaj, 2007a).

Soybean rust (SBR) is caused by the fungus *Phakopsora pachyrhizi* Syd, which is able to spread rapidly and has the potential to reduce soybean yields (van Niekerk, 2009). SBR is considered to be the most destructive foliar disease of soybean. According to Pretorius *et al.* (2001), SBR was identified in KwaZulu-Natal in February 2001. To develop, SBR requires a temperature between 15 °C to 28 °C, with the optimum temperature between 20 °C and 25 °C (Nunkumar, 2006). In addition optimum relative humidity for the development of SBR is between 75 % and 95 % (Nunkumar, 2006). In this study, it was important to assess the risk of SBR occurrence, using relative humidity as a surrogate climate variable for disease risk. Soybean rust is considered to be the most destructive foliar disease of soybeans because of its ability to spread rapidly and it's potential to severely reduce yields (Miles *et al.*, 2003).

The plant has some degree of frost tolerance if frost occurs prior to flowering (FAO, 2012a). Soybean prefers well-drained and deep soils with high fertility in order to achieve optimum yields. The crop is susceptible to waterlogging conditions and the soil pH should be above 5.2, to allow nitrogen fixation. Since the maximum rooting depth is 1.2 m, compacted soils should be avoided (DAFF, 2010a). Table 2.3 summarises the growth criteria of soybean as gleaned from the available literature.

Table 2.3: Growth criteria for soybean cultivation obtained from the literature

Source	**Annual rainfall (mm)**	**Seasonal rainfall (mm)**	**Temp Daily ave (°C)**	**Monthly RH (%)**	**Soil depth (mm)**	**pH**	**Soil texture**
Jewitt *et al*. (2009a) Recommended		550-700 OPT	20-30 OPT 18-35 SUB				
Jewitt *et al*. (2009a) literature review	> 700	> 450					
Smith (1994)	> 700	450-700	18-35 SUB Jan > 19 ABS 20-30 OPT				No very Sandy/ poorly drained
Smith (1998)	> 700	> 450 550-700	20-30 OPT		250-400		
Smith (2006)		550-700			600		
FAO (2006)	600-1 500 OPT 450-1 800 ABS		20-33 OPT 10-38 ABS			5.5-6.5 OPT 4.5-8.5 ABS	Medium, organic
Schulze and Maharaj (2007a)	> 600		JAN > 18				
Nunkumar *et al.* (2006)				< 75			
Additional literature							
Schulze and Kunz (2010)	> 600		JAN > 18				
DAFF (2010a)		500-900	13-30 SUB 25 OPT		300-500		
DAFF (2010a)-At planting			15-18 OPT			6.0-6.5 OPT > 5.2 SUB	
Bassam (2010)	500-750		24-25 OPT 20-25 SUB		300-400	6-6.5	loamy

Note OPT – Optimum; SUB – Sub-optimum; ABS – Absolute; JAN – Month of January; Temp Daily ave – Temperature Daily Average; RH – Relative humidity; pH – Power of hydrogen.

2.3.1.3 Suitability for biodesel production

The Biofuels Industrial Strategy of the Republic of South Africa identified three primary field crops to be considered as feedstocks for domestic biodiesel production, namely sunflower, canola and soybeans (DME, 2007). According to Spark *et al*. (2010), the use of by-products from biofuel processing can contribute significantly to the economy of South Africa. The relatively high market value of oilcake provides soybean the greatest potential as a first generation feedstock. Hence, it is believed that the relatively high market value of soybean oilcake in particular may result in soybeans having the greatest potential as a first generation biodiesel feedstock than canola and sunflower (Meyer *et al*., 2008).

2.3.2 Grain sorghum (*Sorghum bicolor*)

Sorghum belongs to the *Poaceae* family and is a perennial crop grown in temperate regions (Schulze and Maharaj, 2007b). The genus sorghum consists of both wild and cultivated species (Menz *et al.,* 2002). Sorghum possesses both primary and secondary roots. Initially, the primary roots provide nutrients to the seedlings and this function is then taken over by the secondary roots. The stem is succulent and solid, with a diameter of between 5 to 30 mm. Self-pollination usually occurs in sorghum (Menz *et al.,* 2002), since only about 6 % is natural cross-pollination (DAFF, 2010b). Sorghum is usually planted from October to mid-December in South Africa and it is normally harvested from January to April (DAFF, 2010b).

2.3.2.1 Present distribution

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

The South African grain sorghum production trend for the 1997/98 to 2009/10 growing season is illustrated in Figure 2.1. This figure shows the seasonal fluctuation in production and consumption of grain sorghum. During the 2000/01 growing season, production sharply increased as a result of larger plantations, especially the bitter cultivars (Mashabela, 2012). This season illustrates that the country can provide higher quantities of grain sorghum if the demand exists. Production also increased in the 1997/98 and 2004/05 growing seasons (Lemmer, 2009), due to higher price anticipations (Mashabela, 2012). Due to current market conditions, grain sorghum farmers are expected to decrease plantings and shift to maize because of its higher profitability (Mashabela, 2012).

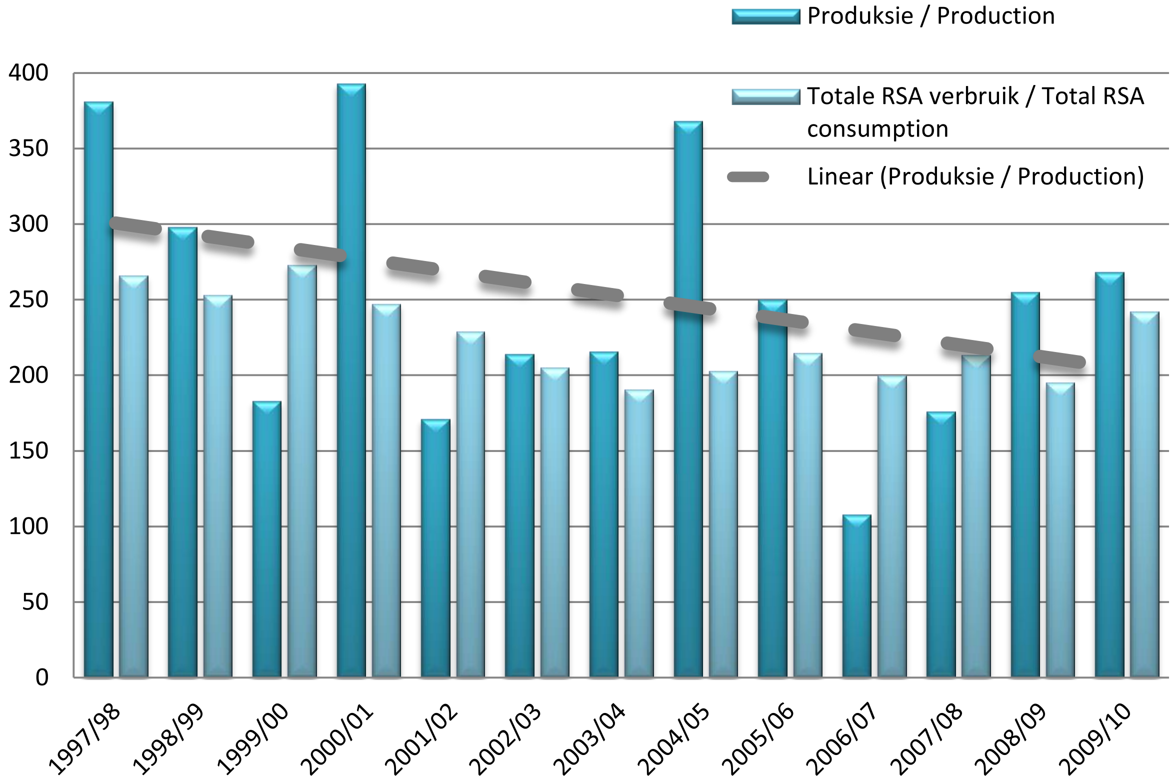


Figure 2.1: Annual grain sorghum production and consumption (x 1000 tons) in South Africa from 1997/98 to 2009/10. The linear trend line shows the decline in production over the 13-year period (Lemmer, 2009).

2.3.2.2 Growth criteria

According to DAFF (2009), the adequate annual rainfall range for grain sorghum is between 300 to 750 mm. Floral initialisation can be stopped by early drought, whilst late drought stops leaf development (DAFF, 2009). Du Plessis (2008) provided similar figures stating that, in the drier western parts of South Africa, about 400 mm of annual rainfall is required, and in the wetter eastern parts, about 800 mm is required. Sorghum requires warm weather for germination and growth, whilst freezing temperatures are detrimental to sorghum (du Plessis, 2008). The optimum daily maximum temperature for germination ranges between 20 and 35 °C (DAFF, 2009) and the germination minimum temperature ranges between 7 and 10 °C (du Plessis, 2008; DAFF, 2010b). The crop prefers a soil temperature of 15 °C or above, with sufficient water at a preferable depth of 100 mm (du Plessis, 2008). Sorghum is grown in drier regions because the crop is drought-resistant, requiring < 300 units of water to produce one unit of dry matter (Smith, 1998). The crop is drought-tolerant because the leaf is covered by a thick waxy layer, which reduces transpiration (DAFF, 2010b).

Sorghum can be grown in a wide range of soils, including loams, deep sandy loams, cracking clays and low-potential shallow soils with the high clay content. The roots can reach a depth of up to 2 m and they grow laterally and downward. Sorghum can survive in soils that are not suitable for maize production, but grows poorly on sandy soils. Unlike other crops, sorghum can tolerate alkaline salts, but the optimum pH (KCL) range between 5 and 8.5 (du Plessis, 2008; DAFF, 2010b). The optimum clay content in soils ranges between 10 and 30 %. Short periods of waterlogging can be tolerated by sorghum in comparison to maize (du Plessis, 2008; DAFF, 2009). Table 2.4 summarises the optimum growth criteria of grain sorghum as gleaned from the available literature. The areas climatically suited to the optimum growth of grain sorghum are expected to be similar to that of sweet sorghum.

Table 2.4: Growth criteria for grain sorghum cultivation obtained from the literature

Source	**Annual rainfall (mm)**	**Seasonal rainfall (mm)**	**Temp $_{\text{Daily ave}}$ (^{0}C)**	**Monthly RH (%)**	**Soil depth (mm)**	**pH**	**Soil texture**
Jewitt *et al*. (2009a) Recommended		450-650	20-25 JAN > 21				
Smith (1994)	650-800	450-650 OPT	>10 OPT Germination > 25 OPT JAN > 21, JUL < 16 15-35		1 000-1 500		Light/ Medium textured
Smith (1998)	650-800	450-650	> 25 OPT JAN > 21 15-35		500-700 (light soils) 300-500 (heavier)		Light/ Medium textured
Smith (2006)	650-800	450-650	> 25 OPT JAN > 21 15-35		500-700 (light soils) 300-500 (heavier)		Light/ Medium textured
FAO (2006)	500-1 000 OPT 300-3 000 ABS	400-600 OPT 300-700 ABS	22-35 OPT 8-40		500-1 500	5.5-7.5	heavy, medium
Schulze and Maharaj (2007b)		300-1 200	25 OPT JAN > 21 15-35	< 60			
Additional literature							
du Plessis (2008)	>400 DRY >800 WET		27-30 OPT <21 SUB 7-10 (MIN)		250, <500 drier conditions	5.5-8.5	
DAFF (2009)	300-750		20-35 Germination 22-26 Flowering			5-8.5	wide range of soils
DAFF (2010b)	300-750		27-30 OPT 21 SUB 7-10 (MIN)		2 500	5.5-8.5	No sandy soils
Bassam (2010)	400-600		27-30 OPT 8-10(MIN)			5.0-8.0	
Schulze and Kunz (2010)	600	300-1 200	25 OPT JAN > 21 15-35	< 60			

*Note:*OPT – Optimum; SUB – Sub-optimum, ABS – Absolute; DRY – Ideal for drier regions; WET – Ideal for wetter regions; RIP – ideal for ripening; JAN– Month of January; JUL – Month of July MIN – monthly Minimum, MAX – monthly Maximum; Temp Daily ave – Temperature Daily Average; RH – Relative humidity; pH – Power of hydrogen.

Ergot is caused by the fungus and poses a serious threat to sorghum seed production worldwide. The stigmas and occasionally the ovaries are mainly infected by this pathogen. Ergot is promoted by hot and humid weather conditions which increase epidemics. The ideal conditions for ergot development are a daily temperature of around 19 °C, high RH and cloudy conditions during anthesis. In Figure 2.2, the trend line shows a reasonable correlation between ergot and minimum relative humidity. This figure shows that values above 40 % to 80 % are needed to trigger ergot outbreaks.

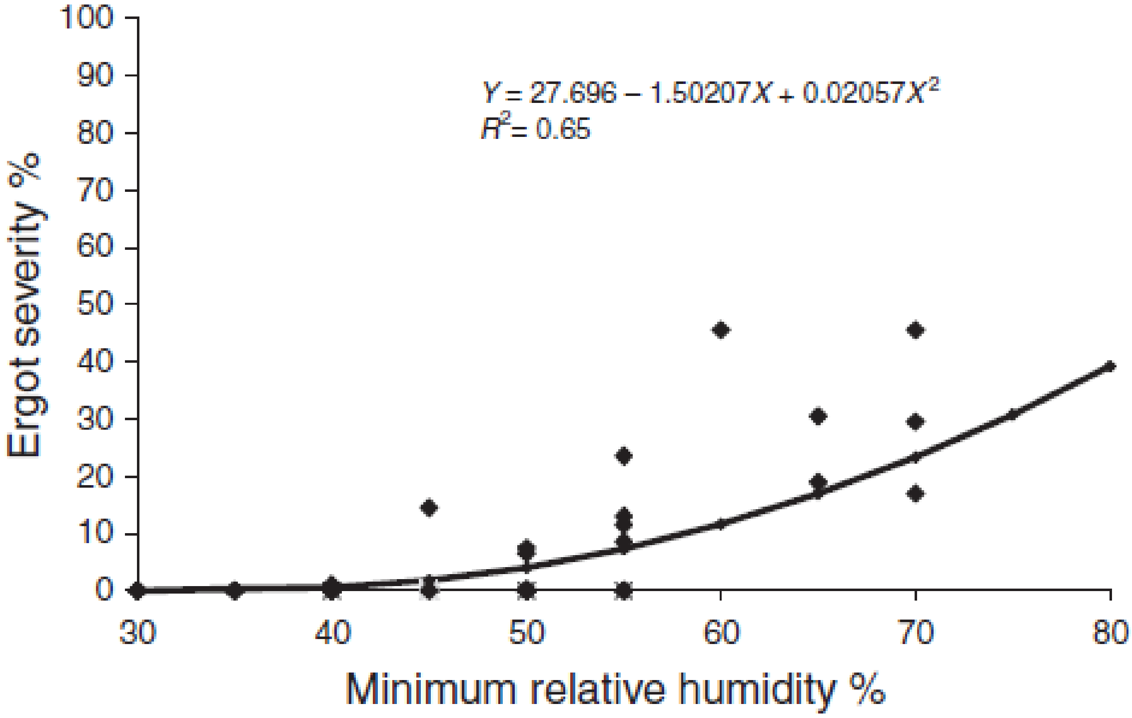


Figure 2.2: Effect of minimum relative humidity recorded 1–3 days after anthesis initiation on ergot severity observed in sorghum hybrids (Montes *et al.*, 2009)

2.3.2.3 Suitability for ethanol production

Large parts of South Africa are better suited to sorghum rather than maize because the crop is drought-resistant, which makes it more suitable crop for emerging farmers (DoE, 2012). As noted earlier in Section 2.4.2.1, grain sorghum farmers are expected to decrease planting and shift to maize because of its higher profitability (Mashabela, 2012). Biofuel production may provide an alternative market for grain sorghum, thus providing a potential boost in planted areas and grain production. Table 2.1 (*cf.* Section 2.3.3) highlights two processing plants that have selected grain sorghum as the preferred feedstock.

2.3.3 Sugarcane (*Saccharum officinarum* L.)

Bioethanol is produced from cane mainly in Brazil (OGTR, 2008). Sugarcane belongs to genus *Saccharum officinarum* L. of the *Poaceae* (grass) family (Duke, 1983). Sugarcane is a tall perennial monocotyledon crop, with stalks 3 – 5 m tall which are 2 – 3 cm thick. The crop has not adapted to survive freezing conditions and is dependent on abundant sunshine for healthy growth. It re-emerges when cut, thus enabling multiple harvests to be obtained from a single planting. For commercial sugar production, it is considered a long-term monoculture and can be grown on a large-, medium- and small-scale (Watson *et al.,* 2008). It is harvested between 9- to 24-month intervals, depending on the growing conditions and the variety planted (Tammisola, 2010). In addition, there are on-going investigations in South Africa into sugarcane varieties that are suitable for energy production (Jewitt *et al.,* 2009a).

2.3.3.1 Present distribution

Sugarcane originated in the South Pacific Islands and New Guinea (Duke, 1983). It is largely geographically distributed in the lower latitudinal areas found on either side of the Equator, with the majority being cultivated between 0° and 33° latitude (Watson *et al.*, 2008). Sugarcane is grown in 14 cane-producing areas is South Africa which extend from the Eastern Cape (Northern Pondoland) through the coastal belt of KwaZulu-Natal and the Midlands, to the Mpumalanga Province (DAFF, 2012). The current sugarcane mill areas are shown in Figure 2.3.

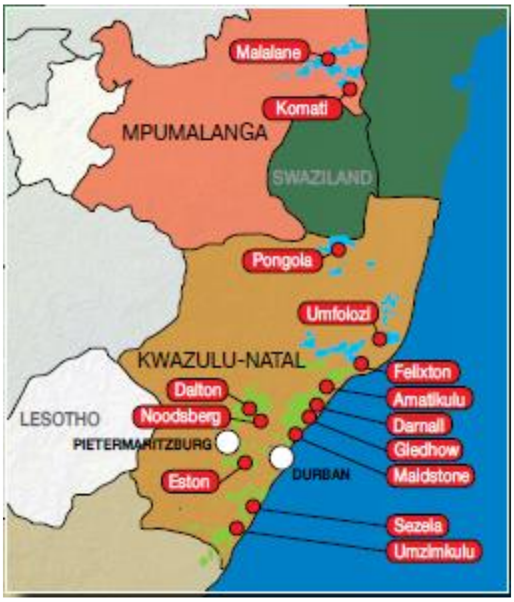


Figure 2.3: Mill locations for sugarcane (SASA, 2012)

2.3.3.2 Growth criteria

Sugarcane grows comparatively slowly during both the early and late stages of its growth cycle. The productivity of this crop is dependent on the two most important ecological requirements for efficient growth, namely adequate moisture and temperature (Tarimo and Takamura, 1998). Sufficient water distribution over the growing season is a major requirement to satisfy sugarcane production. To ensure that growing conditions are sufficiently moist, the minimum annual precipitation should be 850 mm. For optimum production, 1 300 mm of rainfall should fall per year, which is equivalent to approximately 110 mm per month (Smith, 1998). Sugarcane yield is directly proportional to the amount of water used under prevailing climatic conditions.

The optimum mean daily temperature for rooting and sprouting of the planted stem is > 20 °C. Stalk growth is optimum at 22 – 30 °C and 10 – 20 °C is necessary for ripening (to reduce vegetative growth and to increase sucrose levels) (Smith, 1998; Tammisola, 2010). Maximum temperatures below 20 °C and above 30 °C result in reduced growth for sugarcane (Smith, 1998).

Sugarcane has no special soil requirements and therefore does well under a range of soil conditions (Tammisola, 2010). The crop grows best in well-structured and aerated loams and sandy soils, with the optimum pH around 6.5, but the plant can survive in soils with a pH of

4.5 – 8.5 (Watson, 2008; Tammisola, 2010). Sugarcane prefers growing in 1 m deep soils, with plant available water content greater than 150 mm. However, roots may extend to a depth of up to 5 m. The crop prefers a water table below 1.5 – 2.0 m, since waterlogging can increase the susceptibility to root diseases and bacterial infections (Watson *et al.*, 2008). Accumulated annual sunshine duration greater than 1 200 hours is required to achieve optimum growth (Smith, 1998). Table 2.5 summarises the optimum growth criteria of sugarcane as gleaned from the available literature. The literature sources used by Jewitt *et al.* (2009a) in the scoping study are presented as well as additional literature from 2008 onwards.

Table 2.5: Growth criteria for sugarcane cultivation obtained from the literature

	Mean Annual Rainfall (mm)	**Monthly Total Rainfall (mm)**	**Temp $_{\text{Daily ave}}$ (^{0}C)**	**Monthly RH (%)**	**Soil depth (mm)**	**pH**	**Soil texture**
Jewitt *et al*. (2009a) Recommended	850 MIN 1 300 OPT	120	22-32 OPT 20-34 ABS	< 70			
Jewitt *et al*. (2009a) literature review							
Smith (1994)	850-1 500		22-30 OPT 10-20 RIP		> 1 000		
Smith (1998)	850-1 500		22-30 OPT 10-20 RIP		1 000		
Smith (2006)	850-1 500		22-30 OPT 10-20 RIP		1 000		
FAO (2006)	1 500-2 000 OPT 1 000-5 000 ABS				> 1 500	5-8	
Schulze *et al.* (2007a)	850 MIN 1 300 OPT	120	22-32 OPT 10-20 RIP	< 70 RIP	1 000		
Additional literature							
DAFF (2012)	1 100-1 500		20-35	80-85 OPT	1 000-1 500	6.0-7.7	Sandy loam
Watson *et al*. (2008)	1 200-1 500		26-34 OPT 10-20 RIP	< 70	> 400	4.5-8.5 SUB 5.5-7.5 OPT	Loam
Schulze and Kunz (2010)	850 MIN 1 300 OPT	120	22-32 OPT 10-20 RIP	< 70	1 000		
Bassam (2010)	1 500-1 800 DRY 2 500 WET						Heavy
Tammisola (2010)	1 500-2 500		22-30 OPT 10-20 RIP			6.5 OPT 5-8.5 SUB	
Muok *et al.* (2010)	1 000-1 800 SUB 1 200-1 800 OPT		20-30 OPT 12-38 SUB				Loam to clay

Note: MIN – Minimum; OPT – Optimum; SUB – Sub-optimum, ABS – Absolute; DRY – Ideal for drier regions; WET – Ideal for wetter regions; RIP – ideal for ripening; JUN – Month of June; JUL – Month of July; Temp Daily ave – Temperature Daily Average; RH – Relative humidity; pH – Power of hydrogen.

2.3.3.3 Suitability for ethanol production

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

2.4 Other Potential Feedstocks

Although soybean, grain sorghum and sugarcane are considered strategic biofuel feedstocks (DoE, 2014), Jewitt *et al*. (2009a) highlights other potential feedstocks. These include sugarbeet, sweet sorghum, cassava and maize for ethanol production, as well as sunflower, canola, Moringa and Jatropha for biodiesel production. Each of these feedstocks is discussed briefly in the sections that follow.

2.4.1 Sugarbeet (*Beta vulgaris*)

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

2.4.1.1 Present distribution

The crop originated from Asia and is now grown in many countries (FAO, 2007). The countries that produce large quantities of sugarbeet are the US, UK, Canada, Russia, Poland, Germany and Turkey (FAO, 2007). In 2011, production of sugarbeet was about 234 million tons from about 5.9 million ha (FAO, 2012b). The growing period of the crop is normally from 140 days up to 200 days. Sugarbeet can be grown in dry areas and is harvested in five to six months (Brandling, 2010). According to FAO (2012b), commercial yields range from 40 to 60 t.ha^{-1} of fresh beet with 15 % sugar content (after 160 to 200 days of growth). Sugar yield is determined by both tuber size and sugar concentration. In mild climate regions, sugarbeet is harvested and delivered to the factory for processing within a few days. In regions with cold winters, the harvest is delayed until freezing temperatures are anticipated (Campbell, 2002).

2.4.1.2 Growth criteria

Sugarbeet is grown in different climates, but mainly in temperate zones (Cattanach *et al.*, 1991). The optimum daily minimum temperature for seed germination is 7 to 10 °C, but seeds can also germinate at 5 °C. During vegetative growth, higher day temperatures are preferred. To obtain higher sugar yields, the hourly night temperature should range between 15 and 20 °C and the hourly day temperature should vary between 20 and 25 °C in the latter part of the growing period (FAO, 2012b). Daily maximum temperatures greater than 30 °C can greatly decrease sugar yields during this period (FAO, 2012b). The total water requirement for the growing season varies from 550 to 750 mm (FAO, 2007).

Sugarbeet can also be grown in the sub-tropics and is known for its high tolerance to saline and alkaline soils (FAO, 2012b). It is also grown as a summer crop in maritime, prairie and semi-continental climates. In addition, sugarbeet can be grown as a winter or summer crop in Mediterranean regions and some arid environments (Campbell, 2002). Diseases can significantly reduce the potential crop yield if precautionary measures are not taken. If disease occurs in the early stages of sugarbeet establishment and growth, it may destroy the entire crop.

2.4.2 Sweet sorghum (*Sorghum bicolor* L. Moench)

Sweet sorghum is an indigenous C_4 grass with high biomass yield potential (Schulze and Maharaj, 2007b). Sweet sorghum is not a photoperiod sensitive crop like sugarcane and reaches physiological maturity after three to five months (Watson *et al.*, 2008). It differs from grain sorghum because its grain yields are lower whereas its stalks have higher sugar content (Sakellariou-Makrantonaki *et al.*, 2007). Thus, sweet sorghum is characterised by higher sugar content in the stalk when compared to grain sorghum. Sucrose levels increase up to 70 % with maturity, with the balance in the form of glucose and fructose (Watson *et al.*, 2008).

Sweet sorghum has been reported as a crop with low input costs, based on its drought tolerance and C_4 photosynthetic pathway. The crop requires minimum fertiliser input, therefore it can be cultivated on marginal lands (Calvino and Messing, 2011).

2.4.2.1 Present distribution

The distribution is the same as that of sweet sorghum in section 2.3.2.1 above.

2.4.2.2 Growth criteria

The seasonal rainfall range deemed adequate for sweet sorghum is 300 – 1200 mm in the growing season. It can achieve optimum growth with 800 mm per annum and is normally irrigated where annual rainfall is less than 600 mm (Watson *et al.*, 2008). According to Watson *et al*. (2008), sweet sorghum requires a third of sugarcane's total water requirements. Sweet sorghum can be grown in the tropics and sub-tropics and as a summer crop in temperate regions, with the optimum daily mean temperature around 25 °C and a January mean greater than 21 °C (Smith, 1998). Maximum temperatures below 8 °C and above 40 °C result in minimum growth (Watson *et al.*, 2008). The crop requires a large difference in temperature between day and night after flowering, which benefits the accumulation of sugar in the stalk and nutrients in the seed. Mean daily temperatures below 20 °C increase the growing period by 10 to 20 days for every 0.5 °C drop in temperature (Smith, 1998).

Sweet sorghum is compatible with a variety of soils (e.g. from sandy soils to heavy clays), but prefers deep and well-drained light- to medium-textured soils. In comparison to sugarcane, the crop has the ability to tolerate a wide range of drainage conditions, including waterlogged soils (Watson *et al.*, 2008). According to Watson *et al*. (2008), sweet sorghum's deep rooting structure reduces the crop's susceptibility to short-term drought stress. In addition, the crop can tolerate a pH from 5.5 to 8.5, as well as some degree of salinity.

2.4.3 Cassava (*Manihot esculenta crantz*)

Cassava belongs to the *Euphorbiaceae* family and is extensively grown as an annual crop in the tropical and sub-tropical regions of Africa (Ogola and Mathews, 2011). According to Grace (1977), cassava is a shrubby perennial plant with a fibrous root system. The crop can grow up to a height of about five meters and has large palmate leaves. The feeder roots grow vertically from the stem and penetrate to a depth of 50 – 100 cm. Depending on the environment, the dominant photosynthetic pathway of cassava varies between C_3 and C_4, with plants in lower temperatures following a C_3 pathway and those in higher temperatures following a C_4 pathway (Oyetunde, 2007). There are several varieties of cassava found in Africa and they are grouped into bitter and sweet varieties. Bitter cassava is described as a crop that requires extensive processing before consumption (Oluwole *et al.*, 2007). Cassava has been chosen as a potential biofuel feedstock because of its drought tolerance, potential production on marginal land and low skill input requirements (Wicke, 2011). Cassava is planted from November to December in South Africa and is harvested from October (DAFF, 2010c).

2.4.3.1 Present distribution

Cassava originated in Mexico, Central America and North-eastern Brazil (FAO, 2012c). The crop was introduced in Africa during the sixteenth century (FAO, 2012c). Compared to cassava's long history in Africa, production in South Africa is insignificant. Currently, it is produced by smallholder famers in lowland areas of Mpumalanga and KwaZulu-Natal (Ogola and Mathews, 2011). Although it can be grown under harsh climatic and soil conditions, the crop is susceptible to a wide variety of pests and diseases.

2.4.3.2 Growth criteria

Cassava is a drought tolerant crop and can be grown under rainfed agriculture and grows where annual rainfall is between 500 mm and 3 500 mm (FAO, 2012c). The optimum annual rainfall for cassava in South Africa is between 1 000 and 1 500 mm (Allemann and Coertze, 1996). In general, cassava requires a warm humid climate and frost-free conditions, but can withstand short periods of frost (DAFF, 2010c). The absolute maximum temperature range for cassava is between 10 and 40 °C (i.e. growth stops below 10 °C and above 40 °C) (DAFF, 2010c). The optimum maximum temperature for growth of cassava in South Africa, as indicated by DAFF (2010c), ranges from 25 – 30 °C, but maximum temperatures above 29 °C can adversely affect crop growth (DAFF, 2010c).

A wide range of soils can be considered for growing cassava, including sandy loam and loam soils that are moist, deep, well drained and fertile (DAFF, 2010c). Cassava planted in South Africa usually has roots that vary from 10 – 100 cm in length and up to 15 mm in diameter. Cassava grows poorly in waterlogged soils, but it can grow in sandy and clay soils (FAO, 2012c; Allemann and Coertze, 1996). The texture of the soil should be friable enough to allow tuber development (FAO, 2012c).

2.4.4 Maize (*Zea mays* L.)

Maize belongs to the *Poaceae* family and is an annual C_4 grass and a staple food in South Africa (Duke 1983). The stem varies in height from less than 0.6 m to 5.0 m, depending on the genotype (du Plessis, 2003). The stem is divided into nodes and internodes, is cylindrical in shape and solid. The crop grows straight with 60 – 80 cm culms, produces broad leaf blades and the stems are filled with pith. The leaves alternate in opposite rows on the stem and are spirally arranged (du Plessis, 2003).

According to DAFF (2008), the crop is planted from: a) the beginning of October to the first of November in the cooler, eastern producing areas, b) the last week of October to mid-November for central regions and c) from the last two weeks of November to mid-December for the drier western areas of South Africa. The weeds should be controlled in the first six to eight weeks after planting (DAFF, 2008).

Even though yellow maize produces high protein animal feed, South Africa is currently a net importer of animal feed. However, about 30 % of yellow maize can be used in the biofuel industry, from which animal feed is produced as a by-product (Makenete *et al*., 2008). The surplus of yellow maize in South Africa has been recommended as a biofuel feedstock, although it is currently excluded by the National Biofuels Industrial Strategy (DME, 2007).

2.4.4.1 Present distribution

It is believed that maize originated in Mexico during prehistoric times (DAFF, 2008). The most likely countries of origin for maize include Africa, Asia, Mexico and America. Maize is currently distributed worldwide and is grown where warm summers prevail. Maize in South

Africa is produced in the provinces of Mpumalanga, Northern Cape, Free State, North-West, Gauteng and KwaZulu-Natal (DAFF, 2008).

2.4.4.2 Growth criteria

Maize requires an optimum precipitation of 450 – 600 mm during the growing season, but it can be produced under irrigation when precipitation is around 350 mm (NDA, 2005). According to DAFF (2008), water shortage is a limiting factor in the cultivation of maize. The crop is grown in temperate and tropical climates that are frost-free. Maize requires 120 – 140 frost-free days in order to prevent damage. According to NDA (2005), the crop requires a January mean temperature of between 19 and 24 °C and a daily mean temperature greater than 22 °C. Daily maximum temperatures above 32 °C reduce the grain yield of maize (NDA, 2005). Maize is considered to be a short-day plant or day-neutral, because its growth is very sensitive to radiation (FAO, 2012d).

Maize grows in a wide range of soils, but prefers naturally-deep and easily-tilled soils (DAFF, 2008). The crop is susceptible to waterlogging, so soils should be well-drained and well-aerated. The fertility should be well-maintained for the crop to grow continuously. Maize is also moderately sensitive to saline conditions (FAO, 2012d).

