MULTIOBJECTIVE MODELLING OF BIOFUEL SUPPLY SYSTEMS

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BY

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"I know the meaning of plagiarism and declare that all the work in the document, save for that which is properly acknowledged, is my own"

EXECUTIVE SUMMARY

Biomass was the world's primary source of energy in the transportation sector until the late 1920's when cheap and abundant fossil fuel brought about the petroleum fuel paradigm, and bioenergy usage was virtually abandoned. The threat of constantly depleting fossil fuel reserves and the ever-increasing evidence of climate change associated with the use of fossil fuels have, however, sparked renewed interest in the use of bioenergy in recent years, forcing energy planners and policy-makers to rethink its role in the energy system for the coming years. In particular, liquid biofuels have been receiving the most attention throughout the world for their potential to substitute conventional transportation fuels.

South Africa has also recognized the need to integrate biofuels into the national energy mix, and consequently the government has established a National Industrial Biofuels Strategy, which sets a national biofuel target of 2% of road liquid transport fuels for 2013. Contrary to the international situation, the main driver for the development of a biofuels industry in South Africa is the need to create a link between the country's first and second economies, and this centres around the development of agriculture and the use of currently underutilized land in those areas of the country that were previously neglected by the apartheid regime. Because of the scarcity of arable land in South Africa, however, it is necessary to facilitate the effective utilisation of this limited resource if sustainability and maximum return on input are to be achieved. The aim of this thesis is to determine the optimal land use options offered by different bioenergy crops and technologies available to South Africa for the development of the most efficient and sustainable agriculture-based biofuels industry.

A review of relevant literature showed that biofuels are a potential low-carbon energy source, but whether they actually offer the carbon savings depends on the location, type of feedstock and method of production, and life-cycle assessment methods were found to be the right tools for analysing the sustainability of biofuel supply chains. It was also found that land use change and deforestation for biofuel production strongly influence the success and sustainability of bioenergy systems, and that their effects should always be taken into account in analysing the environmental and social impacts of bioenergy systems from a life-cycle perspective. The literature review further revealed that while energy modelling can be used to analyse bioenergy systems from an economic viewpoint only and life-cycle assessment tools can be adequately used to analyse their social and environmental aspects, multiobjective optimization is the best method for integrated analysis of all three dimensions.

The system analysed in this thesis comprises of underutilized arable land that can be used for growing maize, wheat, sugarcane or sweet sorghum for ethanol production, and soybean, sunflower or canola for biodiesel production, depending on the different area suitabilities of these crops in South Africa.

Firstly, analyses of energy balances and land use change were carried out on the respective biofuel supply chains, and the results showed that the production of biofuels from maize grain, wheat grain, sugarcane, sweet sorghum cane, soybean, sunflower and canola in South Africa all result in net energy gains, with sugarcane having the highest Net Energy Balance ratio of 3.72 while maize grain had the lowest at 1.20. The results also showed that bringing land that has not been cultivated for a period of two years into biofuel production results in a once-off carbon debt of about 13,900 kgCO_2/ha which the biofuels can only repay if their production and use avoid the emission of greenhouse gases in each subsequent year. Sugarcane ethanol was found to have the shortest repayment period of 3 years, while sweet sorghum ethanol and maize grain ethanol would not be able to repay the carbon debt under the assumptions of this thesis.

These analyses were followed by the development of a multiobjective optimization model which was then applied to the system. The model simultaneously maximises three objectives; economic gain by the processing plant, direct job creation in the biofuels industry and greenhouse gas emissions avoided by using the biofuels, all at minimal use of agricultural land. The objectives were chosen as the most prominent economic, social and environmental objectives respectively for the establishment of a biofuels industry in South Africa. Two scenarios were investigated here; a scenario where there is no targeted market penetration of biofuels and scenario of B2 (2% biodiesel mix with 98% diesel) and E8 (8% ethanol mix with 92% petrol) national target.

The results showed that in the absence of a market penetration target, sugarcane is the most preferable crop for maximising all three objectives wherever it can grow throughout the country. In the Western Cape areas where sugarcane cannot grow, canola is the most preferred for maximising avoided greenhouse gas emissions and job creation. For maximising economic gain in these areas, however, canola is only better than wheat but it is actually more economical to leave the land uncultivated than to use it for growing crops for biofuels production. In the areas outside the Western Cape where sugarcane cannot grow, sweet sorghum is the most preferred for maximizing both economic gain and job creation, while sunflower and canola are the most preferred and second most preferred crops respectively for maximizing avoided greenhouse gas emissions. A trade-off analysis of the objectives in the absence of a national market target revealed that an estimated 47 kg of CO_2-eqt emissions per hectare are avoided when maximizing economic gain and job creation, but any additional kilogram of CO_2-eqt emissions avoided thereafter comes at a price of R4.50 of economic gain and 0.2 man-hours of labour.

The results of the model also showed that in the presence of the three objectives are maximized by three distinct crop combinations; economic gain is maximized by growing as much sugarcane as possible for ethanol production and as much canola as possible where sugarcane cannot be grown and then supplementing them with maize and sunflower respectively to achieve the required ratio of B2 and E8.

Job creation is maximised by the same distribution as economic gain except that sweet sorghum, instead of maize, supplements sugarcane. Avoided greenhouse gas emissions, on the other hand, are maximized by growing as much sugarcane as possible for ethanol production and then balancing between sunflower for biodiesel production and wheat for ethanol production to achieve the desired proportion. The crop combination that maximises job creation was found to produce the largest quantity of biofuels per hectare per annum, followed by the combination that maximises economic gain.

Lastly a case study was conducted on a local municipal area of Maluti-a-Phofung to demonstrate the use of the multiobjective optimization model to support biofuel decision-making in South Africa. This area was chosen because it fits all the criteria of the National Industrial Biofuels Strategy of South Africa perfectly, in terms of its history, economic situation and availability of underutilized arable land. An analysis of the current situation in Maluti-a-phofung revealed that local economic development and poverty eradication through job creation would be the two major objectives to be achieved by the development of a local biofuels programme in this area, and that Integrated Development Planning (IDP), would be the right context in which decisions about the areas' approach in developing such a programme would be taken.

Two scenarios were modelled in the case study; a scenario involving only the four crops familiar to the local farmers, namely maize, wheat, soybean and sunflower (four crops scenario), and a scenario where the farmers would be willing to include sweet sorghum in the programme (all crops scenario). A biodiesel plant would be established in the area for biodiesel production while bioethanol crops would be sent to the nearest processing plants outside the bounds of the municipality.

The case study results showed that, in both scenarios, growing wheat for ethanol production would result in maximum net economic gain for the municipal area as a whole, while growing maize and sweet sorghum would result in maximum job creation in the four crops scenario and in the all crops scenario respectively. A trade-off analysis of the objectives showed that while the creation of 6.1 man-hours of labour comes with maximising economic gain, any additional man-hour of labour created thereafter would come at a loss of R11.30 and R193.00 of economic gain to the municipality in the all-crops scenario and in the four crops scenario respectively. The Maluti-a-Phofung IDP team would then use this information to pick the scenario and the crop combination that best represent the interests of the people of Maluti-a-Phofung.

It was recommended that the model be broadened in future research to incorporate other objectives like water usage and plant capital cost which can influence the choice of crops and processing technologies.

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This thesis is dedicated to my wife 'Mampepuoa and our little baby girl Mpepuoa.

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MODEL INPUTS

Indices & Sets

$i \in I$ = {Biodiesel, Bioethanol}

$j \in J$ = {Maize, Wheat, Sugarcane, Sweet sorghum, Soybean, Sunflower, Canola}

$k \in K$ = {grain processing, cane processing, oilseed processing}

B = {Soybean, Sunflower}

S = {Maize, Wheat}

Variables

x_j fraction of land occupied by crop *j*

Functions

V(x) Economic gain objective

G(x) Avoided greenhouse gas emissions objective

W(x) Job creation objective

Parameters

y_{ij} Yield of biofuel *i* produced from bioenergy crop *j*

C_i Selling price of biofuel *i*

C_{BP_j} Selling price of by-product of bioenergy crop *j*

C_{elec} Price of electricity

C_{market_j} Market price of crop *j*

$C_{process_j}$ All post-harvest costs of processing crop *j*

$\emptyset_{BP_j}$ Amount of by-product produced per litre of biofuel from crop *j*

$\emptyset_j$ Tonnes of crop *j* required to produce a litre of biofuel

$\emptyset_{elec_j}$ Amount of by-product produced per litre of biofuel from crop *j*

φ_{agric_j} Agricultural emission factor of crop *j*

$\varphi_{process_{ijk}}$ Processing emission factor

E_{chem_k} Emission factor of chemicals used in processing plant *k*

E_{energy_k}	Emission factor of fossil energy used in plant *k*
E_{trans_j}	Emission factor associated with transportation of crop *j*
$E_{BFtrans_i}$	Emission factor of transporting biofuel *i*
E_{labour}	Emission factor associated with human labour
E_{steel}	Emission factor associated with steel
$E_{concrete}$	Emission factor associated with concrete
δ_{labour_k}	Labour requirements of processing technology *k*
$\emptyset_{steel_k}$	Steel requirements of processing technology *k*
$\emptyset_{concrete_k}$	Concrete requirements of processing technology *k*
γ_{jk}	Matrix that matches the crops to the correct processing technologies
$h = 8$	number of working hours per day
$W_{p\_agr,j}$	Number of permanent agricultural workers required per ha of *j* grown
S_j	Length of farming season for crop *j*
$L_{t\_agr,j}$	Temporary agricultural labour required for growing crop *j*
$L_{pro,k}$	Labour requirements of processing technology *k*
$F_{i,j}$	Flow of biofuel *i* produced from crop *j*
σ_{land}	Fraction of the underutilized land that is currently being cultivated
P_j	Profit made by farmers from selling crop *j* at market price
$P_{2,j}$	Profit made by farmers from selling crop *j* at 2nd grade market price
g_2	Fraction of emerging farmers' grains (maize & wheat) currently sold as second grade
δ_j	Cost of transporting crop *j* to processing plant
$P_{BP,s\_sorghum}$	Profit made by farmers from selling sweet sorghum grain

ACRONYMS

CAIT	Climate Analysis Indicator Tool
CDF	Clean Development Fund
CO2-eqt	Carbon dioxide equivalent
DCs	Developing countries
DEAT	Department of Environment and Tourism
DME	Department of Minerals and Energy
DoA	Department of Agriculture
DPLG	Department of Local and Provincial Government
DSS	Decision support system
ERC	Energy Research Centre
FDC	Free State Development Corporation
GHG	Greenhouse gas
IDP	Integrated Development Plan
IPCC	International Panel on Climate Change
LDCs	Least Developed countries
LED	Local Economic Development
LIHDs	Low-input high-diversity mixtures
LTMS	Long Term Mitigation Scenarios
NEB	Net Energy balance
NEB-ratio	Net Energy Balance ratio
NICs	Newly Industrialized Countries
RIDCs	Rapidly Industrialising
UNFCCC	United Nations Framework Convention on Climate Change

1. INTRODUCTION

This chapter sets the scene for the thesis by outlining the background of the project, the problem addressed by the thesis and the key objectives. The scope is laid out and the chapter then concludes by summarizing the structure of the rest of this thesis.

1.1. Background

Biomass was the world's primary source of energy in the transportation sector until the late 1920's, which saw the emergence of seemingly abundant and cheaper petroleum oil. So the oil liquid fuel paradigm took root and gave rise to the petroleum refinery and distribution network. Everyone simply abandoned biomass and focused on petroleum oil. Even machinery which was originally designed to run on ethanol from biomass was modified to run only on gasoline (Miller, 2005).

The energy crisis of the 1970s, however, sparked renewed interest in the synthesis of fuels and materials from bio-resources. But this interest quickly waned as the oil price fell again in the decades that followed and global consumption of liquid petroleum tripled in the ensuing years. With the current global energy consumption, the demand of oil is projected to grow by more than 50% by 2025, and most experts agree that we will soon reach "peak oil", if we have not reached it already (Ragauskas et al., 2006;Buchanan, 2006). Even with new technologies and new sites to search, oil will run out in 50 to 100 years.

This depletion of crude petroleum oil is not the only problem of reliance on petroleum fuels for energy; the negative environmental effects associated with their continued use pose even further problems. According to the International Panel on Climate Change (IPCC, 2007) the use of fossil fuels is the main reason for the increased atmospheric concentration of carbon dioxide which is resulting in anthropogenic global climate change. Indeed the warming of the climate system is indisputable, "*as is now evident from observations of increased global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (IPCC, 2007).*

These are some of the reasons which, in recent years, have forced the world to rethink the role of biomass in the energy sector. Since 1976 there has not been a single new petroleum refinery built in the United States. Instead more than 85 bioethanol plants, based on the standard sugar fermentation process using maize kernels as feedstock, have been built (Miller, 2005). The same is true for the world's largest bioethanol producer Brazil. It would thus seem that the world is experiencing the beginning of an entirely new energy paradigm.

Biomass is a renewable energy resource with the advantage of being greenhouse gas neutral if used efficiently. If derived from sustainable agricultural practices, biomass energy also provides an opportunity for developing countries to utilise their own resources, resulting in increased job and wealth creation, as well as the attraction of international benefits and investment (Ugarte, 2005). With modern technologies, biomass can be converted into useful energy carriers: heat, electricity and biofuels (solid, liquid and gaseous fuels). Of these bioenergy carriers, liquid biofuels have, in recent years, received the most attention throughout the world for their potential to substitute conventional transportation fuels. According to Hamelinck (2004), the global transportation sector is almost entirely based on fossil fuel and it represents about 27% of the world's secondary energy consumption; a percentage that is expected to increase to 29 – 32 % in 2050. This implies that biofuels are envisaged to take up a significant share of the world's energy consumption in the coming years.

South Africa has also recognised the need to reduce its dependence on fossil fuels as the primary source of energy. In 2003 South Africa's deputy minister of Minerals and Energy (DME, 2003) declared that the time has come for renewable energy to take its rightful place in the South African Energy Sector, and to play a significant role in contributing towards sustainable development. It was in this context that the government established a target for 2013 of 10,000 GWh renewable energy contributions to the final national energy consumption, of which 30% should be in the form of liquid biofuels (DME, 2007;DME, 2003).

Contrary to the international situation, however, the main driver for the development of a biofuel industry in South Africa is neither the constantly increasing oil prices, the issue of energy security nor anthropogenic climate change, but the need to create a link between the country's first and second economies. This involves stimulating economic development and reducing poverty by creating sustainable income-earning opportunities in under-developed areas (DME, 2007). According to the Industrial Biofuels Strategy of the Republic of South Africa (DME, 2007), the focus is primarily on "*the promotion of farming in areas that were previously neglected by the apartheid system and areas of the country that did not have market access for their produce, most of these areas are in the former homeland areas*". Thus the issue of land use is central to the development of South Africa's biofuel industry.

While the National Biofuels Study, which was commissioned to support the development of the Biofuels Strategy, shows that an agriculture-based biofuel industry in South Africa is likely to encounter problems relating to small-scale subsistence farming, emerging farmers and scarcity of arable land, it gives no insight into how efficient land use may be achieved (National Biofuels Task Team, 2006). Moreover, the National Biofuels Study is primarily an economic impact study, and therefore its analyses were mainly concerned with optimization of economic benefits, and only when this had been achieved were the analyses of maximizing the social and environmental benefits conducted. Thus the overall interdependence of the different socio-economic and environmental objectives of the National Biofuels Strategy and the subsequent effect that their optimization has on land use are still largely unknown.

1.2. Problem Statement

Globally the increasing shift from the use of conventional petroleum fuels in the transportation sector to liquid biofuels is mainly motivated by issues of energy security and anthropogenic global warming. In South Africa, however, the development of a biofuel industry is primarily seen as a local economic development and poverty alleviation issue, especially in those areas of the country that were previously neglected by the apartheid regime. The Biofuels Industrial Strategy of South Africa is thus structured such that it centres on the development of agriculture in these areas. In fact, only those biofuels produced from crops grown in these areas will qualify for government support. Arable land, however, is very limited in South Africa; with only 14% of the total land in South Africa receiving enough rainfall for arable crop production. Clearly the percentage of arable land that fits the criteria of the Industrial Biofuels Strategy and that can be dedicated to biofuel production is even smaller. There is, therefore, a need to facilitate the effective utilisation of this limited resource if sustainability and maximum return on input are to be achieved.

Given a fixed amount of arable land dedicated to biofuels production, a choice of energy crops that can be locally grown and a choice of processing technologies for these crops, the problem is that of land-use optimization, such that the economic, social and environmental objectives of the National Biofuels Strategy are satisfied in the best possible way.

1.3. Objectives

Specific objectives of this thesis are:

1. To analyse the Life-cycle energy balances, climate change mitigation potentials and economic performances of the various biofuel supply chains available to South Africa, involving the different bioenergy crops that can be grown locally
2. To determine the environmental effects of land use change in the development of an agriculture-based biofuels industry in South Africa
3. To develop a multiobjective model for minimizing land use in the biofuel industry, while optimizing one objective from each of the economic, social and environmental spheres of the industry
4. To demonstrate the use of multiobjective optimisation models as decision support systems for bioenergy decisions both at national and local government levels

1.4. Key Questions

The thesis seeks to answer the following key questions:

- Based on the current agricultural practices and various crop yields in the country, how much return on energy input can be achieved by the different biofuel supply chains?
- What are the climate change implications of land use change in the development of a biofuel industry in South Africa? If there are negative effects, how long would it take for the biofuels to ultimately repay the initial “carbon debt”?
- Given a fixed amount of arable land and a choice of energy crops that can be locally grown, which crop distribution will result in optimum land use in the South African biofuel industry? What are the factors affecting this optimum crop distribution?
- What are the land use options available to South Africa to achieve its biofuel target of 2% market penetration of liquid road transport fuels involving B2 (2% biodiesel mix with 98% diesel) and E8 (8% bioethanol blend with 92% petrol) beyond 2013 with minimal resource utilization?
- What effects do commodity and fossil fuel prices have on the optimum crop distributions?

1.5. Scope and Limitations

This study analyses the possible biofuel supply chains for an agriculture-based biofuels industry in South Africa. This includes agricultural land and practices, technologies, fuel prices and commodity prices specific to South Africa. The overall optimisation model algorithm, however, is developed as an open multi-objective optimisation model that can easily be applied to other areas, provided that appropriate physical data and constraints for that area are available.

The main limitation of this thesis is that the life-cycle analyses carried out herein are only cradle-to-blending-station assessments which exclude the end-use of the biofuels, thus the results obtained cannot readily be compared with results of the studies assessing the energy balances and environmental burdens of the different crops on the basis of passenger kilometres driven. Another limitation to the analyses in this study is that ability of the livestock industry to absorb the oilmeal by-products from biodiesel processing has not been considered.

1.6. Thesis Outline

The following figure summarises the outline structure of this thesis:

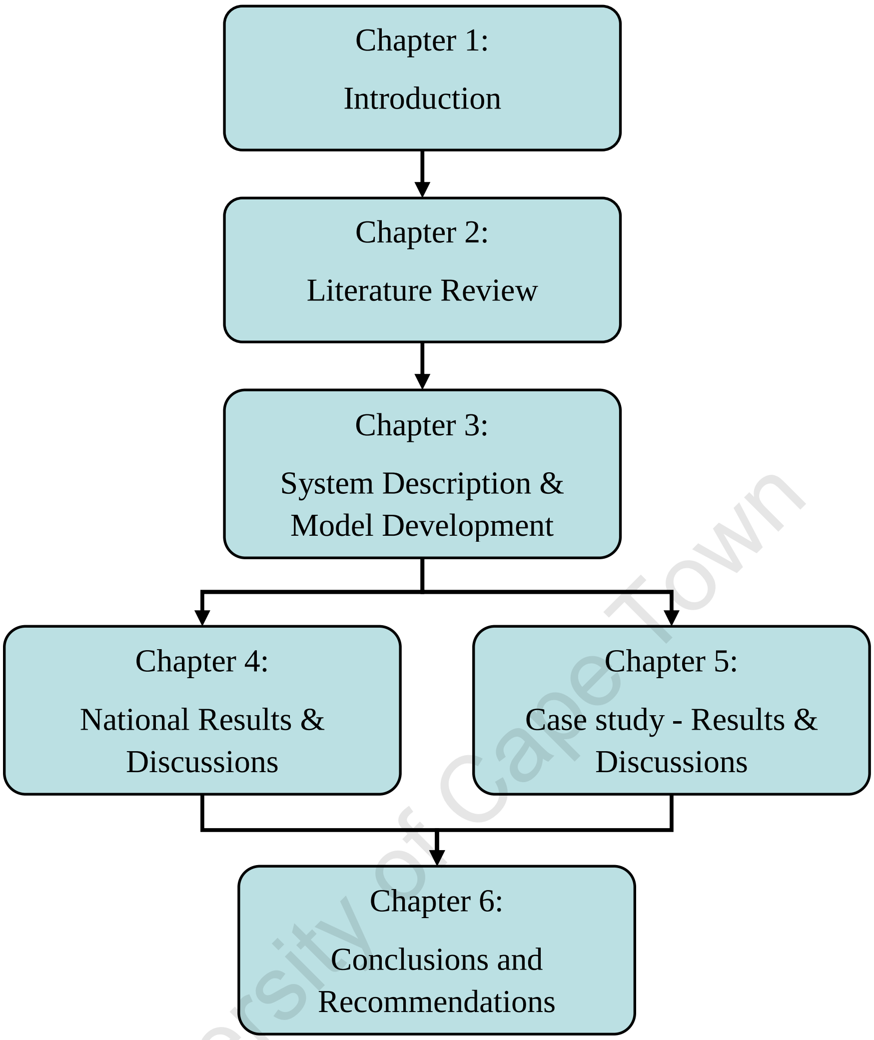


Figure 1. 1: Outline of thesis structure

Chapter 1 has introduced the thesis and given overviews of the purpose of the research and the context in which the research was carried out.

Chapter 2 is a review of relevant literature which begins by looking at bioenergy developments both globally and nationally. The subsequent sections of Chapter 2 then discuss the various methods and tools for analysing and modelling the sustainability of bioenergy systems, with specific focus on biofuels. This chapter concludes with a summary of findings that form an outlook for the rest of the thesis.

Chapter 3 presents a detailed description of the system to be analysed and describes the chosen methods of analysis. The proposed multiobjective optimisation model is also presented and discussed in this chapter. The chapter then closes with a discussion of the inventory preparation.

Chapter 4 and Chapter 5 are essentially results and discussion chapters. While the former presents and discusses results on a national scale, the latter is a case study that applies the developed model to support decision-making at local municipal level.

In Chapter 6 the findings of the preceding two chapters are used to draw conclusions in line with the key questions, after which relevant recommendations are then made.

2. LITERATURE REVIEW

In this chapter, the potential contribution of bioenergy to future global energy supply is discussed, followed by the bioenergy situation in South Africa. Energy planning by mathematical modelling is also reviewed with focus on the appropriate model for South Africa.

2.1. Review of Bioenergy

2.1.1. Bioenergy Supply Chains

Biomass generally refers to any organic matter available on renewable basis, varying broadly from fuel wood gathered from forests and agricultural residues to dedicated energy crops, animal manure and industrial organic residues. Bioenergy is any form of useful energy derived from biomass, and harnessing it can be as simple as open fires using fuelwood or as advanced as modern thermo-chemical and biochemical bioenergy conversion pathways (Bucholtz et al., 2007). Figure 2.1 shows the general classification of biomass feedstocks and their conversion end products via commercially available technologies.

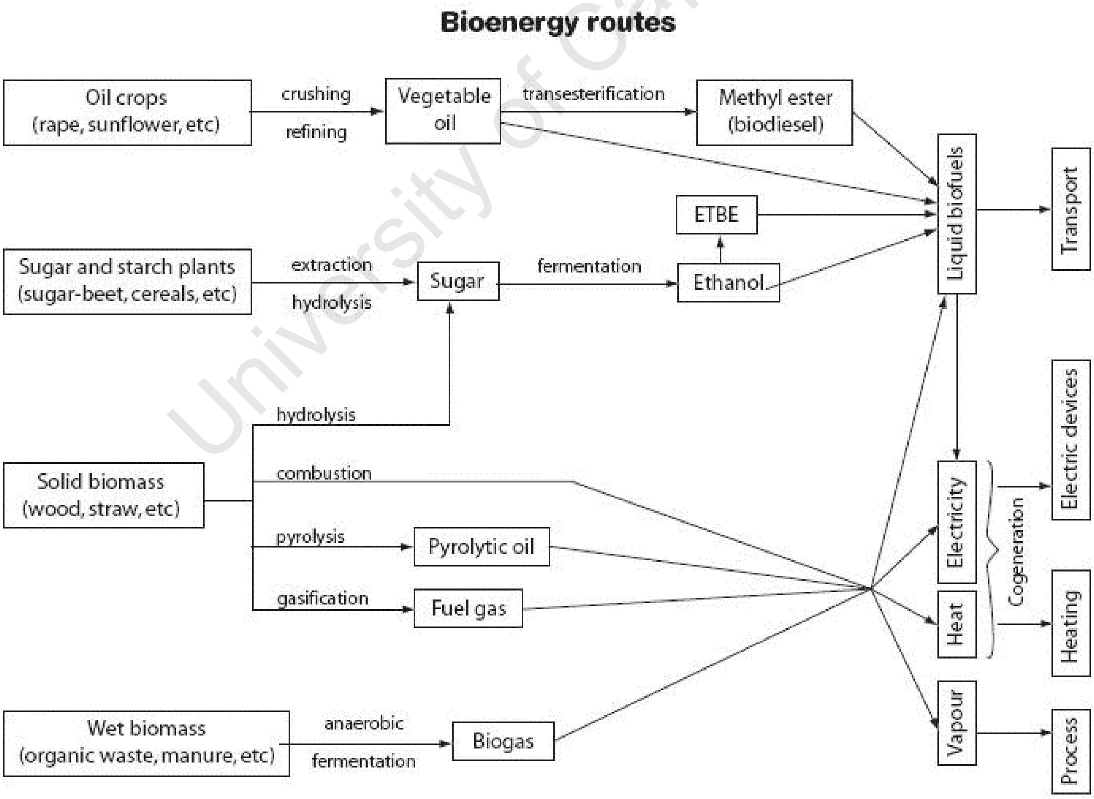


Figure 2. 1: Summary of Common Bioenergy Pathways (European Biomass Association, 2009)

Some feedstocks, such as wood, can be converted directly into useful energy, while others need to be processed into liquid fuels that can in turn be combusted to produce energy.

2.1.2. The Potential of Biomass contribution to Energy

Global fossil fuel use in 1994 was estimated at 302 EJ, while biomass, mostly used for cooking over open fires and mostly unreported in global statistics, was estimated at 55EJ (Hall et al., 1993). In 2004 the total global energy consumption was reported to be 470 EJ and is expected to reach 700 EJ (EIA, 2006) and 1041 EJ (World Energy Council, 2007) in 2025 and 2050 respectively.

Many studies have been undertaken to assess the potential contribution of biomass to the global energy network. In an analysis of a selection of seventeen studies on the potential contribution of bioenergy to the global energy supply, Berndes et al (2003) found the conclusions to vary from below 100 EJ/yr to above 400 EJ/yr in 2050. The Group Planning Division of the Shell International Petroleum Company developed a predictive energy scenario which showed a dramatic expanding role for biomass beginning early in the 21st century, rising to over 200 EJ/yr by 2050 (Kassler, 1994). The Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) also shows a biomass-intensive energy scenario for the world that predicts 75 EJ of modernized, commercial bioenergy production in 2025, reaching over 180 EJ of sustainable biomass use by 2050 (Williams, 1995).

In a preliminary analysis, Marrison and Larson (1996) reported a biomass potential to produce bioenergy of 18.4 EJ/yr in 2025 for Africa alone, while Smeets et al. (2007) estimate it to be between 48 EJ/yr and 389 EJ/yr in 2050, with Sub-Saharan Africa accounting for more than 90%.

2.1.3. Biofuels

Of all modern bioenergy carriers, liquid biofuels have, in recent years, received the most attention throughout the world as potential substitutes of conventional transportation fuels. A biofuel is broadly defined as a solid, liquid, or gas fuel derived predominantly or exclusively from biomass. Liquid biofuels have recently been classified as “first-generation” or “second-generation” biofuels depending on the type of feedstock or technology used to manufacture them. According to the United Nations Conference on Trade and Development (2008), there are no strict technical definitions for these two terms.

First-generation biofuels are primarily produced from sugars, starches, oil bearing crops or animal fats, and tend to only utilize those portions of the plant biomass that are also used as food. Technologies for producing these fuels are generally well established and significant commercial quantities of first-generation biofuels are already produced in many countries around the world.

Second-generation biofuels are those produced from non-edible lignocellulosic biomass such as residues from food crop production or forestry biomass. Technologies for these fuels are neither as well established nor as mature as those of first-generation biofuels, hence the former are not yet produced commercially in any country (UNCTAD, 2008).

The two most common first-generation biofuels are bioethanol and biodiesel:

2.1.3.1. Bioethanol

The most widely-used first-generation liquid biofuel is ethanol (or ethyl alcohol) produced by the biological fermentation of plant sugars and starches. While sugarcane and maize are the most common feedstocks for ethanol production, other feedstocks include wheat, cassava, potatoes, sugar beets and most recently sweet sorghum. Bioethanol can either be blended with petrol to increase the octane level of petrol and used in existing spark ignition engines, or used unblended, in modified 100% alcohol-fuelled engines or even used as hydrous ethanol in any proportion with petrol in flexi-fuel vehicles. The latter practice is common in Brazil (Macedo et al., 2008).

2.1.3.2. Biodiesel

Biodiesel is defined as a monoalkyl ester of long chain fatty acids derived from the transesterification of a triglyceride (vegetable oil or animal fat) with alcohol (methanol or ethanol) in the presence of a base catalyst (Figure 2.2) (Dermibas and Dermibas, 2007).

$$\begin{array}{l} CH_2\text{–}O\text{–}COR_1 \\ | \\ CH\text{–}O\text{–}COR_2 \\ | \\ CH_2\text{–}O\text{–}COR_3 \end{array} + 3\ CH_3OH \rightleftharpoons \begin{array}{l} CH_2\text{–}OH \\ | \\ CH\text{–}OH \\ | \\ CH_2\text{–}OH \end{array} + 3\ R\text{–}COOCH_3$$

Figure 2. 2: methanol-catalysed production of biodiesel

Soybean, rapeseed oil, sunflower oil and palm oil are the most common vegetable oils used for biodiesel production (Mittelbach and Remschmidt, 2004) .

According to Nolte (2007) there are three ways in which biodiesel can be used in compression-ignition engines with little or no modifications to the engines;

- In its pure form as B100 (or neat biodiesel). This gives the maximum reduction in particulate matter, unburned hydrocarbons, carbon monoxide and sulphur dioxide emissions. In this form, however, the solvent properties of biodiesel are at their highest intensity and this may cause accelerated degradation of fuel lines and paint removal near fuel fill ports.
- Blended with petroleum diesel in any proportion, typically between 5% and 50% biodiesel on a volume basis. This approach offers improved engine performance and emission reductions while reducing the degrading impacts of pure biodiesel.

- As an additive to petroleum diesel, typically in proportions of 1%-2% biodiesel on volume basis, to enhance the lubricity of petroleum diesel.

2.2. Bioenergy developments in South Africa

South Africa's economy is one of the most energy-intensive in Africa, heavily relying on fossil fuels as a primary source of energy. The national energy supply is dominated by coal, which accounts for more than 70% of the country's fossil-based energy supply, while biomass is estimated to supply just below 20% of the national energy consumption, mostly in the form of fuel wood consumed in relatively low-efficiency devices or waste products used for electricity and process heat generation in the sugar, pulp and paper industries (Davidson, 2006).

As a result of this high dependence on coal, South Africa is by far the most carbon emission-intensive country in the continent and one of the largest greenhouse gas emitters in the world (Figure 2.3). In terms of energy CO_2 emissions per GDP per purchasing power parity (GDP-ppp), South Africa ranks 24 in the world, surpassing world giants like the USA and Brazil as shown in Figure 2.4. According to data from the Climate Analysis Indicator Tool (CAIT) (2005), South Africa can be ranked between 14 and 65, out of over 200 countries in the world, in terms of greenhouse gas emissions, depending on the number of gases and emission sources being considered. In light of the increasing evidence of global climate change due to increased concentrations of greenhouse gases in the atmosphere, these emission rankings of South Africa have been points of much discussion in recent years, both locally and in the context of international efforts against climate change to which South Africa is party.

The most relevant international climate change effort is the Kyoto Protocol – a multilateral agreement of the United Nations Framework Convention on Climate Change (UNFCCC) to which South Africa acceded in March 2002. This protocol is aimed at achieving stabilization of greenhouse gas emissions in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Under both the convention and the protocol, however, South Africa is recognised as a developing country and as a result, it is not committed to any emission reduction targets during the first commitment period of the protocol ending in 2012.

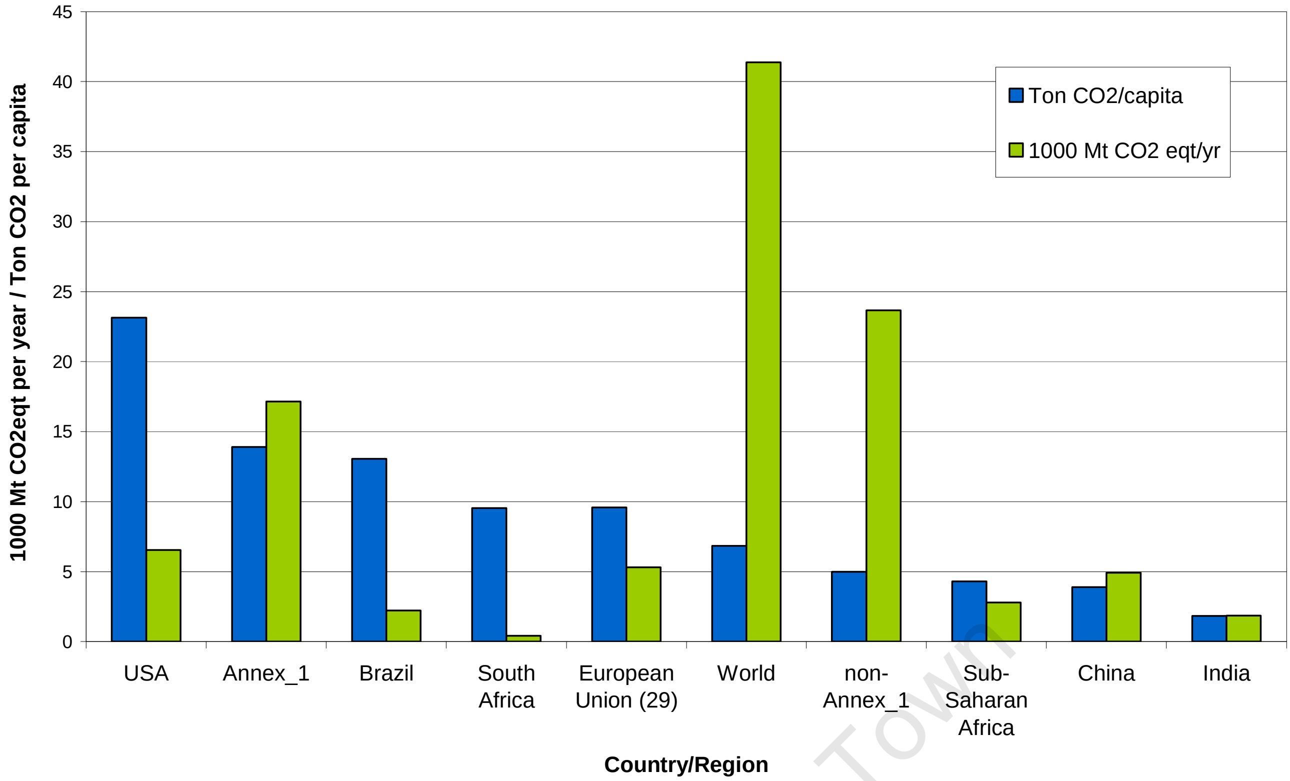


Figure 2. 3: Comparison of country and regional annual emissions, 2000. [Letete and Guma (2008) using data from Climate Analysis Indicator Tool(2005)]

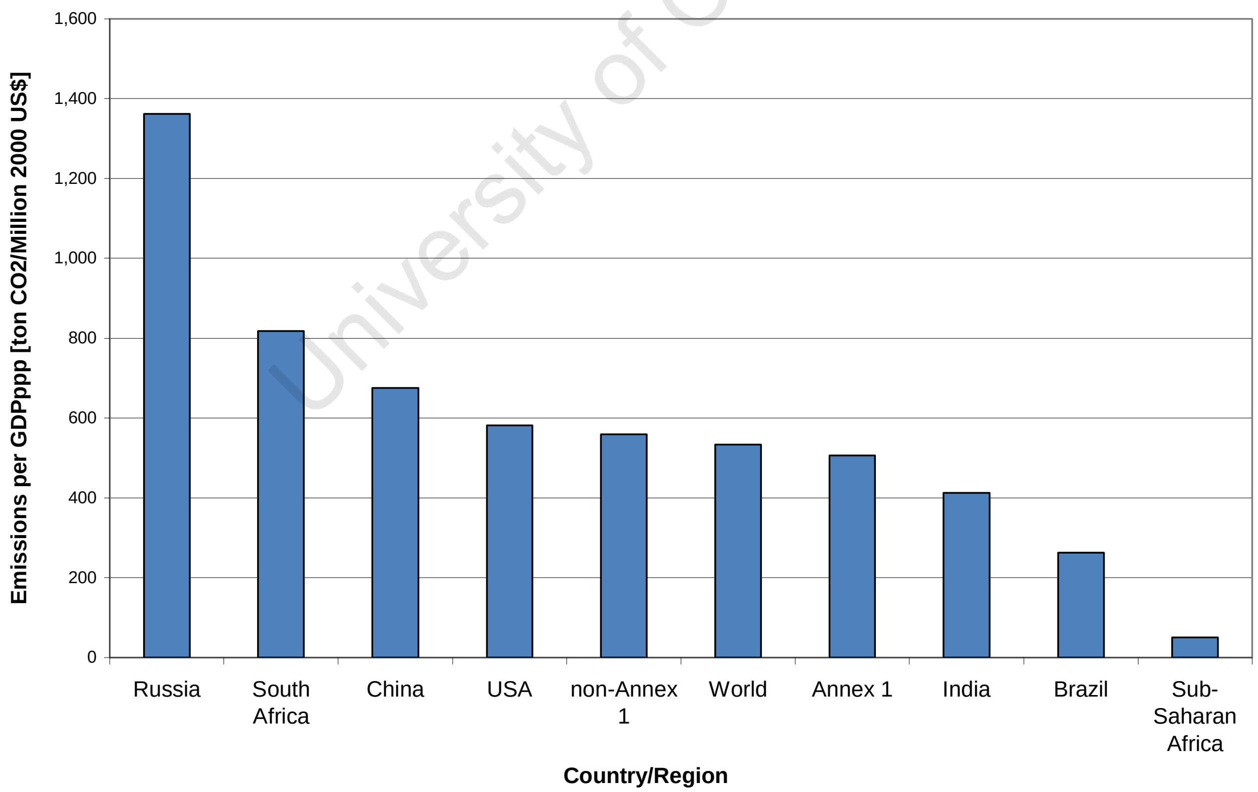


Figure 2. 4: Comparison of country and regional CO_2 emissions per GDP-ppp (2000 US$) from energy and cement production, 2002 [Letete and Guma (2008) using data from Climate Analysis Indicator Tool (2005)]

As the end of the first commitment period of the protocol approaches, however, the UNFCCC has called for stakeholders and governments to come up with options for advancing the international climate change efforts beyond 2012, and below is a summary of the most favoured approaches being proposed (Hohne and Moltmann, 2007;Bodansky, 2004):

1. Contraction and convergence: Under this regime all countries participate with quantified emission targets. Firstly, all countries agree on a path of future global emissions leading to a targeted long-term stabilization of greenhouse concentrations, and then targets are set for individual countries such that per capita emissions converge to the same level for all countries by an agreed time.