2.4.5 Sunflower (*Helianthus annuus* L.)

Sunflower belongs to the *Asteraceae* (*Compositeae*) family (Duke, 1983). Sunflowers are large, annual C_3 plants with a relatively short growing season (FAO, 2006). They have domesticated flowers with a single stalk (FAO, 2010). The leaves are ovate and stems are 0.7 to 3.5 m tall (Smith, 1998). Each individual flower is pollinated during the growing season. Flowers can follow the movement of the sun to prevent diseases and to reduce damage by birds (FAO, 2010; Smith, 1998). The flower head is usually between 7.62 and 15.24 cm in diameter, but it can be more than 30 cm. The flower head is made up of 1 000 to 2 000 individual flowers. Seed development usually takes place 30 days after the last flower was pollinated (FAO, 2010). Sunflowers require 11 days from planting to emergence, 33 days from emergence to head visibility of first anther, eight days from first anther to last anther and 30 days from last anther to maturity (DAFF, 2010d). Sunflower grains are used to manufacture sunflower oil and oilcake. In South Africa, sunflower is planted from November to January and harvested from March to June (DAFF, 2010d). The crop is ranked as the second largest biofuel feedstock in Europe for the production of biodiesel (Marvey, 2008).

2.4.5.1 Present distribution

Sunflower plants originated in western North America and were initially introduced to Europe in 1510 (FAO, 2010). According to Marvey (2008), sunflowers were originally cultivated in sub-tropical and temperate zones around the world. Worldwide, sunflower seed output is estimated around 25 million tons annually and sunflower oil is 10 million tons (from 80 % of sunflower seed production) (Marvey, 2008).

2.4.5.2 Growth criteria

Rainfall requirements for sunflowers range from 400 – 600 mm for about 120 days in their growing season (Smith, 1998). It performs well under drought conditions when compared to other crops such as maize and sorghum. It can survive water stress because of its branched tap root penetrating up to 2 m deep. The critical water stress period for the crop is 20 days before flowering and 20 days after flowering (DAFF, 2010d). Sunflowers can tolerate both low and high temperatures, but they are more tolerant to low temperatures. However, plants are sensitive to high soil temperatures during emergence, particularly those occurring in sandy soils in the North West and western Free State. The optimum maximum daily temperature for growing sunflowers is 18 – 25 °C and the sub-optimum is 13 – 30 °C (Smith, 1998). It thrives best at a mean monthly temperature around 22 °C and a mean January temperature > 19 °C (Smith, 1998). It requires a daily mean temperature (assumption) of at least 14 – 21 °C for satisfactory seed germination, although it can germinate at a temperature of 5 °C (DAFF, 2010d). Sunflowers require 1 500 heat units with a minimum of 7 °C and a maximum of 30°C to complete the growth cycle (Schulze and Maharaj, 2007c).

Sunflowers grow in a wide range of fertile soils, but prefer sandy loam to clay with a clay percentage in the range of 15 – 55 % and a pH value range of 6.0 – 7.5. However, the crop requires soils with good drainage. Under dryland conditions, soils with good water-holding capacities are required (DAFF, 2010d). Sunflowers have a short growing season that ranges from 90 to 120 days for early maturing varieties and up to 120 to 160 days for late maturing varieties (FAO, 2010).

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

Canola and rapeseed are closely related and belong to the *Brassicaceae* family (mustard). Canola is a genetically-altered and improved version of rapeseed. Canola and rapeseed varieties were developed from *Brassica napus* (Ehrensing, 2008). Canola was adopted in 1978 by the rapeseed industry, in order to introduce new varieties of rapeseed in Canada (Seetseng, 2008). Phyto Energy is interested in using canola as a biofuel feedstock (*cf*. Table 2.1 in Section 2.3.3). It is an annual, cruciferous herb with a taproot system. The plant produces tuber-like rutabagas below ground and exhibits rapid growth after establishment (DAFF, 2010e). Canola stem height varies from 75 to 175 cm, with primary and secondary branches. Flowering commences on the main stem from late spring to autumn and the seed develops in early summer to autumn (Duke, 1983). Canola should be planted from April to May and harvested from August to September (DAFF, 2010e). Canola is a dry winter crop, unlike soybean, sunflower and groundnut, which are summer crops. It is therefore suitable as a rotational and a complementary crop to the existing crops in South Africa (Marvey, 2009). Canola is important for both biodiesel and oilseed production (Singh *et al.*, 2008).

2.4.6.1 Present distribution

Brassica napus originated in the Mediterranean region and seed production started during the middle ages in Europe. Canola is now ranked as the second largest source (after soybean) of vegetable oil in the world. Worldwide, it has passed sunflower, peanut and cottonseed oil production during the past 20 years (Raymer, 2002). Canada, China and many western European countries are the main producers of canola. Due to fungus vulnerability, insect pests, bacteria and nematodes, canola distribution is limited to temperate and sub-temperate regions worldwide (Duke, 1983). Canola production in South Africa is relatively new, with only 500 tons produced in 1994, which increased to 44 200 tons in 2005. Canola is grown in the Western Cape as a winter crop (DAFF, 2010e).

2.4.6.2 Growth criteria

Canola requires an optimum rainfall of 400 – 500 mm in the growing season and requires 200 – 210 mm during the flowering stage. Rainfall of 300 mm is ideal for April to October to produce two tons per hectare (Scholtemeijer, 2009). The optimum mean annual temperature for canola production is between 5 and 27 °C (Duke, 1983). According to Seetseng (2008), temperature is an important factor in the growth and development of canola. According to Scholtemeijer (2009), temperatures are optimal at 20 – 25 °C for photosynthesis to take place, the monthly optimal temperature for germination are 15 – 20 °C. There is a direct, proportional relationship between increased temperature and earlier maturity of the crop (Seetseng, 2008). Canola grows in a wide variety of soils, but prefers clay loam soils that are not susceptible to wind erosion. The soil needs to be well-drained and medium-textured, to prevent waterlogging. The optimum soil temperature is 10 °C and the ideal soil pH is 5.5 – 7 (DAFF, 2010e).

2.4.7 Jatropha (*Jatropha curcas*)

The Jatropha genus belongs to the large family of *Euphorbiaceae* and represents about 170 known species (Kumar and Sharma, 2008). The tree has numerous vernacular names, such as *physic nut, purging nut* and *Barbados nut*. The crop normally flowers once a year, but it can flower throughout the year in humid regions (Blesgraaf, 2009).

Fruit capsules containing seeds dry prior to maturation, split into three sections to expose seeds and the capsule changes colour from green to yellow (Feto, 2011). Estimates of tree height range from 5 – 8 m, depending on the growing conditions and have a 30- to 50-year life expectancy. However, the trees are typically pruned to shrub height, to aid in seed collection without the use of ladders. The leaves are deciduous and are 6 – 35 cm broad and 6 – 40 cm long (Holl *et al.*, 2007). The plant exhibits little growth during the dry season and drops its leaves (Brittaine and Lutaladio, 2010). Jatropha is officially recognised as an invasive species in South Africa and therefore, is currently banned for use in biofuel production (DME, 2007). Jatropha starts producing seeds within 12 to 18 months and the maximum productivity level lasts for 4 to 5 years (Holl *et al*., 2007), although it can continue to produce for 40 to 50 years (Jeng, 2008). According to Holl *et al*. (2007), Jatropha oil is inedible and toxic for humans and animals, but has potential in biodiesel production. The main advantages attributed to Jatropha are that it can tolerate arid and marginal soils (Holl *et al*., 2007). Approximately 1 600 to 2 000 litres of oil can be produced from one hectare of a Jatropha crop (Poteet, 2006).

2.4.7.1 Present distribution

Although the Jatropha plant originated in the Caribbean, it is now found in many regions, including India, Africa, South-east Asia, Central and South America (Poteet, 2006). It is believed that Jatropha was distributed by the Portuguese seafarers and is now also found in the tropics and sub-tropics (Brittaine and Lutaladio, 2010). Jatropha is grown at the Ukulinga research farm (UKZN, Pietermaritzburg) and at the Owen Sithole College for research purposes (Holl *et al.*, 2007).

2.4.7.2 Optimum growth criteria

The optimum annual rainfall for Jatropha is 500 – 1200 mm, but it can survive with only 250 to 300 mm of annual rainfall. Higher rainfall can cause fungal attack and can restrict growth (Holl *et al.*, 2007). Jatropha trees can tolerate an annual temperature of 11.0 to 28.5 °C. However, the optimal annual temperature is 20 to 28 °C (FAO, 2006). The plant is not resistant to frost and therefore a daily minimum temperature of -1 °C is fatal to growth, especially during early growth. The Jatropha tree is also sensitive to day-length (Blesgraaf, 2009). Jatropha can survive in many different ecological conditions, such as high temperatures and varied pH (Blesgraaf, 2009). The cultivation limit of Jatropha is 30º N and 35º S and it grows in both tropical and sub-tropical regions.

The tree prefers aerated sandy and loamy soils that are deeper than 45 cm. Clay soils and soils with impaired drainage should be avoided because Jatropha is intolerant to waterlogging (FAO, 2013). The soil slope should be less than 30° (Blesgraaf, 2009) and the optimum pH range is between 6.0 and 8.0/8.5, although it can survive in alkaline soils (Brittaine and Lutaladio, 2010).

2.4.8 Moringa (*Moringa oleifera* Lam.)

Moringa belongs to the *Moringaceae* (Horseradish-tree) family. It is a single-genus family with 14 known species (Rashid *et al.*, 2008). The most frequently used common names are *Marrunggai, Malunggai, Kalamunggai, Katdes* and *Sajina.* Moringa branches freely, is fast-growing and is a softwood tree (Radovich, 2011). The tree is characterised by an umbrella-shaped canopy, it is perennial and usually branches in a disorganised manner. The short stems of Moringa can reach a height of 1.5 to 2 m before branching (Agyepong, 2009). The Moringa leaves are compound, with leaflets (20 to 70 cm long) opposite each other along the softwood stem. The seed pods can reach 20 to 60 cm in length and they are green in colour, hanging down from the branches. The seeds weigh 0.3 g each and have a round shape with seed hulls that are semi-permeable (Agyepong, 2009).

2.4.8.1 The present distribution

Moringa is a commercial crop cultivated mostly in India and Africa. Moringa is indigenous to the Indian sub-continent (Himalayan foothills), but is now distributed across the tropics and sub-tropics of the world. The plant will thrive in a tropical climate, can survive in less fertile soil and can grow in humid/hot dryland conditions (Moyo *et al.*, 2011). The plant is found mainly in areas of the South- and South-east Asia (Radovich, 2011). Moringa is grown at the Hatfield Research Farm (University of Pretoria, South Africa) for research purposes.

2.4.8.2 Growth criteria

The optimum annual rainfall for the Moringa tree ranges from 250 to 1 500 mm and it can also survive under irrigation (Palada and Chang, 2003). Moringa thrives in tropical and sub-tropical regions and requires a daily maximum temperature of 25 to 30 °C for optimum pod and leaf generation. Maximum temperatures below 20 °C negatively affect growth and the crop is tolerant of poor soils and drought conditions (Radovich, 2011). Moringa adapts to different soil types, but well-drained sandy or loamy soils with a neutral pH are most suitable. Moringa can tolerate clay if the saturation level is kept minimal. However, prolonged flooding and poor drainage cannot be tolerated by Moringa (Palada and Chang, 2003; Radovich, 2011).

3. MAPPING SUITABLE PRODUCTION AREAS

In the previous chapter, growth criteria were provided for each potential feedstock. These criteria mainly relate to rainfall (as an index of moisture supply) and temperature (which affects certain physiological growth stages). In the section that follows, an overview is provided for each site factor that affects plant growth. The two sections thereafter discuss various approaches to assess land availability with case studies presented as examples of previous work. The chapter ends with a summary of the literature review and briefly discusses the way forward.

3.1 Factors Affecting Plant Growth and Distribution

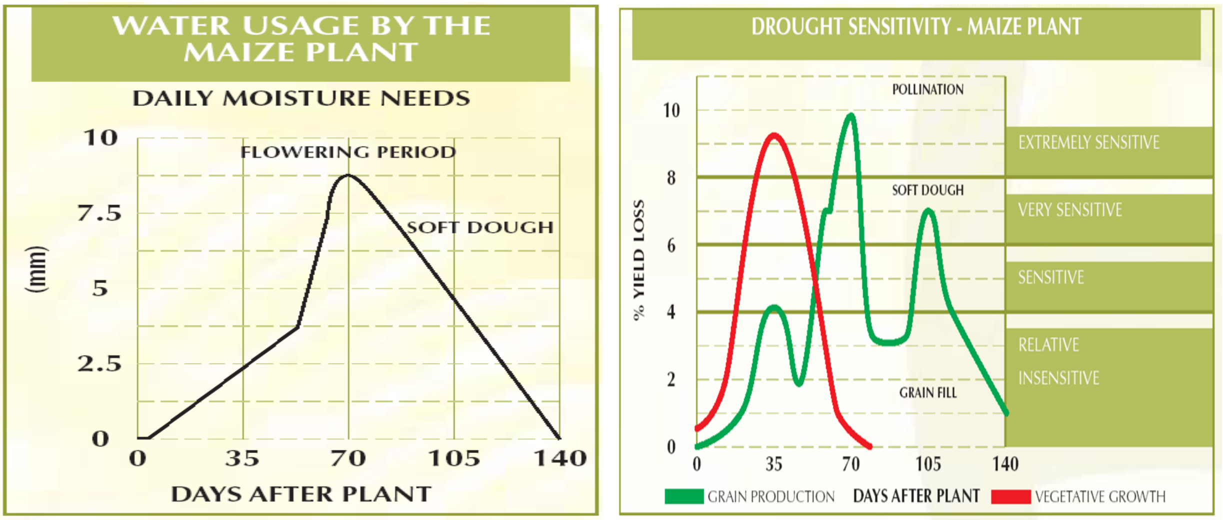
According to Manske (2001), plant growth factors are controlled by internal regulators (i.e. within the plant) that are modified by environmental conditions. Hence, the long-term climatic conditions across a region largely determine the vegetation types found in that region (Manske, 2001). The important climatic factors influencing plant growth are rainfall and temperature, since these abiotic site factors determine the moisture supply and demand (or water and energy availability) at a particular location. Similarly, relative humidity is a surrogate variable that can be used to assess biotic factors affecting planting growth, in particular disease risk.

3.1.1 Rainfall

Water usually accounts for 80 % of the weight of the herbaceous plant and it is a principal component of the plant cell. It is biochemically important as the principal component of physiological processes that occur within the plant (Manske, 2001). According to Manske (2001), water is essential for the maintenance of the rigidity of plant tissues. When water is limited, biological processes such as temperature control, nutrients and metabolite transport can be affected and these can impact plant growth and development (Manske, 2001). Seasonal crop water use, rainfall concentration index and the crop coefficient concept are discussed in the next three sub-sections.

3.1.1.1 Seasonal crop water use

The seasonal crop water use indicates in which months the majority of seasonal rainfall falls. This is important from a crop growth point of view, as most crops are sensitive to water stress during particular growth stages. According to Seckler (2003), most crops are sensitive to water stress at both the vegetative growth and fruit/grain development stages. For example, maize is most sensitive to water stress during pollination and requires more water during the flowering stage (Figure 3.1).



(a) **(b)**

Figure 3.1: (a) Water use by maize under well-watered conditions; (b) Sensitivity of maize to soil water stress (Pannar, 2003)

Figure 3.1b shows that maize is particularly sensitive to water stress at 35 days after planting (during the vegetative growth stage) and again at 70 days after planting (during the grain filling stage). A lack of rainfall during the crop’s peak water use period (i.e. approximately 70 days after planting) will result in a yield loss of up to 10 % (Figure 3.1b). This coincides with the peak water use at day 70 after planting as shown in Figure 3.1a. According to FAO (2013), the maize crop requires most water during mid-season stage (day 75 to day 120) as shown in Table 3.1. This approach is further explained in *cf.* Section 3.1.1.3, using soybean as an example feedstock. Soybean was chosen as the example feedstock because preliminary results were presented for soybean at the Soybean World Conference in February 2013. A number of indices have been developed which highlights the importance of rainfall distribution across the growing season and these are described next in more detail.

Table 3.1: Single crop coefficients (K_c) for each maize growth stage as suggested by FAO (FAO, 2013)

Growth stage	**Length of growth stage (days)**	K_c
Initial	15 – 30	0.30 – 0.50
Development	30 – 45	0.70 – 0.85
Mid-season	30 – 45	1.05 – 1.20
Late-season	10 – 30	0.80 – 0.90
At harvest		0.55 – 0.50

3.1.1.2 The rainfall concentration index

The rainfall concentration index, determined using Markham's (1970) methodology, calculates a value ranging from 0 to 100 %. An index of 100 % implies that all rainfall falls in a concentrated time period (e.g. one month). On the other hand, a concentration index of 0 % implies a similar rainfall amount in each month. Hence, lower values have been used to identify the all-year rainfall season along the southern Cape coastal areas (Schulze and Maharaj, 2007e). Hence, rainfall concentration describes the duration of the rainy season and varies spatially across southern Africa.

Schulze and Maharaj (2007d) calculated rainfall concentrations for each quaternary catchment, whereas Schulze and Kunz (2010) repeated the exercise at the quinary catchment scale. Both studies highlighted that the highest and lowest rainfall concentrations are found in the Limpopo and Western Cape provinces, respectively. Schulze and Maharaj (2007d) highlighted that plant growth is affected by the duration of the rainy season, i.e. whether the rainfall is concentrated over a short period of the year or spread over a longer period. The importance of seasonal rainfall distribution is highlighted by the concept of rainfall concentration.

3.1.1.3 The crop coefficient concept

In hydrology, the crop coefficient is used to estimate crop water use which varies with the crop's growth. The single crop coefficient (K_c) approach combines soil water evaporation and crop transpiration, whereas the basal crop coefficient (K_{cb}) describes plant transpiration only. The crop coefficient is calculated by dividing crop water use (transpiration and soil water evaporation) by the reference crop evaporation. Reference crop evaporation is calculated using solar radiation, air temperature, relative humidity and wind speed data using the Penman-Monteith equation given by Allen *et al*. (1998). Typical values for K_{cb} and K_c for soybean are provided in Table 3.2 and 3.3 respectively. The K_{cb} values indicate that transpiration peaks during the development and mid-season growth stages. However, K_c values show that total crop water use (i.e. evapotranspiration peaks during the mid-season growth stage).

Table 3.2: Basal crop coefficients (K_{cb}) derived from the SAPWAT3 database for each soybean growth stage (van Heerden, 2013)

Growth stage	**Length of growth stage (days)**	**K_{cb}**
Initial	30	0.10
Development	30	1.15
Mid-season	60	1.15
End-season	01	0.90

Table 3.3: Single crop coefficients (K_c) for each soybean growth stage as suggested by FAO (FAO, 2013)

Growth stage	**Length of growth stage (days)**	**K_c**
Initial	20 – 25	0.3 – 0.4
Development	25 – 35	0.7 – 0.8
Mid-season	45 – 65	1.0 – 1.2
Late-season	20 – 30	0.7 – 0.8
At harvest		0.4 – 0.5

The length of each growth stage in relation to soybean’s crop coefficient curve is shown in Figure 3.2. The rate at which the crop develops and the time to reach full canopy cover are affected by weather conditions, in particular mean daily air temperature. Therefore, the length of time between planting and full canopy cover varies with climate, latitude, elevation, planting date as well as cultivar (crop variety). Thereafter, the rate of further physiological development (flowering, seed development and ripening) is more dependent on plant genotype and less dependent on weather. Stress caused by high temperatures or lack of soil water can shorten the mid- and end-season growing periods (Allen *et al.*, 1998).

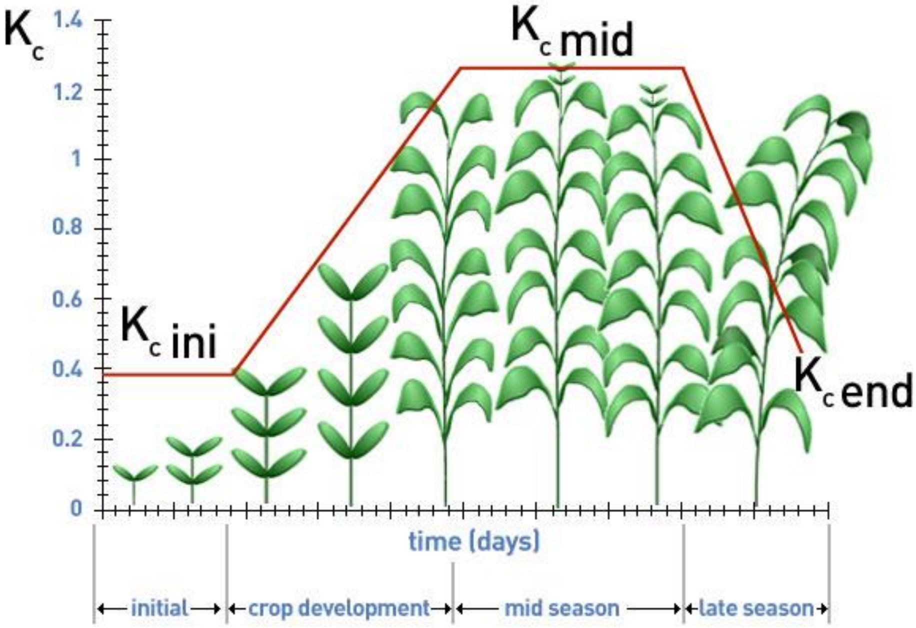


Figure 3.2: Generalised crop coefficient curve based on the single crop coefficient approach (Allen *et al*., 1998)

According to Allen *et al.* (1998), the initial crop coefficient value (K_c ini) varies with the frequency of wetting events during the initial growth period, i.e. K_c ini is large when the soil is wet from frequent rainfall or irrigation events and is low when the soil is dry.

3.1.2 Temperature

Temperature plays an important role in the daytime when plants synthesise carbohydrates via photosynthesis. Schulze (1997) pointed out that temperature is important for a crop at different development stages (e.g. at flowering). According to Smith (2006), photosynthesis increases from 5 °C to an optimum leaf temperature of 30 – 35 °C and then decreases. High maxima can have both a positive effect (e.g. strawberries) and a negative effect (e.g. maize) on plant growth (Schulze and Maharaj, 2007f). If temperatures are too high or too low, plant growth can be negatively affected, e.g. above 35 °C for maize flowering and below 8 °C for bananas (Smith, 2006). According to Schulze and Maharaj (2007f), mean temperature is used to distinguish between three broad thermal divisions of plants under natural vegetation conditions, namely:

(a) Mega-thermal plants (mean monthly temperatures above 20 °C are needed for at least four months of the year),
(b) Micro-thermal plants (mean monthly temperatures below 10 °C for more than eight months are required for growth) and
(c) Meso-thermal plants (plant physiology is adapted to the strong seasonal rhythms of mid-latitudes sites).

The variation of mean monthly temperatures influences the geographic range and the optimum growing areas for certain crop species, in particular for those with a lifecycle extending to one year or less (Schulze and Maharaj, 2007f). From the perspective of crop survival, the climatic distribution of a crop is mostly described by minimum temperature. Most sub-tropical crops may die at 5 °C and below, even if there is no frost. The term *hardiness* refers to a crop's tolerance to low temperatures and thus temperature is one of many factors controlling *hardiness* (Schulze and Maharaj, 2007f). Temperature is influenced by altitude according to adiabatic lapse rates as described by Schulze and Maharaj (2007f).

3.1.3 Relative humidity

High relative humidity (RH) can promote diseases in some crops, e.g. soybean (Smith, 2006), and can create favourable conditions for the growth of certain micro-organisms (Schulze *et al.,* 2007b). Extended high humidity (75-80 %) coupled with extended periods of cloudy weather during the growing season would favour soybean rust infection and eventual epidemics (Caldwell *et al.,* 2002). Humidity is defined as the content of water vapour present in the atmosphere which is measured as a vapour pressure or vapour density. According to Schulze *et al*. (2007b), relative humidity (RH) is defined for practical purposes as the ratio of actual (e_a) to saturated vapour pressure (e_s), expressed as a percentage:

$$\mathrm{RH} = \mathrm{e_a} / \mathrm{e_s} \cdot 100$$

RH generally varies considerably during the course of the day, despite (e_a) remaining relatively constant during the daytime. The reason is due to the curvilinear relationship between saturated vapour pressure and temperature as described by Teten's (1930) law. The maximum RH during a 24-hour period is typically experienced just before sunrise when temperatures are at a minimum. On the other hand, minimum RH is experienced during the hottest part of the day, which typically occurs between one to two hours after midday (or solar noon).

3.1.4 Soils and topography

Adequate soil conditions, including sufficient water and nutrient supply, are required for plant development and successful crop production (Pessarakli, 1994). In terms of plant growth and survival, the main purpose of the soil profile is to help anchor the plant, as well as to provide moisture in between rainfall and/or irrigation events and nutrients throughout the growing season (Pessarakli, 1994).

Topography is a static feature of the physical landscape, which is described by altitude *per se*. In addition, slope (i.e. the rate of change of altitude over distance) is also generally considered a static feature of the physical landscape. Altitude and slope exert a major influence on the macro-, meso- and micro-scale features of climate and also on hydrological and agricultural responses. For example, higher altitudes are generally associated with lower temperatures. Gentle slopes allow more time for water to percolate into the soil profile, whilst steeper slopes result in greater runoff (i.e. less percolation) and increased soil erosion (Schulze and Horan, 2007a).

According to Sys *et al*., (1991), "it is well established that steep slopes (%) poses more difficulties to cultivation than flat land". Steep slopes are subject to higher rates of water runoff and soil erosion (FAO-IIASA, 2007). This property of the landform plays an essential role especially when considering mechanical harvesting (Sys *et al*., 1991).

3.1.5 Land use

Built-up areas include cities, rural clusters, formal residential, informal residential, commercial, industrial and smallholdings (SANBI, 2013). Urban settlements are large and highly concentrated, occupying vast space and are therefore easier to detect using remote sensing than compared to scattered small settlements in rural areas. Major cities such as Cape

Town, Durban and Johannesburg were identified in a national land cover survey undertaken in 2000, whereas small towns such as Wartburg and Cato Ridge were not recognised. It is obvious that large urban areas are not suitable for feedstock cultivation.

The growth and development of the economy in South Africa is mainly controlled by the mining industry (Swart, 2003). The country still relies on the mining sector to generate wealth, which is translated to employment, infrastructure and the economy (Swart, 2003). Thus, mining remains one of the most important sectors of South Africa’s economy due to its provision of jobs, its contribution to the GDP and by sustaining international trade (Swart, 2003). For these reasons, areas currently zoned for mining are therefore considered unsuitable for feedstock production. Schoeman *et al*. (2013) stated that mining areas are not likely to be converted to urban or forestry, even after rehabilitation.

Legislation currently prohibits protected areas from undergoing land use changes to cultivation. Hence, such areas are also excluded for biofuel feedstock production. South Africa is the world’s twenty-fifth most biodiverse nation, containing a wealth of biodiversity within its borders (Reyers *et al*., 2001). The system of protected areas in South Africa is well developed, with 403 terrestrial protected areas covering a total of 332 745 ha (Reyers *et al*., 2001).

South Africa is a relatively dry country covered by bushveld and dry savannah woodlands. However, evergreen forests are found in the high rainfall areas of the southern and eastern coastlines and also in the mountainous regions of the country (DAFF, 2011). The forestry industry has many benefits including ecotourism, timber production, valued biodiversity and also non-timber products, e.g. medicine (DAFF, 2011). Owing to the value of this industry to the country’s economy, existing forest plantations should not be deemed suitable for biofuel production.

The environmental mandate is expressed by three distinct pieces of legislation. These acts are: the Conservation of Agricultural Resources Act (CARA; No. 43 of 1983), the Environment Conservation Act (ECA; No. 73 of 1989) and the National Environmental Management Act (NEMA; No. 107 of 1998). The main objective of CARA is to, *inter alia*, conserve agricultural land, combat erosion and protect natural vegetation. The objective of ECA is to provide protection and controlled utilisation of environmental resources (de Villiers, 2007).

NEMA’s primary objective is to provide co-operative governance on matters affecting the environment. In order to cultivate virgin (i.e. natural) land, the user must be given written permission by the Executive Officer. Virgin land is defined as land that has at no time during the previous ten years been cultivated and is therefore referred to as undeveloped (Niemand, 2011). Owing to the objectives of CARA, natural areas are also considered as unsuitable for biofuel production.

3.2 Overview of Land Suitability Assessment

3.2.1 Land suitability assessment

The definition of land suitability, as proposed by the Food and Agriculture Organisation of the United Nations (FAO) is “the fitness of a given type of land for a defined use”. Land suitability evaluation has no standard criteria or single universal model that can be applied globally. However, the FAO have published guidelines for land evaluation (FAO, 1983), which describe the sequence of activities and procedures typically used in land suitability assessments.

According to the FAO (1976), the relationship between inputs and benefits mainly determines the differences in the degree of suitability. According to the FAO (1976), land can be classified as suitable (S) or unsuitable (N) for a particular use. Suitable means sustained use is expected to give positive results. Similarly, not suitable means land qualities that appear inappropriate for a particular use. The degree of suitability is reflected by land suitability classes. The FAO recommends three suitability classes and two non-suitable classes with the following denominations:

(a) Class S1: Highly suitable;
(b) Class S2: Moderately suitable;
(c) Class S3: Marginally suitable;
(d) Class N1: Currently not suitable; and
(e) Class N2: Permanently not suitable

The classes are numbered in a sequence, where the highest number represents the least suitable and the lowest number represents the most suitable. The land can be classified as not suitable based on, for example, climate constraints (e.g. rainfall and temperature), technical considerations (e.g. soil depth and slope), environmental considerations (e.g. potential damage to biodiversity) or economic considerations (e.g. revenues).

3.2.2 Climatic constraints

As noted above, land can be classified as suitable (S) or not suitable (N) for a particular use (FAO, 1976). In the context of this study, land suitability refers to how appropriate the land parcel is for biofuel feedstock production. An approach developed by Ramirez-Villegas *et al*. (2013) could be used to identify the climatic thresholds to distinguish between suitable (optimum and marginal) *vs*. unsuitable growing areas as depicted in Figure 3.3. For example, not suitable conditions (white areas) in Figure 3.3 relate to FAO class N1. Similarly, optimum conditions (light grey) relate to FAO class S1 and marginal conditions (dark grey) are classified as S3. Figure 3.3 could be adapted to include sub-optimum conditions, which would relate to FAO class S2. Climatic constraints should also consider relative humidity as a surrogate for disease incidence.

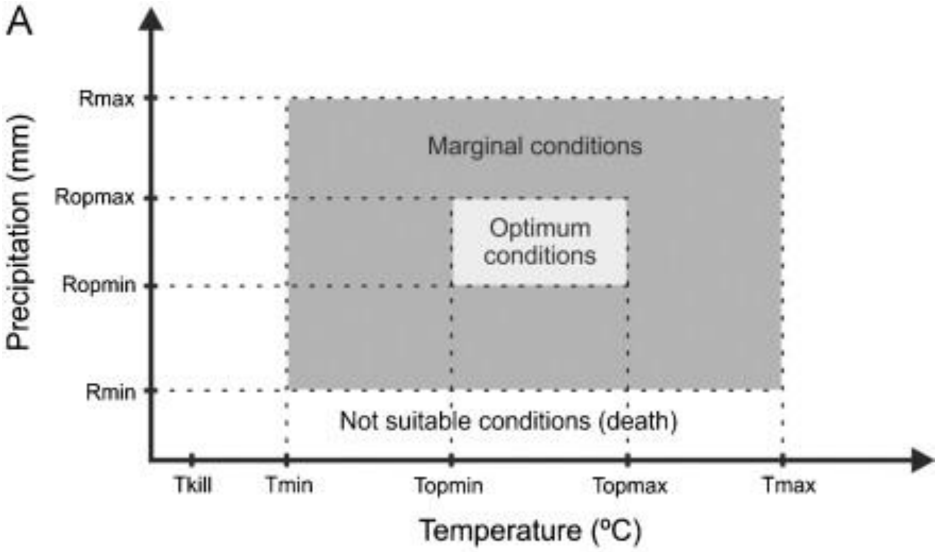


Figure 3.3: Crop suitability based on rainfall and temperature thresholds for growth (Ramirez-Villegas *et al*., 2013)

3.2.3 Technical constraints

The importance of soil depth and slope on plant growth and plant distribution was discussed earlier in Section 3.1.4. McRae and Burnham (1981) identified topographical features such as slope, aspect and elevation as important for consideration in land suitability evaluations. The assessment of topographic attributes is important since they may hinder mechanised used operation in the cultivation of feedstocks. According to Camp (1995; cited by Sibanda, 2008), the evaluation and examination of soil factors (e.g. soil depth and slope) should be an important criteria in land evaluation studies. However, a lack of spatial data at an appropriate scale is often cited as the reason why soils are excluded in assessments of land suitability (Camp 1995; cited by Sibanda, 2008).

3.2.4 Environmental considerations

The sustainability of biofuel feedstock production is of particular concern worldwide as land use change affects sustainability, with certain land use changes considered undesirable (e.g. conversion of forest peat lands to palm oil cultivation in Malaysia) (Schrier-Uijl, 2013). This highlights why current land use should be considered when assessing areas deemed suitable for feedstock cultivation as highlighted previously in Section 3.1.5.

3.2.5 Combining individual suitability ratings

The FAO’s Land Evaluation Guidelines for Dryland Agriculture (FAO, 1983) recommend four methods to combine individual suitability ratings as follows:

(a) Subjective combination: defines overall suitability, based on an understanding of the interaction between different land qualities;
(b) Limiting combination: overall suitability is defined mostly by limitations in one land quality;
(c) Arithmetic procedures: overall suitability is obtained by multiplying or adding values assigned to each suitability class; and
(d) Modelling method: uses models to predict crop yields, based on the relationship between crop requirements and land qualities.

For example, a study conducted by Holl *et al*. (2007) used two methods (namely (b) and (c) above) to assess areas suited to Jatropha. This case study is discussed further in Section 3.3.1, together with three other GIS based studies to assess land deemed suitable for biofuel feedstock production.

3.3 GIS-based Case Studies

A Geographic Information System (GIS) is defined as a tool for capturing, storing, retrieving, manipulating, analysing and displaying spatial data (Malczewski, 2004). It is typically made up of five components *viz*. computer hardware, computer software, spatial data, personnel and procedures. A GIS is a useful tool in “matching” land characteristics of a given area with the site requirements of a particular crop.

The use of GIS in land suitability assessments is common and helps to determine the availability of land resources in a given area, to that required by a particular crop (land use). This section reviews four previous studies that utilised a GIS approach, *viz.* a) potential of *Jatropha curcas* production in South Africa b) physical potential of bioethanol processing plants in Kenya c) the biofuel scoping study and d) bioenergy production in semi-arid and arid areas of sub-Saharan Africa.

3.3.1 Potential of *Jatropha curcas* production in South Africa

The aim of the study by Holl *et al.,* (2007) was to gain an understanding of the biophysical requirements and water resource impacts associated with Jatropha cultivation. A three-phase approach was followed in the methodology, namely:

(a) Cut-off limits were used to map areas where *J. curcas* will not grow under dry land conditions;
(b) A weighted modelling approach involving climate and other data was then used to produce yield estimates finally; and
(c) Finally a more formal equation-driven analysis was undertaken to produce estimates of potential yield (Holl *et al.,* 2007)

Only the first phase is described next, owing to its relevance to this study. The biophysical constraints for growing Jatropha were sourced from a literature review as well as expert opinions. Biophysical parameters included: rainfall (mean annual in mm), temperature (mean annual in °C), soil fertility (ranked value), slope angle (°), frost duration (days), number of days with heavy frost (days) and altitude (m) (Holl *et al.,* 2007). The relevant spatial information to perform the analysis was obtained from the South African Atlas of Agrohydrology and Climatology (Schulze, 1997).

The above criteria were reclassified into specific index categories which were then used to perform the analysis with the following weightings:

(a) Rainfall considered the main driver (weighting 40 %);
(b) Temperature considered the secondary driver (weighting 35 %);
(c) Soil fertility considered to have a slight impact (weighting 10 %);
(d) Combined frost (weighting 5 %);
(e) Slope (weighting 5 %); and
(f) Altitude (weighting 5 %) (Holl *et al.*, 2007).

Figure 3.4 was produced using the threshold values for each constraint, thus eliminating areas where it is not possible to grow *J. curcas*. The majority of the country's interior is not suited to Jatropha due mainly to temperature and frost constraints. Similarly, the western regions are not suitable due to low rainfall (Holl *et al.*, 2007).

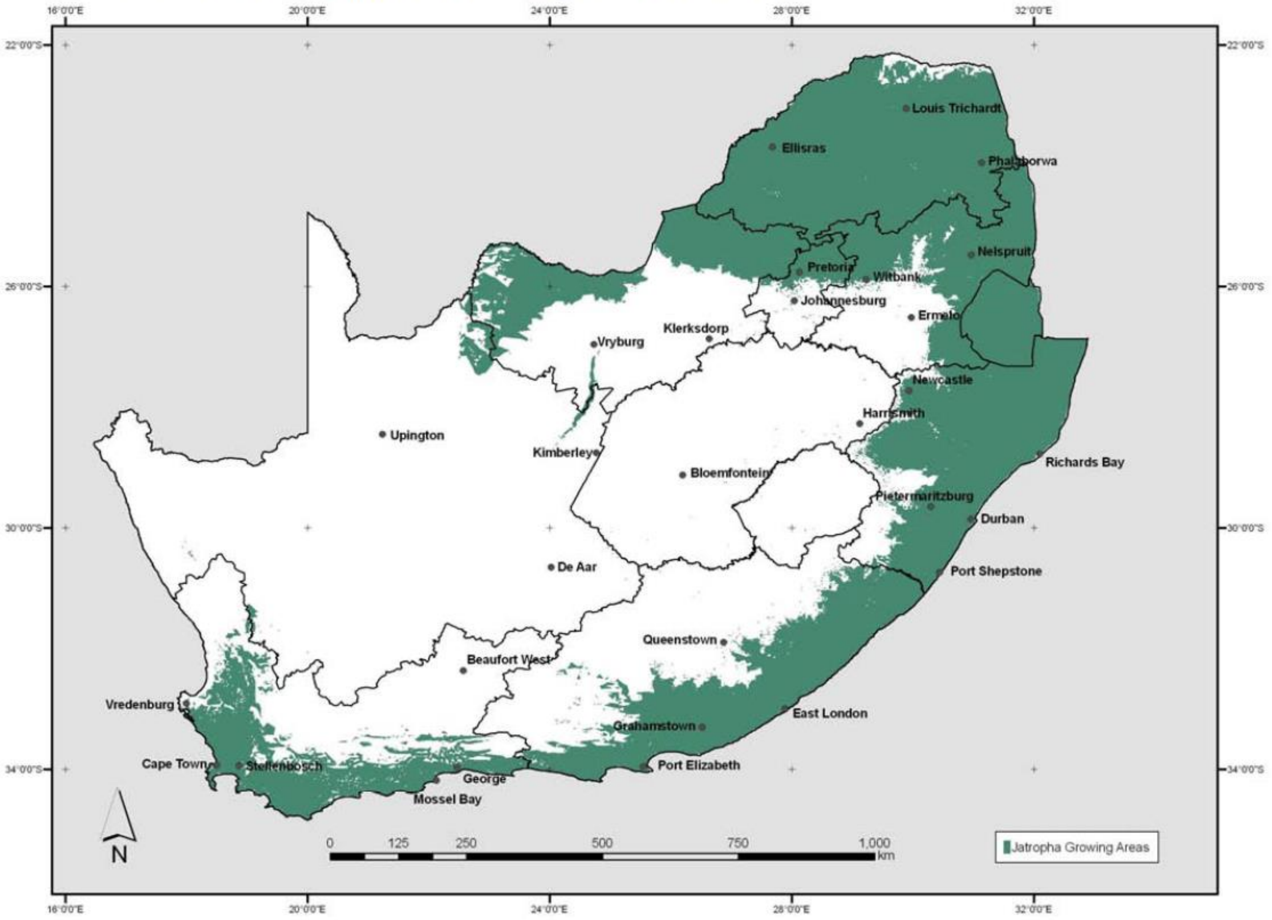


Figure 3.4: *Jatropha curcas*: areas where it can be successfully planted in South Africa

3.3.2 Physical potential of bioethanol processing plants in Kenya

According to Koikai (2008), land suitability evaluation involves "calculating optimal site locations by identifying possible influential factors, creating new datasets from existing data, reclassifying data to identify areas with high suitability and finally, aggregating these data into one logical result of optimal suitability". In essence, Koikai (2008) identified regions with high maize productivity potential in the Nyanza Province (Kenya), where potential bioethanol processing plants could be located.

Table 3.4: Bioethanol plant site selection suitability criteria and ranking values (after Koikai, 2008).

Criteria	Ranking			Weighting	
	High suitability	Medium suitability	Low suitability	Assigned influence of importance	Decimal weighting
	3	2	1		
Major Roads	< 0.5 mi	0.5-1 mi	> 1 mi	3	0.176
Railway	< 1 mi	1.0-3 mi	> 3 mi	2	0.118
Towns	< 1 mi	1.0-3 mi	> 3 mi	3	0.176
Powerlines	< 0.5 mi	0.5-1 mi	> 1 mi	3	0.176
Maize Fields	< 1 mi	1.0-3 mi	> 3 mi	3	0.176
Rivers	< 1 mi	1.0-3 mi	> 1 mi	2	0.118
Airports	< 1 mi	1.0-5 mi	> 5 mi	1	0.059
Total				17	1.000

A site was deemed highly suitable for a bioethanol processing plant if it was located in close proximity (< 0.5 mile) of a major road and powerline (Table 3.4). The location should be within 1 mile of other important infrastructure, e.g. railway, town and airports (Koikai, 2008).

3.3.3 The biofuels scoping study for South Africa

The scoping study on the water use of crops/trees for biofuels in South Africa (Jewitt *et al.*, 2009a) identified the potential growing areas of selected biofuel feedstocks. Optimum growing areas were mapped using climatic requirements for growth that were gleaned from the literature. Soil parameters such as soil depth, drainage and texture were not included in the study. The procedure mainly took into consideration, monthly rainfall and temperature values, as well as the typical planting date and growing season length for perennial feedstocks (Jewitt *et al.*, 2009a).

A commercial GIS software package was used to map climatically optimum growth areas (Jewitt *et al.*, 2009a). Suitable and unsuitable areas were the only two classes considered for mapping purposes. Mean annual rainfall (MAP), monthly rainfall totals (MRT), mean annual temperature (MAT), monthly means of daily average temperature (MMT) as well as daily maximum (T_{MAX}) and minimum temperatures (T_{MIN}) were the climatic attributes that were integrated using GIS (Table 3.5).

Table 3.5: Climatic thresholds for optimum growth of potential biofuel crops derived from available literature (Jewitt *et al.*, 2009a)

Feed stock	**MAP (mm)**	**MRT (mm)**	**MAT (°C)**	**MMT (°C)**	**T_{MIN} (°C)**	**T_{MAX} (°C)**	**Planting date**	**Growth days**
Canola	500-1 000	-	-	-	>5	<25	01 Jun	140
Cassava	>1 000	-	20-29	-	-	-	-	-
Castor	>600	-	-	-	>15	-	01 Oct	180
Jatropha	500-1 500		11-28	-	Frost free areas		-	-
Sorghum	-	450-650	-	20-35 (T_{JAN}>21)	-	-	01 Nov	115
Soybean	-	550-700	-	20-30	-	-	01 Nov	150
Sugarbeet	550-750	-	15-25	-	>-1	-	01 Aug	200
Sugarcane	850-1 500	-	>18	-	T_{JUN}>5 T_{JUL}>5	-	-	-
Sunflower	-	400-600	-	18-25 (T_{JAN}>19)	-	-	01 Dec	125

Note: MAP – mean annual precipitation; MRT – monthly rainfall totals over growing season; MAT – mean annual temperature; MMT – monthly means of daily average air temperature over growing season; T_{MIN} – daily minimum air temperature over growing season; T_{MAX} – daily maximum air temperature over growing season.

Areas climatically suited to the optimum growth of selected feedstocks are highlighted in dark green in Figure 3.5 to 3.7 (Jewitt *et al*., 2009a). For Figure 3.5, the mapping criteria used for soybean were based on a seasonal rainfall of 550 – 700 mm and monthly means of daily average temperature of 20 – 30 °C. Since the planting date was assumed to be 1st November and the growing season 150 days long, monthly rainfall totals were accumulated from November to March (inclusive of start and end months). Similarly, the optimum temperature range was applied to each of the five months. A similar approach was used to produce the sweet sorghum and sugarcane maps. The spatial climate information used in the scoping study was obtained from the South African Atlas of Climatology and Agrohydrology by Schulze (2007).

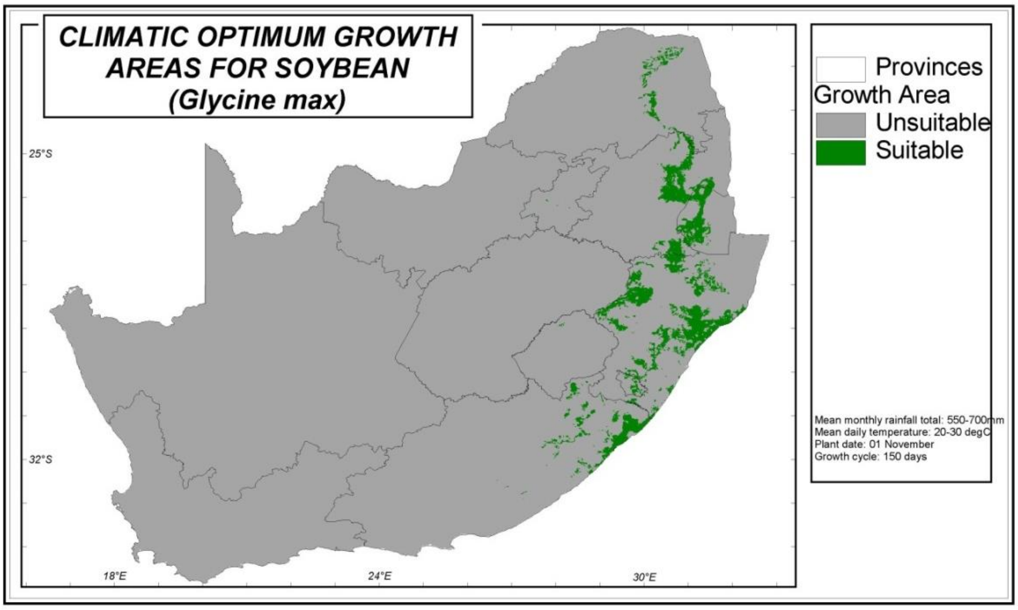


Figure 3.5: Potential growing areas of soybean in southern Africa (Jewitt *et al*., 2009a)

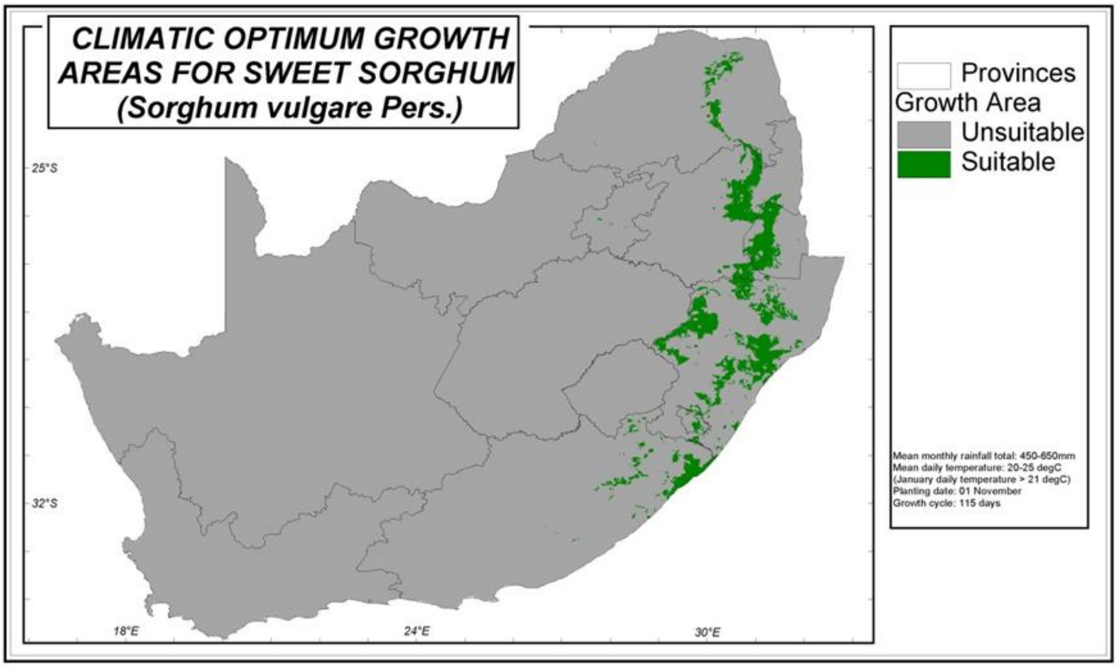


Figure 3.6: Potential growing areas of sweet sorghum in southern Africa (Jewitt *et al*., 2009a)

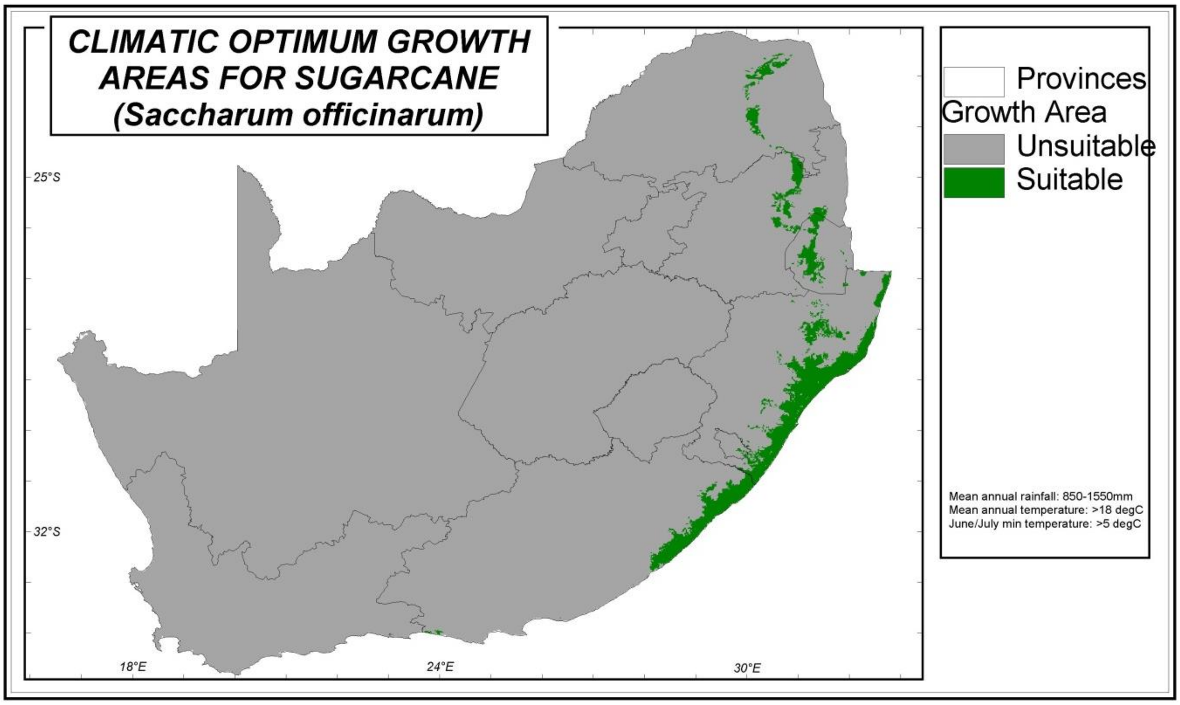


Figure 3.7: Potential growing areas of sugarcane in southern Africa (Jewitt *et al*., 2009a)

The approach adopted in the scoping study was relatively simple, since it only considered the climate and ignored other important edaphic, topographic and biotic growth constraints. The scoping study recommended that these additional factors be included in future studies and that further investigation is also required to differentiate between optimal and marginal land for crop production. This is important since crops grown in optimal areas are likely to use more water than those grown in marginal areas. In addition, the scoping study did not consider current land use or future land use needs. For example, the land required for biofuel feedstock cultivation may compete with additional land required to meet the future needs (e.g. food and housing) of an expanding population. Hence, the maps tend to over-estimate the area of land realistically available for feedstock growth. An example of a study which considered current land use is given next.

3.3.4 Bioenergy production in semi-arid and arid areas in sub-Saharan Africa

A GIS approach was used by Wicke (2011) to assess the current bioenergy production potential of semi-arid and arid regions in sub-Saharan Africa. The feedstocks considered in the study were cassava (ethanol), Jatropha (biodiesel) and fuelwood (heating). Although the study considered various countries, the methodology is expanded further using Tanzania as the example.

Unsuitable areas, including high biodiversity areas (e.g. protected areas, biodiversity hotspots, forests and wetlands), agricultural land for food production (including pastureland) and other unsuitable land uses (e.g. cities, bare rock deserts and water bodies) were “filtered” out using GIS software (Wicke, 2011). Figure 3.8 highlights the unsuitable areas for bioenergy production based on current land use in Tanzania. This study found that the land suitable for bioenergy production was limited mostly by agricultural land use, but also by biodiversity protection and steep slopes (Wicke, 2011).

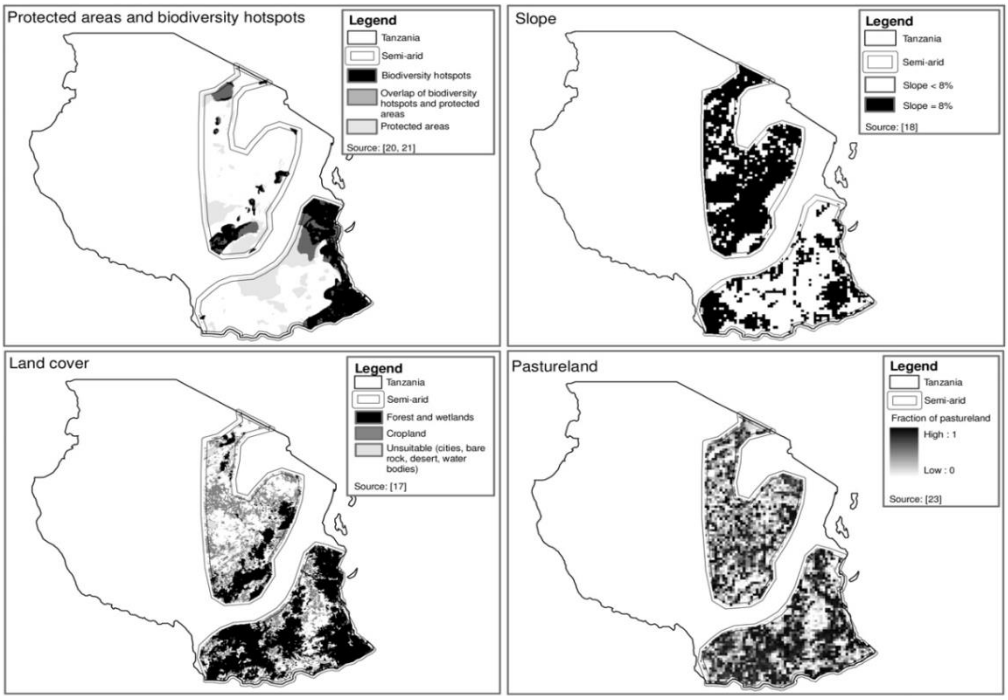


Figure 3.8: Maps of protected areas and biodiversity hotspots, slope, land cover and pastureland in Tanzania in 2000 (Wicke, 2011)

Although current land use was considered, the authors highlighted that it is also important to recognise that future demand for food and feed production may require additional land (due to population growth and dietary changes). This may reduce the availability of land for bioenergy production, assuming that bioenergy should not compete with food production. Therefore, the integration of food, feed and energy production through intercropping, rotational woodlots or hedgerows could minimise the competition for land and the negative impacts associated with land use change (Wicke, 2011).

3.3.5 Summary and the way forward

To re-cap, the background, present distribution and growth requirements of selected biofuel feedstocks were outlined and discussed. The factors affecting plant growth and the justification of their use were also outlined. An overview of land suitability assessment was also provided, together with numerous case studies which identified areas suitable for feedstock production. The next chapter details the approach adopted in this study to assess the potential to grow soybean, grain sorghum and sugarcane in South Africa. The methodology is considered novel and represents a combination of techniques described in the four case studies presented in Section 3.3.

4. METHODOLOGY

This chapter describes the methodology used in this study to map areas optimally and sub-optimally suited to biofuel feedstock production. The approach considers climatic constraints to feedstock growth, but also takes into account other important constraints such as relative humidity, soils and topography. In addition, present land cover and land use information is used to filter out areas considered inappropriate for feedstock cultivation.

Data sources which describe the spatial (and temporal) variation in these site factors are discussed. The growth criteria for each selected feedstock were synthesised from the literature review. Finally, the technique that was developed as well as the software tools used to evaluate the suitability of land for feedstock cultivation are also discussed. As noted in previous chapters, the approach could not be applied to all potential biofuel feedstocks listed in Section 2.5, due mainly to time constraints.

4.1 Data Sources

In order to derive land suitability maps for biofuel feedstock production, five important spatial datasets were collected from different sources. These include monthly rainfall totals, monthly means of daily temperature and relative humidity, as well as soil depth and slope. These data were sourced mostly from the Atlas of Agrohydrology and Climatology (Schulze, 2007) via the Centre for Water Resources Research (CWRR).

4.1.1 Rainfall

In this study, gridded datasets showing the spatial variation in monthly rainfall totals were used to derive seasonal rainfall (i.e. monthly rainfall accumulated over the growing season). It is important to note that mean annual rainfall was not used as an index of moisture supply for plant growth. In South Africa, two projects have provided spatial estimates of rainfall that were derived from rain gauge (i.e. point) measurements. Both projects were funded by the Water Research Commission (WRC). The first project was entitled "*Mapping of Mean Annual Precipitation and Other Rainfall Statistics over Southern Africa*" (Dent *et al.*, 1989), which was superseded by the second project in 2004. The latter project was entitled

"*Development of a Raster Database of Annual, Monthly and Daily Rainfall for Southern Africa*" and the report was finalised in December 2004 (Lynch, 2004).

The Lynch (2004) study developed rainfall databases containing daily and monthly data collected from rainfall recording stations located in the South African Development Community (SADC) region. The SADC region includes South Africa, Namibia, Zimbabwe and Mozambique. Daily data were summed to produce point monthly rainfall totals. Spatial estimates of monthly and annual rainfall were derived from these points using a spatial interpolation technique. The data are raster based where each grid cell is approximately 1.6 by 1.8 km in size. Various in-filling algorithms were used to replace missing data, thus creating a continuous daily rainfall dataset. Figure 4.1 and 4.2 represent the rainfall totals in January and July respectively that were averaged over the entire record length (Lynch, 2004).

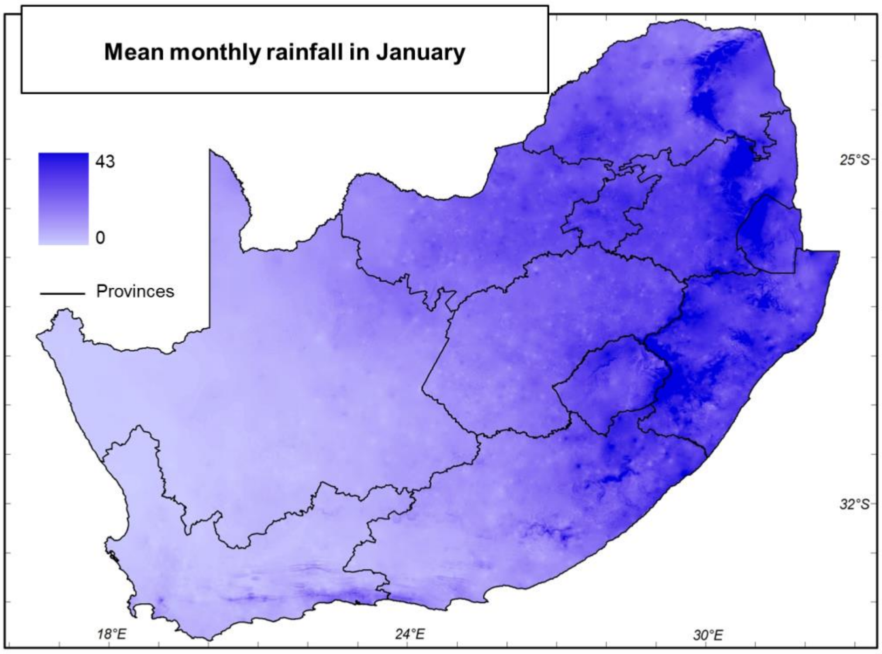


Figure 4.1: January mean monthly rainfall (mm) in southern Africa (Source: Lynch, 2004)

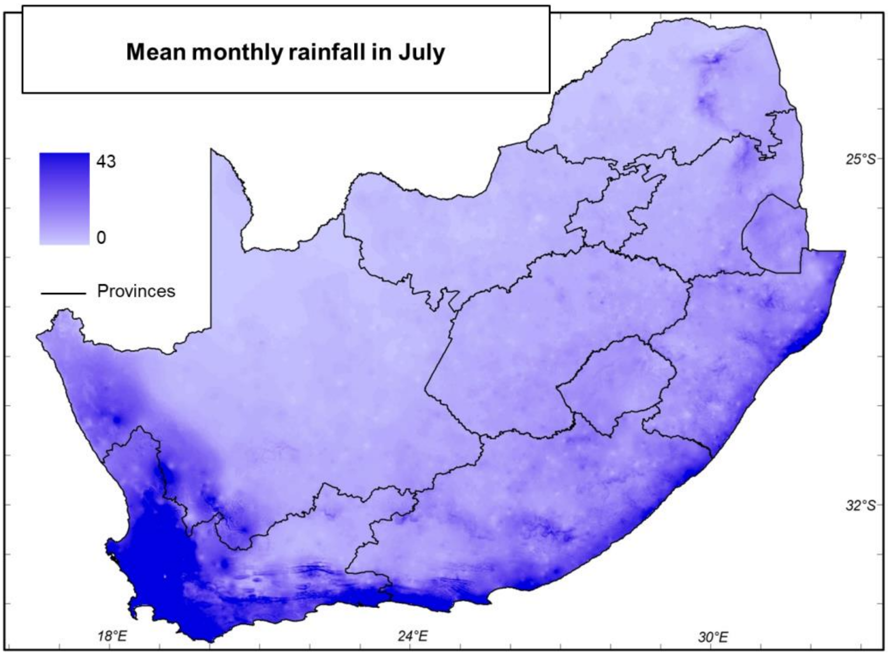


Figure 4.2: July mean monthly rainfall (mm) in southern Africa (Source: Lynch, 2004)

4.1.2 Temperature

Schulze and Maharaj (2007f) developed an extensive database of estimated daily minimum and maximum temperatures, derived for each one minute by one minute (i.e. 1.6 km × 1.8 km) grid cell across southern Africa. Hence, a total of 429 700 daily time series exist, which were estimated from over 970 temperature recording stations. The observed temperature data were quality controlled, with missing values in-filled to produce 51 years (1950-2000) of continuous daily records. Point estimates of daily temperature were derived, using regionally and seasonally determined lapse rates and other physically appropriate spatial interpolation techniques (Schulze and Maharaj, 2007f).

In this study, gridded datasets showing the spatial variation in monthly maximum, minimum and average temperatures were used as an index of moisture demand for plant growth. Figure 4.3 and 4.4 represent the spatial variation in monthly means of daily temperature in January and July, respectively.