2. Common but differentiated convergence: This approach requires the per capita emissions of Annex I countries to immediately start converging to a stabilization level equal for all countries within a set period, while for individual non-Annex 1 countries convergence only starts when their per capita emissions reach a certain percentage threshold of the global average.

3. Multistage: In this approach countries participate in several stages, with differentiated commitments, and countries graduating to higher stages when they exceed certain thresholds. In the first stage countries have no commitments at all, while in the last stage countries receive absolute emission reduction targets until all countries stabilize their per capita emissions to a specified level below 1990 levels.

4. Global Triptych: This is a method of allocating emission allowances among all countries based on several national indicators, while taking into account emission reduction potentials for the different countries. The method calculates emission allowances for the various sectors which are then added to obtain a binding national target.

5. Brazilian Proposal: This approach proposes burden-sharing of greenhouse gas reduction based on the countries' historical responsibility for existing temperature change. As initially presented, this proposal called for reduction commitments of developed countries or contribution to a Clean Development Fund (CDF) if they fail to meet these commitments. The CDF would be used to fund clean development projects and adaptation projects in developing countries.

6. South-North Dialogue: This approach separates countries into six groups, each with a different mitigation, adaptation and financial set of commitments. Under this approach, Annex II countries take on more strict commitments than Kyoto commitments, while other Annex I countries continue to have targets similar to those required by the Kyoto protocol. Newly Industrialized Countries (NICs) and Rapidly Industrialising Developing Countries (RIDCs) would also have

quantified targets, but only on condition that all major Annex I have binding quantified emission reduction obligations. For RIDCs the targets would only be binding on receipt of significant financial and technological assistance from Annex II countries. Instead of targets, Other Developing countries (DCs) and Least Developed countries (LDCs) would adopt obligatory and optional Sustainable Development Policies respectively.

From these proposals, it is clear that most of the international community supports some level of commitment of some of the developing countries in the protocol. This means that South Africa's role in the protocol is very likely to change in the second commitment period to be agreed upon at the 15th United Nations Climate Change Conference of Parties in Copenhagen in 2009. Any commitment for South Africa in the protocol would thus require the country to seriously consider the role of renewable energy sources, including biomass, in the country's economy.

Regardless of the outcome of the Copenhagen negotiations, however, the South African government has already committed to ensuring a climate resilient and low-carbon economy and society, and consequently outlined its vision, strategic direction and policy framework on climate change in July 2008 (Schalkwyk, 2008). Informed by the Long Term Mitigation Scenarios (LTMS) process, the government's strategy includes setting mandatory targets for electricity generated from both renewable and nuclear energy sources and using feed-in-tarrifs as incentives for renewable energy. The final national policy on climate change is envisaged to be adopted by the end of 2010.

Independent of the climate change threat, still, the South African minister of Environmental Affairs and Tourism, Martinus van Schkalwyk, has also declared that another challenge for South Africa in the coming decades "*will be to diversify our energy dependence – developing alternative renewable and non-carbon based sources of energy (DEAT, 2005)*." Echoed also in the government's climate change policy framework, the need for diversifying the country's energy mix and promoting alternative transport fuels has been acknowledged in South Africa as early as the late 1990's, and since then, the government has developed various policies and frameworks aimed at achieving this goal. In 2003, the government published a White Paper on Renewable Energy (DME, 2003); a policy document aimed at creating conditions to bring about integration of renewable energies into the country's mainstream energy economy. The economic, social, and environmental benefits offered by renewable energy are identified in this document as follows:

- Renewable sources of energy have substantial potential to increase security of supply by diversifying the energy supply portfolio and thereby contributing towards a long-term sustainable energy future.

- Renewable energy generation results in the emission of less greenhouse gases, airborne particulates and other pollutants when compared to fossil fuels.
- Renewable energy can be generated centrally and distributed for use near its point of production thus reducing the cost of infrastructure required for energy distribution and energy delivery losses.
- A renewable energy industry that meets international standards will attract investment that would otherwise be lost to the country.
- A sustainable renewable energy programme has the potential for increased industrial growth and thereby supporting a variety of national priorities, including job-creation and sustainable development.
- Renewable energy technologies provide significant potential export market opportunities to the southern African region.

In view of these benefits, the White Paper clearly sets out the government's long term goal as the establishment of a South African renewable energy industry that produces modern energy carriers and offering in future years a sustainable, fully non-subsidised alternative to fossil fuels. As a first step towards achieving this goal, the government has set a target of "*10,000 GWh (0.8 Mtoe) renewable energy contribution to final energy consumption by 2013, to be produced mainly from biomass, wind, solar and small-scale hydro,*" and for utilization in power generation and other technologies like solar water heating and biofuels (DME, 2003).

In 2007, the government released a Biofuels Industrial Strategy of the Republic of South Africa (2007) targeted at "*creating jobs in the energy-crop and biofuel chain, and to act as a bridge between the first and second economies.*" This strategy stresses on the promotion of "*currently underutilized, high potential agricultural areas*" that were previously neglected by the apartheid system and areas that had no market to their produce, most of which are located in the former homelands. The strategy proposes a 5 year pilot period in which a biofuels average market penetration of 2% of liquid road transport fuels (petrol and diesel) will be targeted. This target amounts to 30% of the national Renewable Energy target for 2013, and to meet it, a scenario of E8 (national basis of 8% bioethanol and 92% fossil petrol) and B2 (national basis of 2% biodiesel and 98% fossil diesel) will be adopted (DME, 2007). The strategy, however, has some ambiguities because it does not show how this E8 and B2 scenario is supposed to achieve a 2% national market penetration of biofuels. For food security purposes, however, the strategy proposes that maize be excluded as a feedstock for bioethanol production in this pilot period of the strategy.

There are currently no large scale biofuel producers in South Africa, but there is a lot of interest both in the agricultural and corporate world. Sugar producers and maize farmers represent the majority of the parties looking to drive the South African bioethanol industry, with some of the former having been involved in bioethanol production for the potable and export alcohol markets even before the National Biofuels Industry Strategy was released (DME, 2007). The maize-to-ethanol industry, however, has never taken off due to the restrictions of the National Biofuels Strategy.

Biodiesel, mostly from recycled sunflower oil, is produced on small-scale (less than 300,000 litres per year) by many farmers and small companies across the country (Murray, 2008). Virgin Soybean, sunflower and canola oils have also been used for biodiesel production.

2.3. Sustainability of bioenergy from a life-cycle perspective

Life-cycle analysis is an approach for systematically evaluating the environmental effects of a product or service from the initial gathering of raw materials from the earth until the point at which all residuals are returned to the earth. This concept, known as "cradle to grave", provides a holistic environmental analysis by considering the potential impacts at every stage of the life a product, process, package or activity (Vigon et al., 1993).

Although it is not a single uniform method, life-cycle assessment as a tool for measuring environmental impacts has been standardized to allow comparisons. According to the International Organization for Standardization (ISO, 1997), there are four separate yet interrelated components to every life-cycle assessment:

1 Goal definition and scoping: This entails clearly defining the goal of the study, the functional unit with which alternative products or services are to be compared, the unit processes making up the systems under study and the boundaries of the system. This is the step that defines the analysis and determines the type and detail of information required in the subsequent sections.

2 Inventory Analysis: This is a technical, data-based stage where identification and quantification of energy use, raw material requirements, environmental emissions and waste given off for the entire life-cycle of the product or activity under study are made.

3 Impact Analysis: This is a quantitative evaluation of the impacts of resource requirements and environmental burdens identified in the inventory analysis stage. The eight most commonly used impact categories are listed below:

- Natural resource depletion
- Global warming potential
- Ozone depletion potential
- Ecological toxicity potential

- Acidification potential
- Human toxicity
- Photochemical oxidant creation potential
- Eutrophication potential

These impacts are quantified by internationally-agreed units and potency factors for each source category.

4 Interpretation: At this stage impacts are assessed, and a systematic evaluation of the needs and opportunities to reduce the environmental burdens is employed. This analysis may be both quantitative and qualitative in nature, and many different approaches have been used depending on the goal of the life-cycle assessment.

In bioenergy systems, life-cycle assessment is commonly used to describe environmental sustainability and to "*determine whether bio-based fuels (biofuels) are helping us to achieve the goal of providing environmentally sustainable transportation*" (von Blottnitz and Curran, 2007).

Apart from the "standardized" life-cycle assessment, two other tools have been widely used to determine the sustainability of bioenergy systems; energy balancing and carbon balancing. Although these methods all stem from a common life-cycle approach, these latter two methods are usually simpler and more specific in nature as described below:

2.3.1. Energy balancing

In an energy balance analysis all the fossil energy inputs in upstream processing of the biofuel are calculated and compared with the energy value of the biofuel product and its by-products.

Two indicators are usually employed in energy balance analyses; the first is the Net Energy balance (NEB) defined as:

$$NEB = Energy\ Output_{Total} - Energy\ Input_{Total}$$

and second is the Net Energy Balance ratio (NEB-ratio) defined as:

$$NEB_{ratio} = \frac{Energy\ Output_{Total}}{Energy\ Input_{Total}}$$

where *Energy-Input*$_{Total}$ is the total fossil energy input in upstream processing of the biofuel and *Energy-Output*$_{Total}$ is the energy retrieved from the biofuel and its by-products.

For a bioenergy system to be considered to have some renewability, it must have a positive NEB or NEB-ratio greater than 1, the higher the ratio, the closer the system approaches to complete renewability (complete renewability is a theoretical term that defines a system with a ratio of infinity) (von Blottnitz and Curran, 2007).

2.3.2. *Carbon balancing*

Carbon balancing evaluates the net greenhouse gas emissions of the biofuel through its life-cycle. The most common indicator employed in carbon balancing is *Avoided emissions* which is defined as: The difference of the greenhouse gas emissions that would have resulted from the production, transportation and use of the products that are replaced by all biomass products ($GHG\text{-}emissions_{Replaced\text{-}products}$) and the greenhouse gas emissions released in the upstream production of the biofuel ($GHG\text{-}emissions_{Biofuel\text{-}production}$) as shown below:

$$G(x) = GHG\ emissions_{Replaced\ products} - GHG\ emissions_{Biofuel\ production}$$

Both $GHG\text{-}emissions_{Replaced\text{-}products}$ and $GHG\text{-}emissions_{Biofuel\text{-}production}$ are usually expressed in units of kg CO_2-equivalent.

2.4. Concerns over biofuels

In 2003, Berndes et al. (2003) showed that all the studies undertaken on future bioenergy potential do not provide much insight on how the expanding bioenergy sector will interact with other land uses, and the socio-economic consequences of realizing the reported bioenergy potentials. In particular, the development of the food and materials sector is exogenously defined in these studies, and the bioenergy sector evolves in parallel, using residues and land not required for food or materials production. Hence, according to these studies, the expanding bioenergy sector does not, by definition, affect the food and materials sector. Recent studies (Searchinger et al., 2008;Fargoine et al., 2008), however, have shown that bioenergy industries, especially biofuels, not only compete with other commodities for land but may actually drive all other land-use competitors away in the long run.

The following consequences have been observed to arise from this competition of biofuels with other commodities over land:

1. <u>Accelerated global warming:</u> As a result of increasing demand for biofuels, previously undisturbed ecosystems, especially in the Americas and Southeast Asia are being cleared out to make way for biofuel crops; In Malaysia and Indonesia, tropical rain forests are being burned and converted to palm oil plantations for biodiesel production, while grassland in the United States, primarily rangeland or former cropland currently retired in conservation programs, is

being converted to maize production. Perhaps the case that has brought the most attention is that of the Brazilian Amazon and Cerrado, which are rapidly being converted to sugarcane and soybean plantations.

According to Fargione et al. (2008) soils and plant biomass are the two largest biologically active stores of terrestrial carbon, together storing up to 2.7 times more carbon than the atmosphere, and converting these native habitats to cropland not only takes away the dearly needed sinks of CO_2, but releases all this stored CO_2 into the atmosphere, leading to accelerated anthropogenic climate change.

2. Food price inflation: Studies have also shown that the rise in tortilla prices in Mexico and flour prices in Pakistan can be associated with the increasing demand for food-based biofuels in the Americas and Southeast Asia (Grunwald, 2008). As more grains and oilseed crops are diverted from the food market to the biofuel market, a shortage in food availability is observed, leading to food price increases. According to Searchinger et al. (2008) and Grunwald (2008) this increase in food prices is another cause for deforestation in the Brazilian Amazon and Cerrado; as ethanol demand for maize in the United States increases, soybean and wheat farmers switch to maize, causing the prices of maize, soybeans and wheat to increase by 40%, 20% and 17% respectively. In response to these price increases Brazilian farmers further expand into fields previously used as cattle pastures, displacing ranchers, who in turn clear grazing lands in the Cerrado and the Amazon.

The global warming potentials of the prolonged CO_2 emissions as a result of burning or microbial decomposition of organic carbon stored in plants and soils when native habitats are converted to biofuel croplands have been intensively studied by Fargione et al. (2008). Looking only at the amount of CO_2 released in the first 50 years of this process, which they refer to as the “carbon debt”, Fargione et al. have shown that the debt can be repaid by biofuels over time, provided that the production and combustion of the biofuels have net greenhouse gas emissions that are less than the life cycle emissions of the fossil fuels they displace.

Fargione et al. went further to calculate the biofuel carbon debts and the number of years required to repay these debts for the Brazillian, United States, Indonesian and Malaysian native habitat conversions, and compared them with the cultivation of Low-input high-diversity mixtures (LIHDs) of native American grassland perennials in retired United States cropland. The results, presented as Figure 2.5 below, showed that biofuels produced from crops grown on degraded cropland, especially perennial grasses, and waste biomass would minimize habitat destruction, competition with food production and carbon debts associated with clearing land for biofuel production.

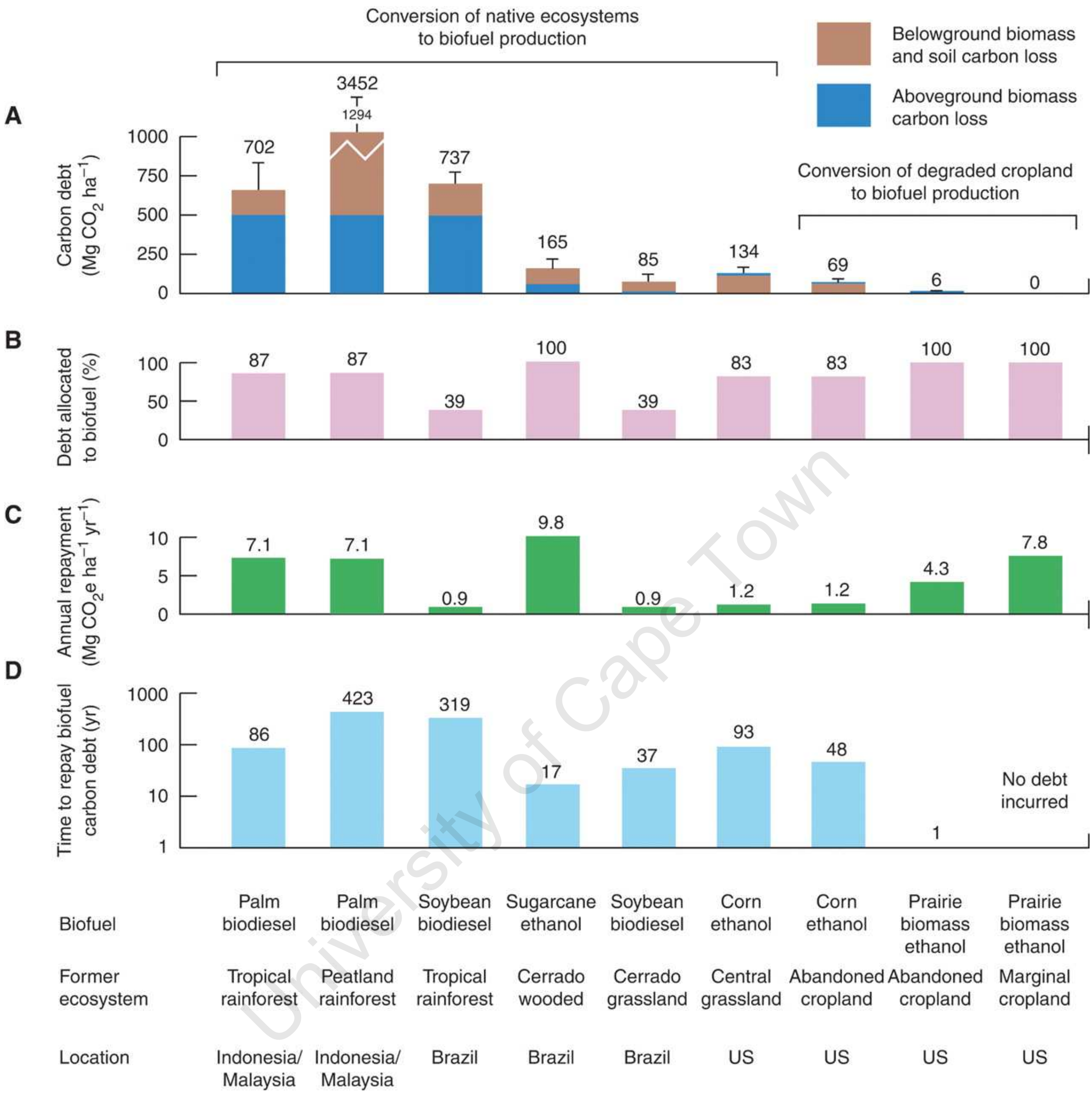


Figure 2. 5: The carbon debts for nine scenarios of converting habitats to biofuel production (Fargoine et al., 2008)

In the quest to replace maize as the main bioethanol feedstock in the United States, the Bioenergy Feedstock Development Program (BFDP) has been conducting research since 1978 to identify and develop fast-growing trees and herbaceous crops, as well as to evaluate the potential crop residues as sources of renewable energy (Ferrell et al., 1995). After screening more than 30 herbaceous crops species during the 1980s (Wright, 1994), switchgrass – a perennial grass species – emerged as the most promising due to its excellent conservation attributes and good compatibility with conventional farming practices (McLaughlin et al., 1999). The research showed that the efficiency of energy production for switchgrass exceeds that of maize by as much as 15 times, and its carbon sequestration rates may exceed those of maize by 20 to 30 times (Table 2.1).

Table 2. 1: Comparative energy flows in producing ethanol from switchgrass and corn (McLaughlin and Walsh, 1998)

Process	Corn[a] (GJ ha^{-1} yr^{-1})	Switchgrass[a] (GJ ha^{-1} yr^{-1})
Crop production	18.9	17.8 (12.8)
Biomass energy[b]	149.5	220.2
Energy ratio *R1*[c]	7.9	12.3 (17.2)
Ethanol production[d]	47.9	10.2
Energy in ethanol[e]	67.1	104.4
Total energy ratio *R2*[f]	1.21	4.43
Net energy gain	21%	343%

[a]Budget data for production and processing corn are from Shapouri et al. [31] Production data are adjusted for 0.73 GJ ha^{-1} machinery production costs. Switchgrass data include costs of on-farm storage and secondary handling or direct transfer to buyer (in parentheses).
[b]Yields assumed were 13.5 Mg ha^{-1} for switchgrass and 301 Bu ha^{-1} for corn. Corn biomass energy includes 18.9 GJ ha^{-1} of energy in corn fiber and no credit for stover.
[c]Biomass energy/production energy.
[d]Includes processing and distribution energy. Switchgrass data are derived from analyses of the saccharification and fermentation processes for ethanol production at the National Renewable Laboratory (Tyson et al. [32]).
[e]Ethanol yields are 2963 l ha^{-1} for corn and 4487 l ha^{-1} for switchgrass with ethanol energy of 23.3 kJ l^{-1} used to calculate production energy.These are based on conversion rates of 386 l Mg^{-1} (2.6 gal Bu^{-1}) for corn and 333 l Mg^{-1} (80 gal ton^{-1}) for switchgrass.
[f]Total output energy/total input energy (processing, production and distribution energy). Output energy includes allowance of 14.2 GJ ha^{-1} credits for coproducts for corn and 19.8 GJ ha^{-1} for combustion of lignin from switchgrass.

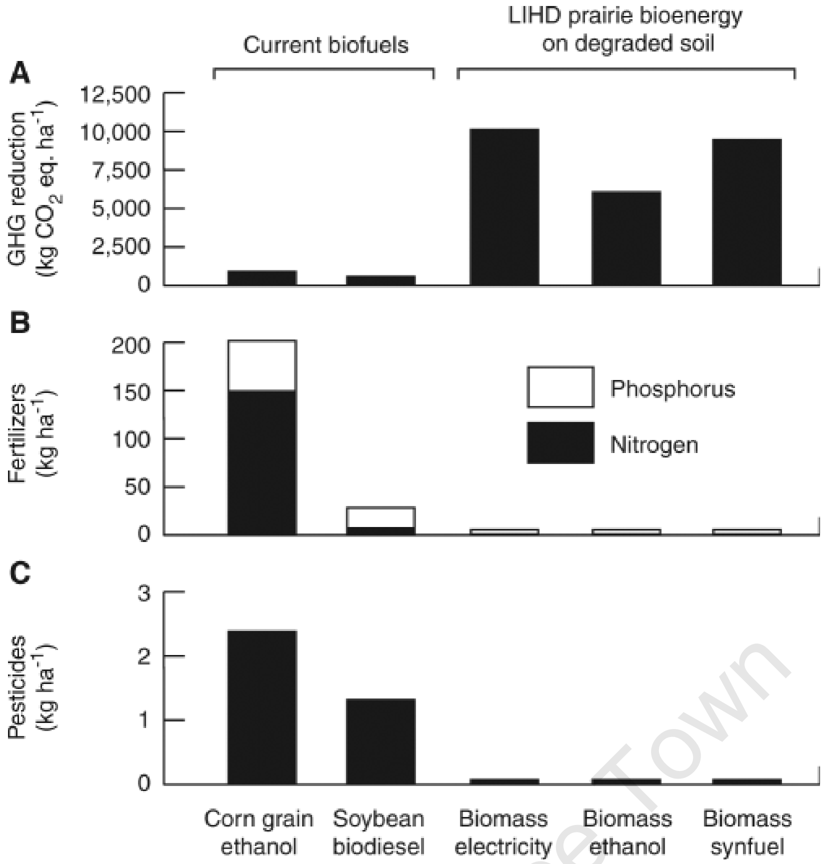


Figure 2. 6: *Comparison of of GHG reduction capacities of food-based biofuels grown on fertile soils with LIHD-based biofuels from agriculturally degraded soil (Tilman et al., 2006).*

Tilman et al. (2006), also, compared the bioenergy potential of monoculture crops, including switchgrass, to LIHDs and found that the latter can provide more usable energy and greater greenhouse gas reductions per hectare than maize grain ethanol or soybean biodiesel (Figure 2.6). Moreover, LIHDs can be successfully grown on agriculturally degraded lands and thus need to neither displace food production nor cause loss of biodiversity via habitat destruction. There are, however, still questions regarding the adaptability and suitability of these perennial grasses in other countries, and further research is still required before they can be used in large scale biofuel production.

2.5. Energy Modelling

In order to facilitate the effective utilisation of bioenergy resources in any country, it is necessary to develop an energy planning discipline that will ensure that sustainability and maximum value added are achieved. According to Cormio et al. (2003), energy planning builds and verifies strategies in energy economy, which is defined as "*that part of economics applied to energy problems, taking into account the analysis of energy supply and demand, as well as implementation of the means for ensuring coverage of energy needs in a national or international context*". Researchers and modellers have been developing integrated energy models linking commercial and renewable energy sources since the late

1970s, and modelling has become a standard tool for planning the efficient use of all energy resources (Jebaraj and Iniyan, 2006).

2.5.1. A Review of Energy models

Energy models are generally classified into two categories: econometric models and process models. The econometric model generally relies on mathematical and statistical methods (such as regression analysis) to study economic systems. Its aim is the empirical validation of theoretical models, as well as the derivation of quantitative statements about the operation of economic aggregates. All econometric models are based on the use and implementation of statistical data (Cormio et al., 2003).

Process models, also known as engineering models, make explicit assumptions about costs, performances and relations between components in the energy system and calculate feasible energy strategies either by optimisation or by the simulation of alternative scenarios (Roos and Rakos, 2000). The optimization model involves the identification of appropriate parameters and decisional variables from which an objective function can be defined. The objective function is the most important part of the mathematical formulation. Within it the components that derive from the problem and the variables are linked to solve the problem and then the condition of minimization or maximization of the objective parameter is given (Nagel, 2000). This is the most important and broadest category of energy planning models.

There are also models incorporating both engineering and econometric forecasting techniques, referred to as 'hybrid models' (Roos and Rakos, 2000).

Energy–economic models can also be categorized as top-down or bottom-up depending on their approaches in examining the linkages between the economy and the energy system (Table 2.2).

Table 2. 2: Characteristics of top-down models and bottom-up models (Nakata, 2004)

Top-down models	Bottom-up models
Use an economic approach	Use an engineering approach
Cannot explicitly represent technologies	Allow for detailed description of technologies
Reflect available technologies adopted by the market	Reflect technical potential
Most efficient technologies are given by the production frontier (set by market behavior)	Efficient technologies can lie beyond the economic production frontier suggested by market behavior
Use aggregated data for predicting purposes	Use disaggregated data for exploring purposes
Based on observed market behavior	Independent of observed market behavior
Disregard the technically most efficient technologies available, thus underestimate potential for efficiency improvements	Disregard market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements
Determine energy demand through aggregate economic indices (GNP, price elasticities), but vary in addressing energy supply	Represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption
Endogenize behavioral relationships	Assess costs of technological Options directly
Assumes no discontinuities in historical trends	Assumes interactions between energy sector and other sectors is negligible

Top-down models evaluate the system from aggregate economic variables, whereas bottom-up models create a more disaggregated picture from the processes and the energy and emissions flows determining the energy systems as well as to take relationships between them into consideration (Nakata, 2004).

Mathematical models have been applied to a variety of energy planning applications, and Table 2.3 provides a classification of the well-known and commonly used models.

Table 2. 3: Typical Energy-economic models (Becker and Barry, 2006)

MODEL	DESCRIPTION	OBJECTIVE
Forecasting Models		
LEAP	Long Range Energy Alternative Planning Model	Provides an information bank, an instrument for long-term projections of supply/demand configurations and a vehicle for identifying and evaluating policy and technology options.
Optimisation Models		
MODEST	Model for Optimisation of Dynamic Energy Systems with Time dependent components and boundary conditions	National, regional and local studies; finds operation profile of existing plants and potential investments that satisfy heat and power demand at lowest cost
MARKAL	Market Allocation Model	Bottom-up, Multi-period, Technology-orientated Energy systems Optimization model
EFOM	Energy Flow Optimisation Model	Energy-orientated, Bottom-up, National level, Optimisation model
OREM	Optimal Renewable Energy Model	Optimum allocation of renewable resources for different end-uses
MESSAGE	Bottom-up Single objective Dynamic linear programming Optimization model	Dynamic systems Engineering optimization model that is used for medium to long-term energy planning, energy policy analysis and scenario development
Geographical Models		
GLUE	Global Land Use and Energy Model	Multi-regional; evaluates bioenergy resources comprehensively and systematically by considering land use competition and biomass flow

The EFOM model has been used by the Commission of the European Communities since the 1970s. They used it in their 'Energy 2000' study in the mid-1980s for a reference projection of the energy systems in member countries; scenario assumptions concerning economic growth levels, oil import prices, and the role of solid fuels and nuclear power were studied (Grohnheit, 1991). MODEST has been applied to a typical local Swedish electricity and district-heating utility and to the national power system in order to minimise the capital and operation costs of energy supply and demand side management (Henning, 1997). Tseng et al. (2005) used MARKAL to simulate the impacts of hydrogen technologies on the US energy system and to identify potential impediments to a successful transition, whereas De Musgrove (1984) used it to analyze minimum discounted cost configurations for the Australian energy system during the period 1980–2020. Bala (1997) used the LEAP model to present projections of rural energy supply and demand and to assess the contributions to global warming. Messner and Schrattenholzer (2000), on the other hand, developed a tool that generates energy–economy–environment scenarios that are consistent in two respects: one is consistency between energy demand and energy supply cost curves owing to a price-responsive macroeconomic production function, and the other is consistency between two scenarios that describe the same economy but where one scenario includes additional constraints on its energy system. The result was a model called MESSAGE-MACRO, which is formed by linking a macroeconomic model, MACRO, with a detailed energy supply model, MESSAGE.

2.5.2. Application of modelling to Bioenergy

Of particular interest to this thesis is the application of these models to bioenergy systems. Roos and Rakos (2000) have shown that in modelling bioenergy systems, three features have to be carefully considered. Firstly, biomass fuel sources and conversion techniques are, more often than fossil fuel systems, dependent on local conditions concerning feedstock supply and energy use, and this restricts the applicability of a model that has been developed under one set of conditions to other situations. Secondly, there are few developed and documented full-scale bioenergy systems in operation, most of which are restricted geographically with prices and flows sometimes not statistically recorded. This causes problems for econometric analyses of biomass fuel markets. Lastly, biomass fuels are frequently by-products generated in another main activity, e.g. forestry, agriculture, and waste management. This means that the different stages in the biomass-to-energy chain often share costs with complementary activities, which constitutes a special challenge for the modeller to acquire insights not only about bioenergy production, but also in the related activities.

Despite these complexities and challenges, modelling has been successfully used in bioenergy planning in many countries. Yamamoto et al. (2000) evaluated the bioenergy supply potentials, land use changes and CO_2 emissions in the world using a global land use model (GLUE), while Lehtila and Pirila (1996) and Cormio et al. (2003) used the energy flow optimization model (EFOM) to support policy planning for the sustainable use of renewable energy, including bioenergy, in Finland and the Apulia region in southern Italy respectively. The environmental constraints are also considered in the latter case. The Long Range Energy Alternative Planning (LEAP) model was used by Kumar et al. (2002) to assess different energy scenario options for Vietnam, namely the replacement of kerosene and liquefied petroleum gas (LPG) by biogas stove, substitution of gasoline by ethanol in transport sector, replacement of coal by wood as fuel in industrial boilers, electricity generation with biomass energy technologies and an integrated scenario including all the options together. Iniyan and Sumathy (2000) analysed the effect of introducing renewable energy sources on the commercial energy scene in India using the Optimal Renewable Energy Model (OREM).

Second and third generation hybrid simulation models like FORECAST and FORCEE, have also been considered for evaluating the sustainability of bioenergy plantations (Kimmins, 1997).

2.5.3. Bioenergy Modelling in South Africa

Bioenergy modelling in South Africa has mainly been concerned with sustainability of traditional biomass usage and meeting the electricity demands:

Banks et al. (1996) used numerical modelling to combine data on fuelwood harvesting, construction timber requirements and the number of people in two settlements in the Eastern Transvaal Lowveld (Athol and Welverdiend) with woody biomass information to investigate the relationship between woodland supply and local wood demand. The results showed that significant changes in per capita fuelwood harvest seriously impacts on households, and it is thus important that the models be utilized within a much broader holistic framework in the development of solutions appropriate for local areas. Likewise, Aron et al. (1991) present a fuelwood supply and demand model which projects likely fuelwood supply deficits to the year 2000 AD.

In recent years MARKAL and LEAP have been employed by the Energy Research Centre (ERC) at the University of Cape Town, primarily for supporting the development of energy policies for sustainable development in South Africa and solving the problem of electrification (ERC, 2007).

In their assessment of the national energy modelling initiatives in South Africa, however, Doppegieter and Du Toit (1999) found that there is a need for an integrated national energy modelling system, with a focus on modelling the interaction between energy and the environment. The study also found that, affordability, flexibility, accessibility, time horizon (± 10-20 yrs) and compatibility constitute the important criteria in a South African energy model.

2.6. Multicriteria Decision-making in Energy Systems

The development of a sustainable bioenergy industry is a particularly complex task because "*its three components – feedstock supply, conversion technology, and energy allocation – are influenced simultaneously by social, economic and ecological factors. "Understanding these factors, their interdependency, and their integration is essential, because failure of just one factor has led to the failure of many earlier attempts to introduce bioenergy systems delivering modern energy*" (Karekezi, 2001). According to Hobbs and Meier (2000) these factors are often conflicting in nature, and the question to be asked is not whether tradeoffs should be made among them, but how they should be made.

According to Munasinghe (2007) there are two major methods for integrated analysis of the social, economic and environmental dimensions of any system: Cost-benefit analysis and multicriteria decision-making. Cost-benefit analysis is a single-valued approach, based on neoclassical economics, which seeks to assign monetary values to the consequences of an economic activity. The resulting costs and benefits, defined as the difference between what would occur with and without the activity being carried out, are combined into one decision-making criterion. These values may be expressed in economic terms (looking at shadow prices and opportunity costs) or financial terms (money profits obtained from an activity using market prices), incorporating all significant social and environmental impacts and externalities as penalties or quantity controls. This method, however, suffers from various drawbacks as listed below (Hobbs and Meier, 2000):

- Many environmental and social effects are difficult to measure, not only in physical terms, but more so in monetary terms
- The basic assumptions of welfare economics are not universally accepted
- The fundamental value judgements concerning, for instance, the worth of a human life are made by analysts and may be buried in the calculations, rather than left in the hands of stakeholders where they belong
- The most valid methods can be difficult or even impossible to apply in practice, leading to the use of more expedient yet less valid methods.

It is these drawbacks of the cost-benefit analysis method that have made Multicriteria Decision-making the most preferable method for integrated analysis, especially in issues that relate to energy and sustainable development. The following subsection presents a detailed outline of the multicriteria decision-making methods for integrated socio-economic and environmental analyses.

2.6.1. *Principles of Multicriteria Decision-making*

Multicriteria decision-making (or multiobjective optimization) is a field of methods used to analyse problems with several, often conflicting, objectives, goals, criteria, attributes or performance indices and to facilitate agreement among diverse stakeholders. A multiobjective optimization problem consists of a number of objectives to be optimized simultaneously under a set of constraints. Without loss of generality, a multiobjective problem can be stated mathematically as:

$$\min_{x} \; f_i(x); \qquad i = 1, 2, \dots, N$$

$$\text{Subject to:} \begin{cases} g_j(x) = 0; & j = 1, \dots, M \\ h_k(x) \leq 0; & k = 1, \dots, K \\ A \leq x \leq B \end{cases}$$

where f_i is the i-th objective function, x is a decision vector that represents a solution and N is the number of objectives. M and K are the numbers of equality and inequality constraints respectively, while A and B are explicit variable bounds.