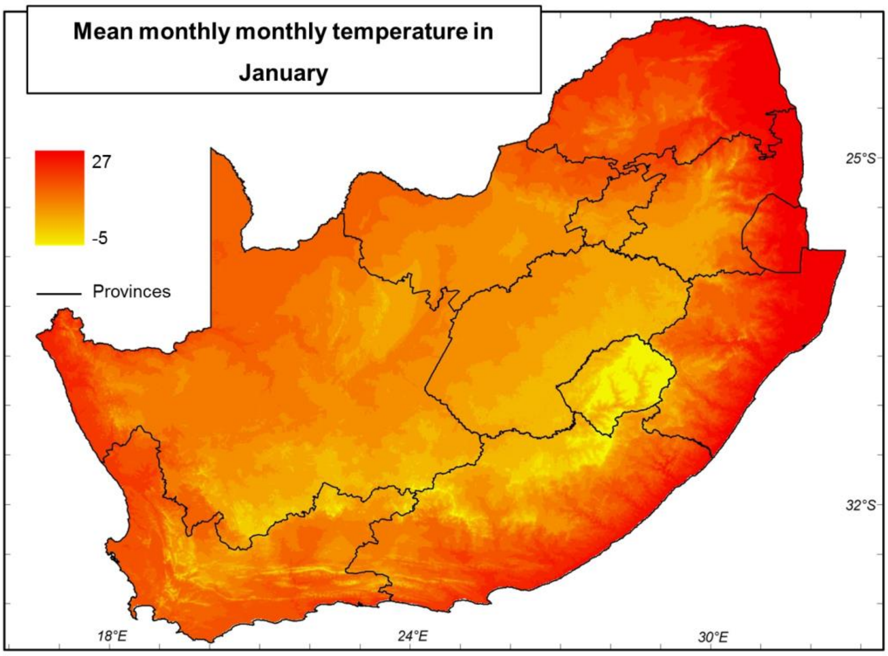


Figure 4.3: January monthly means of daily average temperature (°C) in southern Africa (Source: Schulze and Maharaj, 2007f)

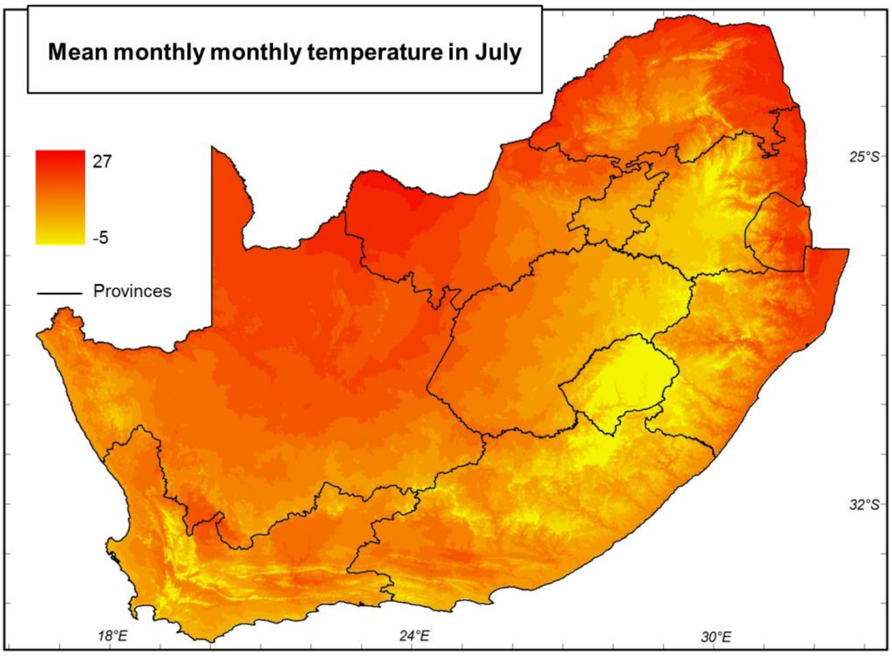


Figure 4.4: July monthly means of daily average temperature (°C) in southern Africa (Source: Schulze and Maharaj, 2007f)

4.1.3 Relative humidity

As noted previously (*cf*. Section 3.1.3), relative humidity (RH) is calculated as the ratio of actual to saturated vapour pressure. According to Schulze *et al*. (2007b), uncorrected actual vapour pressure is predictable month-by-month in South Africa, using predominantly geographical factors and regression equations. The uncorrected actual vapour pressure was assumed to be constant throughout the day in computations of daily RH_{min} and RH_{max}. However, saturated vapour pressure is a function of air temperature and thus varies daily and within the day. Hence, RH_{min} and RH_{max} can also vary from day to day (Schulze *et al*., 2007b). Figure 4.5 and 4.6 represent the spatial variation in mean monthly relative humidity in January and July respectively.

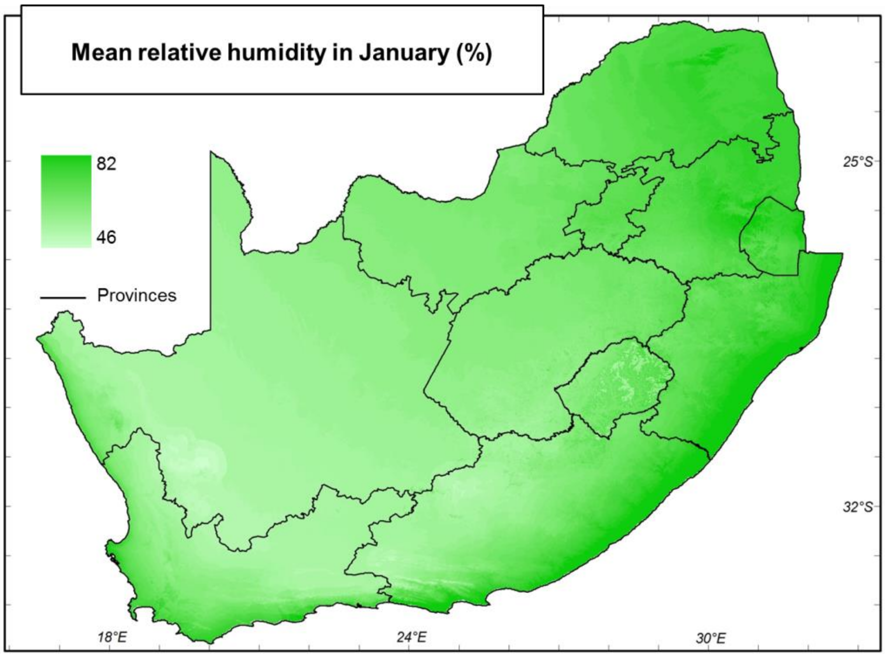


Figure 4.5: January mean monthly relative humidity (%) in southern Africa (Source: Schulze *et al*., 2007b)

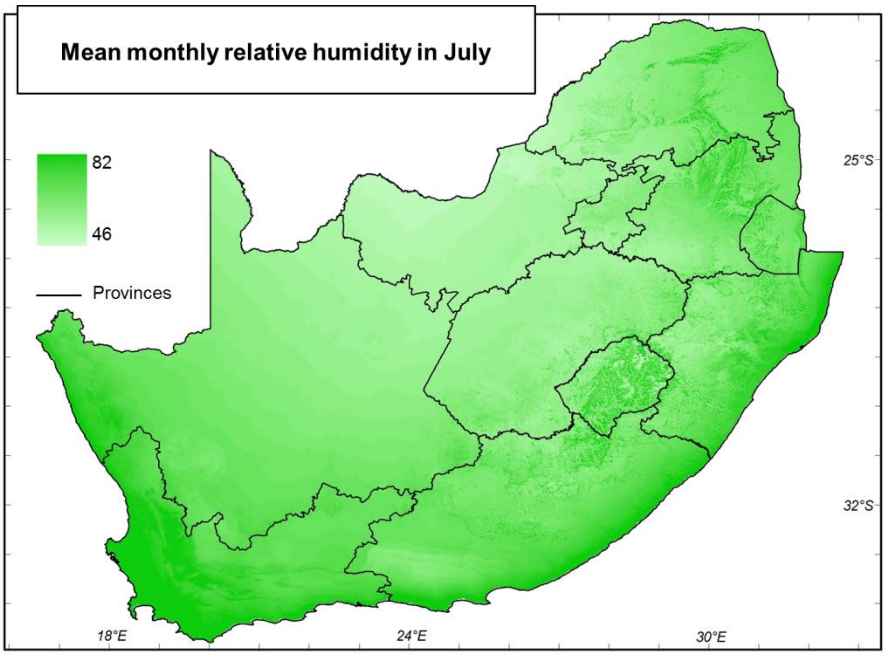


Figure 4.6: July mean monthly relative humidity (%) in southern Africa (Source: Schulze *et al*., 2007b)

4.1.4 Slope

According to Schulze and Horan (2007a), altitude for South Africa was mapped at a spatial resolution of one arc minute i.e. at a grid spacing of approximately 1.6 × 1.8 km. The gridded altitude values were derived from various sources. Initial altitudes values were collated from 1:250 000 topographic sheets during the Dent *et al*. (1989) study of spatial rainfall. These initial values were then modified and corrected with the 200 m Digital Elevation Model (DEM) obtained from the Surveyor General (Schulze and Horan, 2007a). The 90 m DEM was obtained from Weepener *et al.* (2011) and used to calculate slope (percentage rise). The slope dataset was converted from floating point grid to an integer grid to assist in reducing computational time.

4.1.5 Soil depth

Soil depth information was derived from the 1:250 000 land types derived by the Institute for Soil, Climate and Water (ISCW), based at the Agricultural Research Council. For the purpose of mapping, this variable was derived for all soil series in southern Africa and its attributes were then area averaged. The subsoil horizon reflects the underlying geology and shows a greater range in depth than the topsoil (Schulze and Horan, 2007b). The total depth was calculated as the sum of the topsoil and subsoil depths.

4.1.6 Land use

Land use describes how mankind utilises land, e.g. for urban living and agricultural food production. Land use and protected areas data were extracted from the Biodiversity GIS (BGIS) website (http://www.bgis.sanbi.org/). The BGIS unit is managed by the South African National Biodiversity Institute (SANBI). Its main objective is to provide easy access to spatial biodiversity planning information. SANBI officially published the National Land Cover (NLC) of 2000 in 2005 (NLC, 2005), which represented an update of the first NLC of 1994 (NLC, 1994) that was originally published in 1996 (SANBI, 2013). The seven land cover classes in the database are mines, plantations, water bodies, urban built-up, degraded, cultivation and natural. The protected areas coverage considers special nature reserves, national parks, nature reserves (including provincial nature reserves), protected Environments, world heritage sites (but, not cultural world heritage sites), marine protected areas, protected forest areas, mountain catchment areas and local authority protected areas.

4.1.7 Summary

Table 4.1 summarises the various data sources used in this study. For additional information pertaining to each dataset, the reader is referred to the reference provided in the table. The section that follows describes the methodology used in this study to evaluate the suitability of land to grow one of the three biofuel feedstocks.

Table 4.1: Sources of climatic (rainfall, temperature & relative humidity), edaphic (soil depth), topographic, slope and land use data used in this study

Datasets	**Description**	**Source**	**Reference**
Rainfall	Monthly rainfall totals	CWRR	Lynch (2004)
Temperature	Monthly means of daily maximum, minimum and average temperature	CWRR	Schulze and Maharaj (2007f)
Relative Humidity	Monthly means of daily average and minimum relative humidity	CWRR	Schulze *et al*. (2007b)
Slope	Digital elevation model	ARC	Weepener *et al.* (2011)
Soil Depth	Depth of topsoil and subsoil horizons	ISCW	Schulze and Horan (2007b)
Land Use	Land use in South Africa	BGIS	Bhengu *et al.* (2008)
Protected Areas	Formal and informal protected areas in South Africa	BGIS	Bradshaw (2010)

4.2 Growth Criteria for Each Feedstock

The growth criteria for each selected feedstock were based on rainfall, temperature, relative humidity, slope and soil depth constraints. The growth criteria were derived from the literature review presented in Section 2.4 (*cf*. Table 2.3, 2.4 and 2.5). The various sources of growth criteria were ranked, with local sources given a higher ranking than the international references. The local, newer sources were also ranked higher than the older references. The work done by Smith (1994; 1998; 2006) has been cited by other authors, including Jewitt *et al.* (2009a) and Schulze (2007). Hence, these secondary information sources were ranked lower than the primary source (i.e. Smith). Table 4.2 summarises the ranking of references used to derive growth criteria for the three selected feedstocks highlighted in Section 2.4.

Table 4.2: Summary table for ranking growth criteria for each feedstock

Soybean		**Grain sorghum**		**Sugarcane**	
Source	**Rank**	**Source**	**Rank**	**Source**	**Rank**
Jewitt *et al*. (2009a) Recommended	4	Smith (1994)	2	Jewitt *et al*. (2009a) Recommended	4
Smith (1994)	2	Smith (1998)	2	Smith (1994)	2
Smith (1998)	2	Smith (2006)	2	Smith (1998)	2
Smith (2006)	2	FAO (2006)	6	Smith (2006)	2
FAO (2006)	6	Schulze and Maharaj (2007b)	4	FAO (2006)	6
Schulze and Maharaj (2007a)	4			Schulze *et al*. (2007a)	2
Additional literature					
Nunkumar *et al*. (2009)	1	Du Plessis (2008)	2	DAFF (2012)	1
Schulze and Kunz (2010)	3	DAFF (2010b)	1	Watson *et al*. (2008)	4
DAFF (2010a)	1	Bassam (2010)	5	Schulze and Kunz (2010)	3
DAFF (2010a)-At planting	1	Schulze and Kunz (2010)	3	Bassam (2010)	5
Bassam (2010)	5			Tammisola (2010)	5

4.3 Mapping Software and Technology

Spreadsheet software developed by Microsoft (Excel Version 2010) was used to develop, test and refine the land suitability model used in this study. The GIS software used to perform the land suitability evaluation was developed by the Environmental Systems Research Institute (ESRI) based in Redlands, California (US). ESRI's ArcGIS (Version 9.3.1) software consists of two components that were used extensively *viz*. ArcMap and Spatial Analyst.

The spatial datasets used in this study were described earlier (*cf*. Section 4.1). All datasets were projected to the Cape datum using the ArcGIS 9.3.1 project wizard tool in the Toolbox. The procedures that were developed and applied to the datasets are described next.

4.4 Data Manipulation and Analysis

The land suitability evaluation required the manipulation of both raster- and vector-based data. However, all datasets were converted to raster format as this format is better suited to land evaluation studies. Raster-based datasets consist of rows and columns of same-sized cells (i.e. grid cells of 1.6 × 1.8 km) on a regular grid and were managed using the ESRI's Spatial

Analyst tool. Raster grid cells are always square in a projected co-ordinate system, but the analysis was carried out in a geographic co-ordinate system (Cape datum), with the reported cell size units in degrees of latitude/longitude. These latitude/longitude grid cells then represent non-square cells of ~200 by 231 m, which corresponds to a cell size of 0.0020833.

The analysis generated new datasets from existing raster data, to create various criteria which served as input for the land suitability evaluation. More specifically, new datasets were generated using the Re-classify tool in Spatial Analyst. For example, the spatial rainfall dataset was re-classified into suitable (i.e. optimum and marginal) and unsuitable classes in terms of feedstock growth. This exercise was repeated for the other raster-based climate datasets (e.g. temperature and relative humidity). These new data layers then formed the input criteria to evaluate the suitability of land for biofuel feedstock cultivation. The Raster Calculator in Spatial Analyst was also used to overlay the input criteria and complete the land suitability assessment.

4.5 Elimination of Unsuitable Areas Based on Threshold Limits

The first phase of the GIS-based methodology concentrated on eliminating all areas where soybean, grain sorghum and sugarcane will not grow due to certain constraints. This approach is similar to that adopted in the Jatropha case study (*cf*. Section 3.3.1). Thresholds for feedstock growth were derived from the absolute values derived from the literature review. For example, soybean requires a minimum seasonal rainfall total of 450 mm as shown in Table 4.3. Such areas were classified as suitable (S or Boolean 1) and all areas with a seasonal rainfall total < 450 mm as not suitable (N or Boolean 0). Thus, all areas classified as not suitable were excluded from further analysis. Seasonal rainfall totals are mean monthly rainfall totals accumulated over the growing season, which is assumed to be November to March (5 months) for soybean and grain sorghum, but annual (12 months) for sugarcane.

Table 4.3: Threshold values used to eliminate areas deemed not suitable for soybean, grain sorghum and sugarcane production

Criteria	**Selected Feedstocks**		
	Soybean	Grain sorghum	Sugarcane
Seasonal rainfall (mm)	< 450 or > 1100	< 400 or > 1200	
Annual rainfall (mm)			< 850 or > 2000
Mean monthly Temperature (ºC)	< 10 or > 33	<15 or > 35	< 15 or > 35 (Sep - Apr) < 8 or > 24 (May – Aug)
Mean monthly relative humidity (%)	> 80		< 30 or > 95 (Sep - Apr) < 20 or > 85 (May – Aug)
Minimum monthly Relative humidity (%)		> 40	
Soil depth (mm)	< 200	< 300	< 400
Slope (%)	> 10	> 10	> 30

4.6 Land Suitability Evaluation Procedure and Ranking of Suitability Criteria

The land suitability assessment considered in this study involved four main steps, *viz*. 1) the identification of land suitability criteria, 2) the ranking of these suitability criteria, 3) weighting of selected criteria, and finally 4) implementing the land suitability evaluation. The starting point was to define the criteria used to identify land deemed suitable for the production of the key selected feedstocks. The next important step involved ranking the criteria which is described next in further detail. This approach is similar to that described by Koikai (2008) in Section 3.3.2.

The study also adopted the approach by Ramirez-Villegas *et al*. (2013) as highlighted in Section 3.2.2. When the rainfall and temperature conditions at a particular location are beyond the absolute thresholds, the conditions are considered not suitable for crop production (N1). The areas were eliminated in the approach described in Section 3. When climatic conditions are between the optimum and absolute thresholds, they are considered marginal (S3). If the conditions are within the optimum range, they are deemed highly suitable (S1).

4.6.1 Rainfall

According to Smith (2006), the optimum planting date for soybean is between 1 November and 20 November and the medium season length is 150 days. The rainfall thresholds given in

Table 4.4 were derived from the growth criteria gleaned from the literature for soybean. In order to avoid unnecessary repetition, the approach is illustrated using soybean as the example feedstock. The thresholds R_{min} and R_{max} represent seasonal rainfall totals that prevent crop loss due to a) inadequate moisture supply (i.e. < 450) mm and b) waterlogged conditions with high disease incidence (i.e. > 1100 mm).

Table 4.4: Seasonal rainfall thresholds to distinguish between optimal and marginal growing conditions for soybean

Rainfall threshold	**Seasonal rainfall total (mm)**
R_{min}	450
R_{opmin}	700
R_{opmax}	900
R_{max}	1 100

The thresholds in the above table relate to FAO classes S1 (700-900 mm), S3 (450-700 mm) or (900-1 100 mm) and N1 (< 450 and > 1 100 mm). As suggested in Section 3.2.2 a sub-optimum class (S2) was introduced to create a buffer between S1 and S3. For example, a seasonal rainfall total of 699 mm (or 901 mm) would be considered marginal and not optimal. Thus, S2 is a buffer between S1 and S3 which is necessary when applying discrete intervals through continuous datasets. Where possible, the rainfall thresholds used to depict the sub-optimum class were also based on the growth criteria gleaned from the literature. The final thresholds used to derive the seasonal rainfall range for each FAO-based suitability class is given in Table 4.5 for soybean. A ranking was then assigned to each suitability class, with the optimum conditions given the highest rank (i.e. 3).

Table 4.5: Seasonal rainfall thresholds and rankings for each suitability class derived for soybean

Code	**Suitability class**	**Seasonal rainfall range (mm)**	**Ranking**
Not	N1	< 450	0
Abs	S3	450 – 550	1
Sub	S2	550 – 700	2
Opt	S1	700 – 900	3
Sub	S2	900 – 1 000	2
Abs	S3	1 000 – 1 100	1
Not	N1	> 1 100	0

4.6.2 Temperature

A similar exercise was conducted to develop the ranking metric for temperature. As highlighted in Section 3.1.2, all plants have lower and upper temperature limits, beyond which the plant may stop growing. These temperature limits differ with species and from one growth stage to another (Schulze, 1997). A distinction was made between thresholds for germination (i.e. in November) and those used for the remainder of the five-month growing season (i.e. December – March) as shown in Table 4.7. This decision was again based on the growth criteria obtained from the literature.

As discussed in Section 4.4, the Re-classify tool in Spatial Analyst was used to create the new ranked grids. The Re-classify tool reads in the class thresholds from an ASCII text file with an example given below. For example, temperatures above 23 but less than or equal to 27 are ranked as 3 (i.e. optimal) (Table 4.6).

Table 4.6: The temperature rankings in December to March

Temperature range		Re-classed values
-99	10	0
10	18	1
18	23	2
23	27	3
27	30	2
30	33	1
33	99	0

Table 4.7: Ranking of each suitability class based on thresholds of monthly means of daily average temperature (ºC) for soybean

Code	**Suitability class**	**Temperature (°C)**		**Ranking**
		Nov	**Dec – Mar**	
Not	N1	< 10	< 10	0
Abs	S3	10 – 13	10 – 18	1
Sub	S2	13 – 15	18 – 23	2
Opt	S1	15 – 18	23 – 27	3
Sub	S2	18 – 25	27 – 30	2
Abs	S3	25 – 33	30 – 33	1
Not	N1	> 33	> 33	0

4.6.3 Relative humidity

According to Schulze (1997), the combination of high relative humidity and high temperatures can create favourable conditions for micro-organisms and insects, thus leading to pest and disease outbreaks. These conditions can also increase the presence of parasites and weeds. Relative humidity suitability classes and scores are summarised in Table 4.8 below. They are based on a study by Nunkumar (2006) who stated that the optimum relative humidity range for soybean rust outbreak is above 75 % (*cf*. Section 2.4.1).

Table 4.8: Ranking of each suitability class based on thresholds of monthly means of daily average relative humidity (%) for soybean

Code	**Suitability class**	**Average relative humidity (%)**	**Ranking**
Opt	S1	< 60	3
Sub	S2	60 – 70	2
Abs	S3	70 – 75	1
Not	N1	>75	0

4.6.4 Soil depth

Due to soil data limitations, only soil depth was evaluated in this study. An accurate soil texture data was not available for the whole country. Table 4.9 summarises the soil depth suitability classes and rankings (i.e. scores) used for soybean. The soil depth thresholds were also gleaned from the literature review.

Table 4.9: Ranking of each suitability class based on soil depth (mm) for soybean

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

4.6.5 Slope

Table 4.10 summarises the slope suitability classes and rankings used in this study for soybean. Hence, Russell (1997) stated that a slope greater than 10 % is considered too steep for production of annual row crops, assuming conventional methods of cultivation and conservation. The reclassify tool in Spatial Analyst was again used to derive ranked grids for both slope and soil depth. Hence, slopes above 10 % were assigned to FAO class N1 (i.e. currently unsuitable for cultivation)

Table 4.10: Ranking of each suitability class based on slope (%) for soybean (Russell, 1997)

Code	**Suitability class**	**Soil slope (%)**	**Ranking**
Opt	S1	0 < 4	3
Sub	S2	4 – 8	2
Abs	S3	8 – 10	1
Not	N2	> 10	0

4.6.6 Overall weighting of each suitability criteria

The five suitability criteria defined above (*cf.* Section 4.6.1-4.6.5) were assigned weightings according to their importance in determining feedstock survival at a particular location. These subjective weightings were based on expert opinion (Bertling and Odindo, 2013) and ranged from most important (40 %) to least important (10 %), as shown in Table 4.11. The weightings are similar to those used by Holl *et al.* (2007) in the Jatropha study (*cf.* Section 3.3.1).

According to Bertling and Odindo (2013), rainfall is most important to crop survival, because plants cannot grow without an adequate water supply. Temperature and slope are not as important as rainfall but are more important than relative humidity and soil depth. Relative humidity and soil depth are least important because diseases can be prevented (by spraying with fungicides) and soil depth can be modified using tillage. These weightings were then normalised (i.e. dividing by the summed weightings) to create a decimal weighting for each criteria. This approach is similar to that used by Koikai (2008) as given in Section 3.3.2.

Table 4.11: Weighting assigned to each suitability criterion (Bertling and Odindo, 2013)

Suitability criteria	Relative weighting (%)	Decimal weighting
Rainfall	40	0.4
Temperature	20	0.2
Relative humidity	10	0.1
Soil depth	10	0.1
Slope	20	0.2
Total	**100**	**1.0**

In this study, the arithmetic procedures method (discussed in Section 3.2.5 was used to assign the overall land suitability score to each grid cell. Each suitability score was calculated by multiplying the reclassified ranked (i.e. data) by the decimal weighting. All suitability scores were then summed to obtain the total suitability score. Hence, if a particular grid cell is ideally suited to the optimum growth of soybean, it is assigned a total suitability score of 3. Similarly, a ranking of 1 assigned to each suitability criteria would produce a total suitability score of 3. Hence, rainfall contributes a maximum score of 1.2 out of the total of 3 (Table 4.12).

Table 4.12: Total suitability score obtained when each suitability criterion is ideally ranked

Suitability criteria	Ranking	Decimal weighting	Suitability score
Rainfall	3	0.4	1.2
Temperature	3	0.2	0.6
Relative humidity	3	0.1	0.3
Soil depth	3	0.1	0.3
Slope	3	0.2	0.6
Total		**1.0**	**3.0**

4.7 GIS Approach

4.7.1 Distribution of seasonal rainfall over the growing season

Table 4.10 in Section 4.6.6 considered rainfall as the most important suitability criterion. However, feedstock growth is not only affected by the total seasonal rainfall as highlighted in Section 3.1.1, but also the distribution of rainfall over the growing season.

As indicated in Section 3.2.2, the optimum seasonal rainfall range for soybean is 700 – 900 mm (accumulated from November to March). However, soybean yield would be significantly different if the seasonal rainfall a) was evenly distributed over the five month growing season (i.e. 140 – 180 mm per month), compared to b) the majority of rainfall occurring over a 2-month period.

A unique approach was adopted in this study whereby the crop coefficient (K_c) concept was used to determine the optimum distribution of rainfall over the growing season. Growth stages were related to months, using the length of each development stage. Hence, appropriate K_c values were assigned to each month and subsequent rainfall totals were then derived for that month. The K_c values were first normalised and then used to calculate rainfall thresholds in each month for each suitability class. As shown in Table 4.13, most rainfall should fall in February, based on when K_c peaks. Thus, a minimum of 450 mm of seasonal rainfall is required for soybean to grow, of which 129 mm should fall in February and 107 mm in January. The figures are based on K_c values obtained from FAO (FAO, 2013). The K_c values relate well to stress, with K_c highest when stress during the grain filling stage can result in high yield loss (*cf.* Section 3.1.1.1). The rainfall thresholds in the table below relate to the suitability classes shown in Table 4.5.

Table 4.13: Distribution of seasonal rainfall in each month of the growing season for soybean, based on FAO crop coefficients (K_c)

Month	**Growth stage**	**K_c**	**K_c norm**	**Monthly rainfall thresholds (mm)**					
November	Ini	0.40	0.095	43	52	67	86	95	105
December	Dev	0.80	0.190	86	105	133	171	190	210
January	Mid	1.00	0.238	107	131	167	214	238	262
February	Mid	1.20	0.286	129	157	200	257	286	314
March	End	0.80	0.190	86	105	133	171	190	210
Total		**4.20**	**1.000**	**450**	**550**	**700**	**900**	**1 000**	**1 100**

For simplicity, the monthly rainfalls shown in the above table were rounded to the nearest 5 mm (Table 4.14). The values were then summed, to ensure that the rainfall thresholds assigned to each suitability class remained unaltered. If discrepancies occurred, the monthly values representing peak water use (i.e. in February) were adjusted accordingly, as highlighted by the italicised values in the table below.

Table 4.14: Distribution of seasonal rainfall in each month of the growing season for soybean, based on FAO crop coefficients (K_c), with values rounded to the nearest 5 mm

Month	**Growth stage**	**K_c**	**K_c norm**	**Monthly rainfall thresholds (mm)**					
November	Ini	0.40	0.095	045	050	065	085	095	105
December	Dev	0.80	0.190	085	105	135	170	190	210
January	Mid	1.00	0.238	105	130	165	215	240	260
February	Mid	1.20	0.286	*130*	*160*	*200*	*260*	*285*	*315*
March	End	0.80	0.190	085	105	135	170	190	210
Total		**4.20**	**1.000**	**450**	**550**	**700**	**900**	**1 000**	**1 100**

As noted earlier, the optimum seasonal rainfall range for soybean is considered to be 700 – 900 mm. Based on FAO crop coefficients, between 65-85 mm of rainfall is required at planting (Table 3.15). However, the majority of the seasonal rainfall (200 – 260 mm) is required in February when soybean water use peaks.

Table 4.15: Ranking of seasonal rainfall in each month of the growing season for soybean

	Monthly rainfall ranges (mm) per suitability class						
Ranking	**0**	**1**	**2**	**3**	**2**	**1**	**0**
November	< 45	045 – 050	050 – 065	065 – 085	085 – 095	095 – 105	> 105
December	< 85	085 – 105	105 – 135	135 – 170	170 – 190	190 – 210	> 210
January	< 105	105 – 130	130 – 165	165 – 215	215 – 240	240 – 260	> 260
February	< 130	130 – 160	160 – 200	200 – 260	260 – 285	285 – 315	> 315
March	< 85	085 – 105	105 – 135	135 – 170	170 – 190	190 – 210	> 210
Seasonal total (mm)	**< 450**	**450–550**	**550–700**	**700–900**	**900–1 000**	**1 000–1 100**	**> 1 100**

A similar exercise was undertaken, but using crop coefficients derived for soybean grown under dryland conditions at Baynesfield, KwaZulu-Natal. The monthly rainfall thresholds (rounded to the nearest 5 mm) are given in Table 3.16. The values for local crop coefficients were derived by Mengistu *et al.* (2014). The local crop coefficients were calculated using total evaporation (i.e. transpiration and soil water evaporation) measured at the Baynesfield Estate trial (Mengistu *et al.*, 2014). The methodology was tested with the locally derived K_c values (i.e. to test sensitivity to the K_c approach).

Table 4.16: Distribution of seasonal rainfall in each month of the growing season for soybean, based on local crop coefficients (K_c) with values rounded to the nearest 5 mm

Month	**Growth stage**	**K_c**	**K_c norm**	**Monthly rainfall thresholds (mm)**					
November	Ini	0.72	0.167	075	090	115	150	165	185
December	Dev	0.72	0.167	075	090	115	150	165	185
January	Mid	1.00	0.232	105	130	160	210	230	255
February	Mid	1.03	0.239	*105*	*135*	*175*	*215*	*245*	*260*
March	End	0.84	0.195	090	105	135	175	195	215
Total		**4.20**	**1.000**	**450**	**550**	**700**	**900**	**1 000**	**1 100**

Based on the locally derived crop coefficient values, the majority of seasonal rainfall should also occur in February, in order to satisfy the peak water requirements of the crop. Thus, rainfall that should fall in February for a ranking of 3 is 175 – 215 mm. However, the optimum rainfall at planting is 115 – 150 mm, which is almost double that based on the FAO crop coefficient approach (i.e. 65 – 85 mm).

4.7.1.1 Rainfall weighting using K_c values

The final step involved weighting the monthly rainfall rankings to obtain an overall rainfall suitability score. K_c values were again used to weight each month's ranking to produce a suitability score for each month, which was then summed (Table 4.17). As noted in Table 4.12, the total suitability score remains 1.2 out of 3.

Table 4.17: Maximum rainfall suitability score when each month's rainfall is ideally suited to soybean cultivation

Month	**Optimum range (mm)**	**Ranking**	**K_c**	**Relative weighting**	**Decimal weighting**	**Suitability score**
November	65 – 85	3	0.40	0.38	0.038	0.11
December	135 – 170	3	0.80	0.76	0.076	0.23
January	165 – 215	3	1.00	0.95	0.095	0.29
February	200 – 260	3	1.20	1.14	0.114	0.34
March	135 – 170	3	0.80	0.76	0.076	0.23
Total	**700 – 900**		**4.20**	**4.00**	**0.400**	**1.20**

4.7.1.2 GIS analysis

Each monthly rainfall grid (for November to March) was re-classified to produce five new datasets, using the Re-classify tool in Spatial Analyst. The cells values ranged from 0 (unsuitable for feedstock growth) to 3 (optimally suited to feedstock growth) shown in Table 4.18.

Table 4.18: Rainfall thresholds (mm) used to re-classify February's rainfall for soybean.

Minimum	Maximum	Ranking
000	130	0
130	160	1
160	200	2
200	260	3
260	285	2
285	315	1
315	350	0

The Raster Calculator in Spatial Analyst was then used to weight each new re-classified rainfall grid (called Rfl_Rec_xx, where xx is the month). The new grids were then summed to calculate the rainfall suitability score (Rfl_Sum) using the following expression:

$$\begin{aligned}\text{Rfl\_Sum} = {} & ([\text{Rfl\_Rec\_11}] * 0.038) + \\ & ([\text{Rfl\_Rec\_12}] * 0.076) + ([\text{Rfl\_Rec\_01}] * 0.095) + \\ & ([\text{Rfl\_Rec\_02}] * 0.114) + ([\text{Rfl\_Rec\_03}] * 0.076)\end{aligned} \tag{4.1}$$

4.7.2 Weighting of monthly temperatures

A similar weighting procedure was adopted for monthly temperatures. As noted in Section 4.1.2, a distinction was made between temperature thresholds for germination (i.e. in November) and those used for the remainder of the five-month growing season (i.e. December – March). A relative weighting was assigned to each month which shows that soybean is more sensitive to temperature stress during the early (i.e. November) and late seasons (February and March). The temperature weightings were based on evidenced provided by DAFF (2010a). At planting, temperature is important because it stimulates germination and young seedlings can be damaged by excessive cold or hot temperatures. Low temperatures during the flowering stage inhibit flower and seed formation (DAFF, 2010a). If the monthly temperature is within the ideal range for each of the five months during the growing season (i.e. ranking of 3 assigned to each month), it produces a maximum temperature suitability score of 0.6 out of 3 (Table 4.19).

Table 4.19: Maximum temperature suitability score when each month’s temperature is ideally suited to soybean cultivation

Month	**Optimum range (ºC)**	**Ranking**	**Relative weighting**	**Decimal weighting**	**Suitability score**
November	15 – 18	3	0.50	0.050	0.15
December	23 – 27	3	0.50	0.050	0.15
January	23 – 27	3	0.50	0.050	0.15
February	23 – 27	3	0.30	0.030	0.09
March	23 – 27	3	0.20	0.020	0.06
Total			**2.00**	**0.20**	**0.60**

The GIS approach is similar to that described in Section 4.7.1.2. In essence, a total of five new re-classified temperature grids were generated (called Tmp_Rec), then weighted and summed to calculate the temperature suitability score (Tmp_Sum), using the following expression:

$$\begin{aligned} \text{Tmp\_Sum} = {} & ([\text{Tmp\_Rec\_11}] * 0.050) + \\ & ([\text{Tmp\_Rec\_12}] * 0.050) + ([\text{Tmp\_Rec\_01}] * 0.050) + \\ & ([\text{Tmp\_Rec\_02}] * 0.020) + ([\text{Tmp\_Rec\_03}] * 0.020) \end{aligned} \tag{4.2}$$

4.7.3 Weighting of monthly relative humidity

The monthly mean of daily average relative humidity should be less than 60 % between November and March, in order to reduce the risk of disease incidence in particular soybean rust (*cf*. Section 4.6.3). Van Niekerk (2010) stated that the period of highest risk of rust outbreak starts from the middle of January and peaks in the middle of February. The assigned relative weighting is thus highest in January and February, to account for these findings.

If the humidity level is within the ideal range for each of the five months during the growing season (i.e. ranking of 3 assigned to each month), it produces a maximum humidity suitability score of 0.3 out of 3 (Table 4.20).

Table 4.20: Maximum humidity suitability score when each month's relative humidity is ideally suited to soybean cultivation

Month	**Optimum range (%)**	**Ranking**	**Relative weighting**	**Decimal weighting**	**Suitability score**
November	< 60	3	0.10	0.010	0.03
December	< 60	3	0.10	0.010	0.03
January	< 60	3	0.30	0.030	0.09
February	< 60	3	0.30	0.030	0.09
March	< 60	3	0.20	0.020	0.06
Total			**1.00**	**0.100**	**0.30**

A total of five new re-classified humidity grids were generated (called Hum_Rec), then weighted and summed to calculate the humidity suitability score (Hum_Sum) using the following expression:

Hum_Sum = ([Hum_Rec_11] * 0.010) +
([Hum_Rec_12] * 0.010) + ([Hum_Rec_01] * 0.030) +
([Hum_Rec_02] * 0.030) + ([Hum_Rec_03] * 0.020) (4.3)

4.7.4 Weighting of soil depth and slope

As highlighted in Section 4.6.6, soil depth and slope are assigned decimals weightings of 0.1 and 0.2 respectively. Hence, slope is deemed twice as important as soil depth in terms of site suitability. Thus, if a grid cell's soil depth and slope conditions are ideal for feedstock growth (i.e. ranking of 3 assigned to the criterion), it produces a maximum suitability score of 0.9 out of 3 (Table 3.21). The ranking of slope is the same for soybean and grain sorghum, but not for sugarcane (*cf.* Table 4.10; Section 4.6.5). It is important to note that the ranking of soil depth is different for each feedstock.

Table 4.21: Maximum suitability score when soil depth and slope are ideally suited to soybean cultivation

Suitability criteria	**Optimum range**	**Ranking**	**Relative weighting**	**Decimal weighting**	**Suitability score**
Soil depth	> 500 mm	3	1	0.1	0.3
Slope	< 4 %	3	2	0.2	0.6
Total			**3**	**0.3**	**0.9**

4.7.5 Normalisation of overall suitability score

As highlighted in Section 4.6.6, the total suitability score is the sum of five suitability scores and ranges from 0 (not suitable) to 3 (optimally suited). The final step involved the normalisation of the total suitability score (i.e. dividing by 3), to produce a range from 0 to 1. The normalised values were then grouped into four classes for mapping purposes. These class intervals were derived by overlaying observed soybean yield data on the final land suitability map for soybean. The overall suitability score would be a minimum of 0.6, based on the weighting assigned to temperature, RH, slope and soil depth. This threshold was derived by considering the western parts of the country where all the site criteria excluding rainfall are ideal. The normalised values were then grouped into four classes for mapping purposes. These class intervals were derived by overlaying observed soybean yield data on the final land suitability map for soybean.

Observed yield data for soybean and grain sorghum production sites was collected by Stats SA (2006/07) who surveyed all magisterial districts in South Africa from March 2006 to February 2007. The yield data for each magisterial district was overlayed on the land suitability maps. The yield information was collected by electronic mail, postal mail, telephonic conversations and personal visits to the farmers. The yield data per magisterial district represents an average of values obtained from the survey (Stats SA, 2007). In addition, no observed yield data were available for the sugarcane production areas. However, cane production areas supplying the main sugar mills were obtained from SASRI and overlayed on the land suitability map for sugarcane (Mthembu, 2014).

4.7.6 Masking with land use

The legend of the land use dataset obtained from BGIS (*cf.* Section 4.1.6) contains explicit classifications, which in this study, were divided into two categories *viz.* absolute “no-go” areas and functional “no-go” areas. Absolute “no-go” areas comprise of land uses that are physically unsuitable for feedstock production. According to the FAO classification (*cf.* Section 3.2.1), such areas are classed as N2 (i.e. permanently not suitable) and include mining areas, urban areas, water bodies and protected areas.

Functional “no-go” areas refer to land uses deemed currently not suitable for feedstock cultivation (*cf*. Section 3.2.1) and include, *inter alia*, commercial forest plantations, natural and degraded land. These land uses were categorised as N1 (i.e. temporally unsuitable for feedstock production).

All grid cells that were identified as suitable for feedstock cultivation (S1, S2 or S3), but which overlapped with land use areas classified as N1 or N2, were excluded (or filtered out) using GIS. Thus, the consideration of present land use reduces the total arable land available for feedstock cultivation.

4.8 Summary

The climatic, edaphic and topographic datasets used in this study were obtained from different sources. All the necessary steps to perform the land suitability assessment were explained in this chapter, using soybean as the example feedstock. Figure 4.7 represents a flow diagram of the steps used in the spatial assessment of feedstock production areas.

A summary of the suitability criteria used for soybean, their rankings and weighting, is presented in Table 4.22 and 4.23. The class intervals and weightings for rainfall were based on FAO and local crop coefficients. Since this approach was repeated for two other strategic feedstocks considered in this study (grain sorghum and sugarcane), their summary tables are given in the Appendix.

The chapter that follows presents the results obtained after applying the criteria, rankings and weightings to the selected spatial databases for each of the three feedstocks. Hence, Chapter five contains the final maps depicting areas optimally and sub-optimally suited to the growth of the selected biofuel feedstocks.

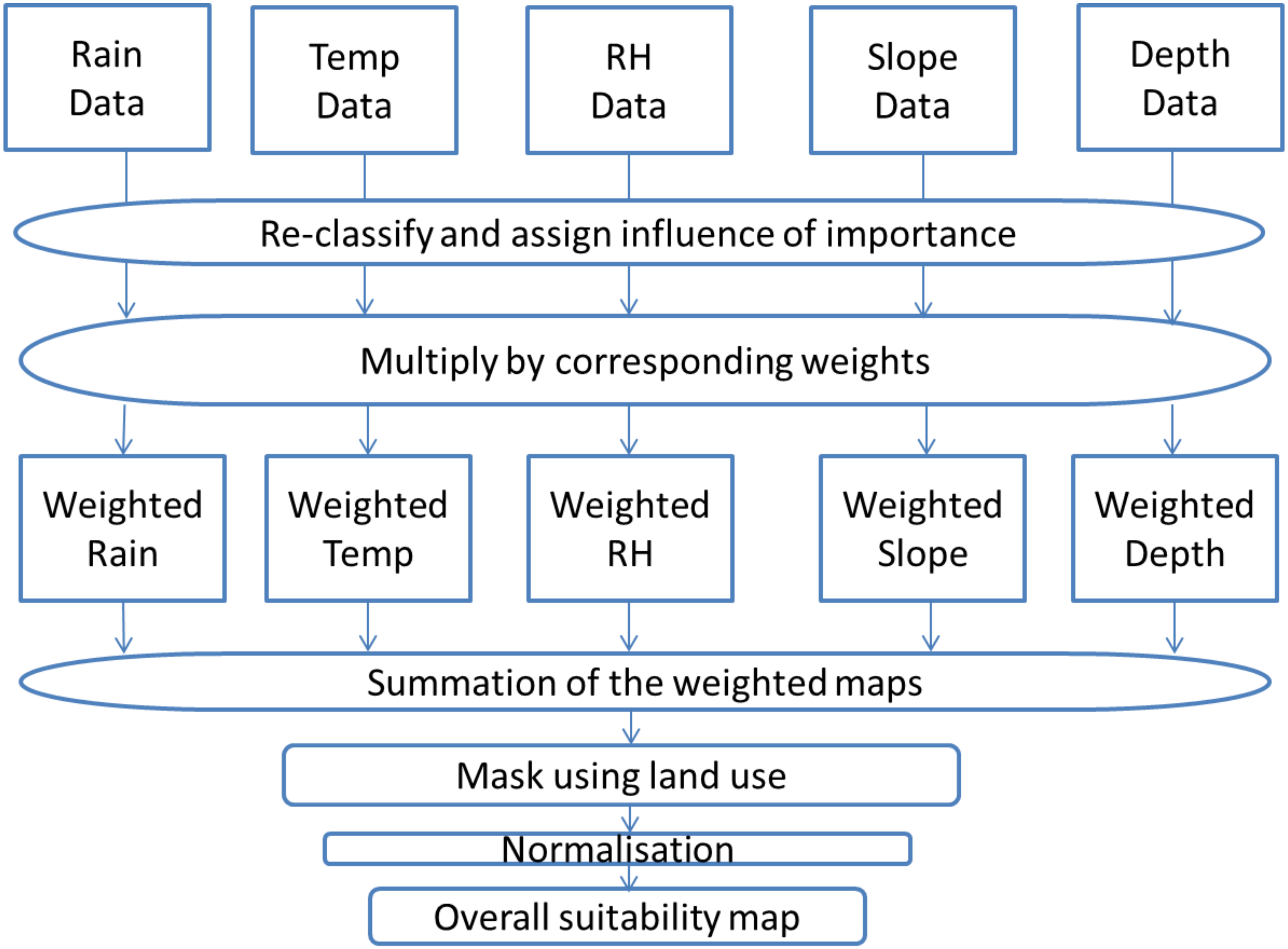


Figure 4.7: Flow diagram showing the methodology used to derive suitability maps for feedstock cultivation (Rain – monthly rainfall, Temp – monthly temperature, RH – monthly relative humidity, Slope – slope, Depth – soil depth)

Table 4.22: Summary of suitability criteria and ranking used to identify areas suitable for soybean cultivation, based on FAO K_c values

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative Weighting	Decimal Weighting
Ranking	0	1	2	3	2	1	0		
Rainfall totals apportioned per month based on FAO crop coefficients (mm)									
November	< 45	045 – 050	050 – 065	065 – 085	085 – 095	095 – 105	> 105	0.38	0.038
December	< 85	085 – 105	105 – 135	135 – 170	170 – 190	190 – 210	> 210	0.76	0.076
January	< 105	105 – 130	130 – 165	165 – 215	215 – 240	240 – 260	> 260	0.95	0.095
February	< 130	130 – 160	160 – 200	200 – 260	260 – 285	285 – 315	> 315	1.14	0.114
March	< 85	085 – 105	105 – 135	135 – 170	170 – 190	190 – 210	> 210	0.76	0.076
	< 450	**450 – 550**	**550 – 700**	**700 – 900**	**900 – 1 000**	**1 000 – 1 100**	**> 1 100**	**4.00**	**0.400**
Monthly means of daily average temperature (ºC)									
November	< 10	10 – 13	13 – 15	15 – 18	18 – 25	25 – 33	> 33	0.50	0.050
December	< 10	10 – 18	18 – 23	23 – 27	27 – 30	30 – 33	> 33	0.50	0.050
January	< 10	10 – 18	18 – 23	23 – 27	27 – 30	30 – 33	> 33	0.50	0.050
February	< 10	10 – 18	18 – 23	23 – 27	27 – 30	30 – 33	> 33	0.30	0.030
March	< 10	10 – 18	18 – 23	23 – 27	27 – 30	30 – 33	> 33	0.20	0.020
								2.00	**0.200**
Monthly means of daily average relative humidity (%)									
November				< 60	60 – 70	70 – 75	> 75	0.10	0.010
December				< 60	60 – 70	70 – 75	> 75	0.10	0.010
January				< 60	60 – 70	70 – 75	> 75	0.30	0.030
February				< 60	60 – 70	70 – 75	> 75	0.30	0.030
March				< 60	60 – 70	70 – 75	> 75	0.20	0.020
								1.00	**0.100**
Soil depth (mm)									
All season	< 200	200 – 300	300 – 500	> 500				**1.00**	**0.100**
Slope (%)									
All season				< 4	4 – 8	8 – 10	> 10	**2.00**	**0.200**
Total								**10.0**	**1.000**

Table 4.23: Summary of suitability criteria and ranking used to identify areas suitable for soybean cultivation, based on local K_c values

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative Weighting	Decimal Weighting
Ranking	0	1	2	3	2	1	0		
Rainfall totals apportioned per month based on local (Baynesfield) crop coefficients (mm)									
November	< 75	075 – 090	090 – 115	115 – 150	150 – 165	165 – 185	> 185	0.67	0.067
December	< 75	075 – 190	190 – 115	115 – 150	150 – 165	165 – 185	> 185	0.67	0.067
January	< 105	105 – 130	130 – 160	160 – 210	210 – 230	230 – 255	> 255	0.93	0.093
February	< 105	105 – 135	135 – 175	175 – 215	215 – 245	245 – 260	> 260	0.95	0.095
March	< 90	090 – 105	105 – 135	135 – 175	175 – 195	195 – 215	> 215	0.78	0.078
	< 450	**450 – 550**	**550 – 700**	**700 – 900**	**900 – 1 000**	**1 000 – 1 100**	**> 1 100**	**4.00**	**0.400**
Monthly means of daily average temperature (ºC)									
November	< 10	10 – 13	13 – 15	15 – 18	18 – 25	25 – 33	> 33	0.50	0.050
December	< 10	10 – 18	18 – 23	23 – 27	27 – 30	30 – 33	> 33	0.50	0.050
January	< 10	10 – 18	18 – 23	23 – 27	27 – 30	30 – 33	> 33	0.50	0.050
February	< 10	10 – 18	18 – 23	23 – 27	27 – 30	30 – 33	> 33	0.30	0.030
March	< 10	10 – 18	18 – 23	23 – 27	27 – 30	30 – 33	> 33	0.20	0.020
								2.00	**0.200**
Monthly means of daily average relative humidity (%)									
November				< 60	60 – 70	70 – 75	> 75	0.10	0.010
December				< 60	60 – 70	70 – 75	> 75	0.10	0.010
January				< 60	60 – 70	70 – 75	> 75	0.30	0.030
February				< 60	60 – 70	70 – 75	> 75	0.30	0.030
March				< 60	60 – 70	70 – 75	> 75	0.20	0.020
								1.00	**0.100**
Soil depth (mm)									
All season	< 200	200 – 300	300 – 500	> 500				**1.00**	**0.100**
Slope (%)									
All season				< 4	4 – 8	8 – 10	> 10	**2.00**	**0.200**
Total								**10.0**	**1.000**

5. RESULTS AND DISCUSSION

The previous chapter explained the methodological approach and tools used to meet the objectives of this study. This chapter presents and discusses the results obtained from the analysis, with maps for soybean (the example feedstock) shown in this chapter and the other two feedstocks (e.g. grain sorghum and sugarcane) shown in the appendix (*cf*. Section 8.1 and Section 8.2).

5.1 Elimination of Unsuitable Areas

Figure 5.1 highlights areas that are deemed unsuitable for soybean production and should be eliminated. In other words, grid cells were deemed unsuitable if one or more of the site criteria for growth were not met (i.e. class N; Boolean 0). Thus, areas in green highlight grid cells where all criteria for feedstock growth are simultaneously met (class S; Boolean1). This approach is identical to that adopted in the scoping study by Jewitt *et al*. (2009a), with the exception that additional site criteria were considered in this study. This study included not only climatic factors (rainfall and temperature) but also biotic (relative humidity), edaphic (soil depth) and topographic (slope) factors. The incorporation of additional criteria was based on the recommendations by Jewitt *et al.* (2009a).

The GIS Boolean functions (in the Raster Calculator) were applied to the site factors which are deemed to affect feedstock growth (i.e. mean monthly rainfall totals, mean monthly temperatures, mean monthly relative humidity, slope and soil depth). The length of the growing season and the planting dates were obtained from available literature resources as described in Chapter 2. The thresholds used for each criterion were given in Table 4.3 (*cf.* Section 4.5). The inclusion of relative humidity as a surrogate available for soybean rust excluded the humid areas along the coastline of Kwazulu-Natal and the Eastern Cape. Swaziland and Lesotho are excluded due to lack of land use data for these neighbouring countries. Figure 5.1 shows a much larger area suitable to soybean than that provided by the scoping study (Figure 3.5; of Section 3.3.3).

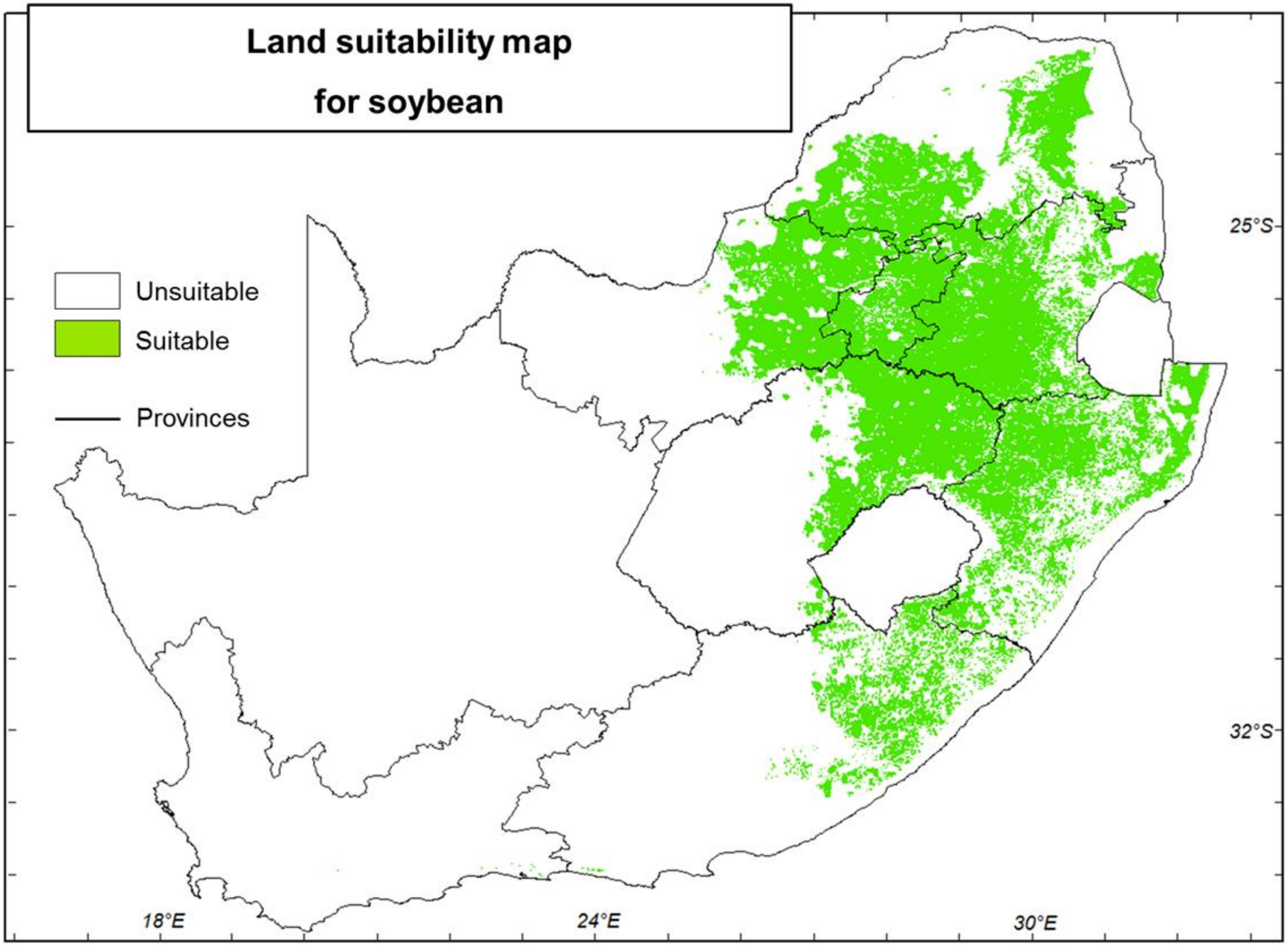


Figure 5.1: Potential (i.e. suitable) growing areas for soybean

Similarly, a comparison of Figure 8.1 (Appendix) with Figure 3.6 from the scoping study shows a substantial increase in suitable area for grain sorghum. The reason for this is that the scoping study mapped optimum growing areas, whereas this study mapped suitable growing areas (which range from optimum to marginal). Finally, the difference between Figure 8.2 with 3.7 for sugarcane is explained by the use of annual temperature in the scoping study and monthly temperatures in the present study.

5.2 Land Suitability Evaluation

The monthly crop coefficient concept was introduced in this study to determine the feedstock's water requirements over the growing season. The crop coefficients were apportioned per month to match the temporal rainfall datasets available for southern Africa.

5.2.1 Rainfall

Figure 5.2 illustrates the weighted rainfall surfaces used in the suitability evaluation for the example feedstock (soybean). The map was derived using Equation 4.1 in Section 4.7.1. This equation provides a summed weighting of 1.2, if the monthly rainfall is optimal (i.e. score of 3) across the entire five month season. This value is then normalised to 1 (i.e. 1.2/3=0.4). In terms of crop water requirements under rainfed conditions in South Africa, soybean cultivation is satisfactory along the eastern regions of the country, but unsuitable in the drier western part of the country. The Northern Cape, Western Cape, and the western parts of the Eastern Cape, Free State and North-West province are deemed as unsuitable for soybean production. The rainfall in the Free State, North West and western parts of Limpopo is marginally suitable for soybean production. Table 5.1 shows that 62.70 % of grid cells fall in the 0.00 class similarly, 0.11 % of grid cells fall in the range of 0.35 – 0.40, which is deemed highly suitable for soybean production. The weighting in Figure 5.1 of 0.4 relates back to Table 4.11, the values closer to 0 are unsuitable and values approaching 0.4 are highly suitable.

Table 5.1: Histogram of normalised rainfall suitability scores for soybean

Suitability classes	Value	Grid cell count	% of total land area
Unsuitable	0.00	265094	62.70
Suitable	0.01 – 0.05	032320	07.64
Suitable	0.05 – 0.10	043786	10.36
Suitable	0.10 – 0.15	033122	07.83
Suitable	0.15 – 0.20	016332	03.86
Suitable	0.20 – 0.25	015406	03.64
Suitable	0.25 – 0.30	009391	02.22
Suitable	0.30 – 0.35	006918	01.64
Suitable	0.35 – 0.40	000452	00.11

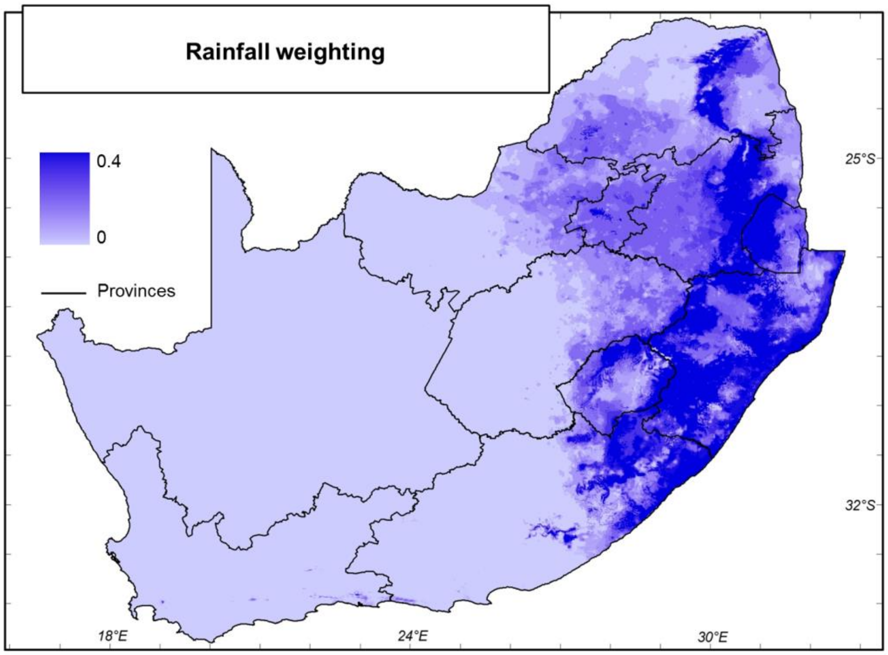


Figure 5.2: Weighted (and normalised) rainfall suitability map for soybean, based on FAO crop coefficients.

5.2.2 Temperature

Figure 5.3 illustrates the weighted temperature surface used in the suitability evaluation for soybean. The map was derived using Equation 4.2 in Section 4.7.1. This equation provides a summed weighting of 0.6, if the monthly temperature is optimal (i.e. score of 3) across the entire season (five months). This value is then normalised to 1 (i.e. 0.6/3=0.2). The map highlights the higher altitude areas which area deemed too cold for soybean cultivation. A comparison of Figure 5.2 and 5.3 shows that rainfall is more limiting to soybean production than temperature. Table 5.2 shows that 90.89 % of grid cells fall in the range of 0.15 – 0.20, which are deemed highly suitable for soybean. The weighting in Figure 5.2 of 0.2 relates back to Table 4.11, the values closer to 0 are unsuitable and values approaching 0.2 are highly suitable.

Table 5.2: Histogram of normalised temperature suitability scores for soybean

Suitability classes	Value	Grid cell count	% of total land area
Unsuitable	0.00	21709	05.14
Suitable	0.01 – 0.05	01400	00.33
Suitable	0.05 – 0.10	00815	00.19
Suitable	0.10 – 0.15	14585	03.45
Suitable	0.15 – 0.20	38400	90.89

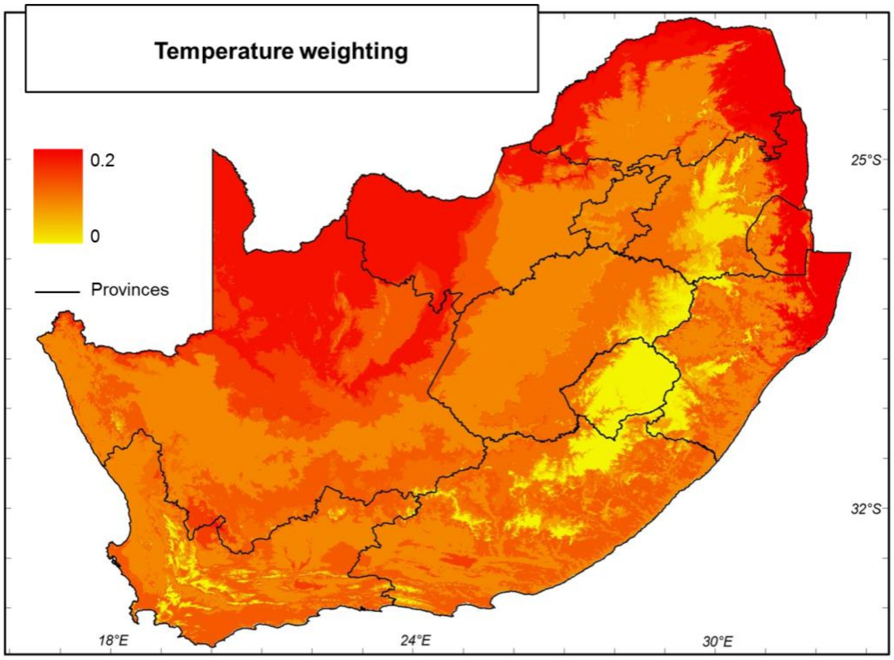


Figure 5.3: Weighted (and normalised) temperature suitability map for soybean

5.2.3 Relative humidity

Figure 5.4 illustrates the weighted relative humidity (RH) surfaces used for soybean. The map was derived using Equation 4.3 in Section 4.7.1. This equation provides a summarised weighting of 0.3, if the monthly RH is optimal (i.e. score of 3) across the entire season (five months). This value is then normalised to 1 (i.e.0.3/3=0.1). All the grid cells with a monthly RH greater than 75 % are assigned a value of 0 (unsuitable), 70 – 75 % a value of 1 (marginally suitable), 60 – 70 % a value of 2 (moderately suitable) and 0 – 60 % a value of 3 (highly suitable). The map highlights the more humid conditions along the eastern coastline (i.e. areas considered marginal for soybean) compared to the interior (especially towards the west), where conditions are less humid. The weighted approach does not eliminate coastal areas as unsuitable for soybean production as does the Boolean-type approach discussed in Section 5.1. Table 5.3 shows that 88.76 % of grid cells fall in the range of 0.05 – 0.10, which are deemed highly suitable for soybean. The weighting in Figure 5.3 of 0.1 relates back to Table 4.11, the values closer to 0 are unsuitable and values approaching 0.1 are highly suitable.

Table 5.3: Histogram of normalised relative humidity suitability scores for soybean

Suitability classes	Value	Grid cell count	% of total land area
Unsuitable	0.00	003683	00.87
Suitable	0.01 – 0.05	043809	10.37
Suitable	0.05 – 0.10	375014	88.76

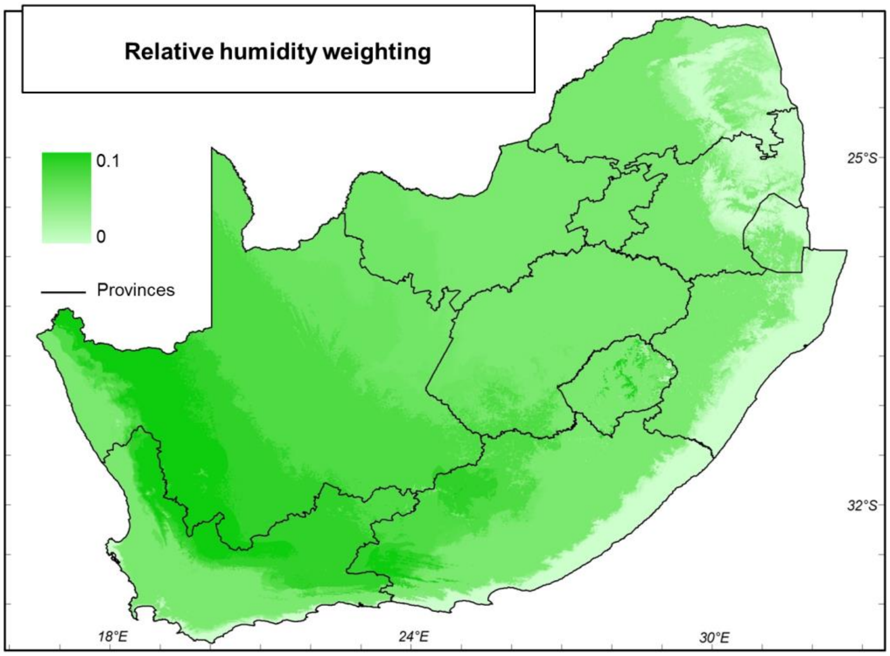


Figure 5.4: Weighted (and normalised) relative humidity suitability map for soybean

5.2.4 Slope suitability

Figure 5.5 illustrates the weighted slope surface for soybean. All grid cells with a slope greater than 10 % were assigned a value of 0 (unsuitable), 8 – 10 % a value of 1 (marginally suitable), 4 – 8% a value of 2 (moderately suitable) and 0 – 4 % a value of 3 (highly suitable) for soybean. These values are multiplied by a weighting of 0.2 which gives a maximum score of 0.6 for optimum sites (i.e. slope < 4 % and finally normalised by dividing by 3 to give final score up to 0.2). The map highlights the mountainous regions, which are often associated with higher rainfall, but colder temperatures. Table 5.4 shows that 51.38 % of grid cell count falls in the range of 0.15 – 0.20, which are deemed highly suitable for soybean. The weighting in Figure 5.4 of 0.2 relates back to Table 4.11, the values closer to 0 are unsuitable and values approaching 0.2 are highly suitable.