Unlike a single optimization problem, a multiobjective problem has no single optimal solution that simultaneously optimizes all objective functions; instead a set of efficient, *Pareto optimal* solutions is obtained. A *Pareto optimal* set of solutions is a set that cannot be improved in one objective function without deteriorating its performance in at least one of the rest. In other words a *Pareto optimal set* is an efficient or non-dominated set of solutions to the multiobjective optimization problem. Without loss of generality, if all objective functions are for minimization, a feasible solution x_a dominates another feasible solution x_b if the following two conditions are satisfied:

1. $f_i(x_a) \leq f_i(x_b)$ for every i =1, 2, …, N;

2. There exists $j \in \{1, 2, \dots, N\}$ s.t. $f_j(x_a) < f_j(x_b)$

If any of the above conditions is violated, then solution x_a does not dominate solution x_b. The *Pareto optimal* set is, therefore, made up of those solutions x_b for which there exists no solution x_a satisfying both conditions. In the absence of any other information, none of the *Pareto optimal* solutions can be said to be better than the other, and usually a decision maker is needed to provide additional preference information and to identify the “most preferred” solution. For a given *Pareto optimal* set, the corresponding objective function values in the objective space are called the *Pareto front*.

2.6.2. Multiobjective optimization solution methods

Depending on the phase in which the decision makers are brought in to express their preferences, the methods for solving multiobjective optimization problems are classified as a priori, interactive or a posteriori (Hwang and Masud, 1979). In a priori methods, decision makers express their preferences before the solution process in the form of goals or weights for the objective functions. The major drawback about these methods is that it is very difficult, and therefore rare, for the decision makers to know and be able to accurately quantify their preferences beforehand. In interactive methods phases of dialogues with decision makers are interchanged with phases of calculations and the process usually converges after a series of iterations to the most preferred solution. The problem with these types of methods is that the decision makers never get to see the whole picture, and the most preferred solution is only "most preferred" in relation to what they have seen so far. In a posteriori methods (or generation methods) a sufficient representation of the most efficient solutions is first generated and then the decision makers are involved in order to select, among them, the most preferred one (Mavrotas, 2007).

Because decision makers are hardly available and interaction with them is generally difficult, posteriori (or computational) methods are usually the most favourable since they only involve the decision makers in the second phase, when all alternatives have been determined. The three most common computational methods are the parameter space investigation method, the weighting method and the ε-constraint method:

2.6.2.1. The Parameter Spacing Method

The Parameter spacing method is particularly suitable for solving low-dimension multiobjective problems that are highly nonlinear and non-convex in nature. It is basically a random sampling procedure involving the following steps (Lim et al., 1999):

i. Sampling points on a uniform grid in the space of the decision variables constrained only by finite bounds
ii. Evaluating the objectives and constraints at each point
iii. Discarding the points that do not satisfy the inequality constraints
iv. Ordering the objective vectors and retaining the non-dominated points.

After one such run, the programmer sets goals on the objectives and tries to find objective vectors that satisfy them. If the objective vectors satisfying the goals cannot be obtained, goals are either relaxed or more points are sampled. This process is repeated until a sufficient number of solutions are obtained.

According to Steuer and Sun (1995), it is practically impossible to apply this method to problems with more than ten variables because of the amount of computational work required.

2.6.2.2. The Weighting Method

Here the multiobjective optimization problem is reduced to a single optimization problem by combining the objectives to form a weighted sum of the objective functions as follows:

$$\min_{x} \left\{ U(f_i, \propto_i) = \sum_{i=1}^{N} \propto_i f_i(x) \right\}$$

$$\text{Subject to:} \begin{cases} g_j(x) = 0; & j = 1, \dots, M \\ h_k(x) \leq 0; & k = 1, \dots, K \\ A \leq x \leq B & \\ \sum_{i=1}^{N} \propto_i = 1.0; & 0.0 \leq \propto_i \leq 1.0 \end{cases}$$

By varying the weighting factors, $\propto_i$, different non-dominated solutions are obtained.

2.6.2.3. The ε-constraint method

In the ε-constraint method one objective function is optimized using the other objective functions as constraints, and incorporating them in the constraint part of the model as follows:

$$\min_{x} \quad f_1(x)$$

$$\text{Subject to:} \begin{cases} g_j(x) = 0; & j = 1, \dots, M \\ h_k(x) \leq 0; & k = 1, \dots, K \\ A \leq x \leq B & \\ f_i(x) \leq \varepsilon_i; & (i \neq 1, 2 \leq i \leq N) \end{cases}$$

The different non-dominated solutions are obtained by parametrically varying the RHS of the constrained objective functions ε_i.

This method has several advantages over the weighting method (Mavrotas, 2007):

1. For linear problems, the weighting method is applied to the original feasible region, which results in a set of corner (or clustered) solutions that provide little insight into the shape of the complete trade-off curve. The ε-constraint method, on the other hand, alters the original feasible region and, therefore, able to give solutions that are more representative of the Pareto curve.
2. Unlike with the weighting method, unsupported non-dominated solutions in multiobjective integer and mixed integer programming problems can be obtained with the ε-constraint method.
3. In the weighting method the solutions are strongly dependant on the scaling of the objective functions. The objective functions, therefore, need to be brought to a common scale before optimization is done; a process that is not necessary in the ε-constraint method.

4. Unlike with the weighting method, the number of the generated non-dominated solutions can easily controlled with the ε-constraint method by properly adjusting the number of grid points in each one of the objective function ranges.

2.7. Summary of the Literature Review and outlook

The following conclusions can be drawn from the literature review:

- More than half of the global potential of biomass contribution to the energy sector lies in the sub-Saharan part of Africa, and the extent to which this potential can be unlocked is greatly dependant on the location, choice of feedstock and method of production.

- Biofuels are a potential low-carbon energy source, but whether they actually offer the carbon savings depends on how they are produced. Producing biofuels from crops grown on degraded land and waste biomass minimizes habitat destruction, competition with food production and carbon debts associated with clearing land.

- South Africa has set bioenergy targets for 2013 in light of various economic, environmental and social benefits to be gained therein, and to achieve these goals, there is need for an energy planning discipline that will facilitate the effective utilisation of this renewable energy source so that sustainability and maximum value added are achieved.

- Land use change and deforestation for biofuel production have a strong influence on the success and sustainability of bioenergy systems and their effects should always be taken into account in analysing the environmental and social impacts of bioenergy systems from a life-cycle perspective.

- While energy modelling can be used to analyse bioenergy systems only from an economic view and life-cycle assessment can be used to analyse the social and environmental aspects, multiobjective optimization is the best method for analysing the interactions and tradeoffs between all three dimensions.

Having painted an overall picture of the whole thesis in the first chapter and reviewed what already exits in literature in this chapter, the next chapter then describes the system under study and the methodological approach of the thesis in detail.

3. SYSTEM DESCRIPTION AND MULTICRITERIA MODELLING

3.1. Adopted Methodology

Based on the analysis of the introductory chapter and the findings of the literature review, the following methodology was adopted:

Firstly, spreadsheet-based analyses of the energy balances and land use change effects of the different biofuels were carried out. Then a 3-objective nationwide optimization model was developed to quantify and to analyse trade-offs among the different social, environmental and economic objectives of the biofuel industry for different biofuels, and to determine the crop combinations that offer the most optimal benefits for the country as a whole.

Although a model at national level is useful for showing a broad picture of how national targets and objectives can be achieved optimally with minimal land use, it is important to realise that the areas of the country that fit the criteria of the National Biofuels Strategy are not grouped together in one part of the country, but are scattered all over the 9 provinces of the country, with varying geographic and climatic characteristics. Each area is thus unique in terms of the type of energy crops that can be grown, the yields of the suitable energy crops and the infrastructure that is available to support biofuel production. This means that the different areas will adopt different biofuel programmes to suit each individual area. Thus a model was also developed for a local municipal area specifically to demonstrate how multicriteria modelling can also be used to aid decision-making at local government level for a local biofuel programme.

The next sections of this chapter present and describe the system under study, and outline the specific methodological procedures in greater detail. The inventory preparation method is also presented.

3.2. System Description

The system modelled in this dissertation is the supply chain network of bioethanol and biodiesel produced from biofuel crops grown in South Africa. This thesis investigates the use of "currently underutilized, high potential agricultural land" to produce bioenergy crops that are transformed via different processing techniques to produce appropriate biofuels. These biofuels are then transported to local blending stations for blending with liquid petroleum fuels. Figure 3.1 is a representation of the biofuel supply chain modelled in the thesis.

The shaded block in Figure 3.1 represents an aggregation of all pieces of agricultural land in different parts of the country that are dedicated to biofuel production, where a range of bioenergy crops can be grown in any combination, subject to crop suitability in the different areas. Depending on the type, the crops are then taken to grain processing plants, cane processing plants or oilseed processing plants where different technologies are employed to transform them to either bioethanol or biodiesel.

3.2.1. Processing Technologies

The different processing technologies considered in this thesis are discussed below:

3.2.1.1. Grain processing

Although there are currently no industrial-scale plants in the country producing bioethanol from grains, there has certainly been a strong interest in this processing technology in recent years, both from the corporate world and the government. The main issue that has been holding back the actual implementation is the development of the Industrial Biofuels Strategy which was only published in November 2007.

The most predominant early venture was that of Ethanol Africa; a corporation between maize farmers, technologists and specialists in the clean technology market. The main focus of Ethanol Africa was to unlock the value contained in maize through the conversion of maize to ethanol. In 2005 the company released its eight year plan to build eight grain processing bioethanol plants from 2005 to 2012 around the central and north eastern part of the country, starting with Bothaville in the heart of South Africa's maize triangle (Ethanol Africa, 2007). This, however, was before the release of the final Biofuels Industrial Strategy which excludes maize in the initial (five year pilot) period of biofuel development in South Africa.

In 2006 the Western Cape Provincial Department of Agriculture also published the findings of a study, carried out by Grain South Africa on their behalf, on the feasibility of an ethanol plant based on wheat produced in the Western Cape. Their report presents a bioethanol plant with a capacity of 108 million litres per annum and capable of utilizing cereals other than winter wheat as feedstock (Lemmer, 2006).

In this thesis, all the nine grain processing plants are included in the model; those proposed by Ethanol Africa and the one proposed by the Western Cape provincial Department of Agriculture. For the purposes of the model, it was assumed that the latter plant is located in the Swartland, the largest wheat growing area in the Western Cape Province. It was further assumed that all the plants are capable of processing all types of grain at the same efficiency. All the plants are modelled as dry milling plants that produce only DDGS as by-product.

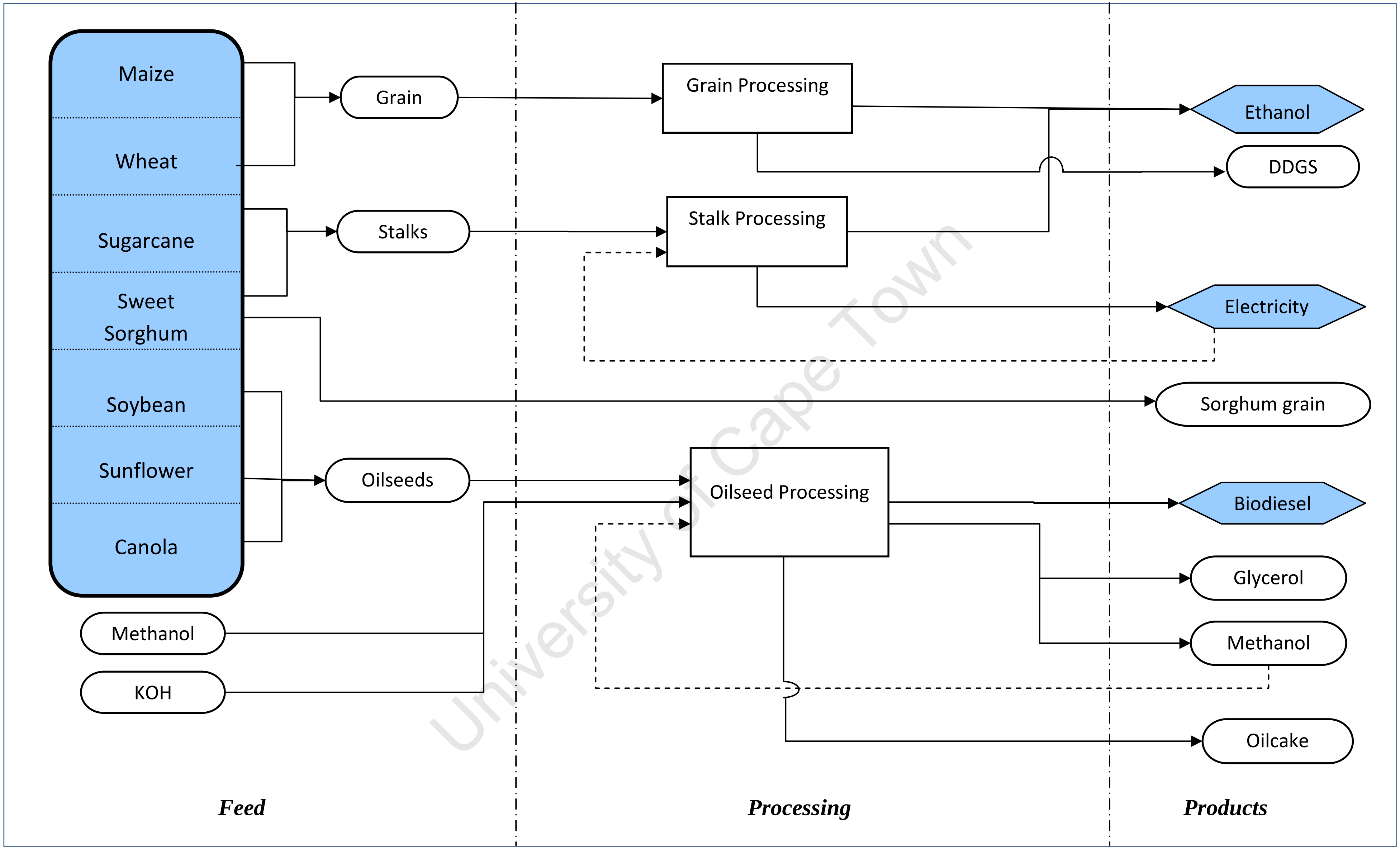


Figure 3. 1: Biofuel supply chain network modelled in this thesis

3.2.1.2. Cane Processing

Sugar mills are the only existing plants in the country with the technical know-how to process cane into bioethanol. There are 14 sugar mills in South Africa, situated around the eastern Kwazulu-Natal area and the north-eastern part of Mpumalanga, within the sugarcane growing areas of the country. These are considered to be the only cane processing bioethanol plants in the model. All the mills are able to co-generate electricity and process heat from bagasse for their energy needs.

Figure 3.2 shows the locations of all the ethanol plants considered in this thesis.

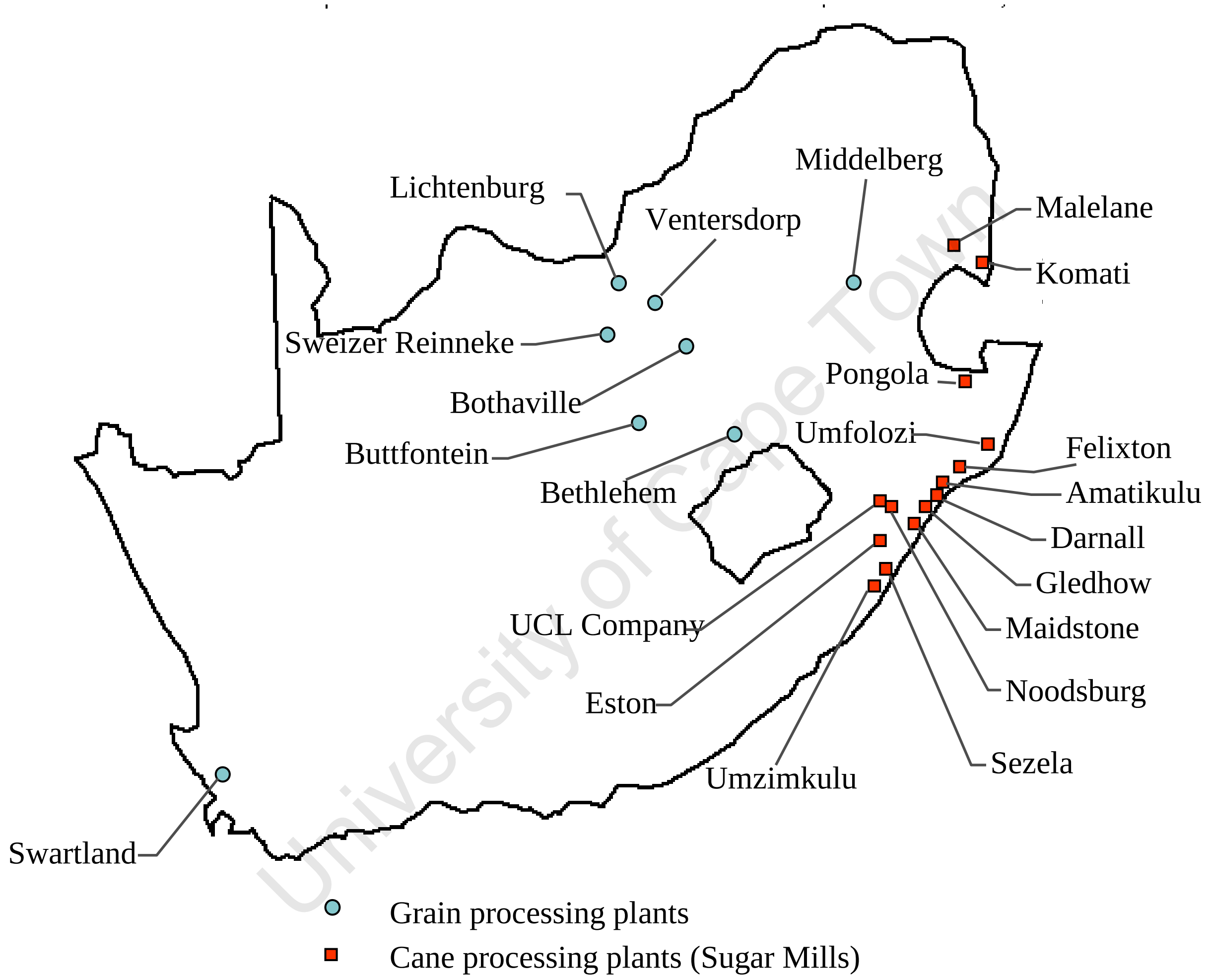


Figure 3. 2: The locations of all the bioethanol plants in the model

3.2.1.3. Oilseed Processing

According to Bender (1999) and Amigun (2008) biodiesel production does not reflect any significant economies of scale. In South Africa, where development of the biofuel industry is strongly attached to rural community development, regional biodiesel production is therefore more suitable than a few large centralised plants. Amigun and von Blottnitz (2005) carried out size optimization of biodiesel plants in

South Africa using *Jatropha curcas* as feedstock and concluded that the optimal plant size lies in the range of 1500 kg/hr – 3500 kg/hr.

The specifications of oilseed processing plants modelled in this thesis were based on a scenario presented by Nolte (2007): Assuming an optimal plant size of 2500 kg/hr, Nolte proposes the use of containerized biodiesel plants manufactured by a Dutch biodiesel equipment specialist, BioKing®, with production capacities of 2640 kg/hr. These plants consist of 20 tonne/hr hexane oil extractors, transesterification systems and batch glycerol purifiers (Appendix A).

Other specific properties of the plants are summarized below:

1. They are small and relatively easy to move around
2. They are fitted with continuous transesterification reactors with high yields and fast reaction times
3. For biodiesel/glycerol separation centrifuges are used, thereby speeding up the whole process
4. The methanol obtained from the glycerol purifier can be recycled to reduce processing costs
5. Only the hexane extractor is powered by electricity while the rest of the plant is fitted with a burner and generator that run on some of the biodiesel and glycerol produced by the plant.

In this thesis it is assumed that each biodiesel plant can adequately service one local municipal area, and it can either be permanently located at centre of the municipal agricultural area or periodically be moved between two or three oilseed-growing areas within the municipality.

3.2.2. Bioenergy Crops

Seven bioenergy crops have been considered in this thesis; two grains, two sugar crops and three oilseeds. This section discusses all these crops in detail.

3.2.2.1. Maize

Maize is the most important grain crop in the Southern African Development Community (SADC), being the primary feed grain for animals and a staple food for people. South Africa is by far the largest producer of maize in the continent with an average production of 8.5 million tonnes per year between 1993 and 2007. About 60% of maize produced in South Africa is white and the remainder is yellow maize (DoA, 2006).

For food security purposes the National Industrial Biofuels Strategy (DME, 2007) excludes the use of maize to produce bioethanol in the initial phases of the biofuels industry development. The strategy further states that this restraint on maize will only be lifted once "*certainty on the ability of the current underutilized land to produce has been ascertained and the necessary measures are in place to guard against extreme food inflation*".

The focus of this thesis is solely on the use of currently underutilized land dedicated to biofuels production, and therefore it is not inappropriate to include maize in the model. It was assumed that only yellow maize is dedicated to bioethanol production.

3.2.2.2. Wheat

Wheat is the third most important field crop in South Africa, after maize and sugarcane, in terms of value of production. As a staple food, however, wheat is only surpassed by maize in importance, especially in the rapidly urbanizing areas of the country. In South Africa wheat is produced primarily for human consumption with only small quantities of poorer quality wheat used as animal feed. Before the 1970's wheat was only produced in the winter rainfall area of the Cape but has since been grown in the Free State and other parts of the country (FPM, 2004). In the Western Cape, wheat remains the primary grain of focus for bioethanol production, while other feedstocks under consideration include triticale, barley and other forage crops grown in smaller quantities.

3.2.2.3. Sugarcane

South Africa used ethanol produced from sugarcane as fuel for automobiles as early as the 1920's through to the 1960's when the world saw the emergence of cheap and abundant crude petroleum oil. The South African sugarcane growing industry is composed of approximately 50 000 registered cane growers who produce some 20 million tons of sugarcane per annum in areas around the 14 sugar mills, extending from the Eastern Cape through kwaZulu-Natal to the subtropical area of Mpumalanga (FPM, 2004). Although the South African Sugar Industry produces some by-products, the industry has sugar as its only significant commercial product, which makes it susceptible to fluctuations in the world sugar market (Wienese and Purchase, 2004). According to the first national biofuels report (Germishuis, 2006), the production of ethanol from sugarcane "*has the potential to enhance the sustainability of the sugar industry in South Africa and to stimulate growth both industrially and agriculturally in the areas where the industry operates*". Sugarcane is one of the two crops specifically targeted by the national Biofuels Industry Strategy to drive the bioethanol industry in South Africa.

3.2.2.4. Sweet Sorghum

Sorghum is a C4 crop which finds its origins in the central-eastern part of Africa. Sorghums are drought resistant crops, making them favourable for growth in semi-arid areas where maize would not thrive

(Grassi, 2001). Sorghums are generally classified as grain sorghum, fibre sorghum and sweet sorghum depending on their characteristics and use.

In South Africa grain sorghum is the only type of sorghum produced commercially, mainly cultivated on low-potential, shallow soils with high clay content in the Free State, Limpopo, Mpumalanga and North West provinces. Although it is the third most important grain in the country, after maize and wheat, grain sorghum only contributes a small percentage to the total domestic grains. Sorghum grain is mainly used for human consumption and the animal market serves as an outlet channel for surpluses since sorghum can be used to successfully substitute maize as an energy source (FPM, 2004).

Sweet sorghum is similar to grain sorghum but features more rapid growth, higher biomass production, wider adaptation and, most importantly, higher sugar content in the stalk (Reddy, 2007). The latter characteristic makes sweet sorghum well suited for making sugar in China and liquid food sweeteners in India. In Southern Africa the juicy sweet sorghum stems are used in the food market as snack (Balole, 2001). Sweet sorghum is seen as the most versatile field crop for its ability to produce multiple products at the same time: grain for human consumption from its ear-head, sugary juice and bagasse from its stalk and also green foliage that can be used as fodder for animals. This characteristic of sweet sorghum has seen it gain world attention as a promising bioenergy crop and alternative raw material for the production of ethanol (TNAU, 2007). Since 1983, research has been undertaken in China, India and, more recently, Australia to breed and test new hybrids of sweet sorghum for use as raw material in ethanol production (Gnansounou et al., 2005;ICRISAT, 2006;Hallam, 2007).

This thesis looks at a scenario where South African farmers use their experience with grain sorghum to grow sweet sorghum for ethanol production. The modelled system assumes that only the sorghum stalk is used for ethanol production while the grain is directed to the food market in an attempt to address food security as opposed to threatening it.

3.2.2.5. Soybean

Soybean is a relatively difficult crop to grow, ideally requiring warm, fertile clayish soils. In South Africa, the crop is mainly grown in Mpumalanga, the Free State and Kwazulu-Natal with small quantities cultivated in the other north-eastern provinces. The main use of soybean in South Africa is in the animal feed market. Over a period of 10 years the production of soybean in the country increased 5-fold, from 80 000 tonnes in 1996 to 424 000 tonnes in 2006. This increase is attributed to the growing interest in soy products by South Africans because of the associated health benefits, and also the farmers' view of soybean as an economical replacement for maize and a crop for the future (FPM, 2004).

The world's largest producer of Coal-to-liquid fuels, SASOL, has shown interest in building a 400 000 ton/yr soybean fed biodiesel plant. According to Prasad and Visagie (2005) soy appears to be the most appropriate crop because, apart from the oil used for making biodiesel, it also produces soymeal as by-product. The latter is needed by both the animal feed and human consumption markets for alleviating protein deficiency.

3.2.2.6. Sunflower seed

The primary use of sunflower seed in South Africa is in the production of oil and oilcake for human and animal consumption respectively. Because of its relatively high resistance to drought, sunflower is mainly grown in the marginal production areas of the Free State and North West Province. Sunflower seed is the major source of plant oil for human consumption in the country, with local production meeting only about half the national demand while the balance is made up of imports and other locally produced oil seeds. The demand for sunflower seed is strongly dependant on the demand for its oilcake because, unlike soymeal, sunflower meal is characterized by a high fibre content which restricts its inclusion in pig and poultry feeds (FPM, 2004).

The national Biofuels Industrial Strategy proposes the use of sunflower seed as a major feedstock, together with soybean and canola, for the development of a local biodiesel industry.

3.2.2.7. Canola

Canola refers to genetically selected and nutritionally superior rapeseed that contains oil with less than 2% ericic acid and less than 30 µmol/g aliphatic glucosinulates (Tesfamariam, 2004). In South Africa, canola is mainly grown in the Western Cape Province, although since 2001, small quantities have also been planted in the northern parts of the country. In the wheat producing areas of the Western and Southern Cape, canola is becoming increasingly important for crop rotation as it provides a disease break for cereal crops and allows the use of alternative weed and pest control chemicals while also diversifying farm income (Hardy et al., 2004). Canola competes with other oilseeds both in the human consumption and the animal feed markets. The unique fatty acid composition of canola oil, however, provides a niche market for it as a healthier choice for human consumption, thus it is expected that its consumption in the human market will continue to rise (FPM, 2004).

As the major oilseed grown in the Western and southern Cape, canola has become the primary focus for biodiesel production in these areas and there are several private companies looking to explore this new energy venture. The Biodiesel centre, housed in Bellville in greater Cape Town, is one such organization which is currently conducting tests and creating awareness on the use of canola for biodiesel production.

3.2.3. *Land suitability of biofuel crops*

In 2006 the national Department of Agriculture released the findings of a study on the land suitability of potential biofuel crops in South Africa based on crop requirements, soil types and climate. Undertaken by the Agricultural Research Council's Institute for Soil, Climate and Water (ARC-ISCW), the study looked at maize, sorghum, sugarcane and sugar beet as potential bioethanol crops, and soybean and sunflower as potential biodiesel crops.

Of the crops considered in this thesis, only wheat and canola are not included in the ARC-ISCW crop suitability study. For the purposes of the model in this thesis, it was assumed that in the Western Cape the suitability of wheat is the same as that of canola, equalling some 418,000 hectares - the maximum area ever used in that province for wheat cultivation (Grain SA, 2008). To determine the land suitability of canola and wheat outside the Western Cape, maps of the global land suitabilities of crops developed by the Food and Agricultural Organization were used (FAO-AGLL, 2003). From these maps, the suitability of canola was estimated to be 55% of that of soybean, while the land suitability of wheat was estimated at 75% of the suitability of maize in the same area. The land suitability maps from both studies are shown in Appendix B.

Based on the two studies and the assumptions above, the land suitability of the crops in the thesis can be summarized as shown Table 3.1 below (Schoeman and van der Walt, 2006;FAO-AGLL, 2003):

Table 3. 1: National Crop Suitability

CROP	National Suitability		Western Cape	Rest of SA
	million hectares	%	%	%
Maize	20.83	81.3	0	81.3
Wheat	16.62	62.6	1.6	61.0
Sugarcane	1.52	5.9	1.4	4.5
Sweet sorghum	25.20	98.4	0	98.4
Soybean	14.68	57.3	0	57.3
Sunflower	22.63	88.3	0	88.3
Canola	8.07	33.1	1.6	31.5
Available Land	**25.62**	**100**	**1.6**	**98.4**

If the national suitability of the bioenergy crops shown in Table 3.1 above is also considered to be a representation of the suitability of these crops in the currently underutilized agricultural land nationwide, then the land dedicated to biofuels modelled in this thesis can be represented by Figure 3.3 below. The outside circles in Figure 3.3 depict the total land suitable for biofuel cultivation in the respective areas. The area suitable for biofuel crops in the Western Cape area is only 1.6% of the total suitable area in the country, and the only bioenergy crops that can be grown in this area are sugarcane, canola and wheat.

Although Figure 3.3 is not drawn to scale, the different diameters of the circles and their concentric nature represent agricultural areas suitable for growing the respective crops, with the intersection of the circles depicting areas of common suitability.

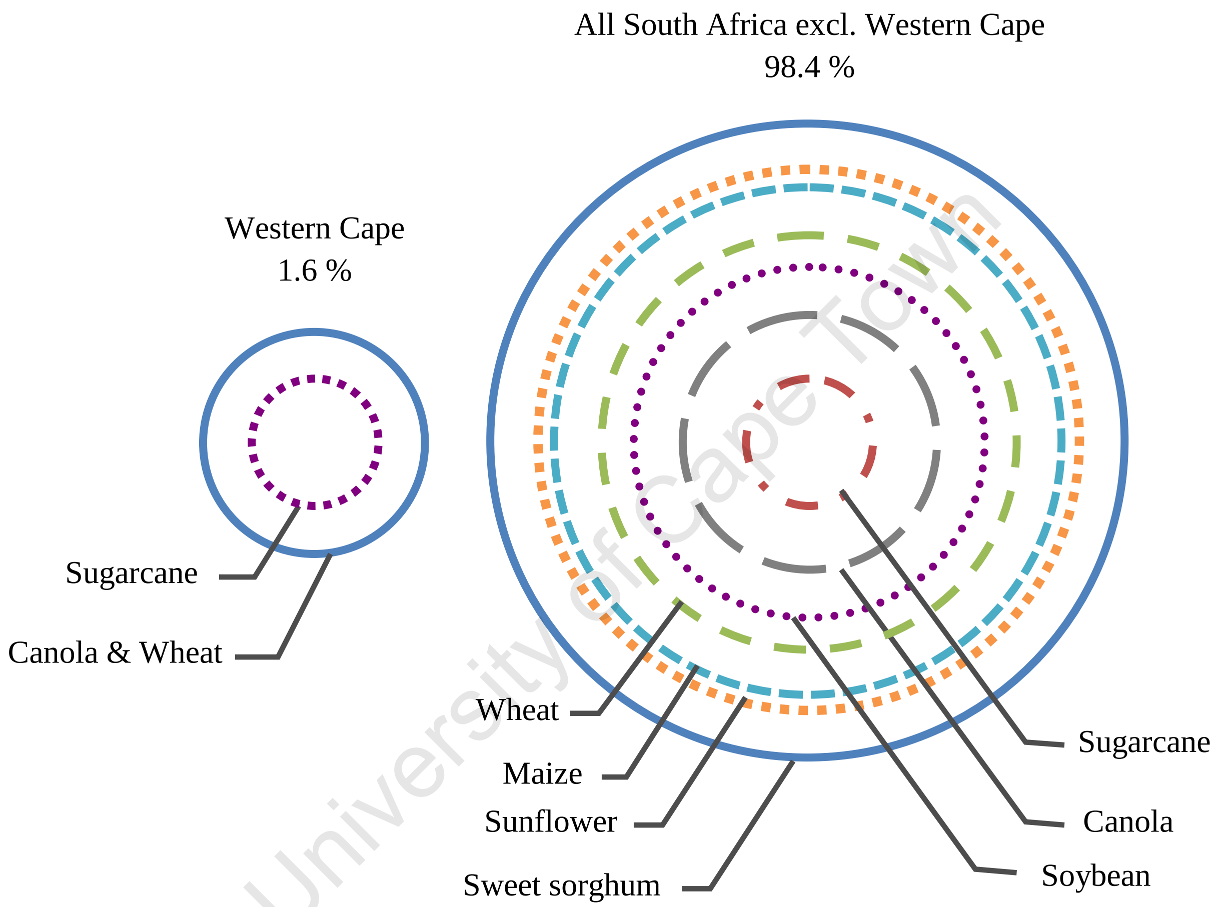


Figure 3. 3: The crop suitability of bioenergy crops as modelled in the thesis

3.2.4. System Boundary

As mentioned in the introduction to this chapter, the modelled system is essentially composed of three sections: The agricultural part, the processing part and the biofuel transport. The agricultural section consists of all activities carried out on the farm to produce bioenergy crops, while the processing section encompasses transportation of crops from the farm to the processing plant and all processing plant activities; finally the biofuel transport part covers the transportation of biofuels from processing plants to blending stations. Biofuel processing basically consists of all post-harvest activities necessary to make the biofuel available for blending.

Table 3.2 below shows all the material and energy inputs to the system. The fossil energy values and environmental burdens of all the inputs are traced back from the manufacturing stages of the inputs. For simplification, all farm machinery and processing plant equipment are assumed to consist entirely of steel, while processing buildings are assumed to consist primarily of concrete.

Table 3.2: Material and Energy inputs to the system

CATEGORY	INPUT
Agricultural Inputs	Seeds
	Farm machinery
	Fertilizers & Pesticides
	Fossil Energy for operating farm machinery
	Farm labour
Processing Inputs	Fossil Energy for transporting crops to processing plant
	Processing plant buildings and equipment
	Labour
	Fossil Energy for operating processing plant including energy embodied in chemicals used in plant
Biofuel transport Inputs	Fossil Energy for transporting biofuels to blending station

3.3. Allocation

The ISO 14041 (1998) recommends that allocation be avoided whenever possible, either by system expansion to include additional functions related to the co-products, or by subdivision of the unit process to sub-processes that can be analysed independently. In this thesis, the system expansion approach was adopted. This was done by identifying the products that the biofuel co-products displace in the market, and crediting the co-products with the same amount of energy and emissions as the fossil energy and emissions associated with producing equivalent quantities of displaced products. According to EUCAR (2004) this is a more realistic way of modelling than arbitrarily assigning co-product energy and emission credits based on relative monetary value, energy content or even weight.

Five types of by-products are produced in the system; DDGS, green electricity, sweet sorghum grain, oilcakes and glycerol. In this thesis it was assumed that DDGS replaces both soymeal and maize as animal feed, while green electricity and sweet sorghum grain replace electricity from Eskom and grain sorghum grown for human consumption respectively. Both sunflower cake and canola cake replace soymeal as feed for animals. In determining the energy credit and environmental burdens of soymeal, allocation could not be avoided and therefore mass allocation was employed. It was assumed that glycerol replaces synthetic glycerine in the world market.

3.4. Model Objectives

The development of a biofuel industry in South Africa is a process that inevitably affects the economic and social spheres, whilst also impacting on the bio-physical environment. This section identifies and discusses key economic, social and environmental issues affecting the choice and quantity of bioenergy crops grown for biofuels production in different areas of the country. For each of the three spheres, the identified indicator is then defined as an objective for the model.

3.4.1. Economic objective

For investors the return on financial investment of any business venture is the all-important factor that determines whether or not the investors can take part. In the biofuel industry the key economic indicator is value added by the biofuel producer, which can be defined as:

Value Added = (Biofuel revenue + By-product revenue) – (Raw material cost + processing cost).

Here the processing cost includes the cost of all consumables, energy and labour at the processing plant and all transportation costs. In this thesis it was assumed that processing plants buy crops from farmers at market prices and sell the biofuels and by-products at market prices as well.

For modelling at national level the economic objective as thus described – focusing only on processing plant value addition – was deemed appropriate as it is a common way of assessing the economic feasibility of biofuel projects (BFAP, 2007). As will be seen in Chapter 5, however, it was no longer possible at local government level modelling to ignore the other economic benefits associated with agricultural value addition.