Table 5.4: Histogram of normalised slope suitability scores for soybean

Suitability classes	Value	Grid cell count	% of total land area
Unsuitable	0.00	037583	08.89
Suitable	0.01 – 0.05	068788	16.27
Suitable	0.05 – 0.10	030250	07.15
Suitable	0.10 – 0.15	068960	16.31
Suitable	0.15 – 0.20	217240	51.38

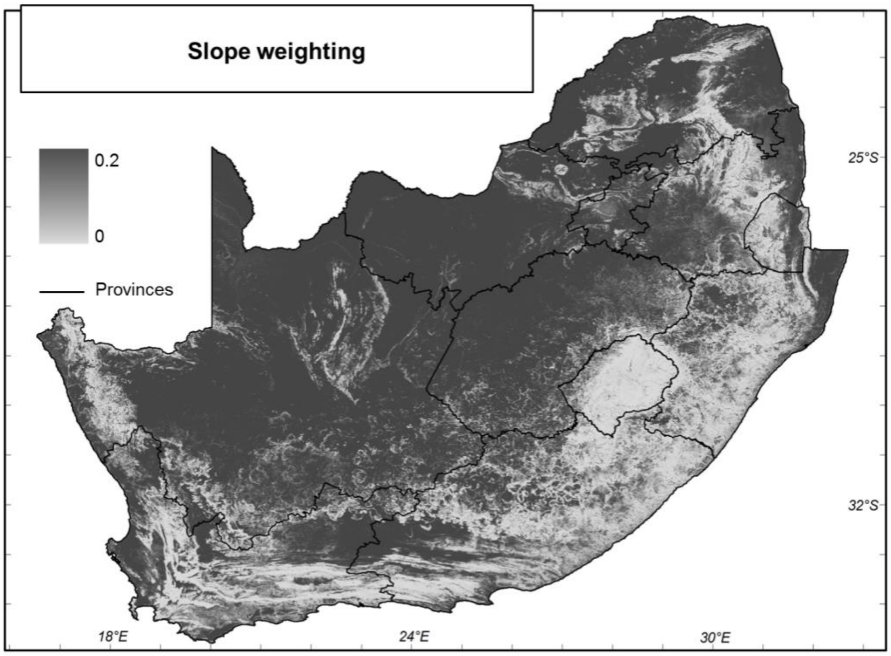


Figure 5.5: Weighted (and normalised) relative slope suitability map for soybean

5.2.5 Soil depth

Soil depth was the only soil parameter considered in this study. Figure 5.6 illustrates the weighted soil depth surface used in the land suitability evaluation. For moisture availability, adequate soil depth is important and all grid cells with a soil depth less than 200 mm were assigned a value of 0 (unsuitable), 200 – 300 mm were assigned a value of 1 (marginally suitable), 300 – 500 mm a value of 2 (moderately suitable) and 500 – 1200 mm a value of 3 (highly suitable). This value is then multiplied by a weighting of 0.1 to give a maximum score of 0.3 (for optimal sites), which is then normalised to give a range of 0.0 – 0.1. Table 5.5 shows that 72.34 % of grid cells count falls in the range of 0.05 – 0.10, which are deemed highly suitable for soybean. The weighting in Figure 5.5 of 0.1 relates back to Table 4.11, the values closer to 0 are unsuitable and values approaching 0.1 are highly suitable.

Table 5.5: Histogram of normalized soil depth suitability scores for soybean

Suitability classes	Value	Grid cell count	% of total land area
Unsuitable	0.00	073172	17.35
Suitable	0.01 – 0.05	043459	10.30
Suitable	0.05 – 0.10	305097	72.34

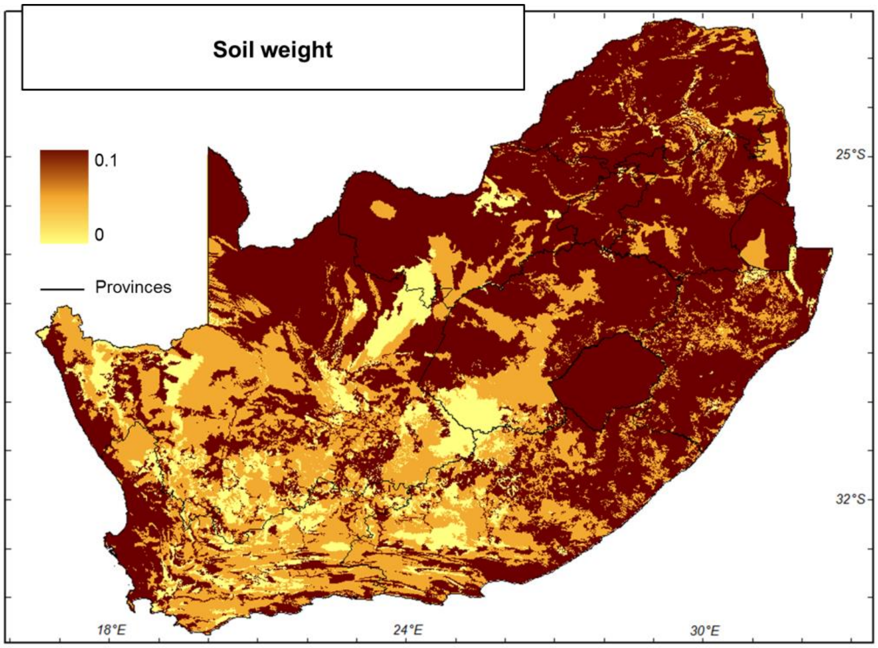


Figure 5.6: Weighted (and normalised) soil depth suitability map for soybean

5.2.6 Summary

The grid cells presented above show the range of suitability for each growth criteria (e.g. rainfall, temperature, relative humidity, slope and soil depth). Rainfall was the most limiting factor followed by temperature and slope, then soil depth and relative humidity.

5.2.7 Land use

All grid cells classified as absolute “no-go” areas (e.g. urban, water, mining) using the National Land Cover dataset were assigned a value of 0 to exclude them from further analysis. This step of the analysis also involved the filtering out of grid cells located in protected areas. The protected areas (formal and informal) were also assigned a value of 0 (unsuitable) and the rest of the country was assigned a value of 1 (suitable).

Functional “no-go” areas refer to land that is under forest plantations and therefore considered unsuitable for feedstock growth from a sustainability point of view. Thus grid cells classified as forest plantations were also assigned a value of 0 and therefore eliminated for biofuel production. The combined and final “no-go” areas are shown in Figure 5.7. However, natural areas and cultivated areas were assigned a value of 1 to allow them to be considered for cultivation of biofuel feedstock.

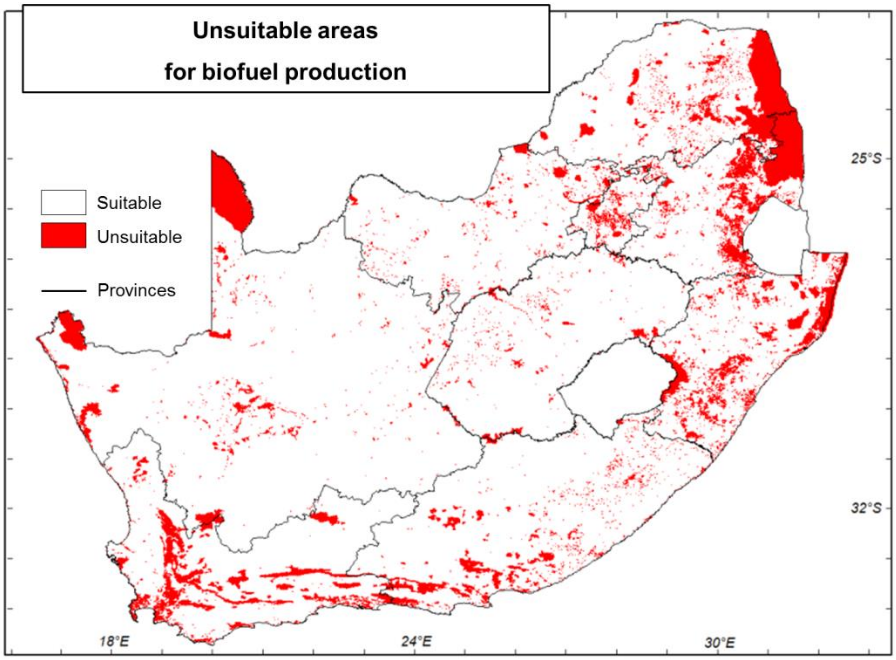


Figure 5.7: Unsuitable land uses for biofuel production

5.2.8 Overall land suitability score

Figure 5.8 represents the final result of the land suitability assessment by summing the weighted rainfall, temperature, relative humidity, soil depth as well as the slope surfaces. This was done in accordance with the arithmetic procedures method (FAO, 1983) as discussed in Section 3.2.5. The final suitability score ranges from 0 (not suitable) to 1 (highly suitable) which is then multiplied by the land use and protected area grids to eliminate both absolute and functional "no-go" areas.

5.2.9 Finalising the map legend

The overall land suitability score ranges from 0 to 1, which was then subdivided into four categories as shown in Table 5.6. All grid cells with an overall suitability score of less than 0.6 were deemed unsuitable for feedstock cultivation. This threshold was derived by considering the western parts of the country where all the site criteria excluding rainfall are ideal. Thus, the overall suitability score would be 0.6, based on the weighting assigned to temperature, RH, slope and soil depth. However, feedstock growth and survival would be negligible due to insufficient rainfall under dryland conditions (not irrigated) and thus considered unsuitable for growth. All grid cells with an overall score of 0.75 or more were considered highly suitable for feedstock production. Hence, scores between 0.60 and 0.75 were assigned to the marginally and moderately suitable categories as shown in Table 5.6.

Table 5.6: Normalised total suitability score used for mapping purposes

Range in total suitability score (normalised)	Suitability for feedstock cultivation	FAO (1976) classification
0.00 – 0.60	Not suitable	N1
0.60 – 0.65	Marginally suitable	S3
0.65 – 0.75	Moderately suitable	S2
0.75 – 1.00	Highly suitable	S1

5.2.10 Sensitivity analysis

Table 5.7 illustrates the importance of individual factors considered in the suitability analysis. The rainfall grid was multiplied by the temperature grid to form a base map (called R*T) with an area of 26.27 Mha. For soybean, relative humidity was not an important criterion consider only 2.40 Mha was eliminated as unsuitable. Soil depth was important, considering 7.02 Mha was eliminated and slope had the second greatest influence eliminating a land area of 10.12 Mha, on the other hand, approximately 2.08 Mha of the base map is classified as currently cultivated and should not be used for feedstock production to avoid food security concerns (i.e. this land should rather be used for food production). The CARA legislation states that virgin land cannot be cultivated without written permission, which affects 10.39 Mha of land. A total of 9.76 Mha of the base map occurs in degraded areas, which are associated with poor soils and with low yields. The absolute "no-go" areas (urban, mining, water bodies and protected areas) only eliminated 0.85 Mha.

Furthermore 3.11 Mha of the base map are currently used for forestry and are thus not suitable for soybean production. Finally approximately 3.01 Mha of the base map are located in the former homelands, where feedstock production should occur if government wishes to use the biofuels industry to alleviate rural poverty.

In terms of grain sorghum production, the base map was approximately 10 Mha larger than that for soybean, which again highlights its potential for biofuel production. However, only 1.99 Mha are located in the former homeland areas. In addition, only small portion (0.40 Mha) of the base map are considered degraded land. On the other hand, 14.74 Mha are currently under natural conditions and thus protected by CARA. Again, slope was the second most important factor limiting potential production areas.

The base map for sugarcane is only 10.67 Mha andd thus this feedstock exhibits the lowest expansion potential of the three feedstocks considered. It is interesting to note that 2.97 Mha of climatically suitable land is located in the former homeland areas. A much smaller area (1.18 Mha) is eliminated due to steep slopes when compared to the other two feedstocks. This is because the critical slope angle is 30 % and not 10 %. Finally, 36.7 % and 32.2 % of the base map are not desirable production areas due to the natural and degraded classification respective.

In summary, soil depth, slope and land cover (in particular natural and degraded) are important criteria for all feedstocks and have the most influence in the mapping approach. Hence, datasets with sufficient resolution are required for these site criteria.

Table 5.7: Sensitivity analysis of climatic, edaphic, topographic and land use factors affecting feedstock production potential

Crops	R*T	R*T* RH	R*T* SD	R*T *SS	R*T *NG	R*T *CU	R*T *NA	R*T *PL	R*T *DE	R*T *FH
Soybean	Suitable	23.87	19.25	16.16	25.42	24.19	15.88	23.16	16.51	03.01
	Not Suitable	02.40	07.02	10.12	00.85	02.08	10.39	03.11	09.76	23.26
	Total	26.27	26.27	26.27	26.27	26.27	26.27	26.27	26.27	26.27
Grain sorghum	Suitable	35.38	26.87	25.51	36.27	34.31	21.93	36.1	36.27	01.99
	Not Suitable	01.29	09.80	11.16	00.40	02.36	14.74	00.57	00.40	34.68
	Total	36.67	36.67	36.67	36.67	36.67	36.67	36.67	36.67	36.67
Sugarcane	Suitable	09.91	10.34	09.49	09.99	09.47	06.75	09.24	07.23	02.79
	Not Suitable	00.76	00.33	01.18	00.68	01.20	03.92	01.43	03.44	07.88
	Total	10.67	10.67	10.67	10.67	10.67	10.67	10.67	10.67	10.67

Note: R – Rainfall; T – Temperature; RH – Relative humidity; SD – Soil Depth; SS – Soil slope; CU – Cultivated; NA – Natural; DE – Degraded; NG – No-go areas; PL – Plantations; FH – Former homelands.

5.3 Sensitivity to Crop Coefficient Values

In this section, the different crop coefficient values suggested in the methodology are compared (e.g. basal *vs*. single; FAO *vs*. local), with a number of important recommendations drawn from the results.

5.3.1 Basal *vs.* single crop coefficient approach

In section 3.1.1, the importance of rainfall distribution across the growing season was highlighted. The crop coefficient concept was used to determine the feedstock's water requirements in each month across the growing season. In this study, the use of basal *vs*. single crop coefficients was compared to test the sensitivity of the methodology. The results show that using single coefficients (FAO), more areas are deemed suitable for soybean production (Figure 5.8) compared to using basal crop (SAPWAT3) coefficients (Figure 5.9) to weight the rainfall. The map (Figure 5.9) shows that the Free State is not suitable at all for soybean production. However, Table 2.2 (*cf*. Section 2.4.3.1) indicates that 22 % of soybean production occurs in the Free State. Thus, the use of basal crop coefficient (K_{cb}) to determine the distribution and weighting of seasonal rainfall is not recommended.

5.3.2 International *vs.* local K_c approach

The local K_c approach (Figure 5.10), identifies more land area more suitable for soybean production than compared to the FAO K_c approach (Figure 5.8). The use of FAO K_c eliminates central parts of Mpumalanga as being suitable for soybean production which is the largest soybean production area (*cf*. Table 2.2). Local K_c values are deemed more applicable to South African growing conditions. The map (Figure 5.10) shows that the Free State is marginally suitable to soybean production.

For grain sorghum, Figure 8.3 (FAO crop coefficients) illustrate that there is more area classified as marginal, particularly in the Free State than compared to Figure 8.4 (local crop coefficients). For sugarcane, Figure 8.5 (FAO crop coefficients) shows that KZN has less suitable areas for sugarcane when compared to Figure 8.6 (local crop coefficients). However, the use of local K_c values slightly reduced the area deemed suitable of soybean, grain sorghum and sugarcane production, when compared to the FAO K_c approach. This study showed that international crop K_c should not be used, but rather local K_c should be applied. According to Allen *et al.* (1998), the user is strongly encouraged to obtain appropriate local information (crop coefficients).

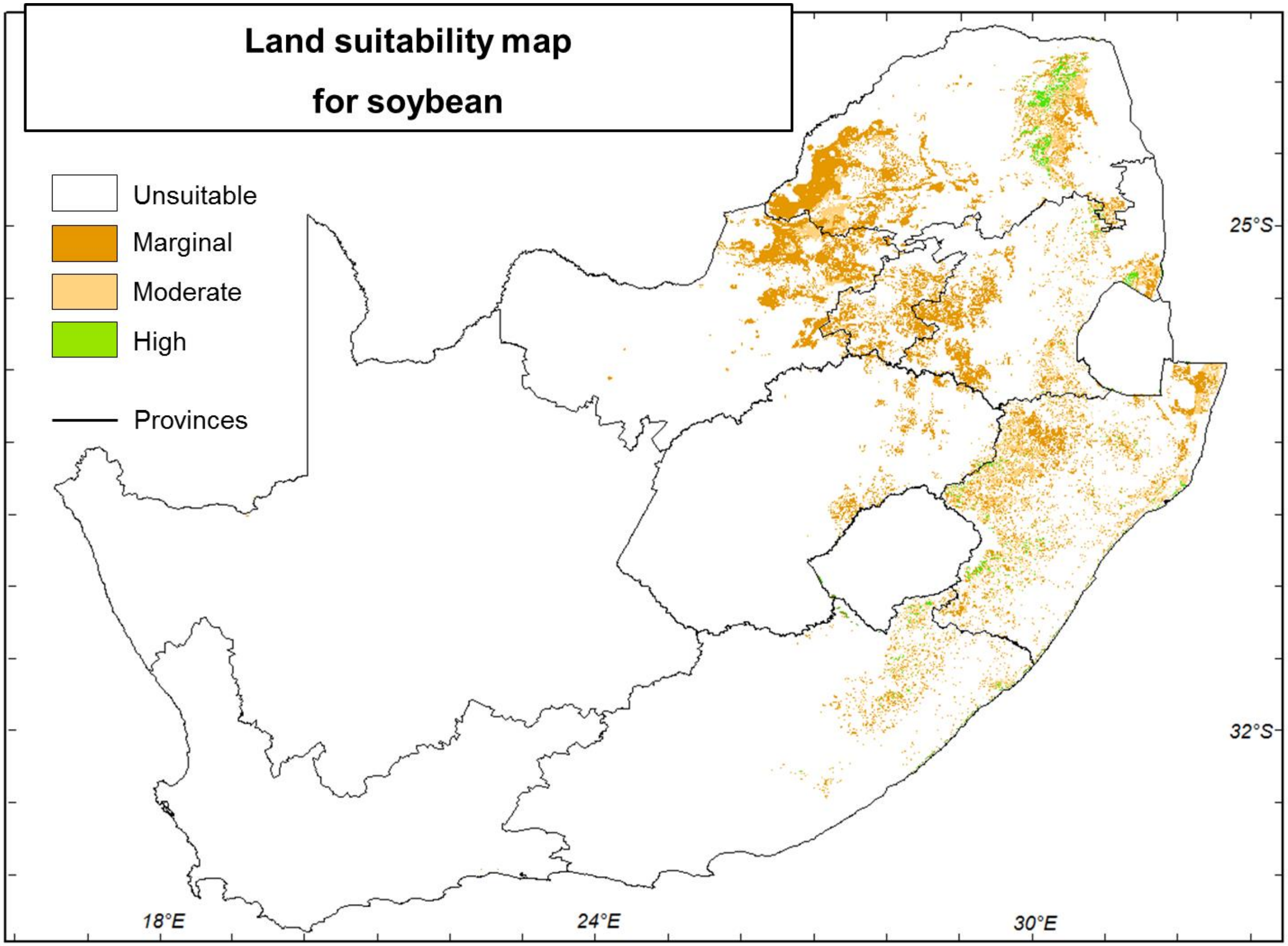


Figure 5.8: Land suitability map for soybean based on single (FAO; i.e. international) crop coefficients

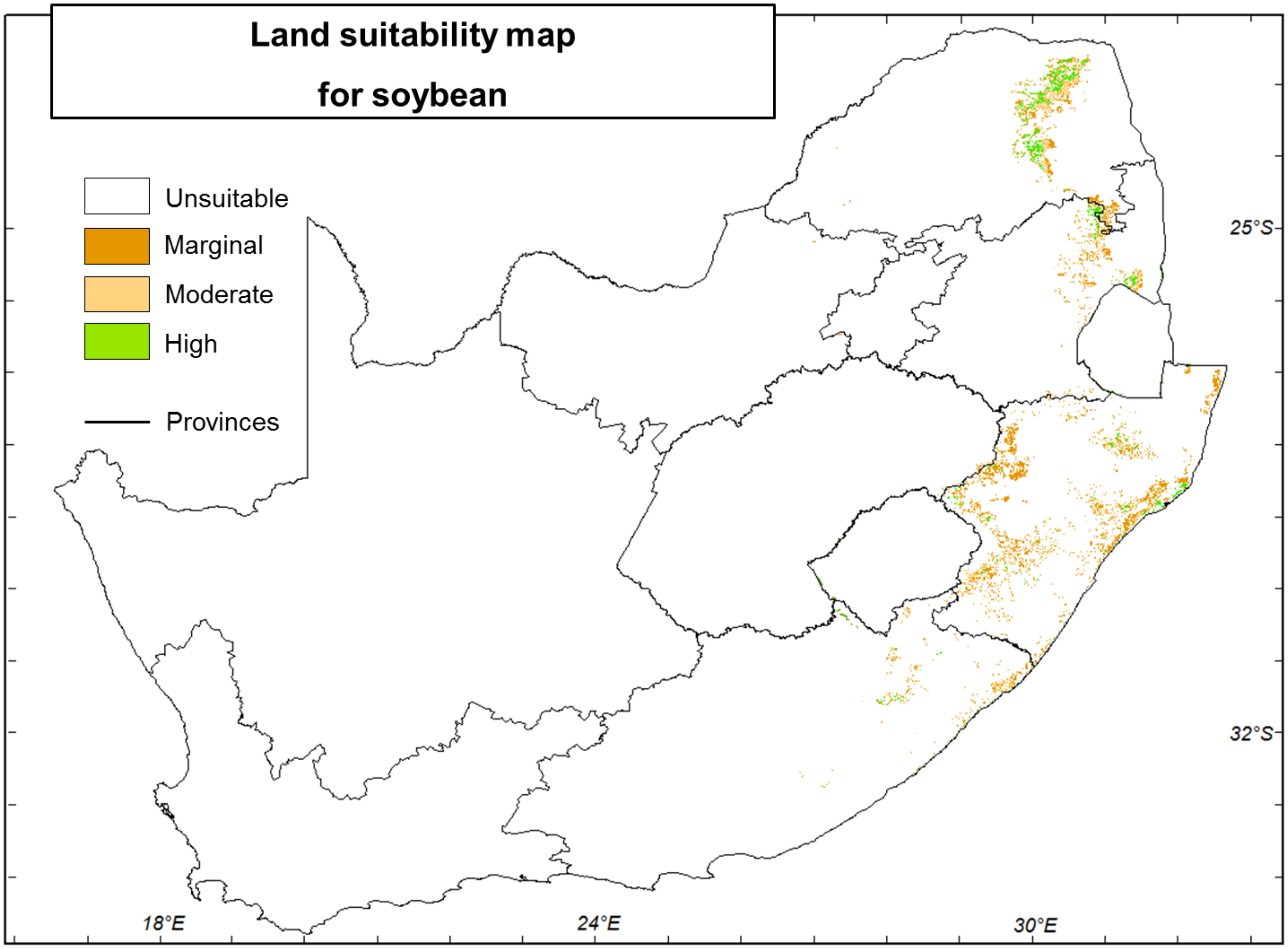


Figure 5.9: Land suitability map for soybean based on basal (SAPWAT3; i.e. local) crop coefficients

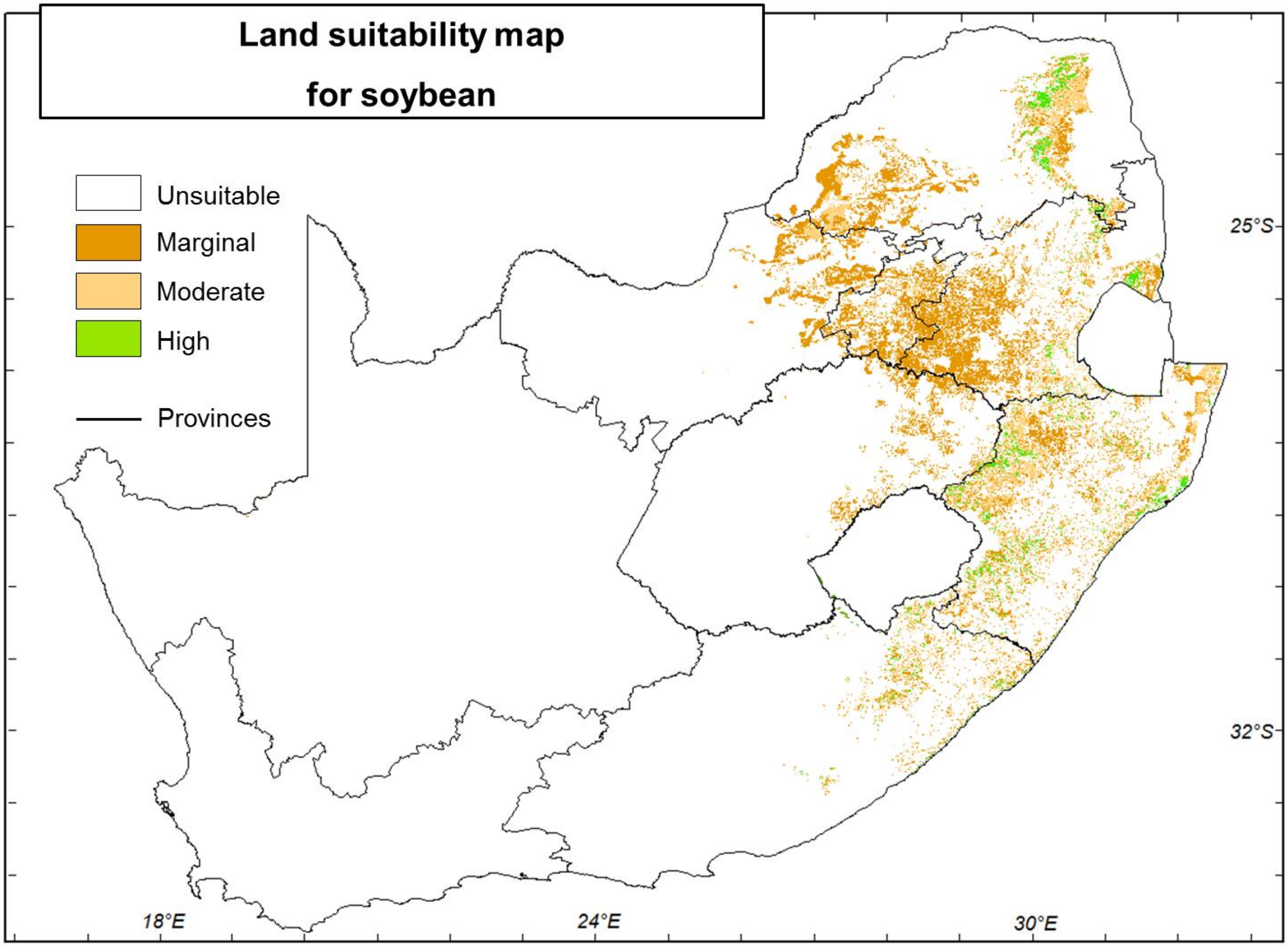


Figure 5.10: Land suitability map for soybean based on single (Baynesfield) crop coefficients

5.4 Map Validation

5.4.1 Comparison with estimated yields

The soybean suitability map produced using local crop coefficients (Figure 5.10) was compared to a soybean yield map (Figure 5.11), produced by Schulze and Maharaj (2007a). The visual comparison showed that the two maps are similar in terms of overall suitability area. However, Figure 5.10 is patchier due to small “pockets” of land being eliminated due to the inclusion of other site criteria.

The comparison showed that the marginal areas of western Mpumalanga, Gauteng and western Limpopo correspond to estimated yields of under 2 $t.ha^{-1}$. Similarly, the highly suitable areas in eastern Limpopo and western KwaZulu-Natal co-incide with higher yielding areas (> 3 $t.ha^{-1}$). A similar exercise was undertaken for sorghum where a yield map (not shown) produced by Schulze and Maharaj (2007b) was compared to the sorghum suitability map (based on local K_c values). The visual comparison again showed good correlation between the marginal areas and estimated yields below 5 $t.ha^{-1}$. The highly suitable area corresponds with yields in excess of 7 $t.ha^{-1}$.

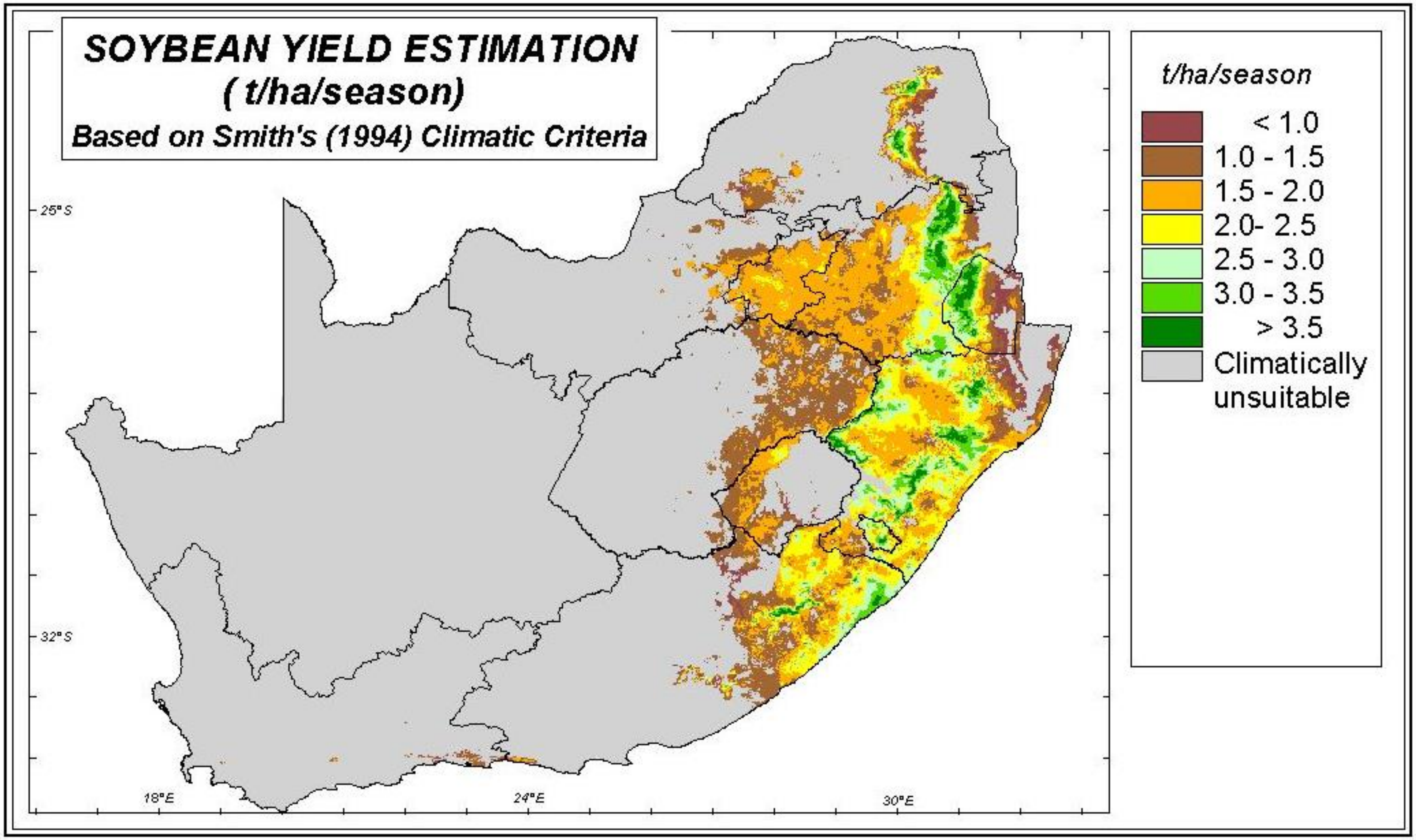


Figure 5.11: Distribution patterns over South Africa of dryland soybean yield estimates according to Smith's climatic criteria (Schulze and Maharaj, 2007a)

5.4.2 Comparison with observed yields

The final map (Figure 5.12) involved an overlay of soybean yields obtained from Stats SA (Stats SA, 2007) for dryland conditions and aggregated to magisterial district level. The dryland yields were used to identify lower production areas (< 1.8 $t.ha^{-1}$) and higher production areas (> 2.0 $t.ha^{-1}$). It is unfortunate that the yield data was aggregated to magisterial district level and not made available at farm level. Nevertheless, the overlay proved useful in assessing whether the highly suitable areas corresponded with the higher yielding areas, with some agreement in Kwa-Zulu Natal near the Lesotho border.

A similar exercise was undertaken to determine if the marginal areas "matched" the lower yielding sites, with good agreement in the Free State and Mpumalanga province. Figure 5.12 shows that soybean farmers are located in the western Free State which is deemed unsuitable for production (based on local K_c values). It is likely that only a few farms occur in this region and that a particular drought resistant cultivar or variety is grown.

It was not possible to compare the grain sorghum suitability map with yield data obtained from the Stats SA census. This was because data were only available for the Free State and Mpumalanga provinces. Figure 8.7 shows that the vast majority of cane production farms are classified as being suitable for sugarcane cultivation.

5.5 Location of Biofuel Processing Plants

According to Figure 5.10, the map shows that most parts of the Eastern Cape province are not suitable for soybean production. Thus, it makes little sense to construct a soybean-to-biodiesel processing plant at Coega (Port Elizabeth) if Mpumalanga, Free State and KwaZulu-Natal are mostly suited to the feedstock. The location of the Cradock sorghum-to-ethanol plant is also illogical considering the low sorghum production potential in the Eastern Cape. On the other hand, the Ubuhle Renewable Energy plant in Jozini (KwaZulu-Natal) is well sited because most parts of KwaZulu-Natal are suitable for sugarcane production (Figure 8.6).

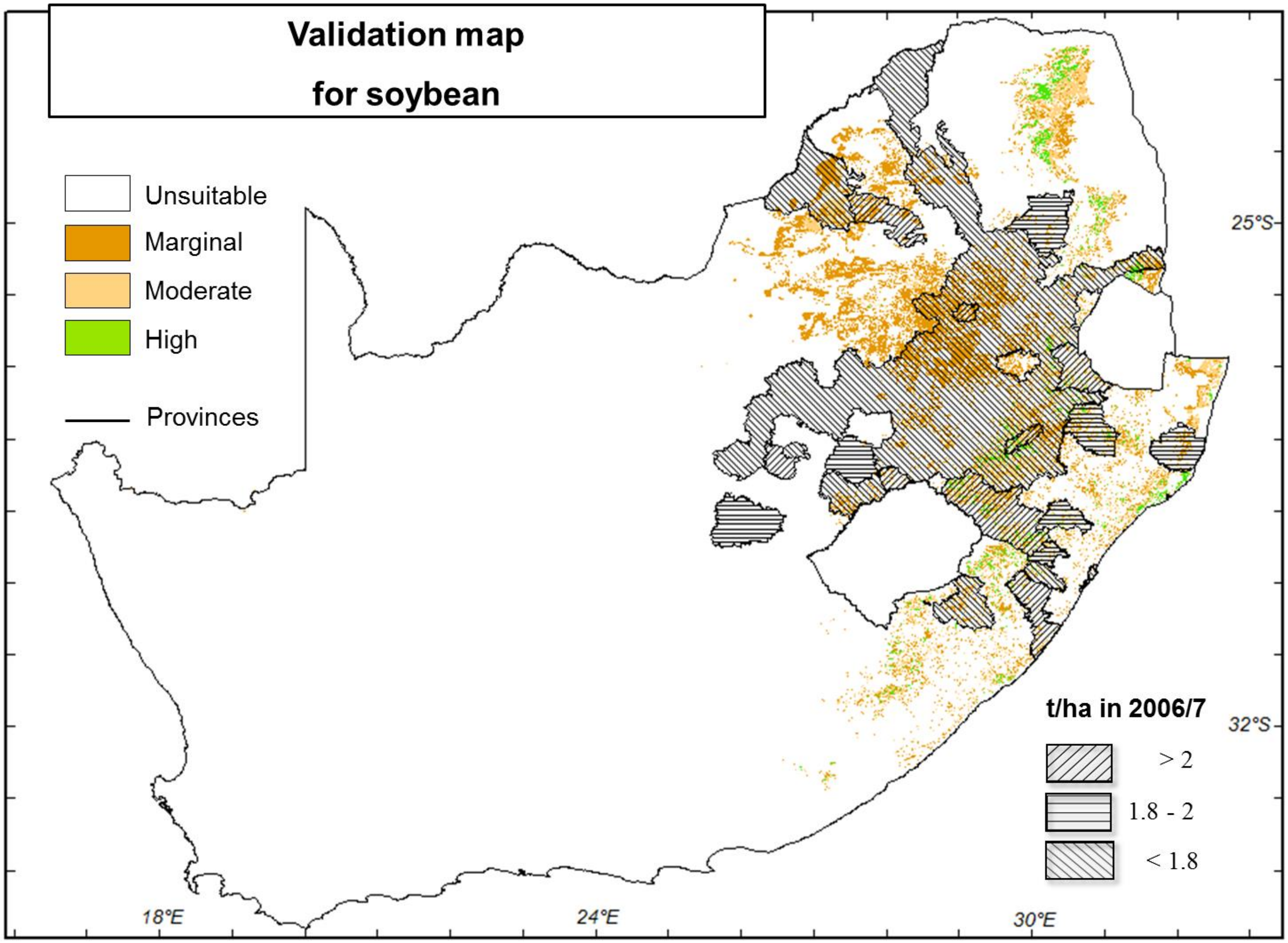


Figure 5.12: Land suitability map for soybean (based on local K_c) with soybean yields obtained under dryland conditions from Stats SA (for each magisterial district)

5.6 Weighted *vs.* Boolean Mapping Approach

The figures provided in Table 5.8 show that the simpler Boolean-type mapping approach tends to over-estimate the land area realistically available to feedstock production. This is particularly so for soybean and grain sorghum where the weighted approach classifies approximately half of the land as suitable, when compared to the Boolean method. The Boolean method used by Jewitt *et al*. (2009a) was discussed earlier in Section 5.1 where a grid cell is either suitable or unsuitable for feedstock production. The figures provided in Table 5.8 also highlight the sensitivity of the mapping approach to the crop coefficients used (i.e. FAO *vs*. local). For soybean using local K_c values, the highly suitable class occupies 0.24 % of South Africa's total area, moderately suitable constitutes 1.68 %, marginally suitable is 4.76 % and the remaining 93.32 % is unsuitable (Table 5.8).

Table 5.8: Land area suited to biofuel feedstock production based on three different mapping approaches

Feedstock	**Area expressed in million ha and percentage of South Africa**										
	High (S1)		Moderate (S2)		Marginal (S3)		Suitable (S1+S2+S3)		Not suitable (N)		Total area (Mha)
	Local crop coefficients										
	Mha	%	Mha	%	Mha	%	Mha	%	Mha	%	
Soybean	0.29	0.24	2.05	1.68	5.80	4.76	8.14	6.68	113.76	93.32	121.90
Sorghum	0.27	0.23	2.59	2.12	4.45	3.65	7.31	6.00	114.59	94.00	121.90
Sugarcane	0.34	0.28	0.46	0.37	1.71	1.40	2.51	2.06	119.39	97.94	121.90
	FAO crop coefficients (or Boolean approach)										
Soybean	0.60	0.49	2.65	2.17	6.07	4.98	9.32	7.65	112.58	92.35	121.90
Sorghum	0.59	0.49	3.43	2.81	3.46	2.84	7.48	6.14	114.42	93.86	121.90
Sugarcane	0.71	0.58	1.44	1.18	3.14	2.60	5.32	4.36	116.58	95.64	121.90
	Elimination of unsuitable areas										
Soybean	-	-	-	-	-	-	19.73	16.18	102.17	83.82	121.90
Sorghum	-	-	-	-	-	-	19.12	15.69	102.78	84.31	121.90
Sugarcane	-	-	-	-	-	-	2.12	1.74	119.78	98.26	121.90

For grain sorghum based on local K_c values the highly suitable class occupies 0.23 % of the total area, moderately suitable constitutes 2.12 %, marginally suitable is 3.65 % and the remaining 94.00 % is unsuitable (Table 5.8). For sugarcane using local K_c values the highly suitable class accounts for 0.28 % of the total area, moderately suitable constitutes 0.37 %, and marginally suitable is 1.40 % and the remaining 97.94 % is unsuitable (Table 5.8).

Based on the figures in Table 5.8, soybean exhibits the highest potential for agricultural expansion in South Africa, with sugarcane having the least potential for expansion. In addition, the maps show that KwaZulu-Natal is the only province capable of producing all three feedstocks in sufficient quantities to meet the projected biofuel demand as determined by the mandatory blending rates.

A comparison of the total area of land suitable for soybean and grain sorghum production highlights that the elimination approach shows more than double that highlighted by crop coefficient approaches. In other words, given that the local K_c approach provides the most realistic estimates of land suitable for feedstock production, these areas are approximately half of those produced by the Boolean approach.

5.7 Summary

This chapter presented and discussed the results obtained from the land suitability assessment completed for soybean, grain sorghum and sugarcane in South Africa. The findings were based on rainfall, temperature, relative humidity, slope and soil depth criteria, with current land use and existing protected areas also taken into consideration. This approach provided a realistic estimate of the land available in South Africa for biofuel production. However, further analysis is required to include other important social and economic factors. The following chapter summaries the main findings as well as recommendations for future studies.

6. CONCLUSIONS

The objectives listed in the introduction are revisited in this chapter. This chapter also provides a summary of the major findings and the conclusions drawn from them. It also highlights some limitations with the methodology as well as providing recommendations for future research.

6.1 Summary of Approach

The main objective of this study was to map areas suitable for the cultivation of selected biofuel feedstocks and to improve the mapping approach used in previous studies. The feedstocks considered were soybean, grain sorghum and sugarcane, which are listed as the preferred feedstocks for biofuel production in South Africa. The literature review on growth criteria added to that undertaken in previous studies. In order to meet the main objective, spatial rainfall data were classified into different suitability classes according to each feedstock's crop water requirements, using the crop coefficient concept. Spatial temperature, relative humidity, soil depth and slope data were also categorised into different classes to facilitate the separation of optimum and sub-optimum growing conditions. Land use datasets were used to exclude areas that are classified as built-up, mining, water bodies and protected as well as to avoid areas currently under forest plantations. It was important to eliminate these so-called "no-go" areas in order to find land area realistically available to feedstock production. This approach helped to obtain a more realistic map of areas that can be planted to biofuel feedstocks. This desktop study made use of the latest available datasets. However, small patches of land may have been ignored (i.e. not highlighted as suitable) due to the coarseness of input climate data, which cannot account for microclimate effects.

6.2 Summary of Findings

The approach used in previous mapping studies (e.g. biofuels scoping study) was improved by including other suitability criteria such as relative humidity, slope and soil depth in the identification of suitable growing areas. By including these factors, it was shown that the potential area for biofuel feedstock production is smaller than that suggested in other studies.

This study showed that the Boolean-type mapping approaches (i.e. where areas are classified as suitable or unsuitable) tend to overestimate the land area considered suitable for feedstock growth.

The importance of rainfall distribution across the growing season and not just total seasonal rainfall was also highlighted in this study. A unique methodology, based on the crop coefficient concept, was used to identify when the crop requires most rainfall during its growth cycle. The importance of using crop coefficients that are applicable to local growing conditions (and not obtained from overseas studies) was also highlighted. The study then showed that basal crop coefficients (based on transpiration only) should not be used, but rather single crop coefficients which also account for soil water evaporation should form part of the approach. An attempt was made to validate the results, but this served only to highlight the lack of observed yield data at an appropriate scale and that validation in a statistical sense was not possible. The output from this study should help guide the way forward for the emerging biofuels industry, by providing information at a more appropriate level for decision-makers and local government.

6.3 Recommendations for Future Research

The results from this study have led to the derivation of the following recommendations:

(a) This study mainly considered the biophysical requirements for biofuel feedstock production. However, it is important to also consider non-biophysical factors related to social and economic constraints which may limit feedstock production.

(b) Biofuel production requires infrastructure such as feedstock storage facilities, biofuel processing plants as well as an adequate transport (road and railway) network. It is therefore vital to conduct proximity studies which account for the distance to/from the required infrastructure. This information can then be used to adjust the assessment of which areas are deemed highly suitable for feedstock production.

(c) From a sustainability view point, it is also recommended that the effects of climate change on optimum growing areas are considered (in particular, to assess the potential shifts in growing regions).

(d) It is also recommended that other climate-related site factors such as vapour pressure deficit and dew point temperature (as opposed to relative humidity), are explored as suitable surrogate variables for disease risk.

(e) Finally, the methodology should be extended to include future land use needs that account for, *inter alia*, the growing population and the need to meet future biodiversity protection targets.

(f) An updated land cover dataset should be used in future studies.

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8. APPENDIX

8.1 Grain sorghum

According to Smith (2006), the optimum planting date for sorghum is between late October and early November, the medium season length is 115 days. However, a similar season length of November to March was adopted for grain sorghum. Table 8.1 represents the distribution of seasonal rainfall in each month of the growing season which better represents longer seasonal varieties based on FAO crop coefficient.

Table 8.1: Distribution of seasonal rainfall in each month of the growing season for grain sorghum, based on FAO crop coefficient (with values rounded to the nearest 5 mm)

Month	**Growth stage**	**K_c**	**K_c norm**	**Monthly rainfall thresholds (mm)**					
November	Ini	0.40	0.095	40	45	60	75	95	115
December	Dev	0.80	0.190	75	85	125	150	190	230
January	Mid	1.00	0.238	95	105	155	190	240	285
February	Mid	1.20	0.286	*115*	*130*	*185*	*235*	*285*	*340*
March	End	0.80	0.190	75	85	125	150	190	230
Total		**4.20**	**1.000**	**400**	**450**	**650**	**800**	**1000**	**1200**

Based on the locally derived crop coefficient values which were derived by Mengistu *et al*. (2014), the majority of seasonal rainfall should occur in January and February in order to satisfy the peak water requirements of the crop. The rainfall that should fall in January and February for a ranking of 3 is 150 – 185 (Table 8.2). However, the optimum rainfall at planting is 75 – 190 mm.

Table 8.2: Distribution of seasonal rainfall in each month of the growing season for grain sorghum based on local crop coefficients, with values rounded to the nearest 5 mm

Month	**Growth stage**	**K_c**	**K_c norm**	**Monthly rainfall thresholds (mm)**					
November	Ini	0.52	0.116	45	50	75	90	115	140
December	Dev	1.00	0.222	90	100	145	180	220	265
January	Mid	1.05	0.233	95	105	150	185	235	280
February	Mid	1.03	0.229	90	105	150	185	230	275
March	End	0.90	0.200	80	90	130	160	200	240
Total		**4.50**	**1.000**	**400**	**450**	**650**	**800**	**1 000**	**1 200**

Table 8.3: Ranking of each suitability class based on thresholds of monthly means of daily average temperature (ºC) for grain sorghum

Code	Not	Abs	Sub	Opt	Sub	Abs	Not
Suitability Class	N1	S3	S2	S1	S2	S3	N1
Ranking	0	1	2	3	2	1	0
Nov – March	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35

Table 8.3 summarises the temperature suitability classes and rankings (i.e. scores) used for sorghum. The temperature thresholds were also gleaned from the literature review. If the monthly temperature is within the ideal range for each of the five months during the growing season (i.e. ranking of 3 assigned to each month), it produces a maximum temperature suitability score of 0.6 out of 3 (Table 8.4). In essence, a total of five new re-classified temperature grids were generated, then weighted and summed to calculate the temperature suitability score.

Table 8.4: Maximum temperature suitability score when each month's temperature is ideally suited to soybean cultivation

Month	**Optimum range (ºC)**	**Ranking**	**Relative weighting**	**Decimal weighting**	**Suitability score**
November	15 – 18	3	0.50	0.05	0.15
December	23 – 27	3	0.20	0.020	0.06
January	23 – 27	3	0.50	0.050	0.15
February	23 – 27	3	0.30	0.030	0.09
March	23 – 27	3	0.50	0.050	0.15
Total			**2.00**	**0.20**	**0.60**

The relative humidity suitability classes and scores are summarised in Table 8.5 below. Ergot severity increases curvilinearly as minimum relative humidity increase above 40 to 80 % as shown in Figure 2.1; (*cf*. Section 2.4.2).

Table 8.5: Ranking of each suitability class based on thresholds of monthly means of daily minimum relative humidity (%) for grain sorghum

Code	**Suitability class**	**Minimum relative humidity (%)**	**Ranking**
Opt	S1	< 40	3
Sub	S2	40 – 60	2
Abs	S3	60 – 80	1
Not	N1	> 80	0

The relative humidity weighting are highest in January because of the ergot attacks when sorghum is flowering (Montes *et al.,* 2009). The crop flowers in January, based on a growing season of 115 days (Montes *et al.,* 2009). If the humidity level is within the ideal range for each of the five months during the growing season (i.e. ranking of 3 assigned to each month), it produces a total suitability score of 0.3 out of 3 (Table 8.6).

Table 8.6: Suitability score when each month's minimum relative humidity is ideally suited to sorghum cultivation

Month	**Optimum range (%)**	**Ranking**	**Relative weighting**	**Decimal weighting**	**Suitability score**
November	< 40	3	0.10	0.01	0.03
December	< 40	3	0.30	0.03	0.09
January	< 40	3	0.40	0.04	0.12
February	< 40	3	0.10	0.01	0.03
March	< 40	3	0.10	0.01	0.03
Total			**1.00**	**0.10**	**0.30**

Table 8.7 summarises the soil depth suitability classes and rankings (i.e. scores) used for sorghum. The soil depth thresholds were also gleaned from the literature review and are deeper than those used for soybean since grain sorghum is a deeper rooted crop (which also helps to prevents lodging). The slope criteria used was the same as soybean one (*cf.* Table 4.9; Section 4.6.5).

Table 8.7: Ranking of each suitability class based on soil depth (mm) for sorghum

Code	**Suitability class**	**Soil depth (mm)**	**Ranking**
Opt	S1	> 800	3
Sub	S2	500 – 800	2
Abs	S3	300 – 500	1
Not	N2	< 300	0

8.2 Sugarcane

In this study, the approach adopted by Jewitt *et al*. (2009b) was used, where the sugarcane production areas in KwaZulu-Natal were sub-divided into three regions *viz*. inland, northern coastal and southern coastal. The irrigated sugarcane production areas were not considered as it is considered unsuitable to irrigate biofuel crop from a sustainability viewpoint. The city of Durban provides the boundary between the northern and southern coastal production regions.

Quinery catchments with an average altitude of 400 m or above are classified as inland. K_c values for inland areas were derived from experiments conducted at Eston in the KwaZulu-Natal midlands. Similarly, experiments conducted at Kearsney Manor and Umzinto provided monthly K_c values for the northern and southern coastal areas respectively (Jewitt *et al*., 2009b). The crop coefficients are based on unstressed sugarcane grown under ratooned conditions (Table 8.8).

Table 8.8: Representative values for crop coefficients (K_c) for unstressed ratoon sugarcane for the three main production areas in KwaZulu-Natal (Jewitt *et al*., 2009b)

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

In addition, crop coefficients for ratooned sugarcane from FAO (2013) were also considered in this study, as shown in Table 8.9. The winter values (Apr-Sep) are below the local K_c values, but the summer values compare more favourably.

Table 8.9: FAO-based crop coefficients (K_c) for unstressed ratoon sugarcane (FAO, 2013)

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

Table 8.10 summarises temperature suitability classes (i.e. scores) used for sugarcane. The temperature thresholds were also gleaned from the literature review. If the monthly temperature is within the ideal range for each of the 12 months during the growing season (i.e. ranking of 3 assigned to each month), it produces a maximum temperature suitability score of 0.6 out of 3.

Table 8.10: Ranking of each suitability class based on thresholds of monthly means of daily average temperature (ºC) for soybean

Code	Not	Abs	Sub	Opt	Sub	Abs	Not
Suitability Class	N1	S3	S2	S1	S2	S3	N1
Ranking	0	1	2	3	2	1	0
Sep – Apr	< 15	15 – 20	20 – 22	22 – 30	30 – 32	32 – 35	> 35
May – Aug	< 08	08 – 10	10 – 12	12 – 14	14 – 20	20 – 24	> 24

Table 8.11: Ranking of each suitability class based on thresholds of monthly means of daily average relative humidity (%) for sugarcane

Code	Not	Abs	Sub	Opt	Sub	Abs	Not
Suitability Class	N1	S3	S2	S1	S2	S3	N1
Ranking	0	1	2	3	2	1	0
Sep – Apr	< 30	30 – 70	70 – 80	80 – 85	85 – 90	90 – 95	> 95
May – Aug	< 20	20 – 35	35 – 45	45 – 65	65 – 75	75 – 85	> 85

The relative humidity suitability classes and scores are summarised in Table 8.11 above. A total of 12 new re-classified humidity grids were generated, then weighted and summed to calculate the humidity suitability score. According to Hull *et al.* (2008), the rate at which rust is able to spread depends largely upon temperature and humidity shown in many studies. High temperatures in conjunction with high humidity levels have been found to be most conducive for the infection of common rust (Hull *et al.*, 2008).

Table 8.12: Ranking of each suitability class based on slope (%) for sugarcane (Russell, 1997)

Code	**Suitability class**	**Soil slope (%)**	**Ranking**
Opt	S1	< 10	3
Sub	S2	10 – 15	2
Abs	S3	15 – 30	1
Not	N2	> 30	0

Table 8.12 summarises the slope suitability classes and rankings used in this study for sugarcane. Hence, Russell (1997) stated that a slope greater than 30 % is considered too steep for sugarcane

production due to soil erosion hazard. Table 8.13 summarises the soil depth suitability classes and rankings (i.e. scores) used for soybean. The soil depth thresholds were also gleaned from the literature review. These thresholds are deeper than those for grain sorghum, since sugarcane is not as drought tolerant. Summary tables for grain sorghum and sugarcane are provided in Tables 8.14 to 8.18 respectively.

Table 8.13: Ranking of each suitability class based on soil depth (mm) for sugarcane

Code	**Suitability class**	**Soil depth (mm)**	**Ranking**
Opt	S1	> 1 000	3
Sub	S2	700 – 1 000	2
Abs	S3	400 – 700	1
Not	N2	< 400	0

Table 8.14: Summary of suitability criteria and ranking used to identify areas suitable for grain sorghum cultivation, based on FAO K_c values

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative Weighting	Decimal Weighting
Ranking	0	1	2	3	2	1	0		
Rainfall totals apportioned per month based on FAO crop coefficients (mm)									
November	< 40	040 – 045	045 – 060	60 – 075	75 – 95	095 – 115	> 115	0.40	0.040
December	< 75	075 – 085	085 – 125	125 – 150	150 – 190	190 – 230	> 230	0.74	0.074
January	< 95	95 – 105	105 – 155	155 – 190	190 – 240	240 – 285	> 285	0.94	0.094
February	< 115	115 – 130	130 – 185	185 – 235	235 – 285	285 – 340	> 340	1.14	0.114
March	< 75	75 – 85	85 – 125	125 – 150	150 – 190	190 – 230	> 230	0.79	0.079
	< 400	**400 – 450**	**450 – 650**	**650 – 800**	**800 – 1 000**	**1 000 – 1 200**	**> 1 200**	**4.00**	**0.400**
Monthly means of daily average temperature (ºC)									
November	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.50	0.050
December	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.20	0.020
January	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.50	0.050
February	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.30	0.030
March	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.50	0.050
								2.00	**0.200**
Monthly means of daily minimum relative humidity (%)									
November				< 40	40 – 60	60 – 80	> 80	0.10	0.010
December				< 40	40 – 60	60 – 80	> 80	0.30	0.030
January				< 40	40 – 60	60 – 80	> 80	0.40	0.040
February				< 40	40 – 60	60 – 80	> 80	0.10	0.010
March				< 40	40 – 60	60 – 80	> 80	0.10	0.010
								1.00	**0.100**
Soil depth (mm)									
All season	< 300	300 – 500	500 – 800	> 800				**1.00**	**0.100**
Slope (%)									
All season				< 4	4 – 8	8 – 10	> 10	**2.00**	**0.200**
Total								**10.0**	**1.000**

Table 8.15: Summary of suitability criteria and ranking used to identify areas suitable for grain sorghum cultivation, based on local K_c values

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative Weighting	Decimal Weighting
Ranking	0	1	2	3	2	1	0		
Rainfall totals apportioned per month based on local (Ukulinga) crop coefficients (mm)									
November	< 45	045 – 050	050 – 075	75 – 090	90 – 115	115 – 140	> 140	0.46	0.046
December	< 90	090 – 100	100 – 145	145 – 180	180 – 220	220 – 265	> 265	0.89	0.089
January	< 95	95 – 105	105 – 150	150 – 185	185 – 235	235 – 280	> 280	0.93	0.093
February	< 190	190 – 105	105 – 150	150 – 185	185 – 230	230 – 275	> 275	0.92	0.092
March	< 80	80 – 90	90 – 130	130 – 160	160 – 200	200 – 240	> 240	0.80	0.080
	< 400	**400 – 450**	**450 – 650**	**650 – 800**	**800 – 1 000**	**1 000 – 1 200**	**> 1 200**	**4.00**	**0.400**
Monthly means of daily average temperature (ºC)									
November	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.50	0.050
December	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.20	0.020
January	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.50	0.050
February	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.30	0.030
March	< 15	15 – 20	20 – 25	25 – 30	30 – 32	32 – 35	> 35	0.50	0.050
								2.00	**0.200**
Monthly means of daily minimum relative humidity (%)									
November				< 40	40 – 60	60 – 80	> 80	0.10	0.010
December				< 40	40 – 60	60 – 80	> 80	0.30	0.030
January				< 40	40 – 60	60 – 80	> 80	0.40	0.040
February				< 40	40 – 60	60 – 80	> 80	0.10	0.010
March				< 40	40 – 60	60 – 80	> 80	0.10	0.010
								1.00	**0.100**
Soil depth (mm)									
All season	< 300	300 – 500	500 – 800	> 800				**1.00**	**0.100**
Slope (%)									
All season				< 4	4 – 8	8 – 10	> 10	**2.00**	**0.200**
Total								**10.0**	**1.000**

Table 8.16: Summary of rainfall suitability criteria and ranking used to identify areas suitable for sugarcane cultivation in the inland and northern coastal regions

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative Weighting	Decimal Weighting
Ranking	0	1	2	3	2	1	0		
Rainfall totals (mm) apportioned per month based local on crop coefficients: Inland region									
September	< 60	060 – 080	080 – 095	095 – 110	110 – 130	130 – 145	> 145	0.29	0.029
October	< 60	060 – 080	080 – 090	090 – 105	105 – 125	125 – 140	> 140	0.28	0.028
November	< 70	070 – 095	095 – 110	110 – 125	155 – 150	150 – 170	> 170	0.34	0.034
December	< 75	075 – 095	095 – 110	110 – 130	130 – 155	155 – 175	> 175	0.35	0.035
January	< 80	080 – 105	105 – 125	125 – 140	140 – 170	170 – 190	> 190	0.38	0.038
February	< 85	085 – 110	110 – 130	130 – 150	150 – 180	180 – 200	> 200	0.40	0.040
March	< 90	090 – 110	110 – 140	140 – 160	160 – 190	190 – 200	> 200	0.41	0.041
April	< 75	075 – 095	095 – 115	115 – 130	130 – 160	160 – 175	> 175	0.35	0.035
May	< 75	075 – 095	095 – 110	110 – 130	130 – 155	155 – 175	> 175	0.35	0.035
June	< 60	060 – 080	080 – 095	095 – 110	110 – 130	130 – 145	> 145	0.29	0.029
July	< 65	065 – 080	080 – 095	095 – 110	110 – 135	135 – 150	> 150	0.30	0.030
August	< 55	055 – 075	075 – 085	085 – 100	100 – 120	120 – 135	> 135	0.27	0.027
	< 850	**850 – 1 100**	**1 100 – 1 300**	**1 300 – 1 500**	**1 500 – 1 800**	**1 800 – 2 000**	**> 2 000**	**4.00**	**0.400**
Rainfall totals (mm) apportioned per month based on local crop coefficients: Northern coastal region									
September	< 70	070 – 090	090 – 105	090 – 105	120 – 145	145 – 160	> 160	0.32	0.032
October	< 70	070 – 090	090 – 105	105 – 120	120 – 145	145 – 160	> 160	0.32	0.032
November	< 75	075 – 100	100 – 115	115 – 135	135 – 160	160 – 180	> 180	0.36	0.036
December	< 70	070 – 095	095 – 110	110 – 125	125 – 155	155 – 170	> 170	0.34	0.034
January	< 80	080 – 100	100 – 120	120 – 140	140 – 165	165 – 185	> 185	0.37	0.037
February	< 80	080 – 105	105 – 120	120 – 140	140 – 170	170 – 190	> 190	0.38	0.038
March	< 80	080 – 090	090 – 125	125 – 145	145 – 165	165 – 185	> 185	0.38	0.038
April	< 70	070 – 090	090 – 105	105 – 120	120 – 145	145 – 165	> 165	0.33	0.033
May	< 70	070 – 095	095 – 110	110 – 125	125 – 155	155 – 170	> 170	0.34	0.034
June	< 60	060 – 080	080 – 095	095 – 110	110 – 130	130 – 145	> 145	0.29	0.029
July	< 65	065 – 085	085 – 100	100 – 115	115 – 135	135 – 150	> 150	0.30	0.030
August	< 60	070 – 080	080 – 090	090 – 105	105 – 130	130 – 140	> 140	0.28	0.028
	< 850	**850 – 1 100**	**1 100 – 1 300**	**1 300 – 1 500**	**1 500 – 1 800**	**1 800 – 2 000**	**> 2 000**	**4.00**	**0.400**

Table 8.17: Summary of rainfall suitability criteria and ranking used to identify areas suitable for sugarcane cultivation in the southern coastal region as well as rainfall threshold based on FAO K_c values