3.4.2. Social objective

The Biofuels Industrial Strategy of South Africa (DME, 2007) reports that the development of a biofuels industry in South Africa is "*driven predominantly by the need to address issues of poverty and economic* *development"*; hence the strategy is specifically targeted at *"creating jobs in the energy-crop and biofuels value chain, and to act as a bridge between the first and second economy."* This implies that job-creation is the single most important social objective to be monitored in any biofuel project in the country.

This thesis focuses only on the direct jobs created within both the agricultural and the processing sections of the biofuels supply chain, and does not consider any jobs created outside the supply chain as a result of the production of biofuels as shown in the following equation:

$$Job\text{-}creation = Agricultural\ Jobs_{\text{-}Permanent} + Agricultural\ jobs_{\text{-}Temporary} + Processing\ Jobs$$

3.4.3. Environmental objective

Although South Africa does not have quantified greenhouse gas emission reduction targets during this first commitment period of the Kyoto protocol, many of the proposals for a post-2012 climate action plan support emission reduction commitments for many developing countries including South Africa. In the very least South Africa will be obliged to make and implement low-carbon sustainable development policies. This means that the carbon dioxide emissions reduction capacity of any bioenergy venture in the country is important in determining its long-term relevance and importance to the country's targets and goals.

The emission reduction capacity of a biofuel supply chain can be expressed as the *Avoided greenhouse gas emissions,* defined as: The difference of the greenhouse gas emissions that would have resulted from the production, transportation and use of the products that are replaced by all biomass products (biofuels and by-products) and the greenhouse gas emissions released as a result of producing the biofuels.

$$Avoided\ GHG\ emissions = GHG\ emissions_{\text{-}Replaced\ products} - GHG\ emissions_{\text{-}Biofuel\ production}$$

3.5. Problem Formulation

The problem is set up as a multi-objective optimization problem, maximizing economic gain, avoided greenhouse gas emissions and the number of jobs created within the supply chain. The basis of the analysis is one hectare of available land dedicated to biofuels production.

In the analysis, two approaches addressing two different key questions are adopted:

In the first approach, the problem is formulated to compare all crops and to determine the overall optimum crop or combination of crops based on the economic, social and environmental objectives selected. Given one hectare of currently underutilized agricultural land, this approach seeks to determine which biofuel crop (and subsequently biofuel) offers the most benefits. A sensitivity analysis of this approach is also useful in establishing the key variables that determine the preference of one biofuel over the other.

The second approach serves to determine a combination of crops that result in optimal land use, based on the selected objectives, to achieve the 2% biodiesel and 8% bioethanol market penetration target proposed by the Biofuels Industrial Strategy of South Africa. In this approach the comparison is solely on the crops competing for the production of the same type of biofuel.

It must be noted that the model objectives as described in section 3.4 above have different system boundaries; while the economic objective is focused on processing plant value addition, the environmental and social objectives look at cradle-to-grave emissions and farm-to-blending station job creation respectively. Full cradle-to-grave analyses for all three objectives would be ideal, but because of the complexities associated with full social and economic life-cycle analyses and the scarcity of data for such analyses, it was not possible to do the full cradle-to-grave analyses for them.

3.6. Objective Equations

In this section, the model objectives outlined in section 3.4 are translated into mathematical equations that can readily be formulated into multi-objective optimization problems.

3.6.1. Maximisation of Economic gain

In section 3.4.1 the Economic Gain or Value added V(x) is defined as:

Value Added = (Biofuel revenue + By-product revenue) – (Raw material cost + processing cost).

If *I* and *J* are sets of biofuels and biofuel crops respectively, defined as follows:

$i \in I$ = {Biodiesel, Bioethanol}

$j \in J$= { Maize, Wheat, Sugarcane, Sweet sorghum, Soybean, Sunflower, Canola}

then the economic gain can be expressed in R/ha/yr as

$$V(x) = \sum_i \sum_j x_j y_{ij} \left(C_i + \emptyset_{BP_j} C_{BP_j} + \emptyset_{elec_j} C_{elec} - \left(\emptyset_j C_{market_j} + C_{process_j} \right) \right)$$

where

x_j = Fraction of Land occupied by bioenergy crop *j*

y_{ij} = Yield of biofuel *i* produced from bioenergy crop *j* [litres/hectare/yr]

$y_{biodiesel,maize} = y_{biodiesel,wheat} = y_{biodiesel,sugarcane} = y_{biodiesel,sweet-sorghum} = 0$

$y_{bioethanol,soybean} = y_{bioethanol,sunflower} = y_{bioethanol,canola} = 0$

C_i = Selling price of biofuel *i* [R/litre]

C_{BP_j} = Selling price of by-product of bioenergy crop *j* [R/kg]

C_{elec} = price of electricity [R/kWh]

C_{market_j} = Market price of crop *j* [R/tonne]

$C_{process_j}$ = All post-harvest costs of processing crop *j* [R/litre]

$\emptyset_{BP_j}$ = Amount of by-product produced per litre of biofuel from crop *j* [kg/litre]

$\emptyset_j$ = tonnes of crop *j* required to produce a litre of biofuel [tonne/litre]

$\emptyset_{elec_j}$ = Amount of excess co-generated electricity from crop *j* [kWh/ha].

3.6.2. Maximisation of Avoided Greenhouse gas emissions

As outlined in section 3.4.2, Avoided greenhouse gas emissions, G(x**),** is defined as an objective function as:

$$\textit{Avoided GHG emissions} = \textit{GHG emissions}_{\text{-Replaced products}} - \textit{GHG emissions}_{\text{-Biofuel production}}.$$

Three types of emissions resulting from biofuel production have been identified:

i. CO_2 emissions from direct consumption of fossil fuels in agricultural and processing operations, including transportation of energy crops and transportation of biofuels. (Direct fossil fuel emissions)

ii. CO_2 emitted during the production and transportation of all chemicals, fertilizers, steel used for making agricultural implements and processing plant equipment, concrete used for industrial buildings, fossil fuels, electricity and seeds. (Indirect fossil fuel emissions)

iii. Emissions that are not related to fossil energy use, comprising of CH_4 and N_2O emissions from the burning of sugarcane trash before harvesting, and CO_2 and N_2O emissions from the soil as a result of fertilizer and lime application. (Non-fossil fuel emissions)

Figure 3.4 below shows all the greenhouse gas emissions from biofuel production.

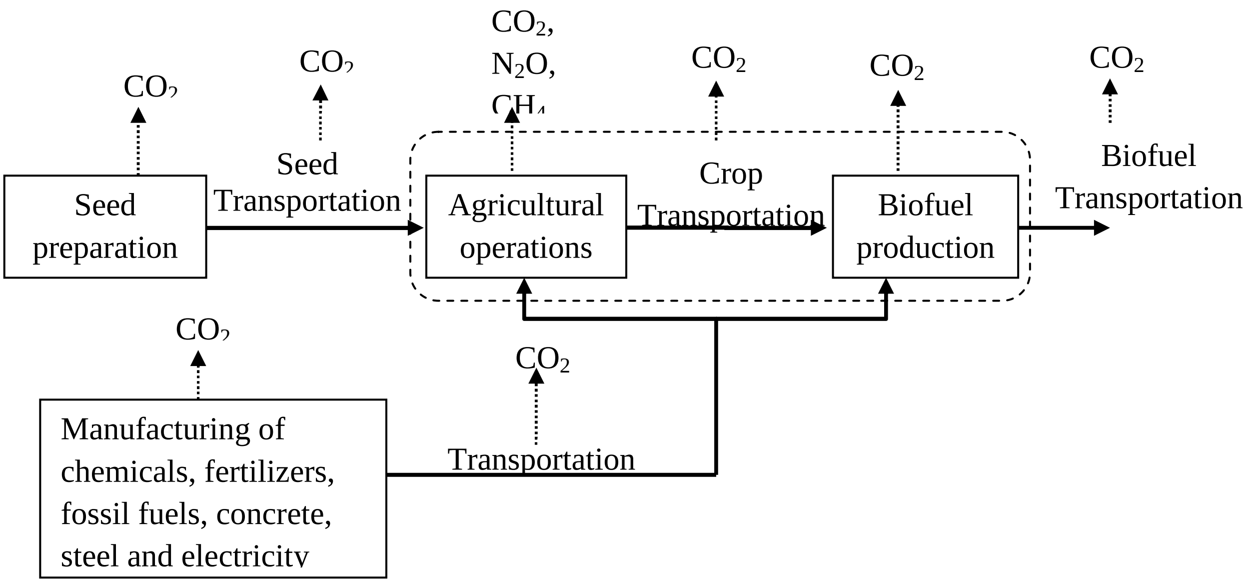


Figure 3. 4: Greenhouse gas emissions associated with biofuel production

If K is a set of biofuel processing technologies such that

$k \in K$ = {grain processing, cane processing, oilseed processing}

then the Avoided Greenhouse gas emissions G(x), in kg CO_2-equivalent/ha/yr, can be expressed as

$$G(x) = \sum_i \sum_j x_j \left[y_{ij} \left(E_i + \emptyset_{BP_j} E_{BP_j} + \emptyset_{elec_j} E_{elec} \right) - \left(\varphi_{agric_j} + y_{ij} \sum_k^K \varphi_{process_{ijk}} \right) \right]$$

where E_i (kg CO_2-eqt/litre), E_{BPj} (kg CO_2-eqt/kg by-product) and E_{elec} (kg CO_2-eqt/GJ)are the life-cycle emission factors associated with the fossil fuels replaced by the biofuels, products replaced by the by-products of the biofuels and replaced Eskom electricity respectively. φ_{agric_j} and $\varphi_{process_{ijk}}$ are the agricultural emission factor and the processing emission factors respectively.

The agricultural emission factor φ_{agric_j} is defined as the total greenhouse gas emissions associated with all agricultural operations of producing crop j. The equation below is an expression of the agricultural emission factor, in kg CO_2-eqt/ha/yr:

$$\varphi_{agric_j} = \sum_{\forall\, Agric\ sources} Amount_{source_j} \cdot E_{source}$$

All sources of greenhouse gas emissions in agricultural operations are given in Table 3.3.

Table 3. 3: Sources of emissions in agricultural operations

Source	Units	
	Amount	**E (Emission factor)**
Seed	kg/ha	Kg CO_2-eqt/kg
Diesel	GJ/ha	Kg CO_2-eqt/GJ
Nitrogen	kg/ha	Kg CO_2-eqt/kg
P_2O_5	kg/ha	Kg CO_2-eqt/kg
K_2O	kg/ha	Kg CO_2-eqt/kg
Lime	kg/ha	Kg CO_2-eqt/kg
Herbicides	kg/ha	Kg CO_2-eqt/kg
Pesticides	kg/ha	Kg CO_2-eqt/kg
Fungicides	kg/ha	Kg CO_2-eqt/kg
Trash burning	kg trash/ha	Kg CO_2-eqt/kg trash
Agricultural machinery	kg steel/ha	Kg CO_2-eqt/kg steel
Agricultural labour	Persons/ha	Kg CO_2-eqt/person

$\varphi_{process_{ijk}}$ is an aggregation of all post-harvest emissions associated with the production of biofuel *i* from crop *j*. Expressed in kg CO_2-eqt/litre/yr, the processing emission factor is given by

$$\varphi_{process_{ijk}} = \Big(E_{chem_k} + E_{energy_k} + \emptyset_j E_{trans_j} + E_{BFtrans_i} + \delta_{labour_k} E_{labour} + \emptyset_{steel_k} E_{steel} \\ + \emptyset_{concrete_k} E_{concrete}\Big) \cdot \gamma_{jk}$$

where

E_{chem_k} = emission factor of chemicals used in processing plant *k* [kgCO_2-eqt/litre biofuel]

E_{energy_k} = emission factor of fossil energy used in plant *k* [kgCO_2-eqt/litre biofuel]

E_{trans_j} = emission factor associated with transportation of crop *j* [kg CO_2-eqt/ton crop]

$E_{BFtrans_i}$ = emission factor of transporting biofuel *i* [kg CO_2-eqt/litre biofuel]

E_{labour} = emission factor associated with human labour [kg CO_2-eqt/person]

E_{steel} = emission factor associated with steel [kg CO_2-eqt/kg steel]

$E_{concrete}$ = emission factor associated with concrete [kg CO_2-eqt/kg concrete]

δ_{labour_k} = labour requirements of processing technology *k* [persons/litre biofuel]

$\varnothing_{steel_k}$ = steel requirements of processing technology k [kg steel/litre]

$\varnothing_{concrete_k}$ = concrete requirements of processing technology k [kg/litre]

γ_{jk} is a dimensionless matrix that matches the bioenergy crops to the correct processing technologies, and is given as follows:

$$\gamma_{jk} = \begin{array}{l} \\ \text{Grain processing} \\ \text{Cane processing} \\ \text{Oilseed processing} \end{array} \begin{array}{ccccccc} \text{maize} & \text{wheat} & \text{sugarcane} & \text{s\_sorghum} & \text{soybean} & \text{sunflower} & \text{canola} \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{array}$$

3.6.3. *Maximisation of job creation*

In this thesis the maximisation of job creation is defined as:

Job-creation = Agricultural Jobs$_{-Permanent}$ + *Agricultural jobs*$_{-Temporary}$ + *Processing Jobs.*

In man-hours/ha/year the Job-creation objective, Z(x), can thus be expressed as:

$$Z(x) = \sum_i \sum_j x_j \left[h \cdot W_{p\_agr,j} \cdot S_j + L_{t\_agr,j} + y_{ij} \sum_k \gamma_{jk} L_{pro,k} \right]$$

Where:

h = 8, is the number of working hours per day

$W_{p\_agr,j}$ = Number of permanent agricultural workers required per ha of j grown

S_j = Length of farming season for crop j [days/yr]

$L_{t\_agr,j}$ = Temporary agricultural labour required for growing crop j [man-hours/ha]

$L_{pro,k}$ = Labour requirements of processing technology k [man-hours/litre]

Detailed derivations of all the objective equations are shown in Appendix C.

3.7. Problem Constraints

There are two primary types of constraints for this model; crop suitability constraints and the land availability constraint.

3.7.1. *Crop suitability constraints*

Section 3.2.3 shows the crop suitability of all the bioenergy crops in this thesis. In this section, these natural limitations of the crops are expressed in equation form as a constraint set, C-SUIT(x), for the model using the values in Table 3.1 above.

The suitability constraints of crops in the Western Cape area are given by the following equations:

$$x_{wheat,w} \leq 0.016$$

$$x_{sugarcaane,w} \leq 0.014$$

$$x_{canola,w} \leq 0.016$$

where $x_{j,w}$ is the amount of land occupied by crop *j* in the Western Cape area, expressed as a fraction of the total arable land in the country.

For the rest of the country, the crop constraints are given by:

$$x_{maize} \leq 0.813$$

$$x_{wheat,r} \leq 0.61$$

$$x_{sugarcane,r} \leq 0.045$$

$$x_{sweet\_sorghum} \leq 0.984$$

$$x_{soybean} \leq 0.573$$

$$x_{sunflower} \leq 0.883$$

$$x_{canola,r} \leq 0.315$$

where $x_{j,r}$ is amount of land occupied by crop *j* outside the Western Cape, expressed as a fraction of the total arable land in the country. For wheat, sugarcane and canola, the total fraction of land occupied by crop *j* is therefore given by:

$$x_j = x_{j,w} + x_{j,r}$$

3.7.2. *Land availability*

The sum of the land areas occupied by the individual crops must always be less than or equal the total available agricultural land. Hence,

$$\sum_j x_j \le 1$$

3.8. Model Formulation

3.8.1. *No target market penetration*

Aggregating all the objectives and constraints, the target-free market penetration problem can be mathematically formulated as a linear constrained multiobjective optimization model as follows:

$$\max_x [V(x), G(x), Z(x)]$$

Subject to:

C-SUIT (x)	Crop Suitability Constraints
$\sum_j x_j \le 1$	Land availability Constraint

3.8.2. *B2 and E8 market penetration*

In this approach an additional constraint needs to be defined to ensure that the model satisfies the target penetration. Based on 2007 national liquid fuels consumption statistics, 2% biodiesel and 8% bioethanol penetration require the production of 217 million litres of biodiesel and 1,522 million litres of bioethanol per annum. In energy terms, these values amount to 7.1 PJ and 32.4 PJ respectively. This means that the available agricultural land must be utilized such that it produces bioethanol and biodiesel in the ratio of 1:4.5 on volumetric basis (Appendix D). This constraint can thus be expressed in mathematical terms as

$$\sum_j F_{bioethanol,j} = 4.5 * \sum_j F_{biodiesel,j}$$

where $F_{i,j}$ is the flow of biofuel *i* produced from crop *j* in litres/hectare/yr defined as

$$F_{i,j} = x_j y_{ij}$$

The B2 and E8 market penetration problem can thus be formulated as follows:

$$\max_{x}[V(x), G(x), Z(x)]$$

Subject to:

C-SUIT (x) — Crop Suitability Constraints

$$\sum_{j} x_j \leq 1$$ — Land availability constraint

$$\sum_{j} F_{bioethanol,j} = 4.5 * \sum_{j} F_{biodiesel,j}$$ — Demand constraint

3.9. Solution Method

The multi-objective optimization problems formulated above were solved in GAMS using the ε-constraint method (Appendix E). The development of the programming code was based on the augmented ε -constraint method and algorithm developed by Mavrotas (2007).

In order to secure the Pareto optimality of the individual optima, the algorithm first uses lexicographic optimization to create a payoff table from which the range of each one of the two objective functions that are going to be used as constraints is obtained. Here all objective functions take turns to be optimized first. Specifically, the first objective function f_1 is optimized first, obtaining max $f_1 = z_1$. Then the second objective function f_2 is optimized subject to the constraint $f_1 = z_1$, in order to keep the optimal solution of the first optimization, giving max $f_2 = z_2$. To keep the optimal solution of the first two optimizations, the third objective function is then optimized by adding the constraints $f_1 = z_1$ and $f_2 = z_2$.

The range of each objective function is then divided into *h* equal intervals, giving a total of *h+1* grid points that are used to vary parametrically the Right Hand Side of the objective functions.

In addition, the algorithm performs an early exit from infeasible loops by starting the bounding strategy for each objective function from the more relaxed formulations (i.e. lower bound for a maximization objective function or upper bound for a minimization objective function) and moving to the most strict formulations (individual optima).

3.10. Inventory Preparation

This section discusses the physical and economic data required for analysis, and where applicable, the techniques and methods used to estimate the values are also outlined.

3.10.1. Inputs

Average national data were used to determine the physical quantities of the inputs to the system, and when such information was not available, international data were used, adopting in the preference those values that best represent the South African situation.

3.10.1.1. Seeds

Based on personal interviews with five maize and soybean farmers in the Eastern Free State, the average seed application rates of maize and soybean were found to be around 12.5 kg of maize seed per hectare and 76.1 kg of soybean seed per hectare (Ntholeng, 2008;Ballod, 2008;Macaphasa, 2008;Makoele, 2008). According to the Agricultural Research Council (ARC, 2008), the optimum planting rate of wheat cultivars in the Cape is about 120 kg per hectare and it was assumed that this is also the case for the rest of the country. In the absence of local application rates for sweet sorghum and sunflower, international rates were used in this thesis. For sweet sorghum cultivation an optimal seed rate of 10 kg/ha (TNAU, 2007) was used, while a seed application rate of 3.5 kg/ha was assumed for sunflower (Kallivroussis et al., 2002) based on agricultural practices in Greece. Hardy et al. (2004) report an average seeding rate of 4.5 kg/ha of canola in the canola farming areas of the Western Cape.

3.10.1.2. Farm fossil fuel use

Farm fuel energy consists of fossil fuel directly used by farm machinery for ploughing, harrowing, fertilizing, weed and pest control, sowing and harvesting. In the 2006/2007 farming season, the average fuel expenses for maize, wheat, soybean and sunflower farming were R505 per ha, R445 per ha, R461 per ha and R439 per ha respectively (Grain SA, 2008). Using the season's average diesel wholesale prices of R5.94 per litre for summer grains and R5.83 per litre for winter grains (DME, 2008), the agricultural fuel use of maize, wheat, soybean and sunflower were calculated to be 85 litres/ha, 78 litres/ha, 76 litres/ha, and 74 litres/ha respectively. Theka (2002) reports a diesel consumption of 88 litres/ha in sugarcane farming in the Kwazulu-Natal province, while Karolina and Hansson (1999) estimate the diesel consumption for Canola farming at 74 litres/ha based on agricultural practices in Sweden. In the absence of local data, farm fuel use for sweet sorghum was estimated at 184 litres/ha using two studies based on agricultural practices in Europe. (Monti and Venturi, 2003;Grassi, 2001)

3.10.1.3. Fertilizers and Agrochemicals

Fertilizer application rates for the cultivation of maize, wheat, sugarcane, soybean and sunflower were obtained from a study by FAO (2005) on South Africa's fertilizer usage, while fertilizer application data relating to canola farming was estimated from conversations with canola farmers in the Western Cape province (Stephenson, 2007). For sweet sorghum, nitrogen application rates were obtained from a study by Balole (2001) based on agricultural practices in Botswana, while potassium and phosphorus rates were based on recommendations by India's Tamil Nadu Agricultural University (TNAU, 2007). The average lime requirement in South Africa was calculated from the 2004 lime sales data obtained from the Fertilizer Society of South Africa (FSSA, 2008) and the total land used for field crops and horticulture in that year (StatsSA, 2005). Local pesticide application rates were only obtained for canola farming from a study by the Protein Research Foundation of South Africa (Hardy et al., 2004), and application rates for all other crops were estimated using studies carried out internationally. Pesticide application data for maize and soybean were obtained from a study by Hill et al. (2006), while application quantities for sugarcane, sweet sorghum and sunflower were taken from studies by Macedo et al.(2008), TNAU (2007) and Kallivroussis et al. (2002) respectively. Table 3.4 below shows the agrochemical application rates of all the energy crops considered in this thesis.

Table 3. 4: Fertilizer and Pesticide application rates

Item	Rate [kg/ha]						
	Maize	**Wheat**	**Sugarcane**	**Sweet sorghum**	**Soybean**	**Sunflower**	**Canola**
Nitrogen	55.0	30.0	92.0	120.0	7.0	12.8	57.5
P_2O_5	30.0	40.0	57.0	40.0	25.0	17.9	41.0
K_2O	6.0	4.0	133.0	40.0	8.0	1.7	24.0
Lime	194	194	194	194	194	194	194
Insecticides	0.1	1.1	0.16	9.0	1.2	---	0.1
Herbicides	2.2	4.9	2.2	1.5	---	2.5	1.0
Fungicides	---	2.0	---	---	---	---	---

3.10.1.4. Machinery and Facility construction

Energy input associated with farm machinery and agricultural sheds was estimated by assuming that all machinery is entirely made of steel (de Beer et al., 1998), and that an additional 50% energy is required for assembly (Graboski, 2002). Using data from Hill et al. (2006) for an average soybean-maize rotation farm, it was estimated that 23.02 kg/ha of steel is required for maize farming while soybean requires 20.83 kg/ha of steel. According to Richards (2000), most grain crops require the same type of machinery to cultivate, hence the agricultural steel requirement of maize represents the steel requirement of all grains, including wheat and sorghum. In determining the fossil energy associated with producing agricultural machinery for sugarcane cultivation, a value of 33.07 MJ/tonne of cane reported by Macedo (1997) was used. In determining the agricultural steel requirements of the crops, it was assumed that all farm machinery is used for 15 years on an average farm of 164 hectares. The latter was calculated from the number of cultivated crop fields in South Africa and the total land they occupy (DoA, 2007).

According to Hill et al. (2006) buildings of the processing plants are mostly composed of concrete, while all industrial processing equipment is made entirely of steel. Considering a 20-year life span for all facilities, Hill calculated the concrete requirements of grain processing plants to be 6.23 g/litre of bioethanol and the steel requirements to be 0.67 g/litre of bioethanol. For oilseed processing plants these values are 8.83 and 1.08 g/litre of biodiesel respectively. For cane processing facility construction, the concrete and steel requirements are 5.11 g/litre and 1.53 g/litre respectively (Macedo et al., 2008). Detailed facility construction energy requirements are presented in Appendix G.

3.10.1.5. Farm and biofuel labour

Personal interviews with five farm owners in the Eastern Free State show that 8 permanent workers are required on average per every 1000 hectares in grain and oilseed farms (Macaphasa, 2008;Makoele, 2008;Moloi, 2008;Ntholeng, 2008). For sugarcane, an award-winning sugarcane farmer in Mpumalanga reports an optimal permanent labour requirement of about 8 workers per 100 hectares (Khosa, 2007). Hill et al. (2006) reports average post-harvest labour requirements of 4.24×10^{-7} workers per litre of grain ethanol and 3.05×10^{-6} workers per litre of biodiesel, while cane ethanol requires about 1.54×10^{-6} according to Ometto et al.(2004). The latter values include workers required at the processing plants and those labourers involved in transportation of feed materials and transportation of the biofuels themselves.

3.10.1.6. Transportation

The average crop transportation distances were determined based on crop area suitability values shown in section 3.2.3 and the number of appropriate processing plants available in that area. For maize and wheat, the average crop transportation return distances are about 196 km and 160 km respectively. On average the transportation distance for sweet sorghum was found to be 558 km. Assuming that each biodiesel plant only processes oilseeds grown within one local municipal area, then the return distance for soybean, sunflower and canola was estimated at 74 km. Detailed distance calculations are shown in Appendix F.

Regional blending and distributing stations are assumed to be located within 250 km diameters of all processing plants. It was assumed that all transportation over return distances shorter than 250 km can be done using a rented 10 ton truck, while all others are done by train.

3.10.1.7. Facility Energy use

Direct grain processing energy requirements were based on data from Ethanol Africa (2007) while oilseed processing energy requirements were obtained from studies by Nolte (2007) and Sosulski and Sosulski (1993). According to Macedo et al. (2008) the bagasse produced from sugarcane and sweet sorghum processing is more than enough to supply the energy requirements of the plant, hence no fossil-based energy is used at the processing plant. Table 3.5 below shows the energy requirements of the different processing technologies.

Table 3. 5: Energy consumption in processing plant per litre of biofuel

Fuel	Units	Grain Processing	Cane Processing	Oilseed Processing		
				Soybean	Sunflower	Canola
Fossil Energy						
Electricity	MJ/litre	1.12	--	2.61	1.25	1.18
Coal	MJ/litre	13.40	--	--	--	--
Renewable Energy						
Bagasse	kg/litre	--	3.30	--	--	--
Biodiesel	g/litre	--	--	9.39	9.39	9.39
Glycerol	g/litre	--	--	4.85	4.85	4.85

3.10.2. Outputs

Table 3.6 shows the crop and biofuel yield data used in this thesis. National average yields of all grains were obtained from Grain-SA (Grain SA, 2008), while sugarcane data was taken from the South African Sugar Association (SASA, 2008). For sweet sorghum only the stalk is used for ethanol production while the grain is used for domestic consumption (Reddy, 2007).

Table 3. 6: Crop and biofuel Yields

Bioenergy Crop	Crop Yields [tonnes/ha/yr]	Biofuel yields [litres/ha/yr]
Yellow Maize	3.03	1,276
Wheat	2.81	1,004
Sugarcane	57.98	4,558
Sweet Sorghum stalk	31.88	2,099
Soybean	1.12	229
Sunflower	0.95	409
Canola	1.14	519

In the absence of local data, the yield of sweet sorghum was estimated based on the national average yield of grain sorghum obtained from Grain-SA (2007). This was done by using the relative sweet sorghum stalk yield to grain sorghum yield of 3.57 in arid and semi-arid areas reported by the International Crops Research Institute for Semi-Arid Tropics (ICRISAT, 2006).

Ethanol production rates of 421 litres/ton of maize (Ethanol Africa, 2007), 358 litres/ton of wheat (Elsayed et al., 2003), 78.6 litres/ton of sugarcane (Ferguson, 1999) and 65.8 litres/ton of sweet sorghum stalk (Gnansounou et al., 2005) were used in this thesis. Using average oil content values of 18% for soybean, 38% for sunflower and 40% for canola, a 95% recovery of oil and a yield of 1 litre of biodiesel per litre of oil the biodiesel conversion rates are therefore 204.5 litres/ton of soybeans (Hill et al., 2006), 432 litres/ton of sunflower seeds (BFAP, 2007) and 454 litres/ton of canola seeds (Richards, 2000).

3.10.2.1. By-Product Credits

The only by-product of maize ethanol production considered in this thesis is DDGS, produced at a rate of 304 kg/ton of maize. For every litre of ethanol produced from maize, enough DDGS is produced to displace 1.077 kg of maize and 0.823 kg of soybean meal as animal feed. 431 kg of DDGS is produced per tonne of wheat processed, and this can be used as animal feed to replace 431 kg of maize and 448 kg of soybean (S&T2 Consultants Inc., 2003). According to Wienese (1999) and Macedo et al. (2008), 259 kg of the 333 kg of bagasse available per tonne of sugarcane can be used to co-generate enough electricity and heat to supply all the processing plant energy requirements with the technology currently available in the South African sugar industry. While Macedo et al. (2008) does not report the efficiency of the technology used by the bioethanol plants in Brazil, Wienese (1999) argues that the efficiency of the technology that is currently used in South Africa's Sugar industry is so low (about 11.5%) that for every tonne of sugarcane processed, the 74 kg of excess bagasse, with a calorific value of 503.9, is only able to co-generate 58.3 MJ of surplus electricity that can be sold as by-product. With sweet sorghum, co-product credits were awarded to both the 37.2 MJ of surplus electricity produced per tonne of cane and the 47.2 kg of grain available per tonne of sorghum cane. It was assumed that a tonne of sweet sorghum grain can displace the same amount of grain sorghum in domestic uses.

For all the oilseeds, both the meal and glycerol are considered as by-products. At a meal recovery of 95%, 779 kg of soymeal and 14.5 kg of glycerol are produced per tonne of soybeans, while 589 kg of sunflower cake and 29.3 kg of glycerol are produced for every tonne of sunflower seeds processed. Similarly, 570 kg of canola meal and 39.5 kg of glycerol are produced per tonne of canola seeds processed. According to Nel (2001) and the Protein Research Foundation (2008) the values of sunflower and canola meals as animal feed are roughly 72 % and 59 % of soymeal on a weight basis respectively. Considering a soybean oil content of 18%, the soymeal is then credited with 82% of the energy and carbon emissions associated with growing soybeans, transporting them to crushing facilities, extracting their oil, and preparing the meal (Hill et al., 2006).

3.10.3. *Energy coefficients and emission factors*

To determine the energy input values for all supply chains in the model, the physical input quantities were multiplied by the appropriate energy coefficients from literature. Energy and emission coefficients of major inputs are shown in Table 3.7.

Table 3. 7: Energy and greenhouse gas emission coefficients of selected inputs

Input	Energy coefficient [MJ/Unit]		GHG Emission factors [kg CO2-eqt/Unit]		Source
	Value	Unit	Value	Unit	
Seeds					
Maize	53.36	Kg	3.85	Kg	(West and Marland, 2002)
Wheat	5.57	Kg	0.40	Kg	(West and Marland, 2002)
Sugarcane	5.9	Ton cane	27.07	ha	(Macedo, 1997)
Sweet sorghum	54.00	Kg	3.15	Kg	(Bacchiet et al., 1992)
Soybean	12.86	Kg	0.92	Kg	(West and Marland, 2002)
Sunflower	52.60	Kg	3.06	Kg	(Kallivroussis et al., 2002)
Canola	6.79	Kg	0.32	Kg	(Hovelius and Hansson, 1999)
Fossil Fuels					
Diesel	50.31	Kg	88.26	GJ	
Petrol	51.02	Kg	81.80	GJ	
Electricity			271.84	GJ	Appendix G
Fertilizers					
N	57.46	Kg	9.08	Kg	(West and Marland, 2002)
P_2O_5	7.03	Kg	1.73	Kg	(West and Marland, 2002)
K_2O	6.85	Kg	0.88	Kg	(West and Marland, 2002)
Lime	1.71	Kg	0.65	Kg	(West and Marland, 2002)
Insecticides	266.56	Kg	37.55	Kg	(West and Marland, 2002)
Herbicides	284.82	Kg	32.43	Kg	(West and Marland, 2002)
Fungicides	288.88	Kg	35.43	Kg	(West and Marland, 2002)
Machinery & Buildings					
Concrete	5.70	Kg	0.82	Kg	Appendix G
Steel	42.10	Kg	11.17	Kg	Appendix G
Labour	1.08E+05	person	9.52	person	Appendix G

The emission coefficients consist of both the direct emissions resulting from the combustion of fossil fuels and the indirect emissions associated with the production and transportation of the inputs.

In the case of diesel and petrol, the energy coefficients were obtained by multiplying the fuels' calorific values by 1.16 and 1.14 respectively to account for manufacturing and transportation of the fuels (EUCAR, 2004). Appendix G shows a more comprehensive tabulation of the emission factors with their detailed calculations and all the underlying assumptions made.

The energy and carbon emission estimations associated with human labour were based on South Africa's annual consumption of non-renewable energy in 2004. The energy consumption of the truck used for deliveries was estimated at 1.56 MJ diesel/km/tonne (Office of Energy Efficiency, 2008), while that of the train was estimated at 0.7 MJ/km/tonne (West and Marland, 2002;Dalzell, 2000). For the purposes of determining the carbon emissions associated with train deliveries, it was assumed that all rail freight journeys in the country are 60.5% electric-powered and 39.5% diesel-powered (IMCSA, 2006).

The output energy and greenhouse gas credits were determined in a similar way to the inputs' energy and carbon emission credits. Here glycerol was credited with energy and environmental burdens equivalent to those associated with the production of the same amount of synthetic glycerol, and according to Delucchi and Lipman (2003), it takes 49.5 MJ of fossil energy to produce a kilogram of synthetic glycerol.

Table 3.8 below shows the by-product greenhouse gas emission factors for the different crops. Detailed calculations of these emission factors are shown in Appendix G.

According to the International Panel on Climate Change (IPCC), the burning of sugarcane trash before harvesting also releases nitrogen oxide and methane emissions equivalent to 0.08 kg CO_2 per kilogram of trash burnt.

Table 3. 8: By-product emission factors

CROP	**kg CO_2/litre**
Maize (DDGS)	0.81
Wheat (DDGS)	1.43
Sugarcane (Electricity)	0.20
Sweet sorghum (grain & electricity)	0.61
Soybean (meal & glycerol)	3.25
Sunflower (meal & glycerol)	1.23
Canola (meal & glycerol)	1.06

3.10.4. Labour requirement and Costing

This section presents the coefficients used in modelling the job-creation and value added objectives.

3.10.4.1. Labour Requirement

Table 3.9 shows the values of the parameters used in modelling the job-creation objective. The cropping season for each crop is the average number of days in a year required to work on the crop from soil preparation to the last day of harvesting. It was assumed that there is only one growing season for each crop. The practice in South Africa is that grains are mechanically harvested, and generally no labour is required for harvesting. For maize, however, the combine harvesters often leave behind large numbers of maize cobs in the field, which are then picked up by manual labourers who usually walk behind the harvesters.

Table 3. 9: Job-creation parameters

Item	Biofuel Crop						
	Maize	**Wheat**	**Sugarcane**	**Sweet sorghum**	**Soybean**	**Sunflower**	**Canola**
No of permanent Agric workers/ha	0.0085	0.0085	0.08	0.0085	0.0085	0.0085	0.0085
Cropping season [days/yr]	150	180	365	150	150	150	180
Temporary Agric labour [man-hrs/ha/yr]	32.9	0	121.0	197.7	0	0	0
Processing labour [man-hrs/litre/yr]	0.0013	0.0013	0.0056	0.0056	0.0025	0.0025	0.0025

According to Makoele (2008) and Lepati (2008) an average of 18 temporary workers are usually required for 40 days for a 137 ha maize farm. The sugarcane industry in South Africa primarily uses manual harvesting with an average performance of 11.5 tons of cane cut per man-day (Langton, 2004). Temporary labour requirements for sweet-sorghum harvesting were based on practices in the United States of America's Kentucky states (Cooperative Extension Service UK, 2008).

Processing plant labour requirements for the grain ethanol plants and cane ethanol plants were based on existing plants in the United States of America (Shapouri and Gallagher, 2005) and Brazil (Ometto et al., 2004;Kumar, 2008), while biodiesel plant labour requirements were based on data from India's Southern Online Bio-Technologies (Kumar, 2008).

3.10.4.2. Costing

Table 3.10 below shows prices of all the crops and commodities, as of 29th February 2008. Grain prices were obtained from Grain SA (SAFEX) (2008), while the sugarcane price was obtained from the South African Sugar Association (2008). According to Nguyen and Prince (1996) sweet sorghum stalks cost the same price as sugarcane stalks. Grain processing costs were based on the wheat processing bioethanol plant proposed in the Western Cape (2008) and the cane processing costs were based on a study by Gnansounou et al. (2005). The detailed processing cost calculations are shown in Appendix H.

Table 3. 10: Manufacturing costs and by-product prices

Crop\Units	**Crop Price**	**Processing Cost**	**By-product Prices**			
			DDGS	Meal	Glycerol	Grain
	R/ton	R/litre	R/kg	R/kg	R/kg	R/kg
Maize	1,805	2.31	2.78	--	--	--
Wheat	3,706	2.35	2.69	--	--	--
Sugarcane	207.54	1.67	--	--	--	--
Sweet Sorghum	207.54	5.04	--	--	--	1.53
Soybean	4,550	3.63	--	4.09	0.0	--
Sunflower	4,935	2.67	--	2.95	0.0	--
Canola	3,500	2.62	--	2.43	0.0	--

According to the Animal Feed Manufacturers Association of South Africa (Tylutki, 2006), maize DDGS costs about 68 % the price of soymeal, while Shurson et al. (2004) reported that wheat DDGS costs about 97 % the price of maize DDGS. Because of the current oversupply of glycerol in the world market, it was assumed that the glycerol by-product from biodiesel production does not have any sales value (Nolte, 2007).

The Biofuels Industrial Strategy of South Africa proposes that bioethanol and biodiesel receive 100 % and 50 % levy exemptions respectively in the initial pilot phase of the biofuel industry development. Based on the prices of petrol and diesel in 2007, these levy exemptions put bioethanol and biodiesel prices at 701 cents and 692 cents per litre respectively. It was assumed that electricity is sold at a Cape Town industrial electricity price of 24 cents per kWh.

3.10.5. Land Use Change parameters

In determining the environmental effects of land clearing and land use change for the purpose of biofuel production, the method of carbon debts, adapted from Fargione et al (2008), was used.

According to the Department of Environmental Affairs and Tourism (2004), almost all of the arable land in South Africa is found within two natural biomes: the grassland biome and the savanna biome. This implies that grass is the main natural vegetation in unutilized and underutilized agricultural areas in the country. A map of the biomes of South Africa can be found in Appendix B. Table 3.11 below presents the parameters used in this thesis for the carbon debt analysis, based on the properties of South African grasses.

Table 3. 11: Growth and carbon sequestration properties of grasses

Parameter	Units	Value
Root / Shoot ratio		2.22
Root biomass	Mg/ha	4.55
Root carbon	kg C / kg root biomass	0.36
Rate of soil carbon accumulation	Mg C / ha /yr	0.69

The average root/shoot ratio and root biomass values were obtained from a study by Snyman (2005) on the seasonal patterns of root and aboveground biomass growth of grasses in semi-arid grasslands of South Africa, while the value of root carbon was estimated from a study on the properties of C4 grasslands in North America (Baer et al., 2002). The rate of soil carbon accumulation was taken from the analysis by Fargione et al.

It is conservatively assumed, in this thesis, that the average underutilized land in South Africa is left uncultivated for a period of two years.

3.11. Conclusion

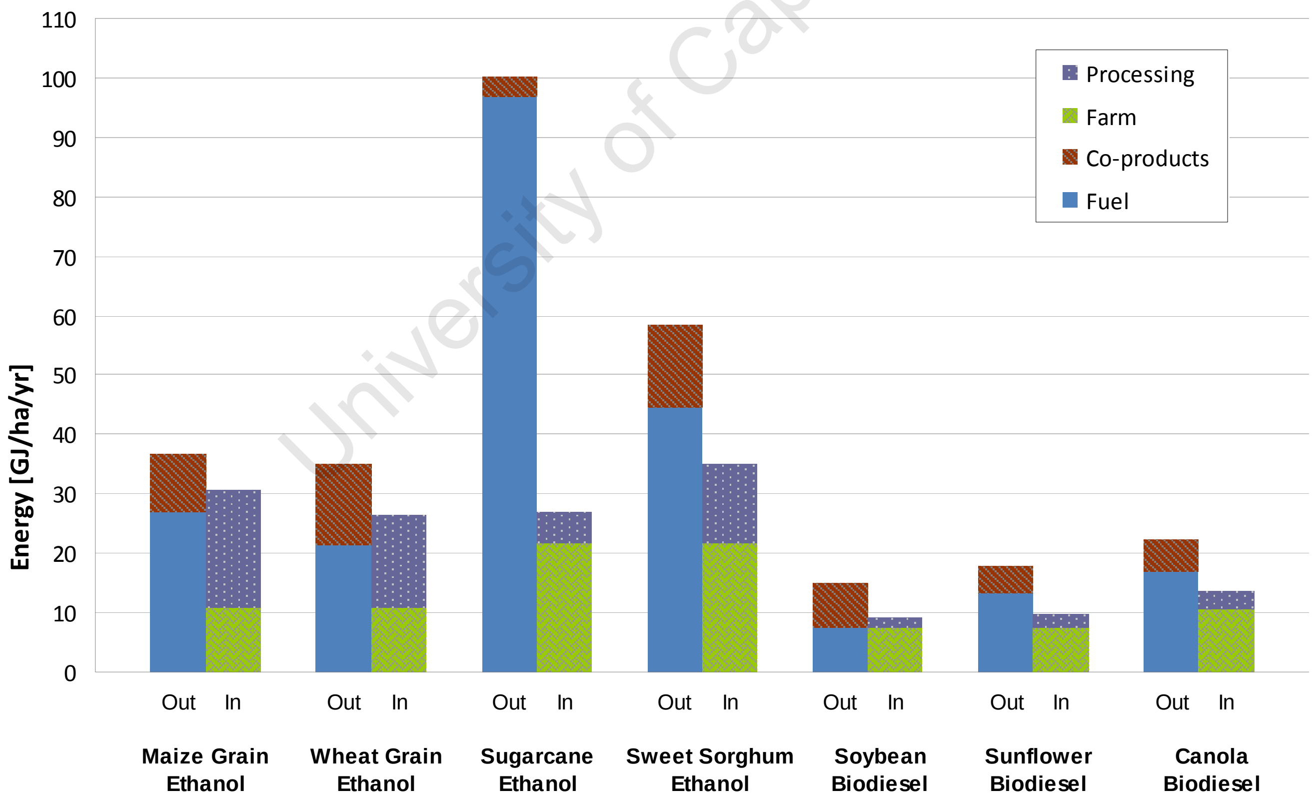
The system studied in this thesis has been presented in this chapter, together with the basic multiobjective optimization model used in the analyses. The inventory preparation method and its underlying assumptions have also been described. The next chapter then presents and discusses the results of the model on a national level in line with the key questions presented in Chapter 1.

4. NATIONAL MODEL RESULTS

This is the major results chapter of the thesis. Firstly the chapter presents the results and discussions of the net energy balance and land use change analyses, after which the results of the two scenarios of the national multiobjective model outlined in chapter 3 are also presented and discussed.

4.1. Net Energy Balances

Figure 4.1 below shows the average Net Energy balance (NEB) and Net Energy balance ratios (NEB-ratio) of producing ethanol from maize grain, wheat grain, sugarcane and sweet sorghum stalk, and biodiesel from soybean, sunflower and canola in South Africa based on 2006/2007 agricultural data. The results show that sugarcane ethanol is the most preferable with NEB of 73.3 GJ/ha/yr and an NEB-ratio of 3.72. In terms of the effectiveness of biofuel production on scarce land, as is presented by NEB values, sugarcane is followed by sweet sorghum ethanol, canola biodiesel, wheat grain ethanol and sunflower biodiesel respectively, with soybean biodiesel and maize grain ethanol showing the least common effectiveness of about 6 GJ/ha/yr.



NEB (OUT-IN):	6.09	8.43	73.33	23.43	5.99	8.07	8.54
NEB-ratio: (OUT/IN)	1.20	1.32	3.72	1.67	1.66	1.83	1.63

Figure 4. 1: Net Energy Balance of biofuels in South Africa

Looking at the return on energy input, as shown by the NEB-ratios, sunflower biodiesel is the second best after sugarcane ethanol, and then follows sweet sorghum ethanol, soybean biodiesel, canola biodiesel and wheat grain ethanol respectively. Here again maize grain ethanol shows the least performance.

Figure 4.1 also shows that the bulk of the energy inputs for sugar-based ethanol and oilseed biodiesel are due to agricultural activities, whereas post-harvest energy inputs are the most dominant for starch-based ethanol. In percentage terms, the contribution of agricultural inputs to the total biofuel inputs is 35.4% for maize ethanol, 40.7% for wheat ethanol, 80.9% for sugarcane, 61.7% for sweet sorghum ethanol, 81.5% for soybean biodiesel, 76.1% for sunflower biodiesel and 78.6% for canola biodiesel. This difference is essentially a reflection of the different types of energy used by the processing plants. Cane processing plants and oilseed processing plants are primarily powered by renewable energy sources which do not require fossil energy inputs, while starch-based ethanol uses large quantities of coal and electricity for steam generation and DDGS drying, which together make up 93.6% and 92.5% of the total post-harvest energy inputs for maize grain ethanol and wheat grain ethanol respectively (Figure 4.3). This use of non-renewable energy in powering grain processing plants is one of the principal reasons for the poor performance of starch-based ethanol in terms of energy balance.

The contributions of the individual agricultural inputs to the total agricultural energy inputs of the biofuels are shown in Figure 4.2 below. It is evident from this figure that fuels used by agricultural machinery and nitrogen fertilizers are the two largest contributors to agricultural energy inputs.

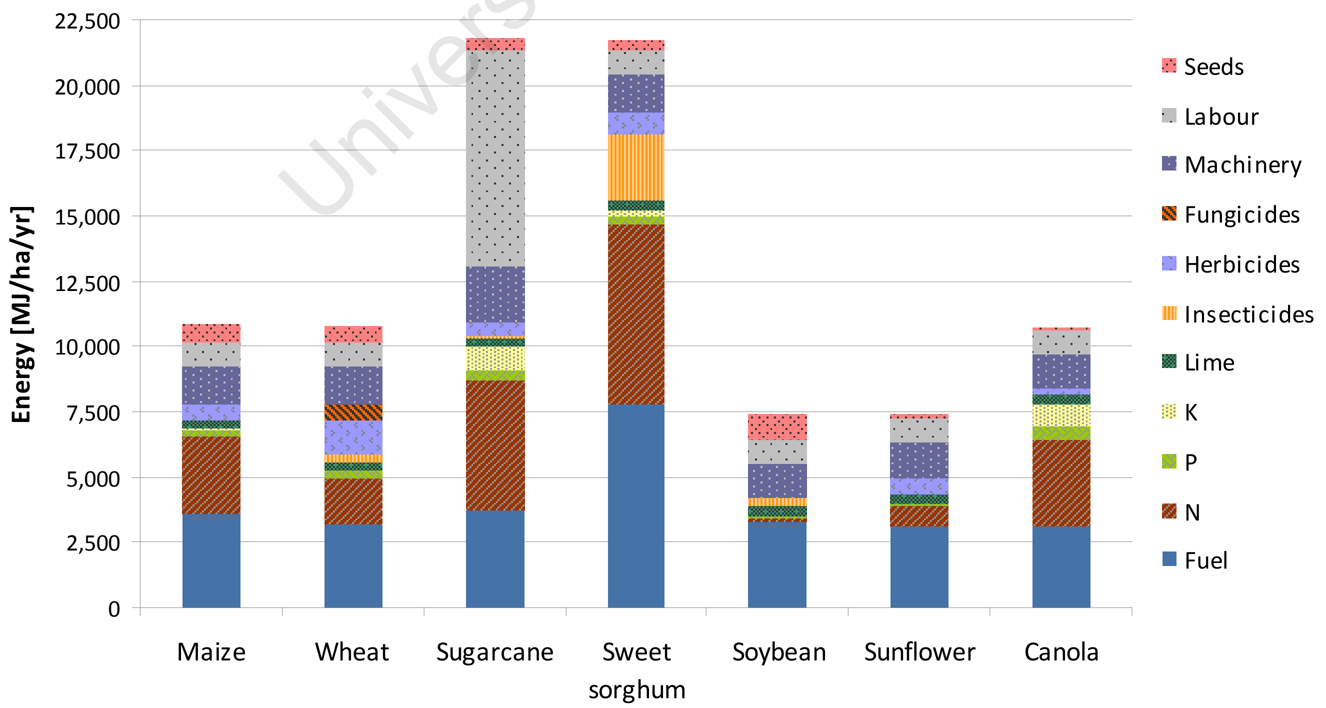


Figure 4. 2: Agricultural energy inputs in biofuel production per hectare

On average, fuel contributes about 33% to agricultural inputs while nitrogen fertilizers contribute about 20%. These are followed by agricultural machinery and labour which both contribute about 13% each. Fungicides make the least contribution to agricultural energy inputs with an average contribution of 0.7%. For sugarcane ethanol, however, the agricultural energy inputs are mostly dominated by labour, which contributes 38% to the agricultural energy inputs alone and 31% to total biofuel inputs. The latter is a clear reflection of the labour intensity of sugarcane cultivation.

Figure 4.3 shows the post-harvest energy inputs in the production of the different biofuels. It can be seen from this figure that crop transportation is the major contributor to post-harvest energy inputs of sugar-based ethanol. For sweet sorghum in particular, crop transportation makes 91.6% of the total post-harvest energy inputs. This is basically due to the long distances involved in transporting sweet-sorghum cane from farming areas across the country to the sugar mills which are only located within a small area in the Kwazulu-Natal province. It should also be noted that the contribution of crop transport to sweet sorghum energy inputs presented in these results is the minimal possible contribution because it was assumed that transportation is done by train. If a 10-ton truck is to be used, then the energy contribution of crop transportation to post-harvest energy inputs would increase by a factor of 2.2, resulting in a contribution of 96.1% to the total energy inputs.

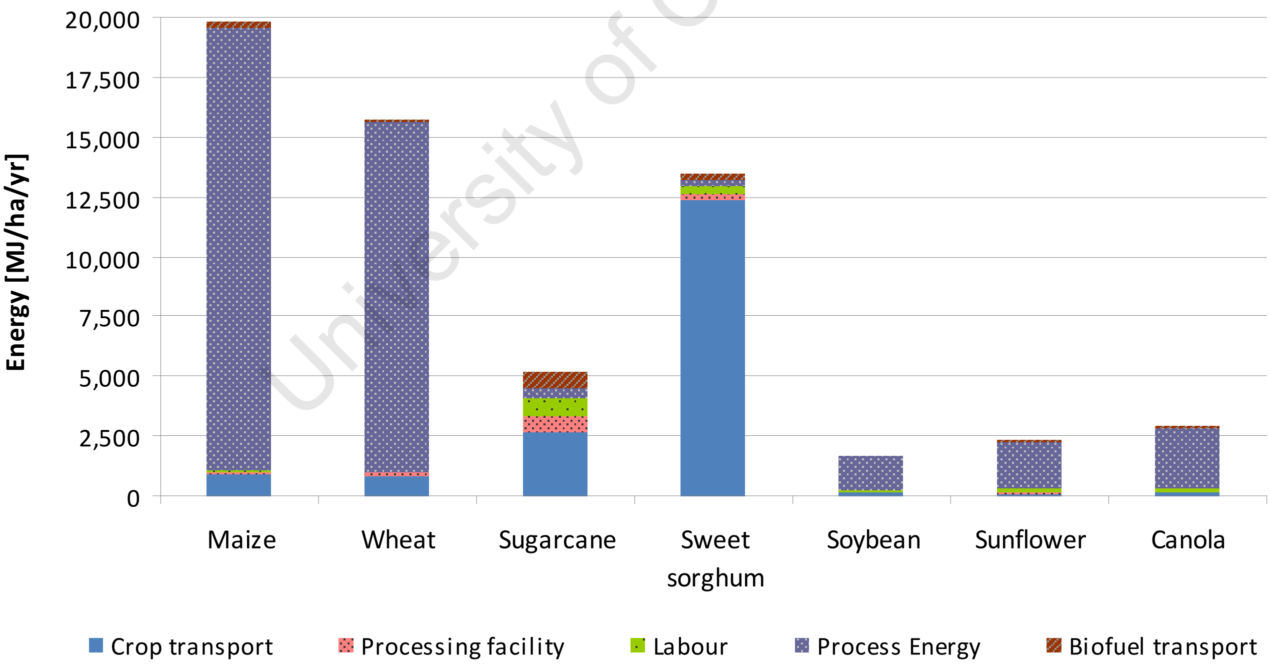


Figure 4. 3: Post-harvest energy inputs in biofuel production

Figure 4.3 also shows that although 92 % of the energy used by the biodiesel plants is renewable, the biodiesel production step is still the single largest contributor of post-harvest energy inputs for all the oilseeds. This is not only a result of the electricity used to drive the hexane extractor, but also the fossil energy required to manufacture and transport the reagents and solvents used in the transesterification process. On its own, the latter contributes to 49%, 63% and 64% of post-harvest energy inputs for soybean biodiesel, sunflower biodiesel and canola biodiesel.

The individual NEB-ratio values for each biofuel are discussed in the following sections:

4.1.1. Maize Grain Ethanol

The difference between the NEB-ratio of 1.20 shown in Figure 4.1 above and that calculated by Ethanol Africa themselves (1.63) is primarily due to the different system boundaries considered in the two cases. While all life-cycle energy inputs of maize grain ethanol from farming to the blending station have been considered in this thesis, Ethanol Africa have only included farm fossil fuel use, crop transportation and processing plant energy use in their analysis; accounting for only 75 % of the energy inputs into the production of maize grain ethanol. The same is true for the National Biofuels Study (2006) which reports an energy balance ratio of 1.36. If only 75% of the energy inputs are analysed in this thesis, the NEB-ratio becomes 1.56. It should be noted, however, that with both the Ethanol Africa and the National Biofuels Study it is not clear how co-product energy allocation was carried out.

4.1.2. Wheat Grain Ethanol

No studies were found on the net energy balance of wheat grain ethanol production in South Africa. Instead two studies based on the production of wheat grain ethanol in Europe were used for comparison; studies by Richards (2000) and Elsayed et al. (2003) which present NEB-ratios of 1.1 and 2.16 respectively. Apart from the fact that the European agricultural inputs and yields are very different from those in South Africa, there are also a number of analytical differences between this thesis and these studies that have led to the different NEB-ratios: While both of these studies exclude the fossil energy inputs associated with labour and the manufacture of agricultural machinery, the study by Richards further excludes energy inputs associated with construction of the processing plant and biofuel distribution. This amounts to 9.5% and 9.1% of energy inputs excluded in the analyses by Richards and Elsayed et al. respectively. With regards to allocation, the study by Richards does not mention any allocation, although the analysis simply excludes energy credits for DDGS. In the study by Elsayed et al. allocation of co-product energy credits is based on market prices and not product substitution, and also it is assumed that wheat straw has a market value hence not ploughed back into the field.

4.1.3. Sugarcane Ethanol

The National Biofuels Study (2006) reports an NEB-ratio of 6.02 for South African fuel bio-ethanol made from sugarcane. Similar to the previous cases, the difference between this value and that of 3.72

reported in Figure 4.1 is mainly due to the difference in the energy inputs included in these analyses. The National Biofuels study leaves out the energy inputs associated with labour, seed production, production of agricultural machinery and facility construction, all of which amount to 45 % of energy inputs that are not accounted for. If the contributions of energy inputs associated with labour, seed production, agricultural machinery production and process facility construction are excluded in this thesis, then the NEB-ratio also increases to 6.81; a value which differs from that reported by the National Biofuels Study by only 13%.

4.1.4. *Sweet Sorghum Ethanol*

Grassi (2001) estimated the NEB-ratio of sweet sorghum ethanol production in Brazil and sub-Saharan Africa at 6.5. Unfortunately the calculations and allocation procedures are not clearly given in that study, making it impossible to conduct a detailed comparison. It was observed, however, that the system boundary definition in the study by Grassi is much narrower than that adopted in this thesis; in particular, the energy inputs associated with production of agricultural machinery, construction of processing facilities and labour have not been included in that analysis. In total, about 8.5% of the fossil energy inputs considered here seem to have been excluded in the study by Grassi. Overall, it was noted that the reason for the poor NEB-ratio in this thesis is the excessive distances assumed for transporting the sorghum cane from the farm to the processing plants.

4.1.5. *Soybean Biodiesel*

The difference between the soybean biodiesel NEB-ratio of 1.66 shown in Figure 4.1 and that of 3.22 calculated by Sheehan et al (1998) for the US Midwest case is a result of two major factors; the different energy inputs considered in the two studies and the different allocation methods adopted in these studies. In the study by Sheehan et al., the energy associated with farm machinery, labour and construction of processing facilities have all been excluded in the energy balance, making up 26% of fossil energy inputs. Sheehan et al. also use mass allocation to assign co-product energy flows instead of product substitution. That notwithstanding, it appears that there is a tangible geographical difference between soybean biodiesel production in the US Midwest and in South Africa, with agricultural practices and yields giving the former an advantage.

The National Biofuels Study (2006) on the other hand reports a net energy balance of 2.40 for biodiesel production in South Africa. As with the study by Sheehan et al., only energy flows contributing to 74 % of the energy inputs have been accounted for in the National Biofuels Study, except that in the latter it is not clear which allocation method was used. If only 74% of the fossil energy inputs to soybean biodiesel production are accounted for in this thesis, the NEB-ratio becomes 2.24, which is 93% of that calculated by the National Biofuels Study.

4.1.6. Sunflower Biodiesel

Studies on the net energy balance of sunflower biodiesel based on South African data were not found, hence a study by Kallivroussis et al. (2002) based on sunflower production in Greece was used for comparison. While Figure 4.1 reports NEB-ratio of 1.83, the study by Kallivroussis et al. reports a net energy balance ratio of 4.5. Apart from the agricultural inputs and yields which are different from those in South Africa, the difference between this value and the one obtained in Figure 4.1 above is a result of two major factors: The difference in system boundaries of the two studies and the different allocation methods adopted. The study by Kallivroussis et al. (2002) only presents an energy balance around the agricultural production of sunflower oil, and do not include the conversion of sunflower oil into biodiesel, thus leaving out a total of 41 % of the fossil energy inputs into the production of sunflower biodiesel. Also in the analysis by Kallivroussis et al., the cake was credited with the energy equivalent to its calorific value (19.6 MJ/kg); a value which is 5 times larger than the value it would be credited with if product substitution was used.

4.1.7. Canola Biodiesel

There have not been any studies on the net energy balance of biodiesel production from canola in South Africa; hence studies based on the production of biodiesel from rapeseed in Europe were used for comparison. Richards (2000) reports a NEB-ratio value of 1.82 while Elsayed et al. report a NEB-value of 2.29. As pointed out in section 4.1.2., both of these studies exclude some energy inputs which are analysed in this thesis. For the production of canola biodiesel, the total percentage of energy inputs that have not been included in these two studies is 18.8% in the analysis by Richards and 17.6% in the analysis by Elsayed et al. The study by Richards also excludes glycerol energy credits.

4.1.8. Conclusions

Despite the use of expansive system boundaries for energy inputs in this analysis, it can be concluded that the South African production of maize grain ethanol, wheat grain ethanol, sugarcane ethanol, sweet sorghum ethanol, soybean biodiesel, sunflower biodiesel and canola biodiesel all result in net energy gains. From an energy balance perspective only, sugarcane is by far the best option for ethanol production in South Africa, while maize is the least preferable.

Having analysed the energy performances of the different biofuels in this section, the next section then looks on their environmental performances, with specific focus on the effects of land use change for biofuel production.

4.2. Environmental effects of Land use change

Table 4.1 below shows all the sources of emissions contributing to the carbon debt that results from converting abandoned or underutilized agricultural land to annual crop cultivation for biofuel production. An estimated total of 13,900 kg of carbon dioxide stored in the grass shoot, grass stem and soil is released to the atmosphere for every hectare of abandoned or underutilized agricultural land that is converted to annual cultivation of energy crops. As described in section 4.3, these are emissions released for the first 50 years of biofuel production which need to be "repaid" by the avoided emissions over the life-time of the production system.

Table 4.1: carbon debt resulting from land use change

Emissions Source	Carbon Debt [kg CO_2/ha]
Aboveground biomass carbon	2,700
Root carbon	6,100
Soil carbon	5,100
TOTAL	**13,900**

According to Figure 4.4, not all the biofuels analysed in this thesis have positive values of avoided greenhouse gas emissions that would enable the biofuels to repay this carbon debt over time. Figure 4.4 shows that the use of maize grain ethanol and sweet sorghum ethanol do not reduce the emission of greenhouse gases; instead their use add 247 and 321 kg of CO_2-eqt emissions respectively to the atmosphere per hectare annually. For maize grain ethanol this failure to reduce greenhouse gas emissions is a result of the vast amounts of coal and electricity required at the grain processing plant, which collectively account for 93% and 52% of post-harvest and total greenhouse gas emissions respectively. In the case of sweet sorghum ethanol, the negative value is primarily due to the emissions released in transporting large quantities of sweet sorghum cane over long distances to the processing plants. Figure 4.5 shows that of all the biofuels analysed, sweet sorghum ethanol exhibit the biggest sensitivity of avoided greenhouse gas emissions to changes in crop transportation – a 30% decrease in sweet sorghum transportation distance from the 553 km average results in an increase from -321 to 417 kg CO_2-eqt per hectare of avoided greenhouse gas emissions. This equates to an increase of 4.4 kg CO_2-eqt/ha in avoided greenhouse gas emissions for every kilometre decrease in transportation distance. This implies that the use of sweet sorghum ethanol can only mitigate CO_2 emissions if the average transportation distance of the sorghum cane to the processing plant is smaller than 418 km.

Emission contributions of the individual steps in the production of all the biofuels are shown in Appendix I.

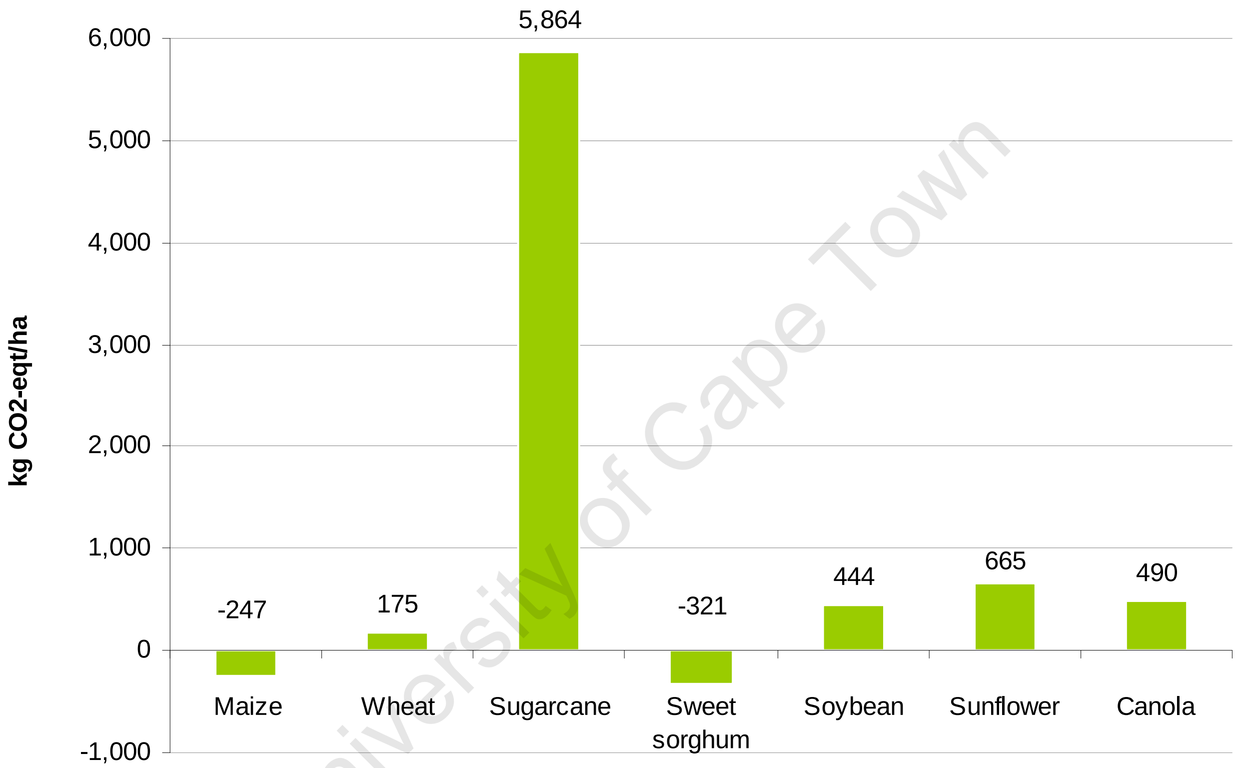


Figure 4. 4: Avoided GHG emissions of biofuels produced from the different energy crops

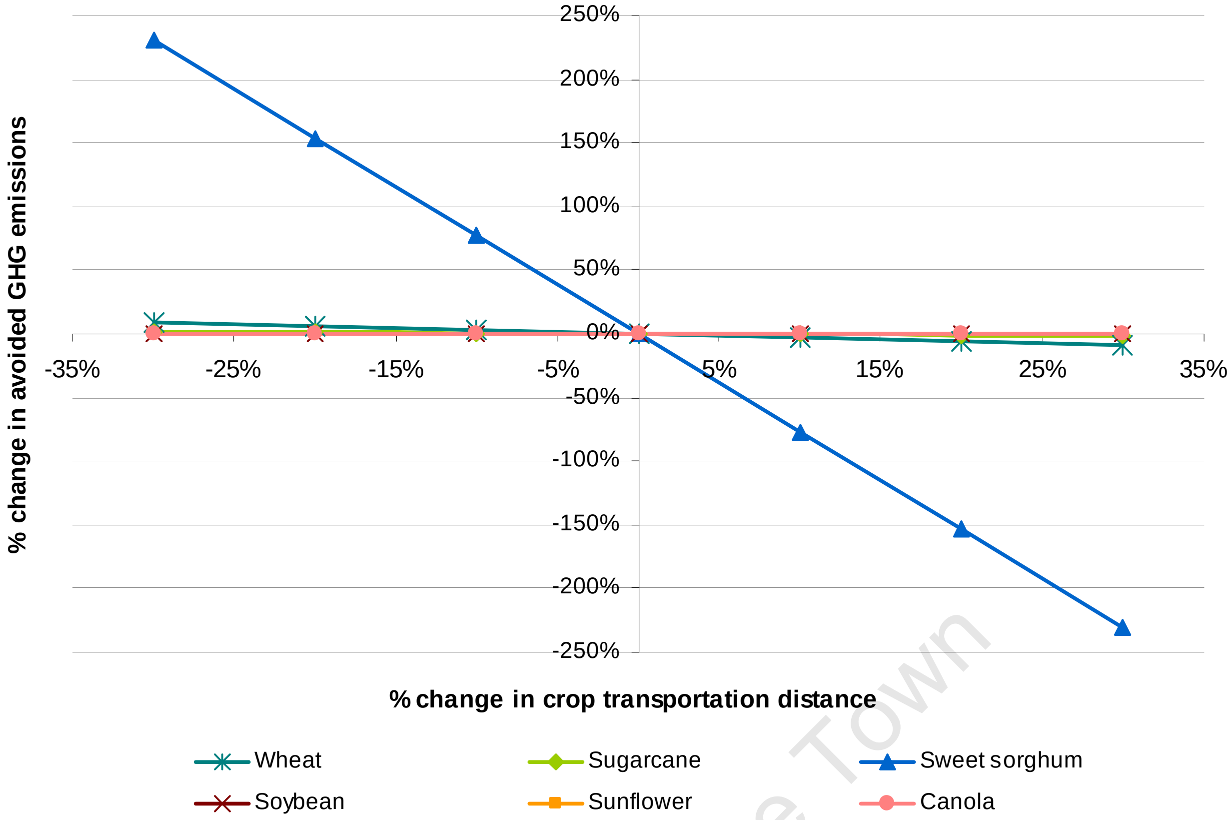


Figure 4. 5: Sensitivity of avoided GHG emissions to changes in crop transportation distances

Figure 4.6 shows the time required by each biofuel to repay the carbon debt based on the annual repayment capacity of each biofuel as presented in Figure 4.4. It would thus take between 3 and 80 years for those biofuels with positive avoided greenhouse gas emissions to completely offset the carbon debt from land use change, with sugarcane ethanol and wheat grain ethanol requiring the lower and upper end values of the range respectively.

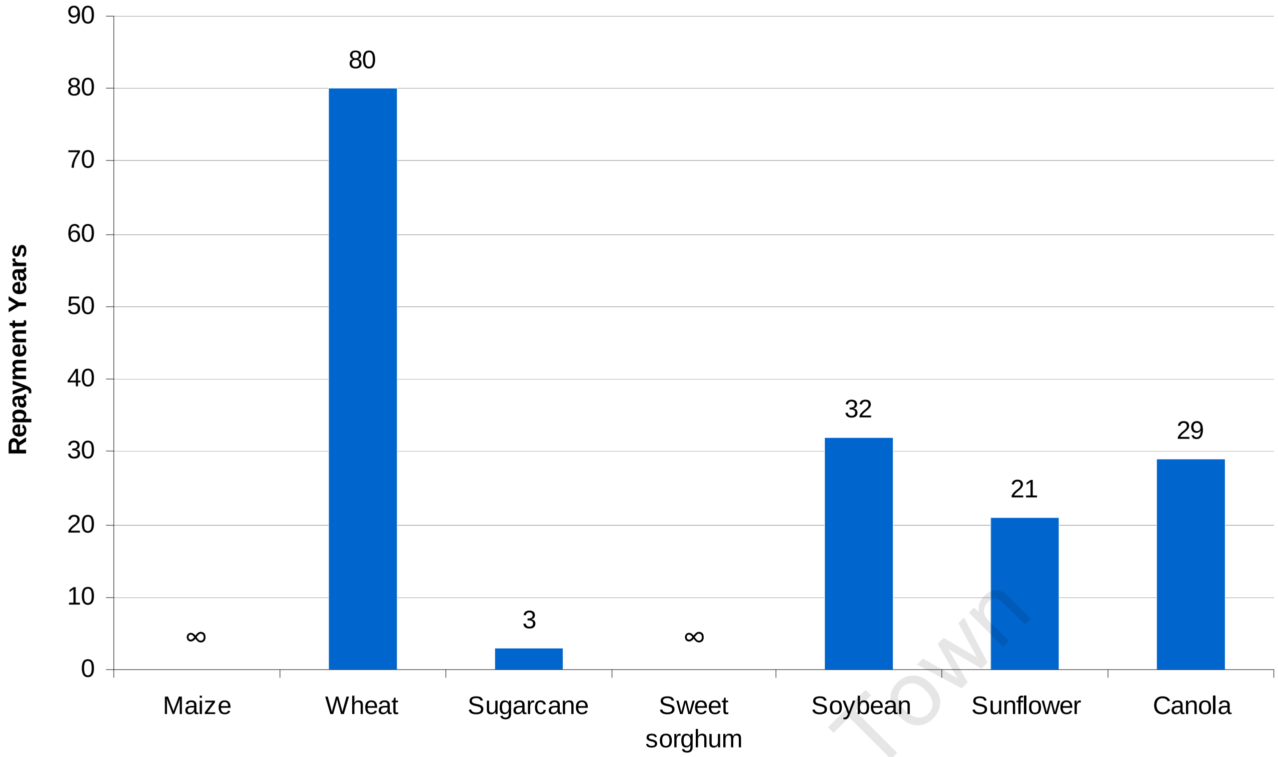


Figure 4. 6: Number of years required to repay the carbon debt.

4.2.1. Sensitivity analysis of the repayment periods

The carbon debt repayment periods of the different biofuels were analysed for sensitivity of two parameters: The number of years that the land is left uncultivated before growing the energy crops and the yields of the respective crops. Both of these parameters tend to vary widely with seasons and places within the country. In the analyses, only the values of the respective parameters were varied while all other values were kept constant.

Figure 4.7 below presents the changes in the repayment period to variations in the number of years that land is left uncultivated. As was expected, the results show that the longer the land is left uncultivated and the grass is left to grow freely, the more carbon is stored by both the grass and the soil, and consequently the longer it will take for the biofuels to repay the debt.

The results also show that the required repayment periods of the different energy crops exhibit different sensitivities to the number of years the land is left uncultivated, with sugarcane ethanol and wheat grain ethanol showing the least and greatest sensitivities respectively. In particular, it would take about 2 years for sugarcane ethanol and 65 years for wheat grain ethanol to repay the carbon debts if the crops were grown on land that had been left uncultivated for a year, while it would take about 6 years and 195 years for sugarcane ethanol and wheat ethanol respectively if the land had been left uncultivated for 10 years.

This shows an increase of about 0.4 years and 14.5 years to the number of repayment years for sugarcane ethanol and wheat grain ethanol respectively for every additional year that the land is left uncultivated. This variation in the sensitivities of the different biofuels is due to the fact that the number of repayment years are inversely proportional to the annual repayment ability of that biofuel; hence the larger the annual repayment, the less sensitive the biofuel's repayment period to changes in the number of uncultivated years. Simply stated, large annual repayments result in small gradients for the curves in Figure 4.7.