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative Weighting	Decimal Weighting
Ranking	0	1	2	3	2	1	0		
Rainfall totals (mm) apportioned per month based on local crop coefficients: Southern coastal region									
September	< 70	070 – 090	090 – 105	105 – 125	125 – 150	150 – 165	> 165	0.33	0.033
October	< 65	065 – 080	080 – 095	095 – 110	110 – 135	135 – 150	> 150	0.30	0.030
November	< 75	075 – 100	100 – 115	115 – 135	135 – 160	160 – 175	> 175	0.35	0.035
December	< 70	070 – 095	095 – 110	110 – 125	125 – 150	150 – 170	> 170	0.34	0.034
January	< 80	080 – 105	105 – 120	120 – 140	140 – 170	170 – 185	> 185	0.37	0.037
February	< 85	085 – 105	105 – 125	125 – 145	145 – 175	175 – 195	> 195	0.39	0.039
March	< 75	075 – 105	105 – 135	135 – 145	145 – 165	165 – 205	> 205	0.39	0.039
April	< 70	070 – 090	090 – 110	110 – 125	125 – 150	150 – 165	> 165	0.33	0.033
May	< 75	075 – 095	095 – 110	110 – 130	130 – 155	155 – 170	> 170	0.34	0.034
June	< 60	060 – 080	080 – 090	090 – 105	105 – 130	130 – 140	> 140	0.28	0.028
July	< 65	065 – 080	080 – 095	095 – 110	110 – 135	135 – 140	> 145	0.29	0.029
August	< 60	060 – 075	075 – 090	090 – 105	105 – 125	125 – 135	> 135	0.27	0.027
	< 850	**850 – 1 100**	**1 100 – 1 300**	**1 300 – 1 500**	**1 500 – 1 800**	**1 800 – 2 000**	**> 2 000**	**4.00**	**0.400**
Rainfall totals (mm) apportioned per month based on FAO crop coefficients									
September	< 60	060 – 075	075 – 090	090 – 105	105 – 125	125 – 140	> 140	0.28	0.018
October	< 70	070 – 090	090 – 105	105 – 125	125 – 145	145 – 165	> 165	0.33	0.026
November	< 80	080 – 105	105 – 125	125 – 140	140 – 170	170 – 190	> 190	0.33	0.030
December	< 80	080 – 105	105 – 125	125 – 140	140 – 170	170 – 190	> 190	0.38	0.036
January	< 85	085 – 110	110 – 130	130 – 150	150 – 180	180 – 205	> 205	0.38	0.039
February	< 85	085 – 110	110 – 130	130 – 150	150 – 180	180 – 205	> 205	0.41	0.039
March	< 80	080 – 110	110 – 130	130 – 155	155 – 185	185 – 190	> 190	0.41	0.039
April	< 70	070 – 090	090 – 105	105 – 120	120 – 145	145 – 160	> 160	0.32	0.039
May	< 70	070 – 090	090 – 105	105 – 120	120 – 145	145 – 160	> 160	0.32	0.039
June	< 60	060 – 075	075 – 090	090 – 105	105 – 125	125 – 140	> 140	0.28	0.039
July	< 60	060 – 075	075 – 090	090 – 105	105 – 125	125 – 140	> 140	0.28	0.032
August	< 50	050 – 065	065 – 075	075 – 085	085 – 105	105 – 115	> 115	0.23	0.023
	< 850	**850 – 1 100**	**1 100 – 1 300**	**1 300 – 1 500**	**1 500 – 1 800**	**1 800 – 2 000**	**> 2 000**	**4.00**	**0.400**

Table 8.18: Summary of other criteria and ranking used to identify areas suitable for sugarcane cultivation

Suitability criteria and ranking									
Suitability class	Unsuitable	Marginal	Sub-optimum	Optimum	Sub-optimum	Marginal	Unsuitable	Relative Weighting	Decimal Weighting
Ranking	0	1	2	3	2	1	0		
Monthly means of daily average temperature (ºC)									
September	< 15	15 – 20	20 – 22	22 – 30	30 – 32	32 – 35	> 35	0.30	0.030
October	< 15	15 – 20	20 – 22	22 – 30	30 – 32	32 – 35	> 35	0.10	0.010
November	< 15	15 – 20	20 – 22	22 – 30	30 – 32	32 – 35	> 35	0.10	0.010
December	< 15	15 – 20	20 – 22	22 – 30	30 – 32	32 – 35	> 35	0.10	0.010
January	< 15	15 – 20	20 – 22	22 – 30	30 – 32	32 – 35	> 35	0.20	0.020
February	< 15	15 – 20	20 – 22	22 – 30	30 – 32	32 – 35	> 35	0.20	0.020
March	< 15	15 – 20	20 – 22	22 – 30	30 – 32	32 – 35	> 35	0.20	0.020
April	< 15	15 – 20	20 – 22	22 – 30	30 – 32	32 – 35	> 35	0.20	0.020
May	< 08	08 – 10	10 – 12	12 – 14	14 – 20	20 – 24	> 24	0.20	0.020
June	< 08	08 – 10	10 – 12	12 – 14	14 – 20	20 – 24	> 24	0.15	0.015
July	< 08	08 – 10	10 – 12	12 – 14	14 – 20	20 – 24	> 24	0.15	0.015
August	< 08	08 – 10	10 – 12	12 – 14	14 – 20	20 – 24	> 24	0.10	0.010
								2.00	**0.200**
Monthly means of daily average relative humidity (%)									
September	< 30	30 – 70	70 – 80	80 – 85	85 – 90	90 – 95	> 95	0.05	0.005
October	< 30	30 – 70	70 – 80	80 – 85	85 – 90	90 – 95	> 95	0.05	0.005
November	< 30	30 – 70	70 – 80	80 – 85	85 – 90	90 – 95	> 95	0.05	0.005
December	< 30	30 – 70	70 – 80	80 – 85	85 – 90	90 – 95	> 95	0.05	0.005
January	< 30	30 – 70	70 – 80	80 – 85	85 – 90	90 – 95	> 95	0.10	0.010
February	< 30	30 – 70	70 – 80	80 – 85	85 – 90	90 – 95	> 95	0.10	0.010
March	< 30	30 – 70	70 – 80	80 – 85	85 – 90	90 – 95	> 95	0.10	0.010
April	< 30	30 – 70	70 – 80	80 – 85	85 – 90	90 – 95	> 95	0.10	0.010
May	< 20	20 – 35	35 – 45	45 – 65	65 – 75	75 – 85	> 85	0.10	0.010
June	< 20	20 – 35	35 – 45	45 – 65	65 – 75	75 – 85	> 85	0.10	0.010
July	< 20	20 – 35	35 – 45	45 – 65	65 – 75	75 – 85	> 85	0.10	0.010
August	< 20	20 – 35	35 – 45	45 – 65	65 – 75	75 – 85	> 85	0.10	0.010
								1.00	**0.100**
Soil depth (mm)									
All season	< 400	400 – 700	700 – 1 000	> 1 000				**1.00**	**0.100**
Slope (mm)									
All season				< 10	10 – 15	15 – 30	> 30	**2.00**	**0.200**
Total								**10.0**	**1.000**

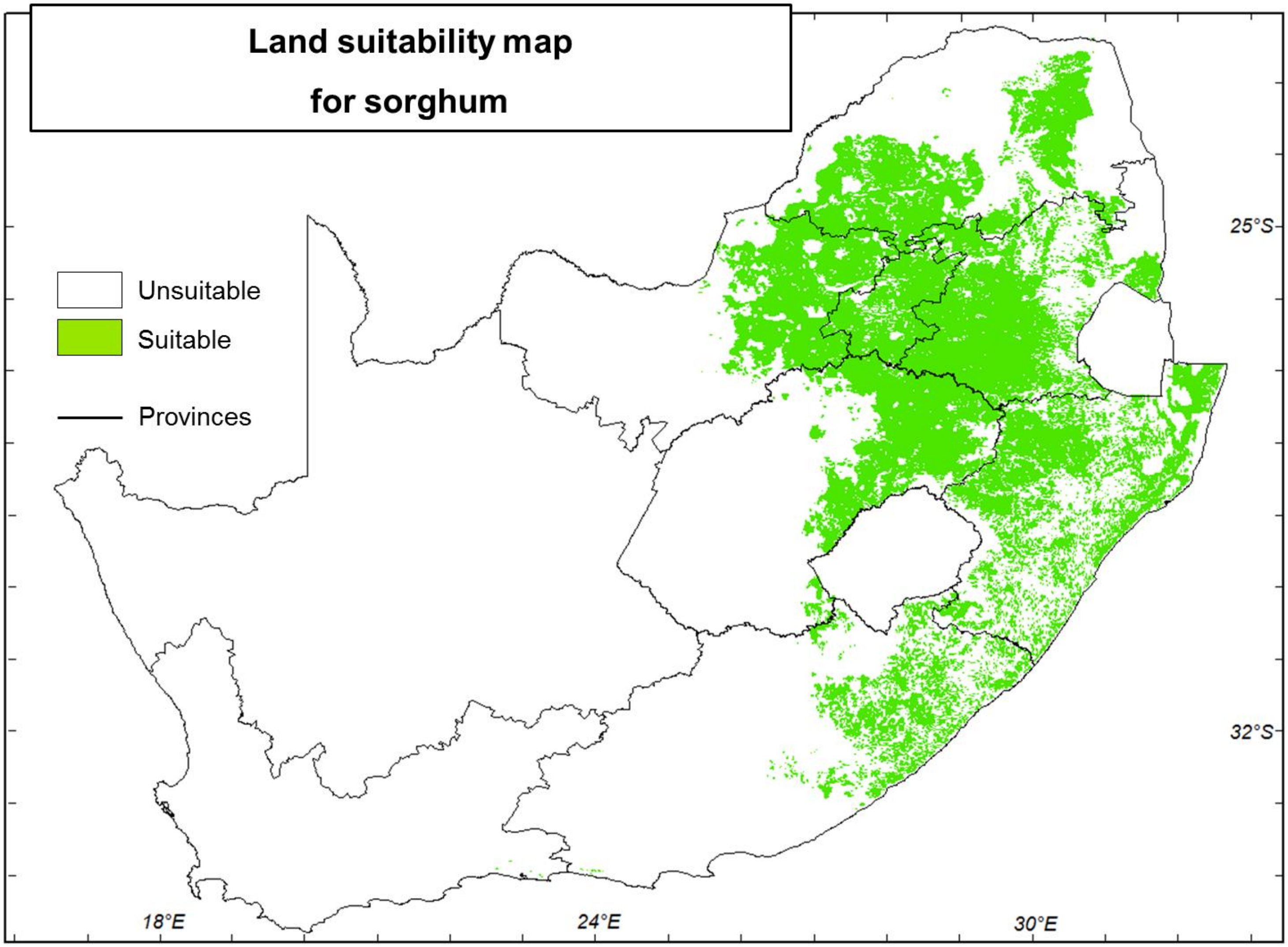

Figure 8.1: Potential (i.e. suitable) growing areas for grain sorghum

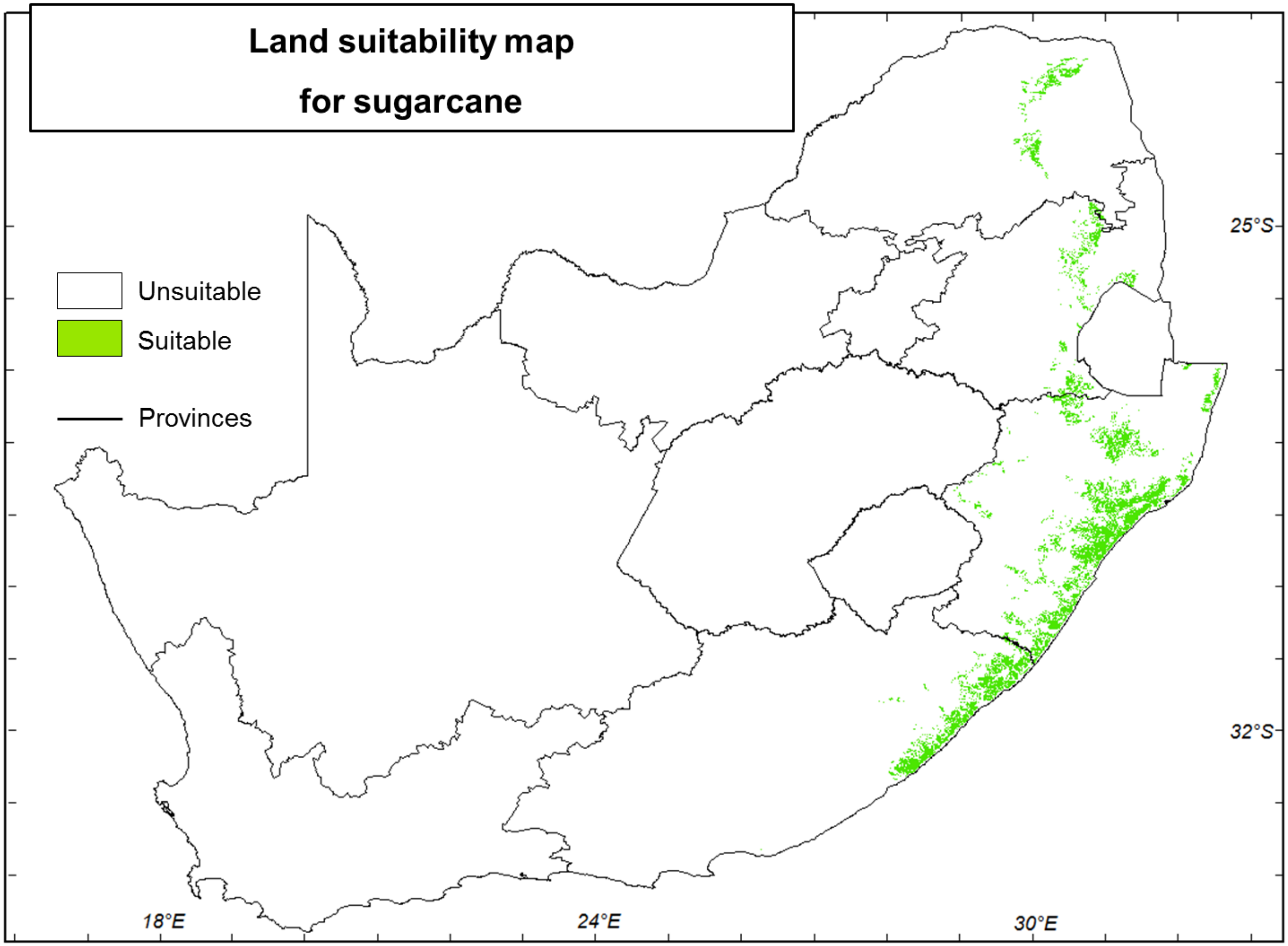

Figure 8.2: Potential (i.e. suitable) growing areas for sugarcane

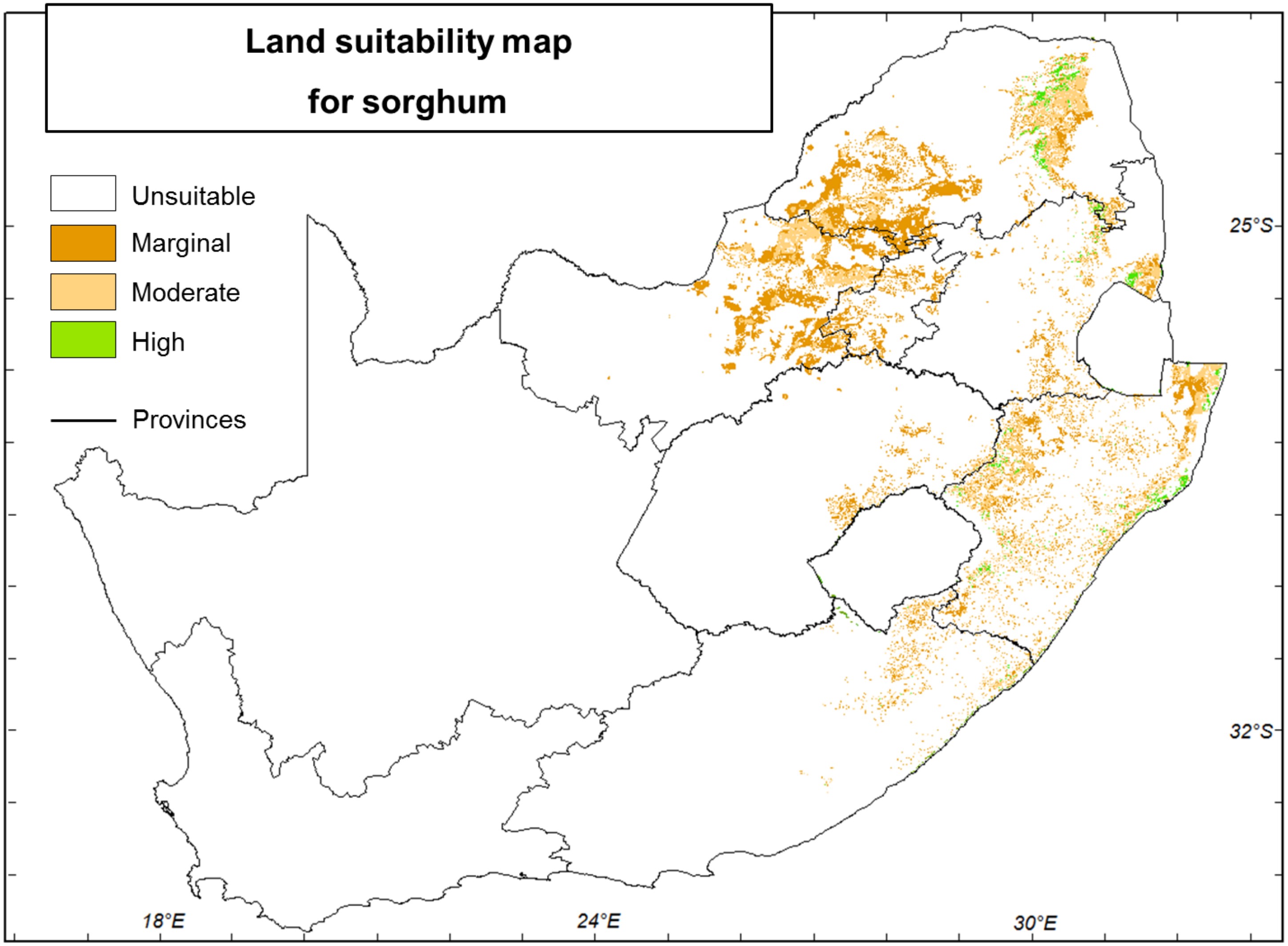

Figure 8.3: Overall suitability map for grain sorghum based on international FAO crop coefficient

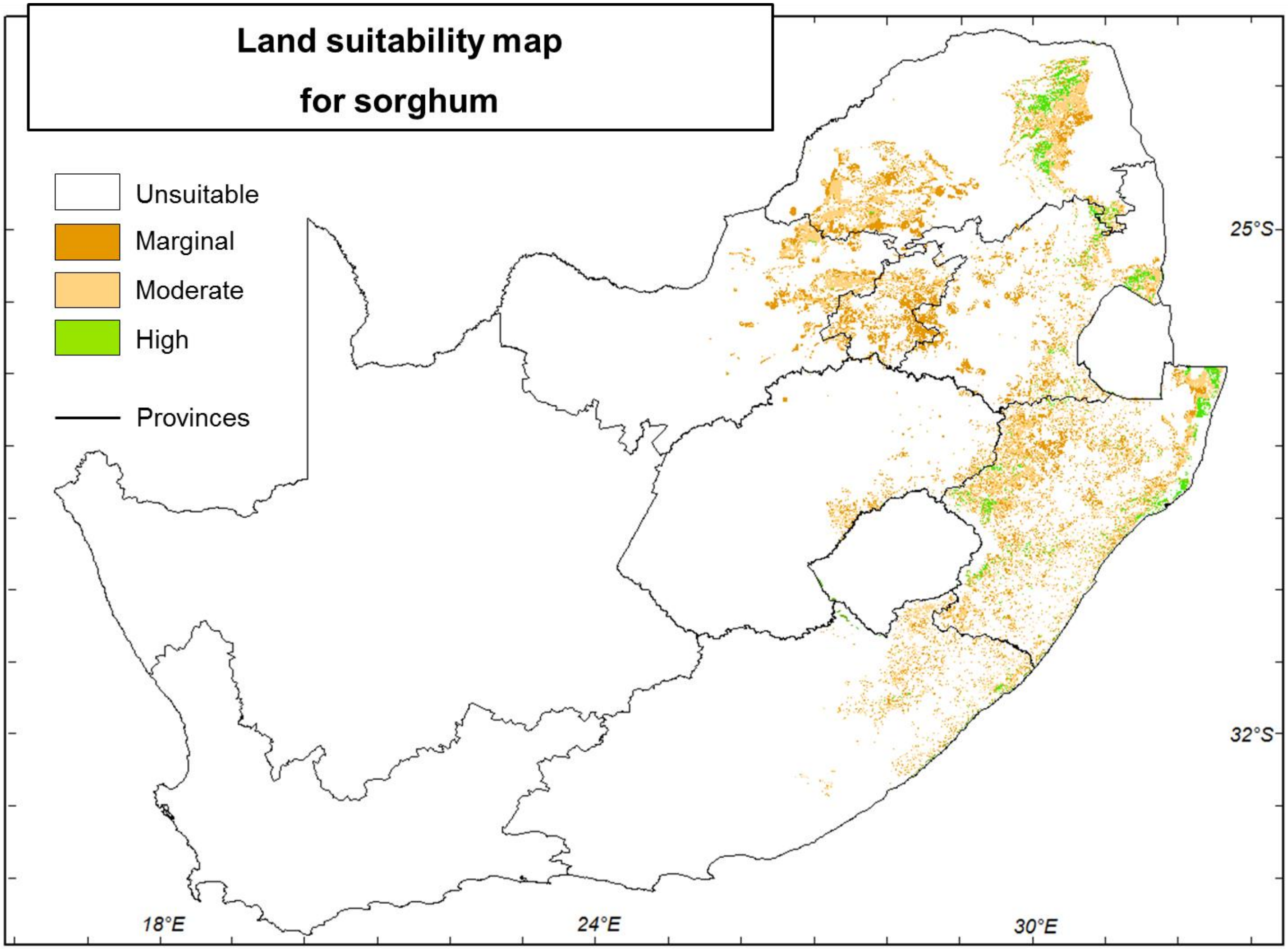

Figure 8.4: Overall suitability map for sorghum based on local (Ukulinga) crop coefficient

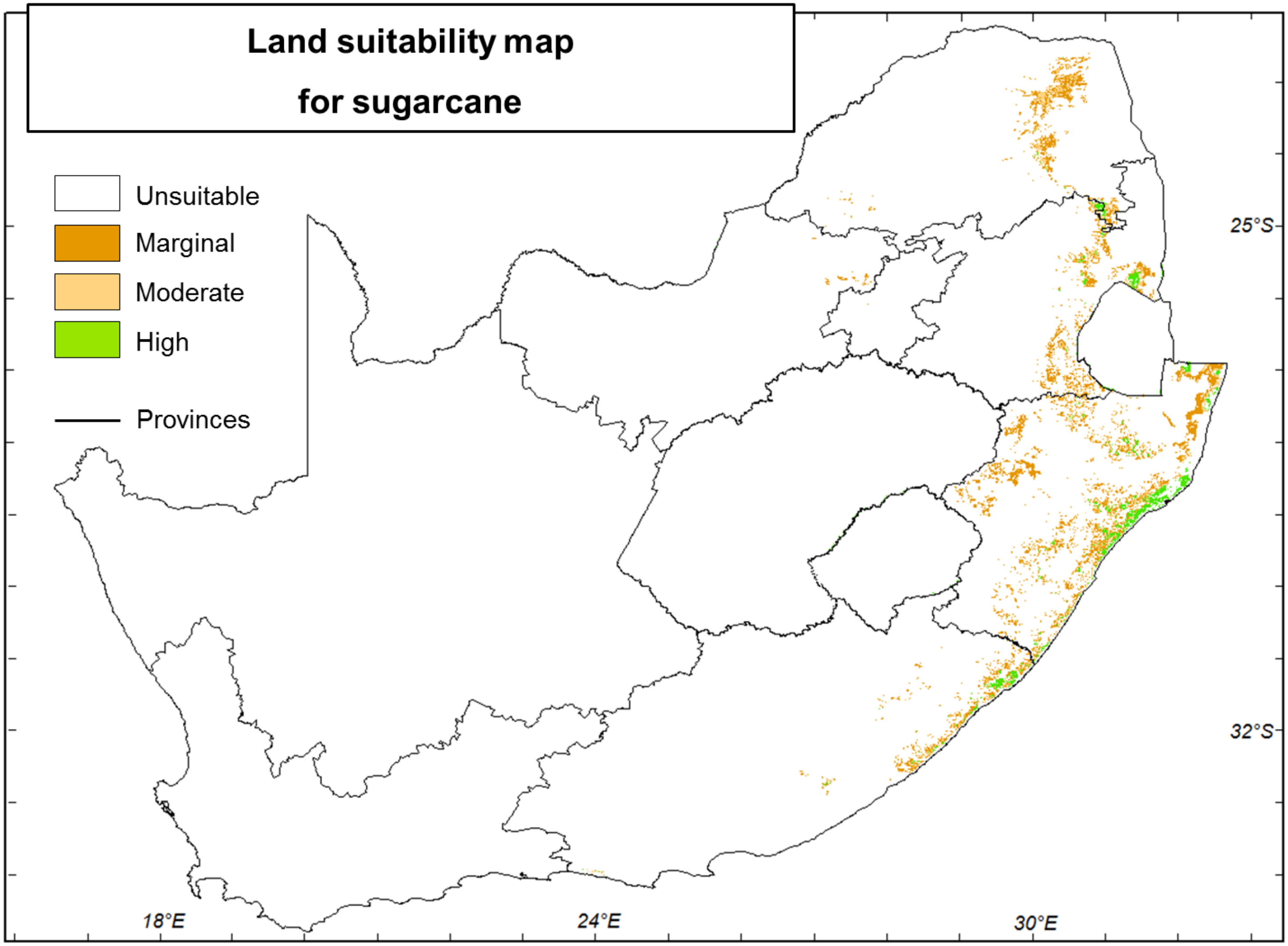

Figure 8.5: Overall suitability map for sugarcane based on international (FAO) crop coefficient

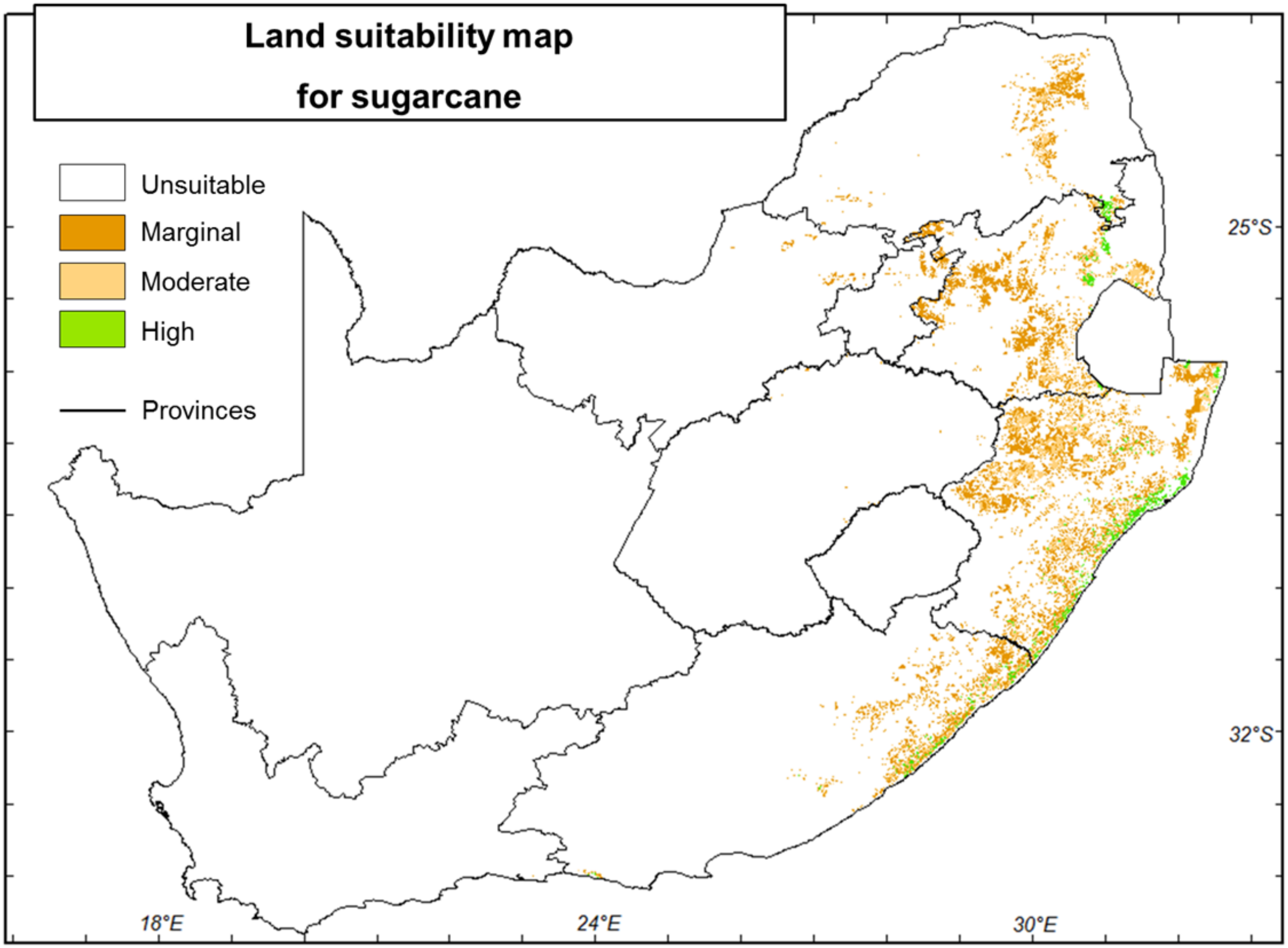

Figure 8.6: Land suitability map for sugarcane based on local Kearsney, Eston and Umzinto crop coefficient

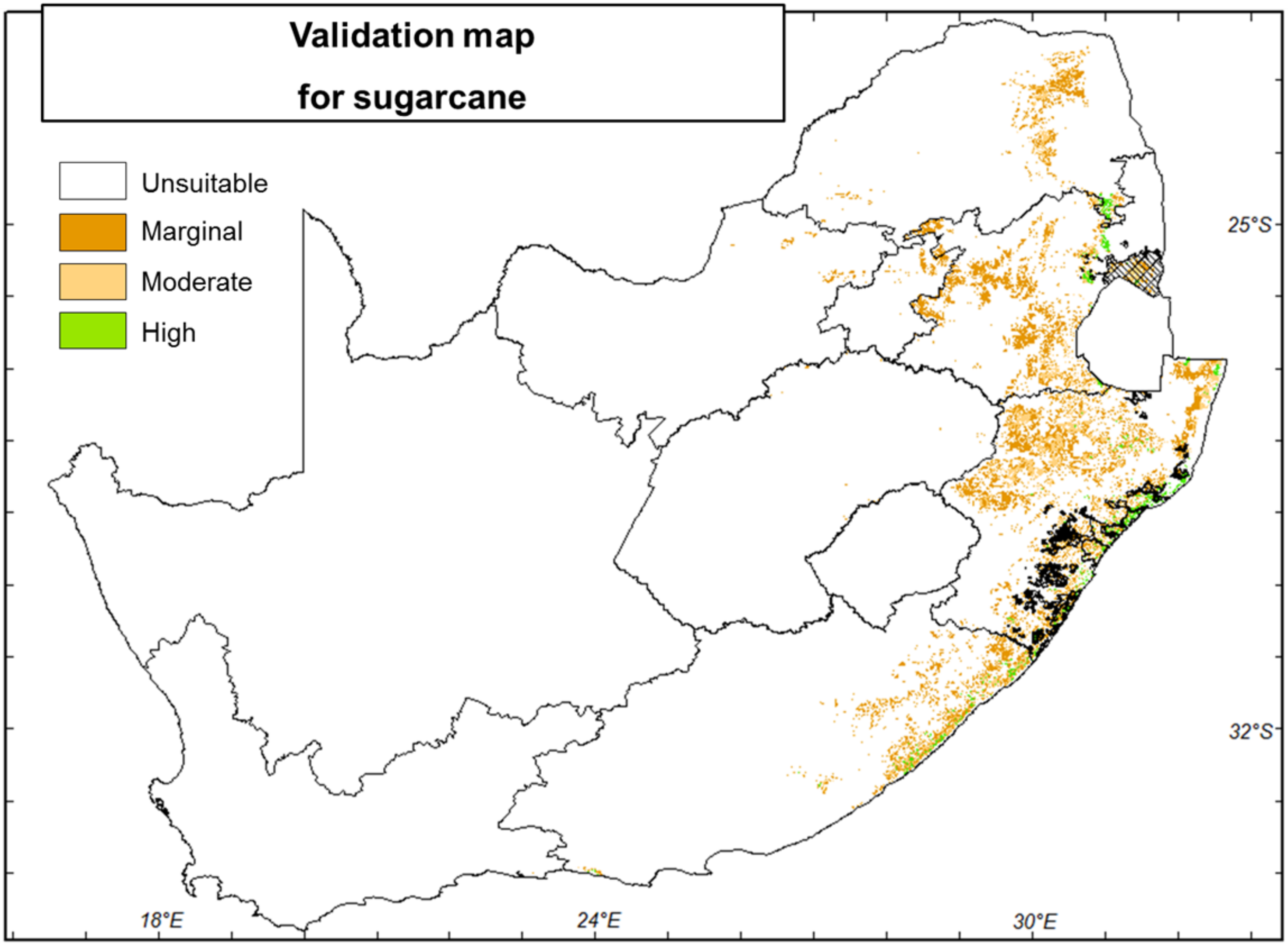

Figure 8.7: Land suitability map for sugarcane (based on local K_c values) with cane production areas obtained from SASRI in 2014