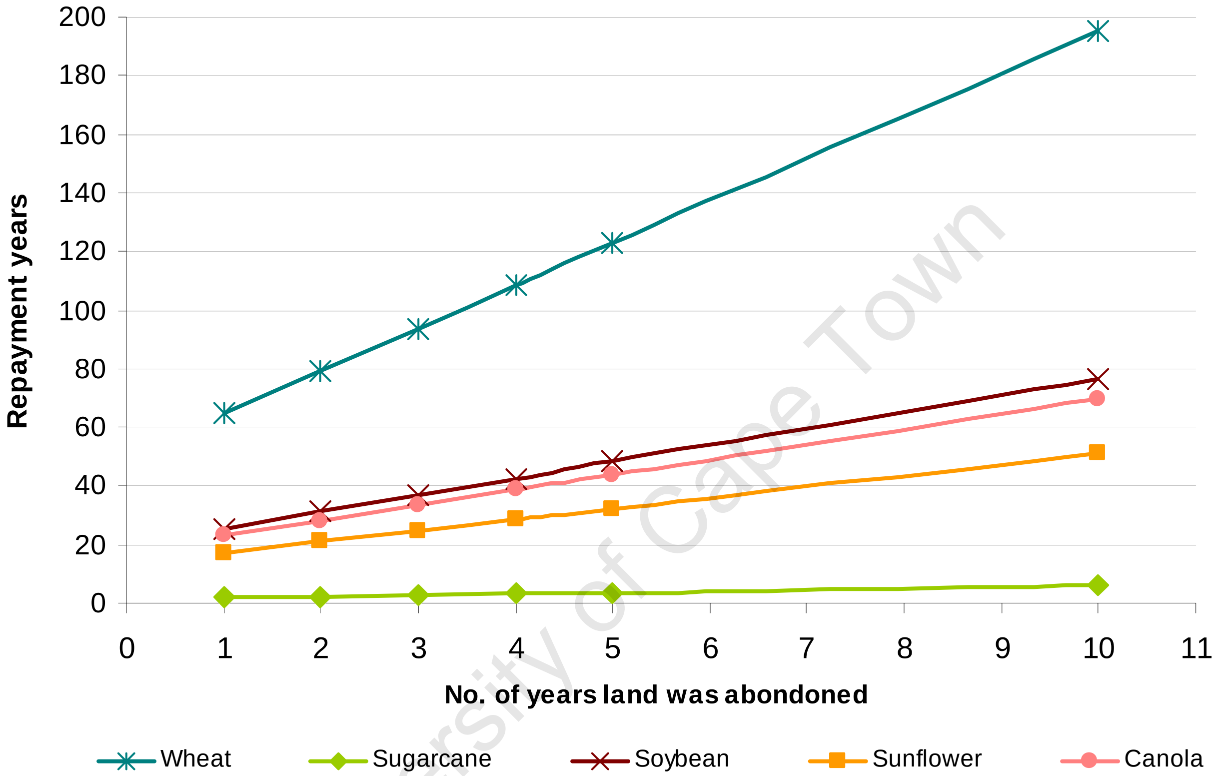


Figure 4. 7: Sensitivity of number of repayment years to number of years land was abandoned

The repayment periods of the biofuels were also analysed for sensitivities in the yields of the respective biofuel crops, and the results of this analysis are shown in Figure 4.8 below. These results show that the carbon debt repayment periods increase exponentially with decreasing crop yields, with sugarcane ethanol and wheat grain ethanol showing the least and greatest sensitivities respectively. Specifically, a 25% decrease in the yield of sugarcane results in a 55% increase in the repayment period, whereas a yield increase by the same percentage only results in a 30% decrease in the repayment period. In the case of wheat grain ethanol, while a 25% increase in the yield of wheat results in a 72% decrease in the repayment period, a decrease by the same percentage takes the avoided greenhouse gas emissions to below zero, implying that production of wheat grain ethanol at those yields would only serve to increase the carbon debt rather than repaying it.

The value of avoided greenhouse gas emissions for each biofuel is actually made up of four parameters – life-cycle emissions from crop production, emissions from post-harvest processing, emissions associated with the replaced fossil fuel and emissions associated with products replaced by the co-products (Appendix I) – therefore its sensitivity to changes in crop yields depends on the magnitude of each of these values for each biofuel. While the last three of these values do vary with changes in crop yields, the emissions from crop production are independent of crop yields, leading to greater sensitivities in avoided greenhouse gas emission, and subsequently in repayment years, for those biofuels with large agricultural emissions and relatively lower biofuels yields.

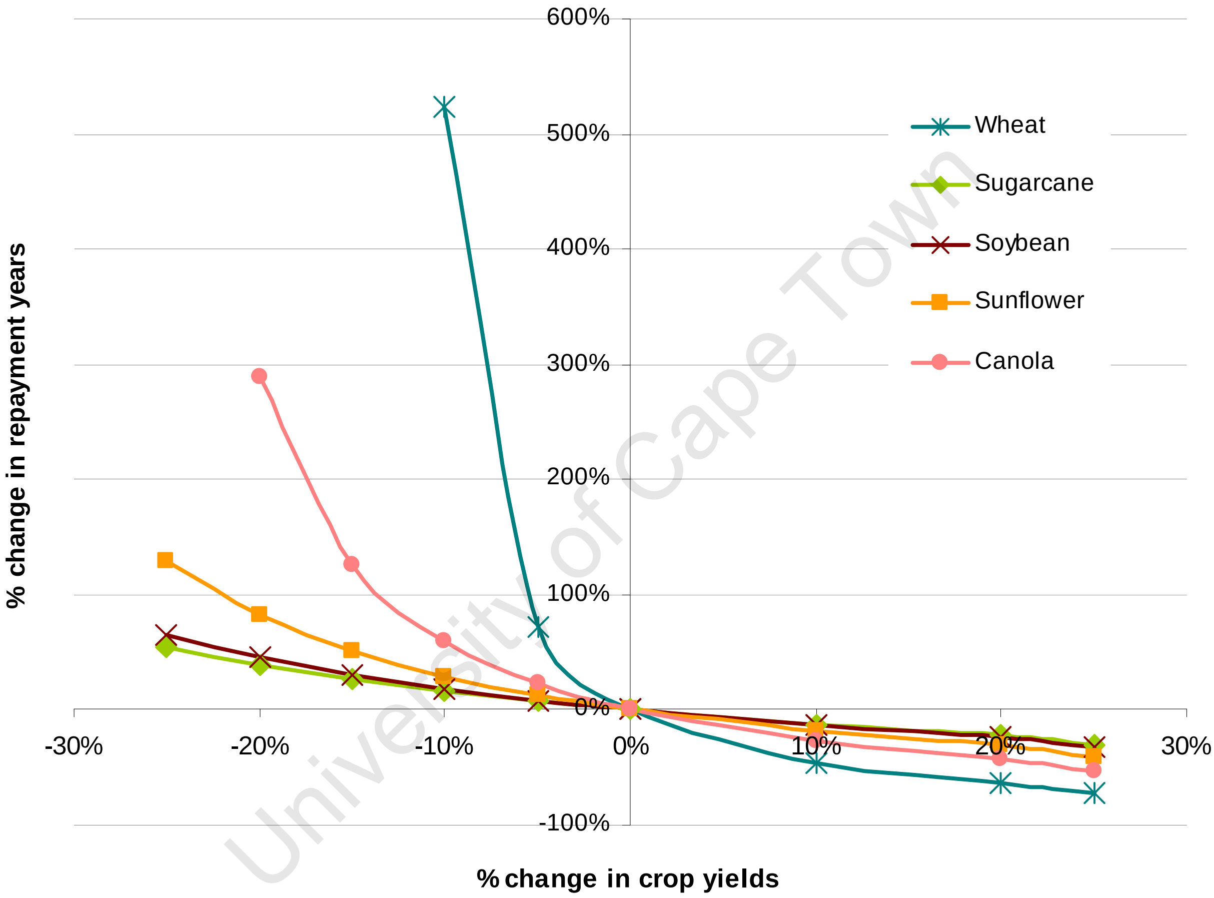


Figure 4. 8: Sensitivity of repayment period to changes in crop yields

Changes in crop yields also have large impacts on the repayment ability of maize grain ethanol and sweet sorghum ethanol. The sensitivity analysis shows that the value of avoided greenhouse gas emissions for maize grain ethanol and sweet sorghum ethanol become positive if the yields of maize grain and sweet sorghum cane increase by more than 42% and 24% respectively. This means that maize grain ethanol and sweet sorghum ethanol can only be able to repay their carbon debt if their respective crop yields are in excess of 4.3 tonnes of maize per hectare and 39.5 tonnes sweet sorghum per hectare.

As pointed before, changes in cane transportation distance also affect the repayment ability of sweet sorghum ethanol. Figure 4.9 below shows the sensitivity of the repayment period with changes in sweet sorghum transportation distance. From this figure, it is clear that if the transportation distance of sweet sorghum cane is below 442 km, the repayment period become less than 100 years and even going down to 10 years for a distance of 166 km.

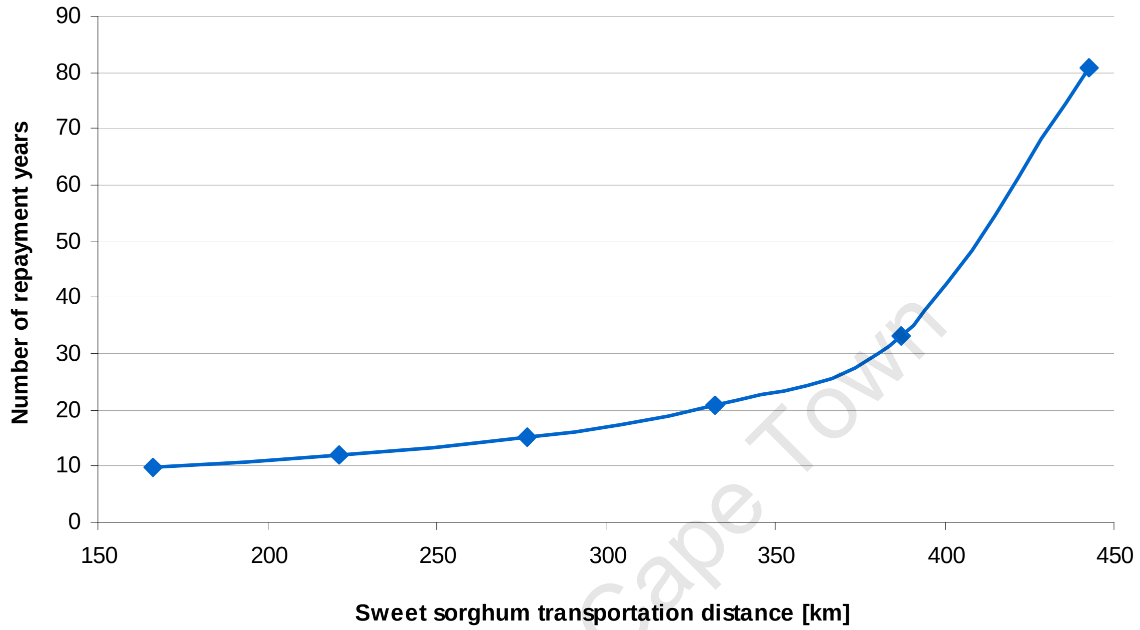


Figure 4. 9: Variation of sweet sorghum repayment period with transportation distance

4.2.2. Conclusions

The results of this section show that the conversion of currently abandoned or underutilized agricultural land to annual energy crop production for biofuels results in a carbon debt, regardless of the type of biofuel or energy crop cultivated. The length of time that each biofuel will take to ultimately offset this debt is dependant on various factors, including crop yields, crop transportation distances and the number of years that the land was left uncultivated.

This section and the previous section have shown that whilst all the biofuels analysed in this thesis have positive net energy balances, their potential to mitigate greenhouse gas emissions varies from very likely to improbable. As both of these are necessary conditions in the development of a biofuels industry in South Africa, the subsequent section therefore explores how these biofuels, and consequently the respective energy crops, can be combined or varied to achieve the objectives of the National Biofuels Strategy to the maximum with minimal use of the agricultural land.

4.3. Results of Multicriteria Modelling

This section presents the results and discussions of the multiobjective optimization model outlined in section 3.8. The first section of these results compares all the energy crops in the absence of a market penetration target and the second section looks at a national target of B2 and E8 market penetration.

4.3.1. No market penetration target

Table 4.2 below is a payoff table of the economic gain, avoided greenhouse gas emissions and job creation objectives in the absence of any specific national market penetration target. The table shows that, based on the biofuel crops assessed in this thesis, the maximum economic gain, avoided greenhouse gas emissions and job creation that can be achieved from the production and utilization of biofuels in South Africa are R3522, 961 kgCO_2-eqt and 228 man-hours respectively per hectare of agricultural land.

Table 4. 2: No target payoff table

Objectives	Units	Values		
		Economic Gain Maximised	*Avoided GHG Emissions Maximised*	*Job-Creation Maximised*
Economic Gain	R/ha	**3,522**	-588	3,522
Avoided GHG Emissions	kg CO_2-eqt/ha	47	**961**	47
Job-Creation	Man-hours/ha	228	33	**228**

The crop distributions that result in the maximum objective values are shown in Figures 4.10 and 4.11. These figures show that both economic gain and job creation are maximized by a crop combination of 93.9% sweet sorghum, 5.9% sugarcane and 0.2% canola on the available land, while avoided greenhouse gas emissions are maximized by a crop combination of 88.3% sunflower, 5.9% sugarcane and 5.8% canola.

These varying crop distributions can be explained by Figures 4.4, 4.12 and 4.13. Firstly, sugarcane ethanol has the highest value for every objective, and therefore it is the most preferred crop in all the areas where it can grow, regardless of the objective to be maximized. In the Western Cape areas where sugarcane cannot be grown, canola is then the most preferred for maximizing all the objectives. It must be noted, however, that for maximization of economic gain, canola is second best from sugarcane, but because it has a negative value for economic gain, it is actually more economical to leave that land uncultivated than to grow canola. In the other areas of the country where sugarcane cannot grow, sweet sorghum is the most preferred to maximise both economic gain and job creation whereas sunflower and canola are the most preferred and second most preferred crops respectively for maximizing avoided greenhouse gas emissions.

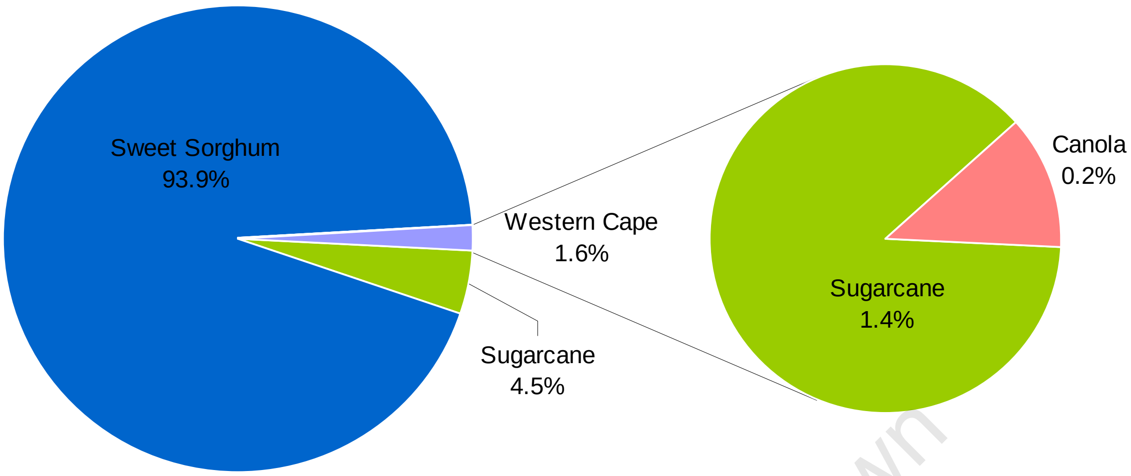


Figure 4. 10: Area-based crop distribution that results in maximum economic gain and job creation – no market penetration target

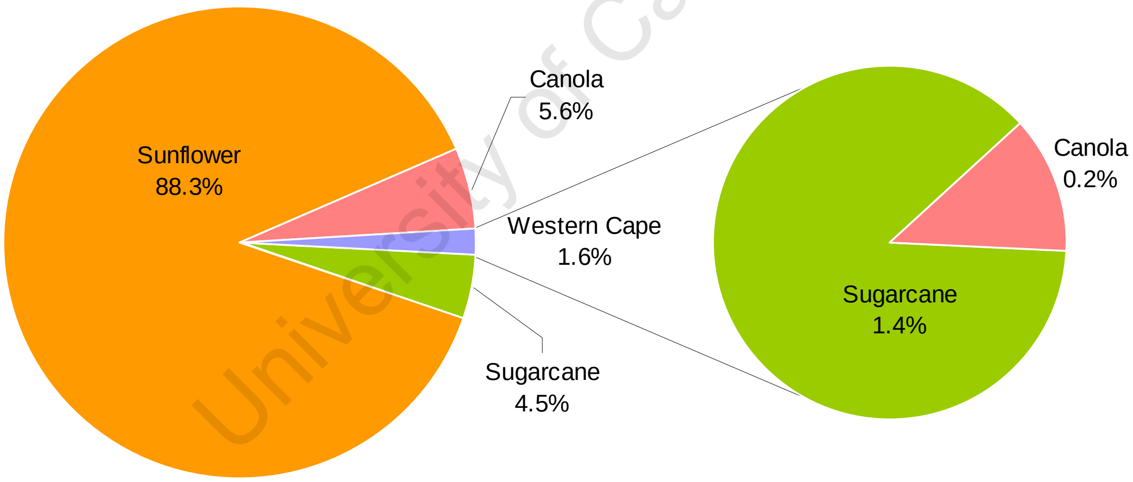


Figure 4. 11: Area-based crop distribution that results in maximum avoided greenhouse gas emissions – no market penetration target

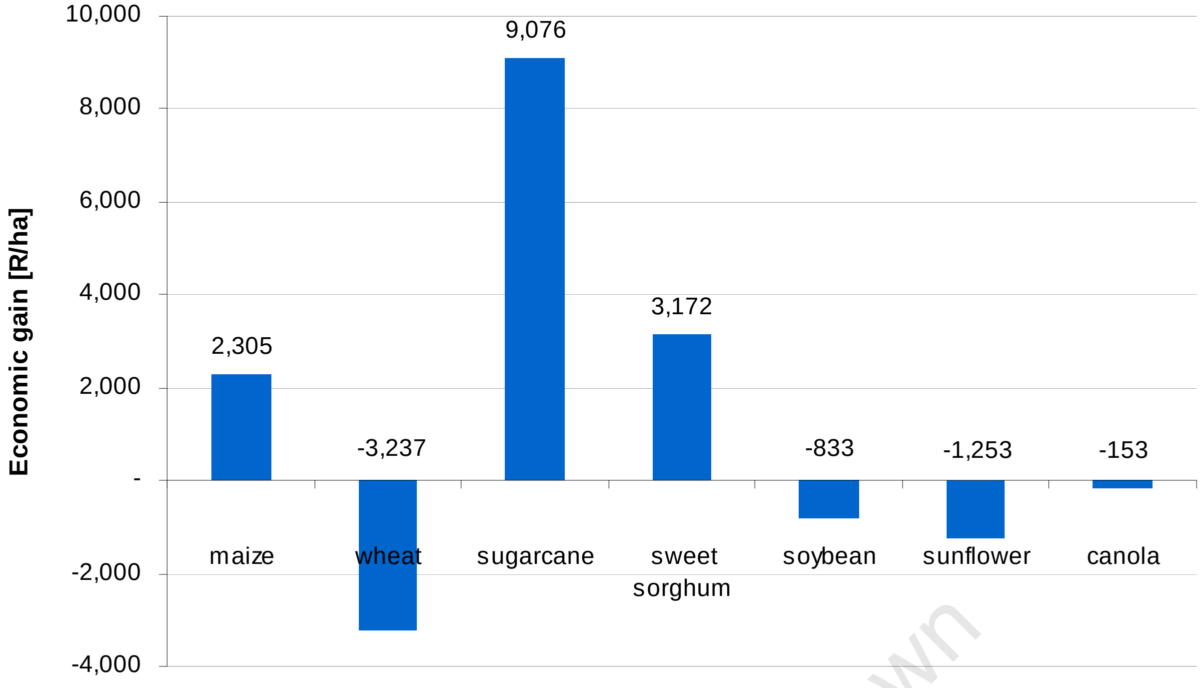


Figure 4. 12: Economic gain abilities of the different biofuels

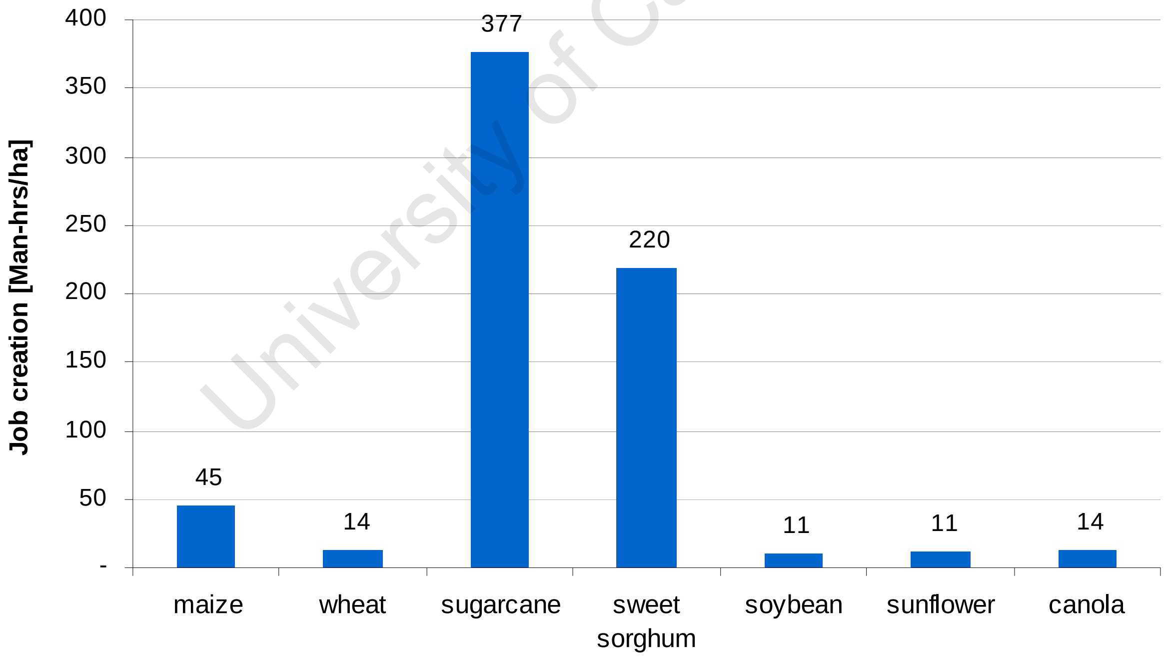


Figure 4. 13: Job creation abilities of different biofuels

The payoff table also shows that whereas economic gain and job creation are maximized by the same crop distribution, avoided greenhouse gas emissions are maximised by a crop distribution that greatly reduces economic gain and job creation from their maximum values. This, therefore, implies the need for a trade-off between these objectives. Figures 4.14 and 4.15 present the trade-off curve (Pareto curve) of the three objectives, in three dimensions and two dimensions respectively, in the absence of a national market penetration target.

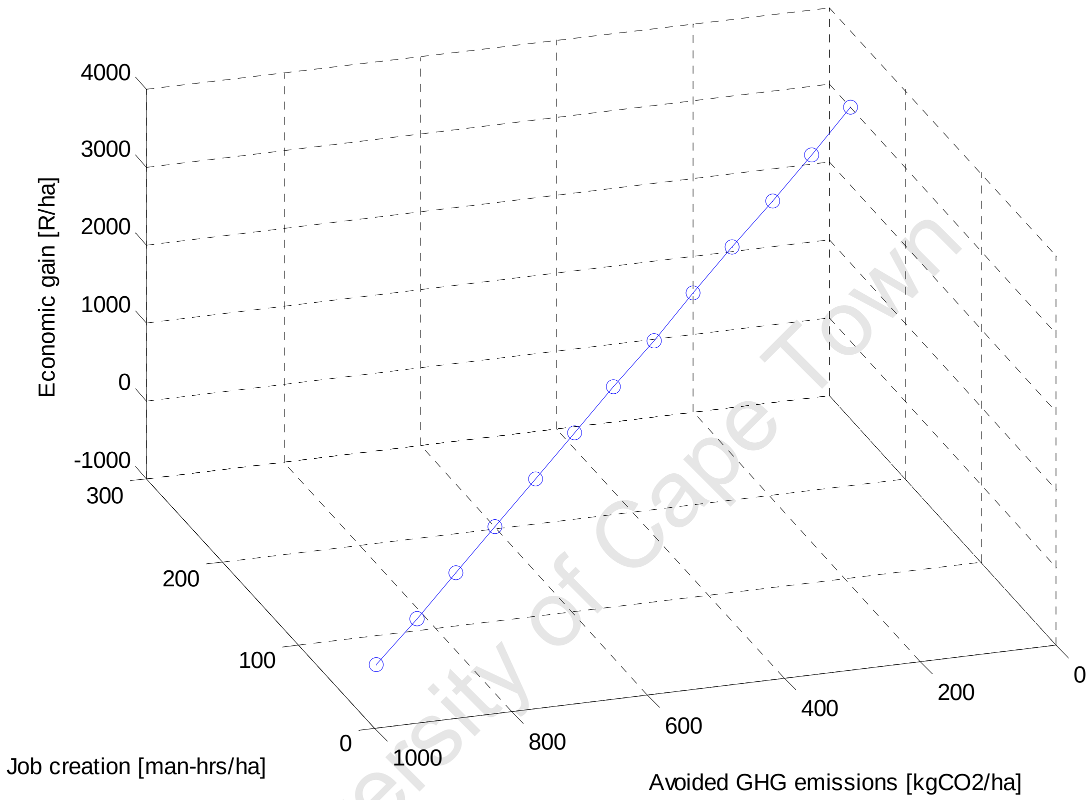


Figure 4. 14: 3-Dimensional trade-off curve (Pareto curve) for target-free market penetration

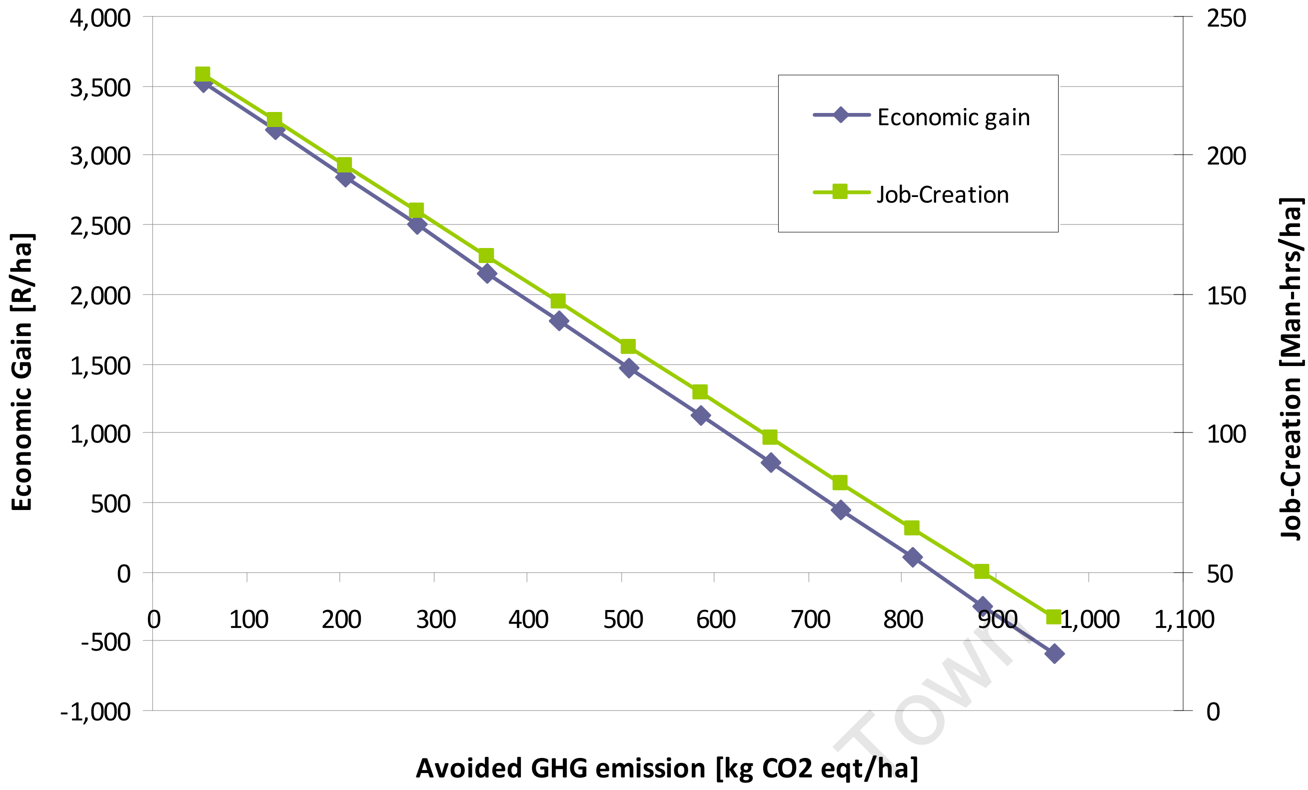


Figure 4. 15: 2-Dimensional trade-off curves in the absence of a market penetration target

The results show that on the one end of the trade-off curve, a maximum economic gain of R3522 and a maximum job creation of 228 man-hours per hectare result in 47 kg CO_2-eqt of avoided greenhouse gas emissions while on the other extreme a minimum economic gain of -R588 and a minimum job-creation of 33 man-hours per hectare avoid as much as 961 kg of CO_2-eqt emissions. In percentage terms the decrease in economic gain and job creation are about 117% and 86% respectively, while the corresponding increase in avoided greenhouse gas emissions is 1940%. This shows that whereas 47 kg of CO_2-eqt emissions per hectare are avoided freely as economic gain and job creation are maximised, any additional kilogram of CO_2-eqt emissions avoided thereafter comes at a cost of R4.50 and 0.2 man-hours.

Figures 4.16 and 4.17 below show the overall crop distributions that result in the optimal objective values of the trade-off curve. The figures simply show that as more land is grown to sunflower and canola, replacing sweet sorghum, the more greenhouse gases avoided and the less the economic gain.

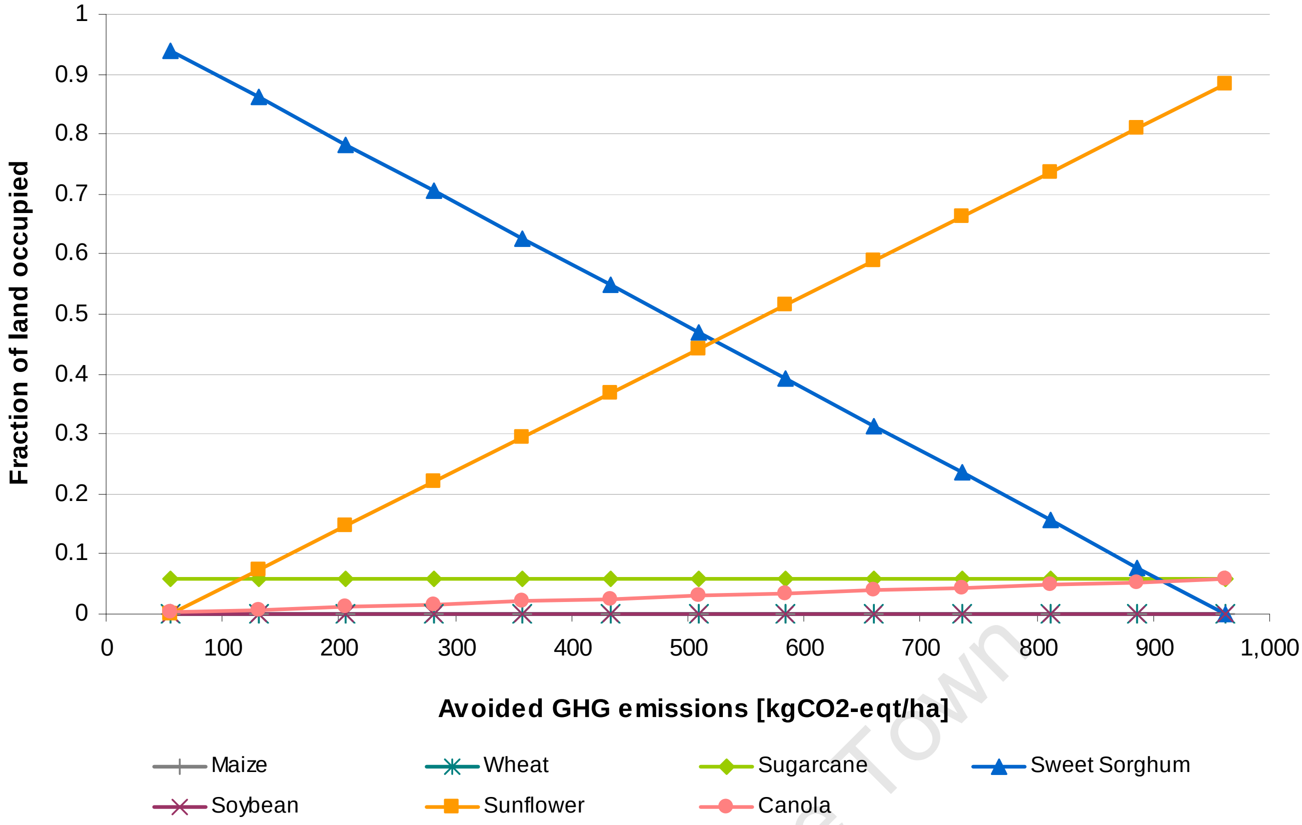


Figure 4. 16: Variation of the trade-off curve crop distributions with avoided emissions

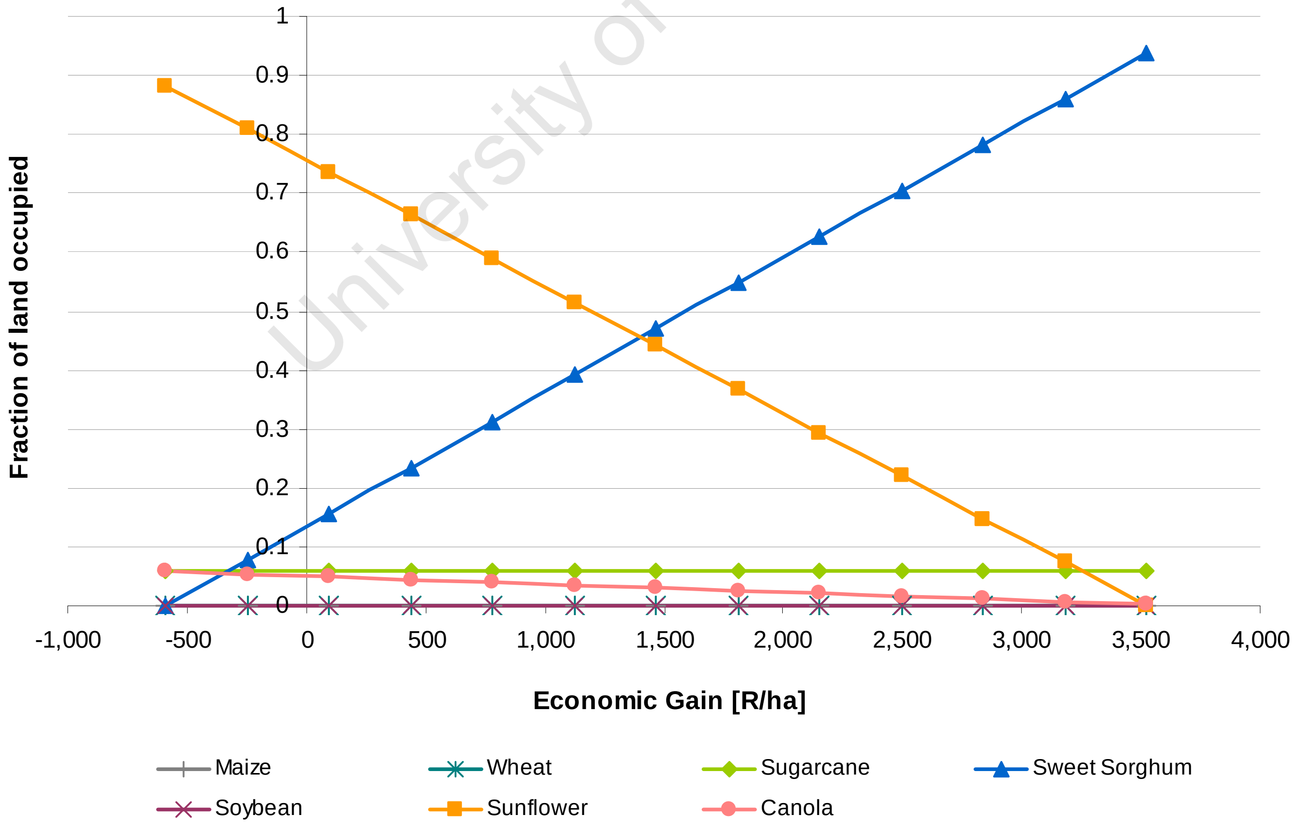


Figure 4. 17: Variation of the trade-off curve crop distributions with economic gain

4.3.1.1. Price sensitivity of crop distributions – No market penetration target

Agricultural commodity prices and fuel prices vary greatly not only from year to year but also with seasons. The former are determined largely by import parity and local stock supply while the latter are dependant on the price of crude oil which in turn is determined by global demand, global supply and political situations in oil producing regions. This subsection presents the results of a sensitivity analysis of the optimal crop distributions to changes in these prices. In this analysis, the crops were grouped into grains, cane crops and oilseeds and then the sensitivity of the optimal crop distributions was analysed for changes in the prices of each group.

The results of the sensitivity analyses are shown in Figure 4.18. Changes in both agricultural commodity prices and fuel prices do not have any impact on either the maximum job creation or the maximum avoided greenhouse gas emissions, therefore Figure 4.18 only presents the impacts of these price changes on the maximum economic gain.

The results show that while a 30% increase in the price of petrol does not have any influence on the optimal crop distribution, a decrease by the same percentage makes it more preferable to grow maize, followed by canola, rather than growing sweet sorghum in those areas where sugarcane cannot grow. Because of the high crop yields and ethanol yields of sweet sorghum, the by-products of sweet sorghum ethanol are worth much less than those of maize grain ethanol on a litre basis; hence the economic gain of sweet sorghum ethanol decreases much faster with decreasing biofuel prices than that of maize grain ethanol. It thus becomes more economical to produce maize grain ethanol than to produce sweet sorghum ethanol at biofuel prices lower than R5.96. Although a 30% decrease in fuel prices results in a comparable economic loss for both sweet sorghum and canola on a litre basis, the high yields of sweet sorghum make its loss much larger than that of canola on a hectare basis, making it more attractive to produce maize grain ethanol.

The sensitivity analysis also shows that a 30% decrease in the purchase price of grains has the same effect on the optimal crop distribution as a 30% increase in the purchase price of sugarcane or sweet sorghum cane. Both of these cases make it more economically attractive to grow maize than to grow sweet sorghum. It also be observed from the figure that neither a 30% decrease nor a 30% increase in oilseed prices affect the optimal crop distribution.

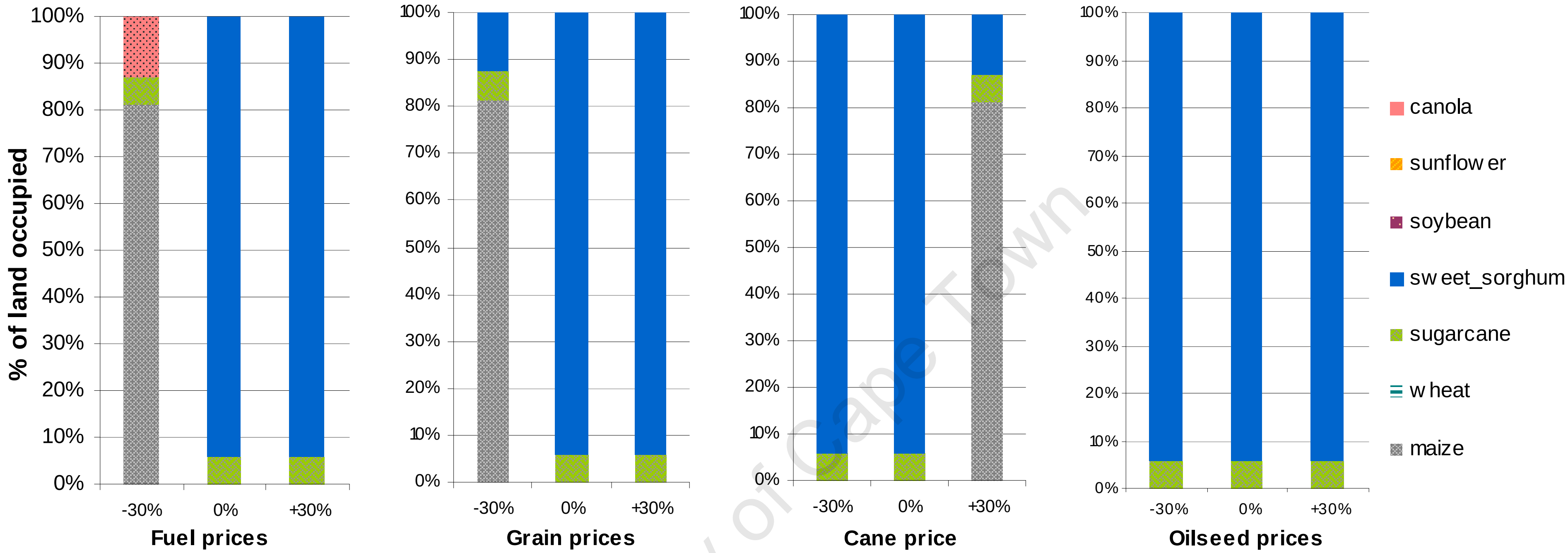


Figure 4. 18: Variation of optimal crop distributions with changes in fuel prices and commodity prices – no market penetration target

4.3.2. *B2 and E8 market penetration*

Table 4.3 below presents a payoff table of the economic gain, avoided greenhouse gas emissions and job creation objectives for a national market penetration of 2% biodiesel and 8% bioethanol. The payoff table shows that the maximum economic gain, avoided greenhouse gas emissions and job creation that can be achieved amount to R1554, 718 kgCO_2-eqt emissions and 118 man-hours per hectare respectively. All the maximum values in this table are smaller when compared with those in Table 4.2, making it apparent that the requirement of a specific national market penetration greatly reduces the maximum values of the objectives that can be achieved per hectare. Specifically, the maximum objective values in this section are lower than those in the previous section by 56%, 25% and 48% for economic gain, avoided greenhouse gas emissions and job creation respectively.

Table 4. 3: B2 and E8 market penetration payoff table

Objectives	**Units**	**Values**		
		Economic Gain Maximised	*Avoided GHG Emissions Maximised*	*Job-Creation Maximised*
Economic Gain	ZAR/ha	**1,554**	-1,663	1,484
Avoided GHG Emissions	kg CO_2eqt/ha	443	**718**	519
Job-Creation	Man-hours/ha	51	34	**118**

Unlike in the absence of a national market penetration, there are three distinct crop combinations that maximise the three objectives for a national market penetration of B2 and E8. Figures 4.19, 4.20 and 4.21 below are representations of these optimal crop combinations.

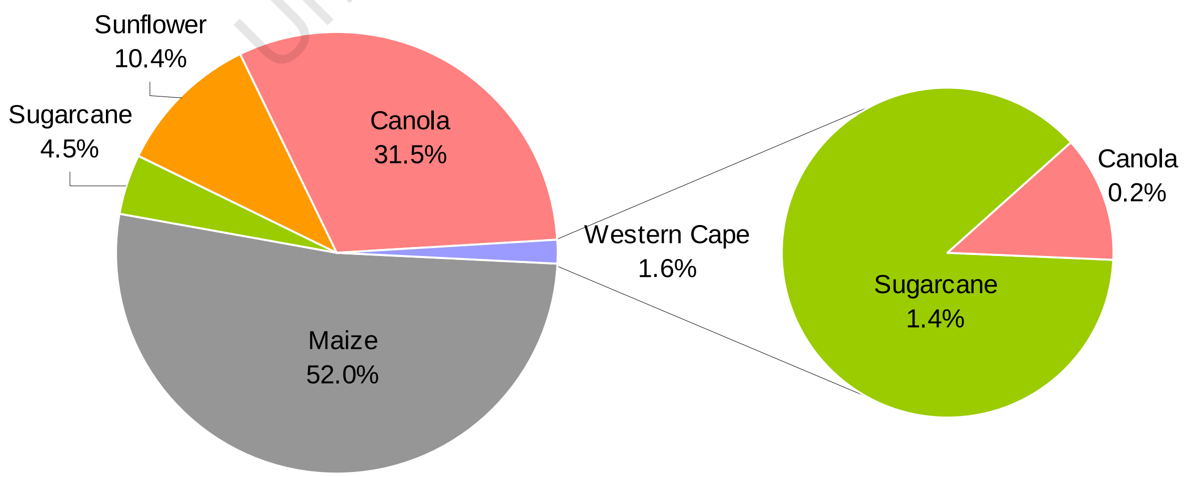


Figure 4. 19: Area-based crop distribution resulting in maximum economic gain – B2E8 market penetration

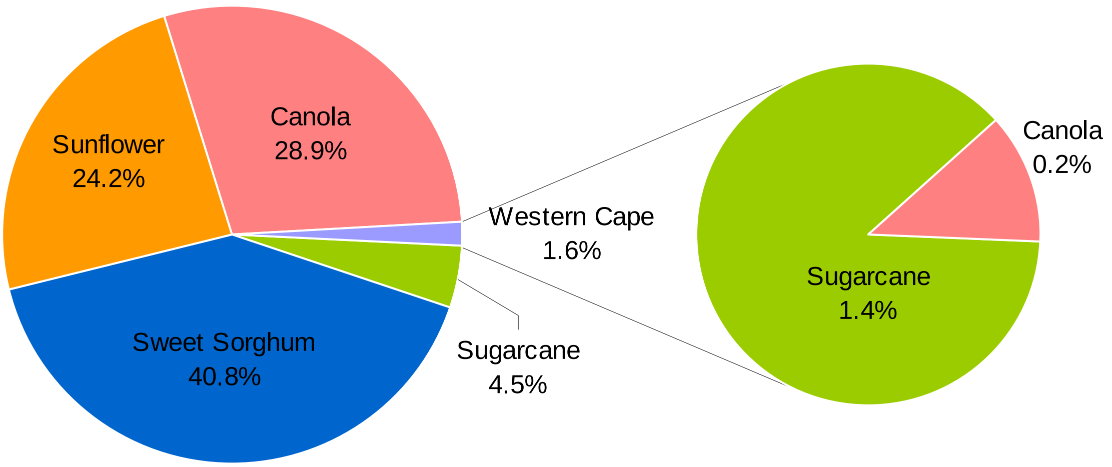


Figure 4. 20: Area-based crop distribution resulting in the maximum job creation – B2E8 market penetration

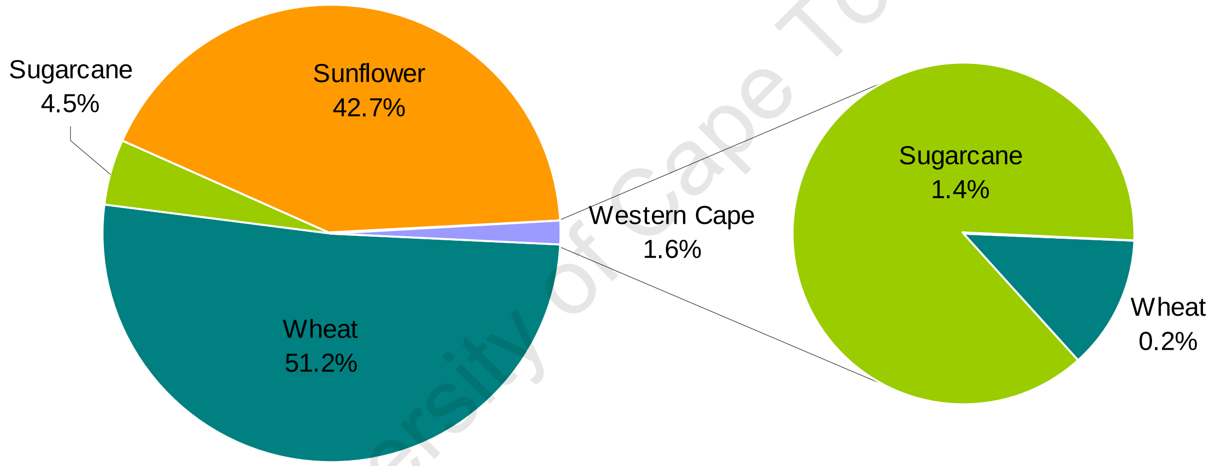


Figure 4. 21: Area-based crop distribution that gives the maximum avoided greenhouse gas emissions – B2E8 market penetration

The maximum economic gain for a national market penetration of B2 and E8 is obtained by growing ethanol energy crops on 57.9 % of the land and oilseeds on 42.1% of the land, whereas the maximum job creation for the same market penetration requires 46.7% and 53.3% of the land to be grown to ethanol crops and oilseeds respectively. The maximum avoided greenhouse gas emissions on the other hand require 57.3% of the land to be grown to ethanol energy crops and 42.7% to oilseeds.

It must be noted, however, that while all these crop combinations lead to the production of the same ratio of biodiesel to bioethanol, the absolute quantities of the biofuels produced are different for the different crop combinations. In particular, the crop combination that maximises economic gain produces 931 litres of ethanol and 204 litres of biodiesel per hectare, while 1125 litres of ethanol and 247 litres of biodiesel are produced per hectare by the crop combination that maximises job creation. In maximising avoided greenhouse gas emissions 787 litres of ethanol and 173 litres of biodiesel are produced per hectare. This implies that the crop combinations that maximise economic gain and avoided greenhouse gas emissions respectively require land that is 1.2 and 1.4 times that required by the crop combination that maximises job creation to produce the same quantity of biofuels.

Because of the different optimal crop combinations required to maximise the different objectives, it is obvious that a trade-off is necessary between these objectives. Figures 4.22 and 4.23 illustrate the nature of the trade-offs required between these objectives in 3-dimensions and 2-dimensions respectively.

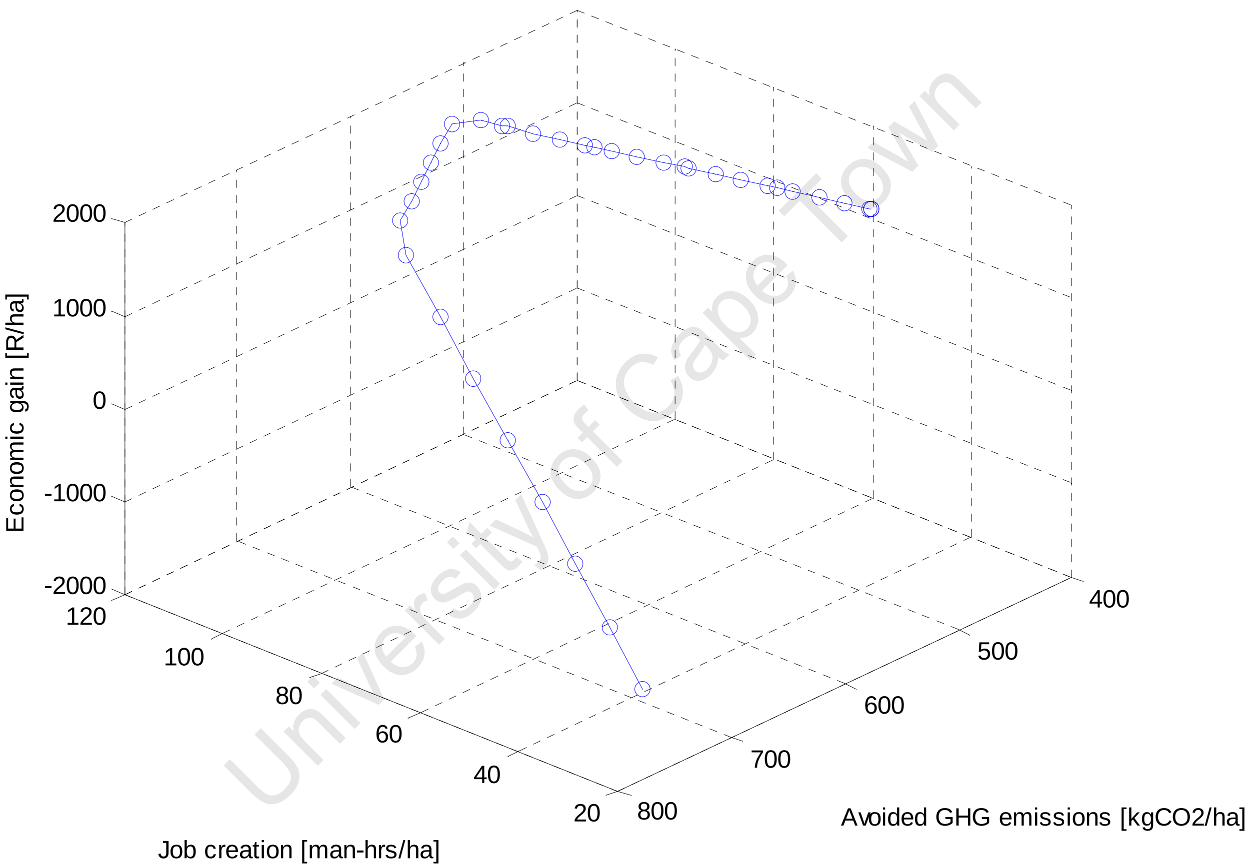


Figure 4. 22: Trade-off curve of the E2E8 market penetration target in 3-dimensions

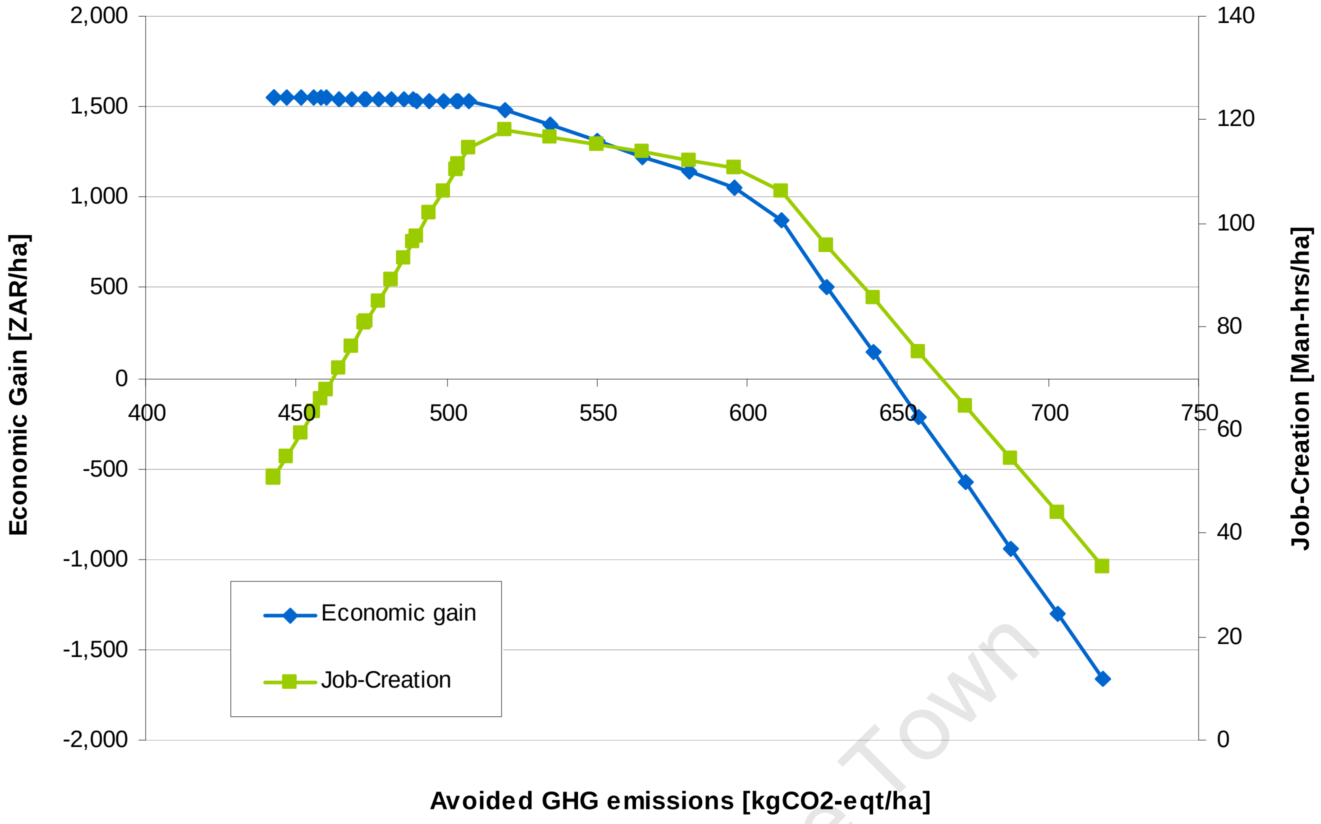


Figure 4. 23: Trade-off curve of the E2E8 market penetration target in 2-dimensions

The trade-off curve can be divided into three segments, which are individually discussed below in relation to their respective crop combinations as presented in Figure 4.24:

The first segment starts from a point where economic gain is maximised and ends with the point that maximises job creation. In this segment economic gain decreases at a very slow rate (R0.40 / kg CO_2-eqt) with increasing avoided greenhouse gas emissions, while job creation increases with increasing avoided greenhouse gas emissions at a rate of 1 man-hour per kg of CO_2-eqt avoided. This segment is basically characterised by maize starting off as the largest occupant of the land and steadily being replaced by sweet sorghum until there is no more maize to replace. The fraction of land grown to sunflower also increases steadily to maintain the constant B2-E8 proportion.

The second segment starts at a point where maize has been completely replaced with sweet sorghum and the latter is the sole bioethanol crop grown in the areas where sugarcane cannot grow. The segment is characterized by sunflower steadily replacing canola until all of the canola has been completely replaced. To maintain the constant B2-E8 proportion, constant sunflower replaces small amounts of sweet sorghum as well. As avoided greenhouse gas emissions increase, the overall result from this segment is an economic gain that decreases at a rate of R5.60 / kg CO_2-eqt and a job creation potential that decreases at a rate of 0.1 man-hours / kg of CO_2-eqt.

In the third and last segment of the trade-off curve the land grown to sweet sorghum is slowly taken over by wheat until all the sweet sorghum is completely replaced. Similar to the other segments, sunflower also sheds some land area to make way for wheat so that the required ethanol-biodiesel ratio is maintained. The overall result from this segment is economic gain and job creation potential that decrease at rates of R23.60 and 0.68 man-hours respectively for every kg of CO_2-eqt emissions gained. The segment ends at a point where avoided greenhouse gases are at a maximum.

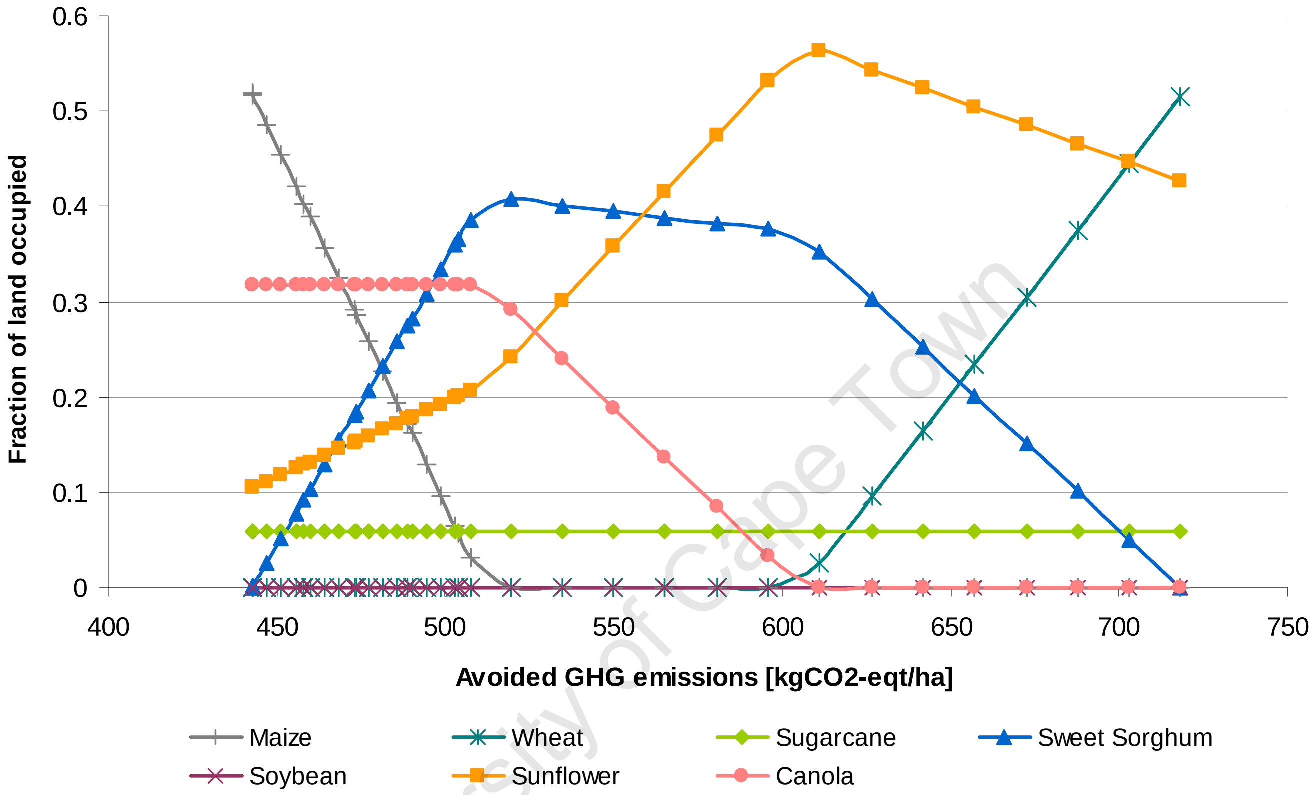


Figure 4. 24: Crop combinations of the trade-off curve that achieves a market penetration of B2 and E8

4.3.2.1. Price sensitivity of crop distributions – B2 and E8 market penetration

The optimal crop combinations for the B2 and E8 market penetration target were also analysed for changes in fuel prices and agricultural commodity prices. Similar section 4.3.1.1 the agricultural commodities were grouped as grains, cane or oilseeds in this analysis.

The results of the sensitivity analysis in Figure 4.25 show that a 30% increase or decrease in all of the prices has an impact on the crop combination that maximises economic gain. A 30% decrease in the price of fuel makes it more economical to plant maize as the only ethanol energy crop while canola and soybean can be grown for biodiesel production. On the other hand a 30% increase in fuel price favours sugarcane and sweet sorghum as the ethanol energy crops whilst canola and sunflower are preferred for the production of biodiesel.

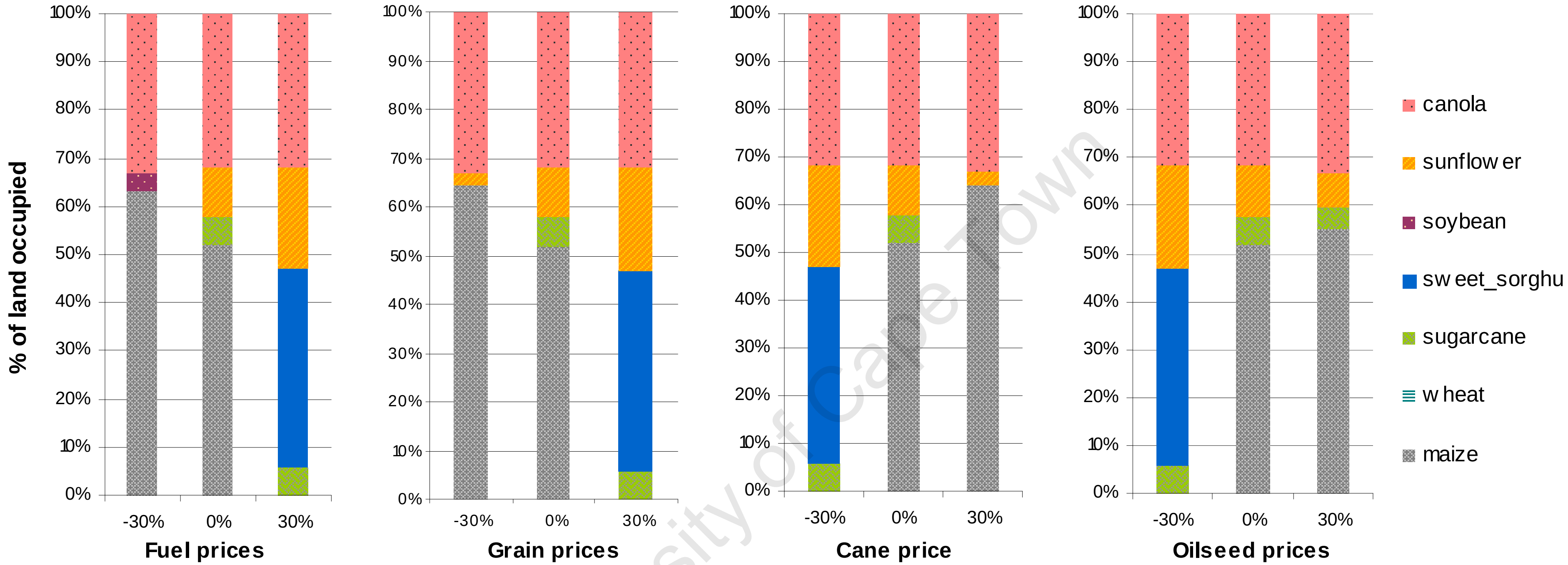


Figure 4. 25: Variation of optimal crop distributions with changes in fuel prices and commodity prices – B2 and E8 market penetration

As with the results of section 4.3.1.1, a 30% decrease in the prices of grains has the same effect on the optimal crop combination as a 30% increase in the price of cane and vice-versa. The decrease in grain prices makes it more economical to grow maize as the only ethanol energy crop while the increase makes cane crops the most economical options. In both of these cases canola and sunflower are the most preferred biodiesel crops.

The results of the analysis also show that a 30% decrease in the prices of oilseeds has exactly the same effect on the optimal crop combination as a 30% increase in fuel prices or a 30% increase in grain prices or a 30% decrease in the price of cane crops – they all favour a combination of 5.9% sugarcane, 41.1% sweet sorghum, 21.3% sunflower and 31.7% canola. This is behaviour that results from a decrease in oilseed prices can be attributed to the fact that it leads to positive a positive economic gain for sunflower biodiesel, and when combined with the already large economic gain of sweet sorghum ethanol, the result is an overall economic gain that surpasses that of any of the combinations involving grain crops. An increase in the oilseed prices on the other hand does not have significant effects on the optimal crop combination.

4.4. Summary of key findings and outlook

The results of this chapter can be summarised as follows:

- All the biofuels analysed in this thesis show positive energy balances and energy balance ratios that are greater than 1.

- The conversion of land to biofuel production results in a 'once-off' carbon debt which the biofuels can only repay if their production and use avoid the emission of greenhouse gases in each year subsequent to bringing that land into agricultural production. It was found that the production of maize grain ethanol and sweet sorghum ethanol do not avoid greenhouse gas emissions under the assumptions of this study, hence would be unable to repay the carbon debt. In the case of sweet sorghum, the assumption of large transport distances associated with the distant location of currently existing sugar mills could be reviewed, whereas in the case of maize, the use of fossil fuels in processing would have to be stopped and replaced by a less greenhouse gas intensive way of providing industrial heat.

- Economic gain and job creation are maximised by a common crop distribution but a trade-off is required between these objectives and avoided green house gas emissions in the absence of national biofuel market penetration targets. For a market penetration target of B2-E8, however, the three objectives are maximised by different crop combinations, hence trade-offs are required between all three. Both of these cases show marked sensitivities to changes in agricultural commodity prices and fuel prices.

This chapter has focused on the optimization of land use for biofuel production on a national scale. The next chapter looks at how this model can be applied to a specific situation and be used to aid decision-making at a local government level regarding biofuel production.

5. MALUTI-A-PHOFUNG LOCAL GOVERNMENT CASE STUDY

In this chapter the use of multiobjective optimization to support decision-making in the development of a biofuels industry is demonstrated at municipal level.

5.1. Area Description

Maluti-a-phofung is one of the five municipalities of the Thabo Mofutsanyana district, which is located in the eastern part of the Free State province, bordering with the kwaZulu-Natal province to the east and the Kingdom of Lesotho to the south. The Maluti-a-phofung municipality is home to 54% of the district population, while covering only 16% of the district surface area, making it the third most populated area in the Freestate at 87 people per km^2 (Business Trust and DPLG, 2007). As shown in Figure 5.1 below the municipality is characterized by three urban complexes around which the whole municipality evolves: The Harrismith complex, Phuthaditjhaba-Qwaqwa complex and the Kestell complex (IDP, 2007).

The Harrismith complex is composed of the town of Harrismith and the two townships of Intabazwe and Tsiame. It is located in the eastern central part of the municipality, around the intersection of the N3 and N5 national roads connecting Durban with Johannesburg and Bloemfontein, respectively. According to the local municipality, the complex derives much of its economic activity from this favourable position at a major junction, its relative proximity to the export harbour of Durban, as well as the large and relatively cheap labour force residing in the region. The town of Harrismith, which forms the economic hub of the complex, is well-serviced in terms of infrastructure and housing, and therefore accommodates the more affluent communities of the municipality. Intabazwe and Tsiame, on the other hand, are characterized by low levels of infrastructure and employment. Intabazwe is a former African township separated from the Harrismith CBD by a mountain and stream, while Tsiame is *"a typical apartheid-engineered dormitory town"* located some 12km west of Harrismith.

The Phuthaditjhaba-Qwaqwa complex comprises of Qwaqwa - one of the former homelands which became part of South Africa in 1994 (Appendix B) – and Phuthaditjhaba – its formal gateway and urban component. The area of Qwaqwa outside Phuthaditjhaba is mostly composed of traditional and informal villages, some of which are so remotely located that only a few rudimentary roads connect them to the rest of the district. The complex is consequently by far the poorest and most densely populated in the district.

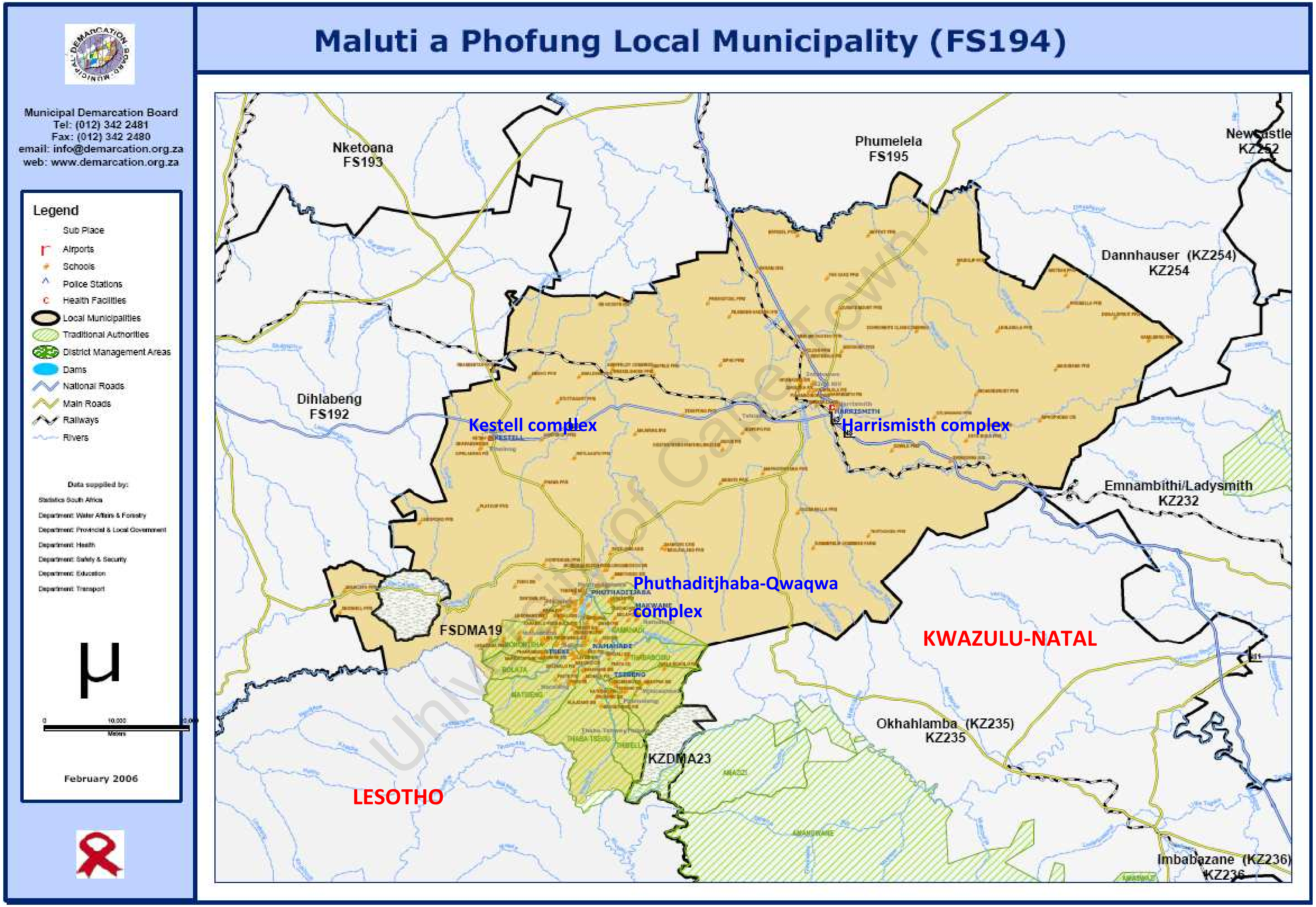


Figure 5. 1: Map of Maluti-a-phofung local municipality (Municipal Demarcation Board, 2008)

The former African township of Tlholong and its neighbouring town of Kestell, both located to the west of Harrismith along the N5 national road, form the smallest complex of the municipality, which functions mainly as a service centre for the surrounding rural and agricultural community.

5.1.1. The economic situation

Under the Regional Industrial Development Programme of the past apartheid government, the Free State Development Corporation (FDC) identified and targeted two areas in Maluti-a-phofung for subsidized industrial development - the Phuthaditjhaba area and Tshiame's Industriqwa - where industrial premises were developed for large investors from outside the area, while smaller factories were developed primarily for local business owners. When the subsidy regime ended, however, most of these industries closed down, whilst others resorted to cutbacks in labour in order to keep profits high. The FDC estimates that only 50% of the developed industrial units in Industriqwa were occupied in 1999, employing less than 1000 people from Tshiame, while the rest travelled on a daily basis to Harrismith or Qwaqwa for employment (IDP, 2007).

The most important sector in Maluti-a-phofung, both in terms of employment and contribution to GDP, is general government services, followed by wholesale and retail trade and manufacturing (Figure 5.2). Agriculture is the second lowest contributor to local GDP, and only contributes 6.7% to employment.

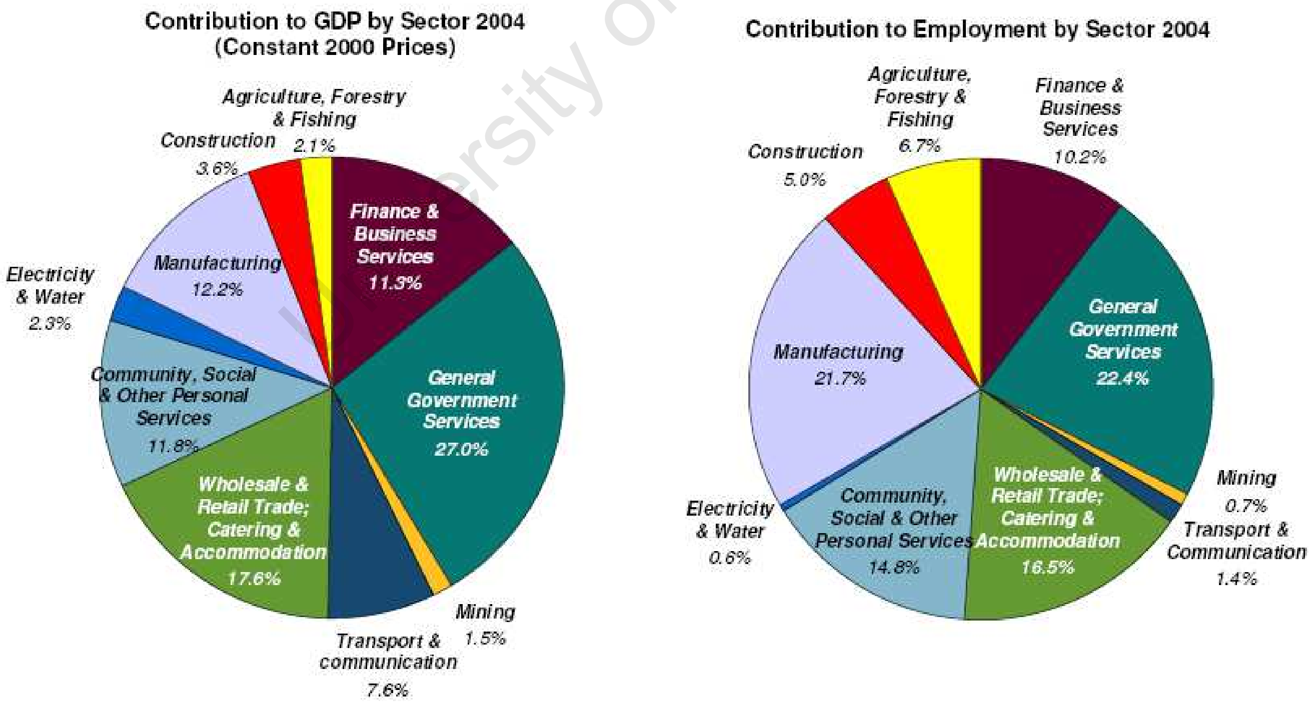


Figure 5. 2: The contribution of each economic sector to GDP and employment in Maluti-a-phofung (Business Trust and DPLG, 2007)

According to Stats-SA (2008), only 22.6% of the potential workforce in Maluti-a-phofung is employed, while over 80% live below the national poverty level (subsistence level) of R 19,200 per annum. For the ten year period between 1995 and 2004, the GDP per capita of Maluti-a-phofung averaged R 6,860 (at constant 2000 prices) - approximately 38% of the provincial average (Business Trust and DPLG, 2007).

In 2001, Maluti-a-phofung was declared one of the most severely impoverished areas in the country and therefore, together with about 23 other regions in the country, was enrolled under two initiatives of the state president –The Urban Renewal Programme (URP) and the Integrated Sustainable Rural Development Programme (ISRDP) – created specifically to address underdevelopment in such areas (Business Trust and DPLG, 2007).

5.1.2. The Agricultural situation

The Thabo Mofutsanyana district as a whole can be described as the most fertile region in the Freestate, with a production capacity and gross income per hectare that are well above the provincial average. On average, Maluti-a-phofung receives between 700 and 800 mm of rain per annum, mostly in the summer seasons.

Similar to many parts of the country, Maluti-a-phofung is characterized by two agricultural practices; commercial farming - which occurs in the flat land surrounding Harrismith and Kestell - and subsistence farming, mainly in Phuthaditjhaba and the surrounding area of Qwaqwa. Maize, wheat, dry beans, sunflower and soybeans are the most popular crops for commercial farmers, while subsistence farming is mainly on livestock, poultry, grain sorghum and vegetables (Business Trust and DPLG, 2007). Grain crops are sold to AFGRI silos and SASKO while cattle are sold at auctions held by co-operatives in the district. Perennial grasses like sugarcane cannot thrive because of the high levels of frost that occur during the winter seasons (Meyers, 2008).

Commercial farming is still dominated by white farmers in Maluti-a-phofung, partly because of the low numbers of land claims in this area compared to other regions of the province. From the late 1980s to the early 1990s, however, a total of 95,896 ha of land were awarded to 114 black emerging farmers in the area between Kestell and Harrismith under the guidance of the Agricultural Development Agency of Qwaqwa (Agriqwa) (Business Trust and DPLG, 2007). The Agriqwa scheme also involved setting up three test farms which acted as support centres for these black farmers in terms of technical advice, training, planning and funding. In 1995, however, this scheme was terminated by government, thus taking away the much needed support for these emerging farmers. Because of lack of financial, management and, in some cases, even technical skills, most of these farmers were left burdened with debt and unable to effectively operate the farms.

Many schemes have since been proposed by various institutions in an attempt to help the black emerging farmers, including partnering with financial institutions like FNB, but failed in the end because they only addressed the problem in part (Meyers, 2008). Since 2006 the following parallel schemes have been tailor-made and adopted to address the problems of these emerging farmers:

i. *The AFGRI Scheme*: In this scheme AFGRI recruits and makes contracts with farmers, via an independent agricultural advisor, to undertake all cultivation activities on the farm and then share all profits 50:50 with the farmer. AFGRI insures and out-sources all farming activities from independent and highly skilled contractors. By 2007 the scheme had attracted some 28 farmers, owning a total of 2,680 ha of arable land, in Maluti-a-phofung. AFGRI's plan is to grow maize exclusively, and start rotating with soybean and sunflower only after 3-4 years (Ballod, 2008). Because of the economies of scale, however, the scheme is only open to farmers with 50 ha of arable crop land or more.

ii. *Department of Agriculture's cooperative scheme*: In this scheme the black emerging farmers, the subsistence farmers and some small-scale farmers (the latter have been awarded pieces of state-owned farm land as caretakers) have been organized into co-operatives, and each co-operative has been given a full set of agricultural machinery and implements by the district Department of Agriculture. The machinery is rented out for a small fee to any farmer who needs to use it, including co-operative members, to generate money for maintaining the machinery. The Department of Agriculture further manages demonstration farms and occasionally holds technical training workshops to support these farmers (Majake, 2008). According to the farmers (Moloi, 2008), this scheme has done very little to solve their problems because there are only a few sets of agricultural machinery available yet all farmers often need to use them at the same time. The limited number of agricultural extension officers and the lack of appropriate skills for most of the extension officers have also contributed to the limited impact of this scheme.

While the two schemes have somewhat reduced the number of struggling black farmers in the area, they have not solved the agricultural problems of the municipality. Many emerging and small scale farmers are still left struggling because the co-operative scheme has failed them and they do not have the minimum crop land requirement of 50 ha for the AFGRI scheme (Moloi, 2008). On the other hand, many of those farmers who meet AFGRI's minimum requirements have remained sceptical about the scheme and opted to rather work their own land as far as they can (Makoele, 2008). In interviews, three of these emerging and small-scale farmers in Maluti-a-phofung stated that most of them believe that the failure of black farmers in the area is mostly due to racial discrimination at the AFGRI and SASKO silos, where their produce, mostly grain, is always labelled as inferior to that of their white counterparts and therefore bought at lower prices (Ntholeng, 2008;Makoele, 2008;Macaphasa, 2008).

5.1.3. Integrated Development Planning

Maluti-a-phofung, like all other local municipalities in South Africa, is required by law to prepare an Integrated Development Plan (IDP), following every Local Government election, to guide the new Municipal Council throughout its five year term. The IDP acts as the principal strategic planning instrument that guides and informs all planning, budgeting, management and decision-making in the municipality (IDP, 2008).

Although the preparation of the IDP is primarily the responsibility of the municipal councillors and municipal officers, the following stakeholders within Maluti-a-phofung are also involved to ensure the relevance of the IDP as the municipality's strategic plan (IDP, 2008):

- *Civil Society*: This group incorporates Ward committee representatives, NGO's in the area, community-based organisations and faith-based organizations.
- *District municipality*: These ensure that local municipal planning aligns well with district planning and plans of other spheres of government
- *Provincial government and Corporate Service Providers*: The former ensure proper linkage between national and local priorities while the latter contribute expertise and technical knowledge. They also ensure that their 5 year plans are integrated into the municipality's 5 year capital programmes.
- *External Support*: Ithuteng Management Consultancy is usually engaged to provide methodological and technical guidance to the IDP process, and to facilitate the planning of workshops. They are also responsible for documenting the outcomes of all planning activities.
- *The public*: This is also involved through structured participation and various forms of media.

The IDP is reviewed on an annual basis to assess the municipality's performance in the previous year, to incorporate new information and changed circumstances and to reflect the budget for the new financial year. The annual strategies for the different priorities of the municipality are also identified and laid out in the form of projects which are assigned to the relevant departments for implementation. Because of Maluti-a-Phofung's limited annual revenue, however, the budget required for the implementation of all the proposed projects is always much greater than the amount that can be allocated to them. Hence the projects always need to be prioritised, with preference given to those that immediately address the basic needs of the community and the well being of the people (Mothekhe, 2008).

In Maluti-a-phofung's 2008/2009 annual review of the IDP (2008), the Local Economic Development and Poverty alleviation sector was by far the largest and most comprehensive; accounting for more than 59% of the budget required for the projects. As outlined in the IDP itself, the main objectives of this sector are:

- To draw investment to the area
- To expand the agricultural and agro-processing sector in the region
- To expand the tourism sector in the region
- To expand the science and technology sector in the region
- To expand the mining and mineral beneficiation sector in the region
- To expand the manufacturing sector in the area
- To strengthen institutional capacity of SMME's and increase the number of viable emerging businesses
- To eradicate poverty
- To protect and secure the environment

According to Thamahane and Nhlapho (2008) the role of the Local Economic Development (LED) office of the municipality in the proposed projects is simply to create a business environment and help establish enterprises which should then be run by the relevant beneficiaries or, in some cases, appointed contractors in the long run. In community-based projects the municipality usually remains involved throughout the life-time of the project as an overseer and advisor.

5.2. Biofuels in Maluti-a-phofung

The Biofuels Industrial Strategy of the Republic of South Africa (DME, 2007) states that:

> *"The strategy targets areas of South Africa that are worst hit by poverty and deprivation. It hopes to generate economic activity, mainly, in the former homelands. Furthermore, only agricultural products grown in the previous homelands by historically disadvantaged farmers will qualify for support."*

This means that the national biofuels strategy is basically an economic and agricultural development programme tailor-made for areas like Maluti-a-phofung.

To achieve its purpose, especially in the agricultural sector, the strategy proposes that the existing agricultural support programmes of the Department of Agriculture, such as the Comprehensive Agricultural Support Programme (CASP), be used to support biofuel crops. In particular, it suggests that the budget of these programmes be increased and their focus be re-directed at capacitating emerging farmers to fully utilize their land.

This section investigates practical ways in which the Maluti-a-phofung specifically can take part in the development of a national biofuels industry based on the tools and the resources available to the municipality.

5.2.1. Feedstock and land use

As shown in section 2.4, waste biomass is the most environmentally friendly and, therefore, most preferable feedstock for biofuel production. In Maluti-a-Phofung the two largest potential sources of waste biomass are the manufacturing industry and the agricultural industry:

- The most significant biomass wastes from the manufacturing sector are sawdust and wood off-cuts from the four furniture-making factories in the municipality. These factory wastes, however, are picked up in small vans and wheelbarrows by local residents and used as firewood. Saw dust is also collected by chicken farmers in the area and used as an insulation material in the chicken sheds (Kwaja Lounge Suits, 2008;Taurus and Tamasa Furnuture, 2008).
- In the agricultural sector, the grain stalks and bean straw that are left in the field after harvesting are also potential feedstock for biofuels. The custom in the area, however, is to bring livestock to newly harvested fields to feed on the stalks and straw, and the little that the animals leave behind is ploughed back into the soil as a means of preserving nutrients (Meyers, 2008).

Therefore there is really no waste biomass available for biofuel production in the municipality. On the other hand, there is plenty of underutilized land in Maluti-a-phofung that can be used for growing energy crops as proposed in the biofuels strategy. The three categories of underutilized land available in the area are as follows:

i. *State land*: According to the Department of Provincial and Local Government (Business Trust and DPLG, 2007), there are 10,000 ha of underutilized semi-urban state land available for agriculture in and around Phuthaditjhaba. This corresponds to about 3,900 ha of underutilized land suitable for crop production (Appendix J).

ii. Land owned by black emerging farmers: Excluding the 2,680 ha that are currently under the AFGRI scheme, an estimated 34,750 ha of crop land owned by black emerging farmers can be classified under underutilized land in the municipality (Appendix J).

iii. Communal land: Most of the communal land in Maluti-a-phofung is not suitable crop cultivation, and therefore, only used for raising livestock. The Department of Agriculture estimates that only about 46 ha of communal land are used for subsistence crop farming in the municipality (Thabo Mofutsanyana district DoA, 2008).

Figure 5.3 below shows the land-use distribution in Maluti-a-phofung.

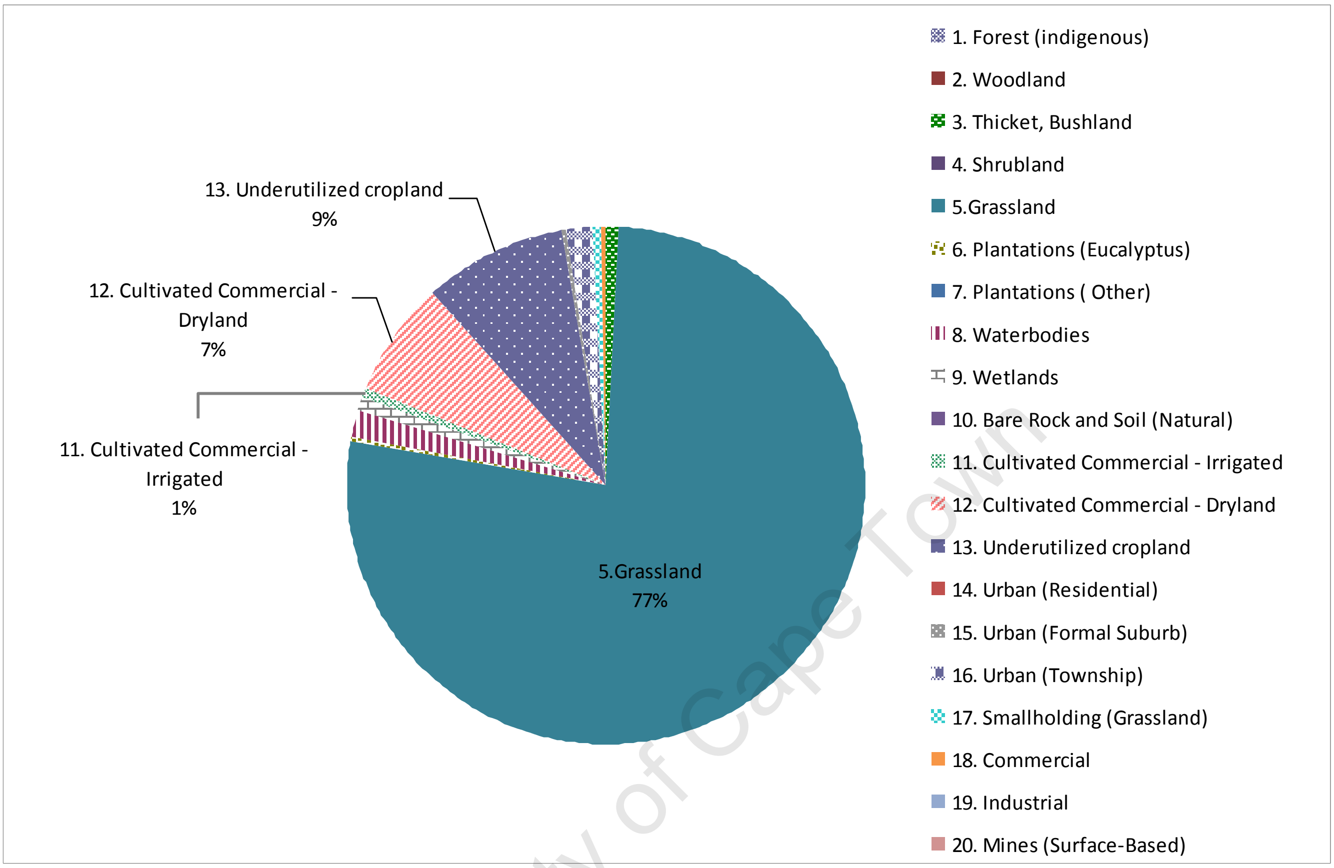


Figure 5. 3: Land-use distribution in the Maluti-a-Phofung municipality (Thabo Mofutsanyana district DoA, 2008)

5.2.2. *Biofuel options for Maluti-a-Phofung*

According to Meyers (2008), the introduction and development of a biofuel industry in Maluti-a-Phofung is the responsibility of both the district agricultural department and the local municipal office. This means that an integrated development planning process – involving the municipal office, the district Department of Agriculture and the farmers – is required to determine the best way for the municipality as a whole to get involved in biofuels. According to the objectives of the municipality's LED programme and the aim of the national biofuel strategy, Maluti-a-Phofung's approach to biofuels development should be able to optimize both economic gain and poverty eradication through job creation in the area.

Based on the biofuel processing techniques outlined in section 3.2.1 and the specific history and characteristics of the area, there are three approaches to biofuels development available to the local municipality of Maluti-a-phofung; the biodiesel-only approach, the bioethanol-only approach or a combination of the two approaches.

5.2.2.1. Biodiesel-only approach

In line with the municipality's objective of promoting local agro-processing, a biodiesel processing plant could be established within the Maluti-a-phofung area through the Local Economic Development (LED) programme. Similar to other LED projects, the daily operations of the plant would be undertaken by either an appointed local contractor or, more preferably, a co-operative of farmers, while the municipal office and the district Department of Agriculture would simply oversee plant activities and offer technical advice respectively. In this approach all the available underutilized land would be used exclusively for growing one or both of the oil crops which are most familiar to the local farmers – soybean and sunflower – for biodiesel production. The biodiesel would then be delivered to the regional blending station while the oil meals would either be sold to the local farmers or marketed outside the municipality depending on the market.

This approach ensures that the entire supply-chain of the biofuel is confined within the limits of the municipality; thus, making Maluti-a-phofung an "exporter" of finished products. The approach also offers the municipality full control over the activities of the supply chain.

5.2.2.2. Bioethanol-only approach

Of the crops considered in this study, maize and wheat are the most appropriate for a bioethanol programme in Maluti-a-phofung. While the climatic conditions of the area prohibit the cultivation of sugarcane completely, the farmers may, however, use their familiarity with grain sorghum to grow sweet sorghum. These energy crops could be grown on the underutilized land available in the municipality and then sent to the appropriate bioethanol plants, outside the municipality, for processing. Based on the bioethanol plant distribution shown in Figure 3.2, the closest grain processing ethanol plant to Maluti-a-phofung would be in Bethlehem, while UCL Company in kwaZulu-Natal is the closest cane processing plant.

In this approach, only the agricultural section of the bioethanol supply chain and the transportation of crops to processing plants are within the boundaries of the municipality, while rest of the activities occur outside the municipality. Although this approach is less demanding to the municipality in financial and administrative terms, it also offers the municipality very little control over the supply chain as a whole.

5.2.2.3. Biodiesel and Bioethanol approach

This is basically a combination of the biodiesel-only approach and the bioethanol-only approach. Here a biodiesel plant would be established within the municipality through the LED programme, but the available land would be used to grow both oil crops and bioethanol crops. The processing of the bioethanol crops would be done in Bethlehem and kwaZulu-Natal as in the bioethanol approach.

The major drawback of this approach is that the operation and sustainability of the biodiesel plant will be strongly influenced by agricultural commodity prices; in the years when the bioethanol energy crops are fetching good prices or the oil crops are fetching poor prices, the farmers will revert to bioethanol crops, leaving the biodiesel plant without feedstock, regardless of whether the economics of biodiesel production may have changed or not.

5.3. The Decision Support System

This section presents a Decision Support System (DSS) that can be used by Maluti-a-phofung's IDP team to decide how the underutilized agricultural land available in the area could best be used for biofuels production such that two of the municipality's top objectives – local economic development and job-creation – are maximised.

Two scenarios are considered in this case-study: the first one is termed the "All-crops" scenario where sweet sorghum is introduced to the farmers as an energy crop that competes with the four energy crops – maize, wheat, soybean and sunflower – that are already grown in the area, and the second, termed the "four-crop" scenario, is where the farmers are not willing to take chances with sweet sorghum and decide to stick to the four crops that they are already familiar with.

5.3.1. DSS Model Equations

5.3.1.1. Economic gain in Maluti-a-Phofung

The first objective – economic gain – is defined here as the net financial gain made by the area of Maluti-a-Phofung as a whole due to the establishment of a local biofuels programme:

I.e. *Economic gain* = *Net profit made in presence of biofuel programme* – *Net profit made in absence of biofuel programme*

While only a certain percentage of the available agricultural land is currently utilized for production into the food market, it is assumed here that the farmers will be able to fully utilize the land under the biofuel programme as argued by the Biofuels strategy. Assuming, therefore, that the processing plants buy the crops from the farmers at market price, the economic gain from the biodiesel supply chain is simply the net profit made by the processing plant plus the extra revenue made by the farmers from utilizing the land fully.

For each oilseed this gain can be expressed as:

Economic gain $_{oilseed}$ = *Processing Plant Profit* $_{oilseed}$ + *(1-LandFraction* $_{currently\ utilized}$*)* Crop Profit* $_{oilseed.}$

For the grain ethanol supply chain it is assumed that rather than having most of their grain produce selling at second grade prices in the food industry, the emerging farmers will be able to sell all their grain at first grade market price to biofuel processing plants. Hence the economic gain in this case is the difference of the profit made from selling the grains at market price to the biofuel processing plants and the profit that the emerging farmers usually make from selling the same amount of their grains in the food industry, plus the gain made from fully utilizing the land.

In the case of sweet sorghum it is assumed that in the absence of the biofuel industry, the farmers would only sell the grain in the food industry while the stalk would either be ploughed back into the field or sold as snack at an insignificantly low price. The biofuel industry, therefore, affords the farmers to sell both the grain and the stalk at market prices.

The overall Economic Gain, V(x), combining the biodiesel economic gain and the economic gain from the grain bioethanol supply chain, can thus be expressed in R/ha/yr as:

$$V(x) = \sum_j x_j \begin{bmatrix} y_{biodiesel,j}\left(C_{biodiesel} + \phi_{BP,j} C_{BP,j} - \left(\phi_j C_{market,j} + C_{process,j}\right) + \left(1 - \sigma_{land}\right) P_j\right) \\ + y_{bioethanol,j}\left(\phi_j \left(P_j - \sigma_{land}\left(g_2 P_{2,j} + \left(1 - g_2\right) P_j\right)\right) - \delta_j\right) \end{bmatrix}$$

Where

σ_{land} = Fraction of the underutilized land that is currently being cultivated

P_j = Profit made by farmers from selling crop j at market price [R/tonne]

$P_{2,j}$ = Profit made by farmers from selling crop j at 2nd grade market price [R/tonne]

g_2 = Fraction of emerging farmers' grains (maize & wheat) currently sold as second grade

δ_j = Cost of crop transportation [R/litre].

If the sweet sorghum supply chain is included in the model, the Economic Gain, V(x) becomes:

$$V(x)=\begin{bmatrix}\sum_{j\in B} x_j y_{biodiesel,j}\left(C_{biodiesel}+\phi_{BP,j}C_{BP,j}-\left(\phi_j C_{market,j}+C_{process,j}\right)+\left(1-\sigma_{land}\right)\phi_j P_j\right)+\\ \sum_{j\in S} x_j y_{bioethanol,j}\left(\phi_j\left(P_j-\sigma_{land}\left(g_2 P_{2,j}+\left(1-g_2\right)P_j\right)\right)-\delta_j\right)+\\ x_{s\_sorghum}\, y_{bioethanol,s\_sorghum}\begin{pmatrix}\phi_{s\_sorghum}P_{s-sorghum}-\delta_{s\_sorghum}+\\ \phi_{BP,s\_sorghum}\left(C_{BP,s\_sorghum}-\sigma_{land}P_{BP,s\_sorghum}\right)\end{pmatrix}\end{bmatrix}$$

where "*s_sorghum*" represents sweet sorghum and the selective sets *B* and *S* are defined as

B = {Soybean, Sunflower}

S = {Maize, Wheat}.

$P_{BP,s\_sorghum}$ = Profit made by farmers from selling sweet sorghum grain [R/tonne]

5.3.1.2. Job-creation in Maluti-a-Phofung

The second objective is job creation; defined here as the direct jobs created in the municipality as a result of the biofuels programme. For Maluti-a-phofung the job creation objective, Z(x), can thus be expressed in man-hours/ha/year as:

$$Z(x)=\sum_i\sum_j x_j\left[\left(1-\sigma_{land}\right)\left(h\cdot W_{p\_agr,j}\cdot S_j+L_{t\_agr,j}\right)+y_{ij}\sum_k \gamma_{jk}L_{pro,k}\right]$$

Detailed derivations of both objective functions are shown in Appendix C.

5.3.1.3. DSS Model formulation

The model for Maluti-a-Phofung's biofuel Decision Support System can thus be formulated as follows:

$$\max_x [V(x), Z(x)]$$

Such that:

$\sum_j x_j \leq 1$ | Land availability Constraint |

5.3.2. *Case-study Inventory*

Table 5.1 below shows the values of the various parameters in the model. These values were determined based on literature and personal communications with black emerging farmers in Maluti-a-Phofung (Appendix J).

Table 5. 1: Model parameters for the case study

Parameter	Biofuel supply chain				
	Maize	**Wheat**	**Sweet-sorghum**	**Soybean**	**Sunflower**
δ_j *[R/litre]*	0.67	0.79	2.14	0	0
P_j *[R/tonne]*	594	2712	145	1213	691
$P_{2,j}$ *[R/tonne]*	498	2600	0	0	0
$P_{BP,j}$ *[R/kg]*	0	0	0.50	0	0

In the analysis, the following assumptions were made for the baseline analysis:

- 50% of the agricultural land available for biofuel production in Maluti-a-Phofung is currently utilized
- All of the black emerging farmers' maize and wheat are currently bought at second grade grain prices in the food industry.

5.3.3. *DSS Results and Discussions*

5.3.3.1. Results of baseline scenarios

Table 5.2 presents the maximum economic gain and job creation attainable in Maluti-a-Phofung for the two biofuel production scenarios. These results show that a maximum of R 3,168 can be gained per hectare of currently underutilized land whether sweet sorghum is included in the local biofuel programme or not. In the case of job creation, however, a maximum of 104 man-hours/ha can be achieved by including sweet sorghum in the local biofuel programme while a maximum of only 22 man-hours/ha is achievable in the absence of sweet sorghum. Based on the 38,700 ha of underutilized agricultural land available within the municipal area, the absolute maximum economic gain attainable is of the order of R120 million, while a maximum equivalent of 1,500 and 320 eight-hour jobs can be created with and without sweet sorghum inclusion respectively.

The results also show that that in both scenarios the maxima of the two objectives result only from the bioethanol supply chain; maximum economic gain is achieved by using the land exclusively for wheat production while maximum job creation is attained by putting all the available land under sweet sorghum production, in the all-crops scenario, or maize in the four-crop scenario. It therefore follows that these two maxima cannot be achieved simultaneously in both cases; maximum job-creation can only be achieved by a compromise in economic-gain and vice-versa.

Table 5. 2: Maxima of objective functions

Maximised Objective	**value**	**Hectare fraction**				
		maize	**wheat**	**Sweet sorghum**	**soybean**	**sunflower**
Economic Gain [R/ha]	**3,168**	0	1	0	0	0
Job creation [man-hours/ha]	**104**	0	0	1	0	0
Economic Gain – Four-crop scenario [R/ha]	**3,168**	0	1		0	0
Job creation – Four-crop scenario [man-hours/ha]	**22**	1	0		0	0

Figure 5.4 below presents trade-off curves of the objectives for the two scenarios. The figure shows that if all crops are included in the local biofuels programme the maximum economic gain results in the creation of only 5.9% of the maximum creatable number of jobs, while the maximum job creation achieves a net gain of 65.2% of the maximum possible economic gain.

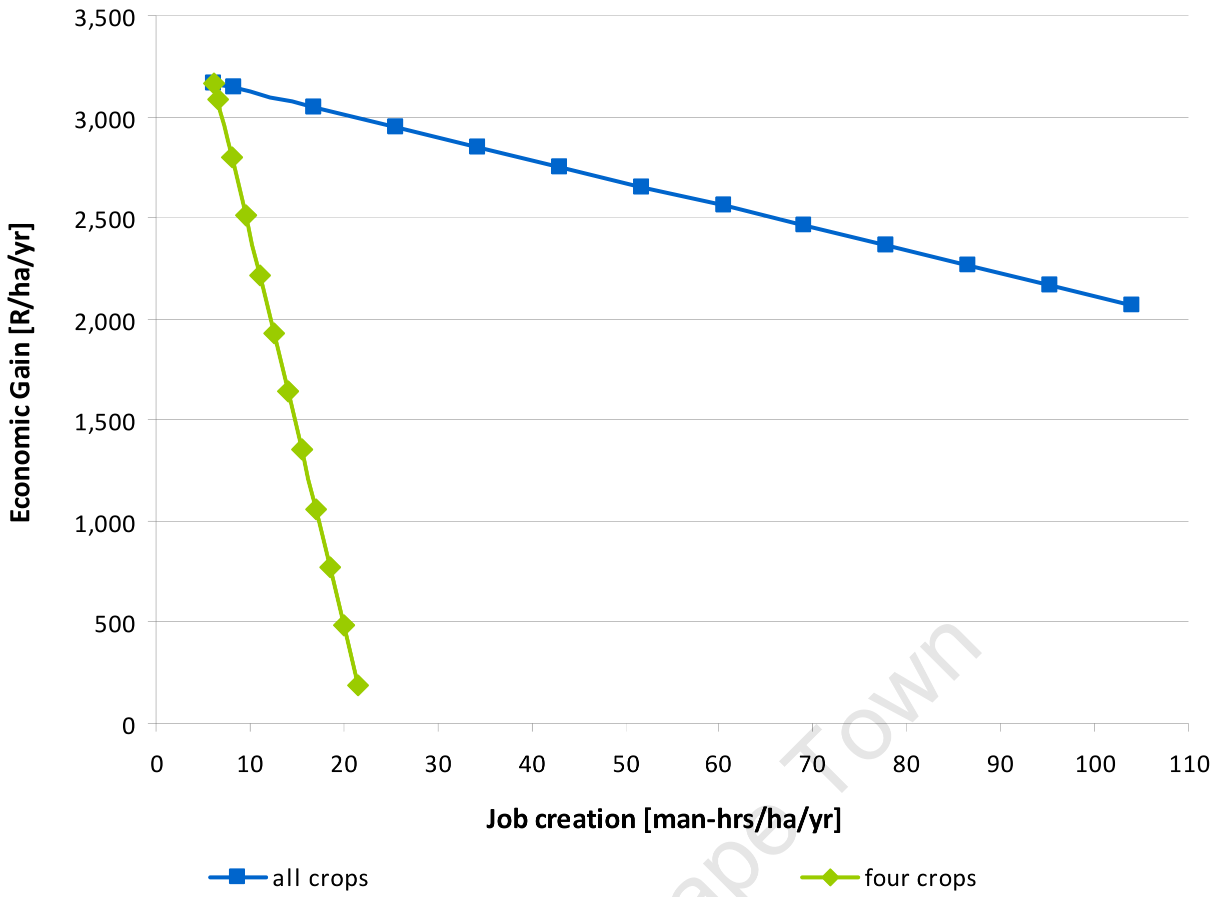


Figure 5. 4: Economic gain and job creation trade-off curve for Maluti-a-Phofung

In the four-crop scenario, however, the maximum economic gain only creates 28.4% of the maximum obtainable jobs, while the maximum job creation results in 6.0% of the maximum attainable economic gain. This means that while 6.1 man-hours of labour are created automatically in both scenarios as economic gain is maximised, any additional man-hour created thereafter comes at a cost of R11.30 and R193.00 to the municipality in the all-crops scenario and in the absence of sweet sorghum respectively.

The crop combinations that result in the Pareto optimal trade-off values of the objectives are shown in Figures 5.5 and 5.6 for the sweet sorghum scenario and the four-crop scenario respectively. These figures simply show that the more wheat is replaced by sweet sorghum, in the all-crops scenario, or maize, in the four-crop scenario, then the more jobs are created and the less economic gain is achieved.

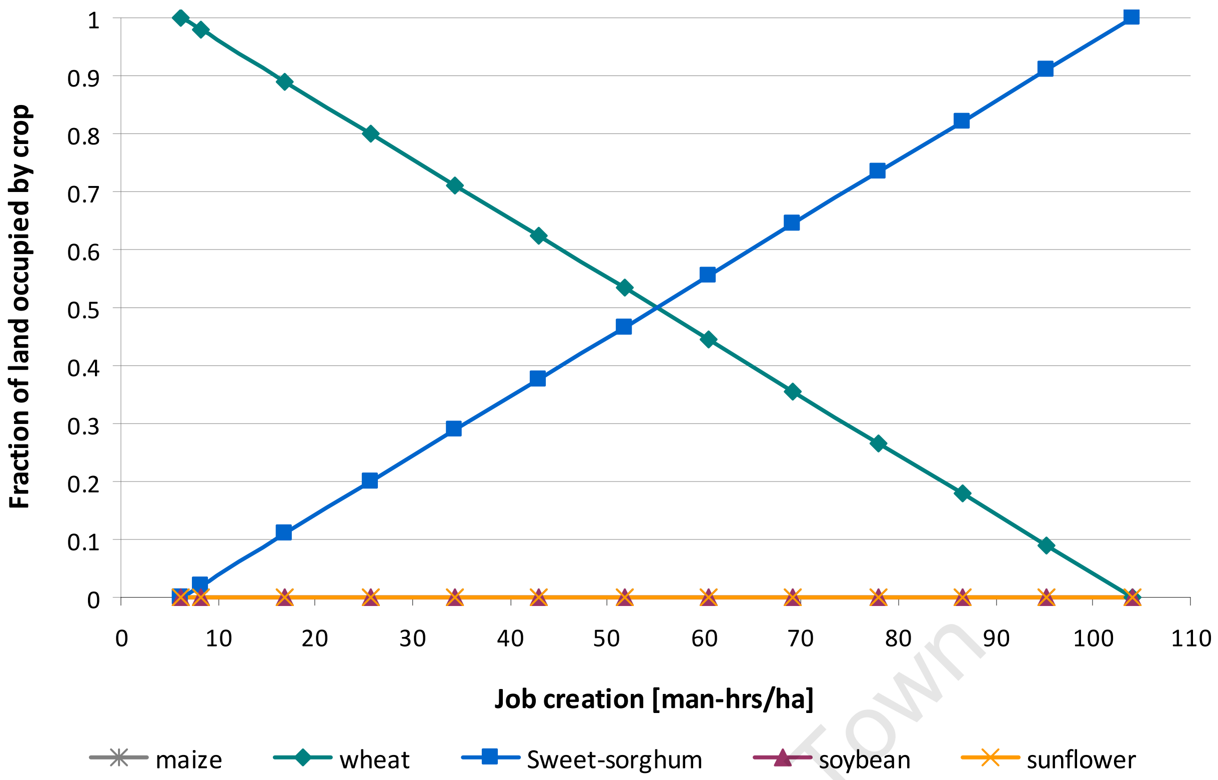


Figure 5. 5: Pareto optimal crop distribution of the all-crops scenario

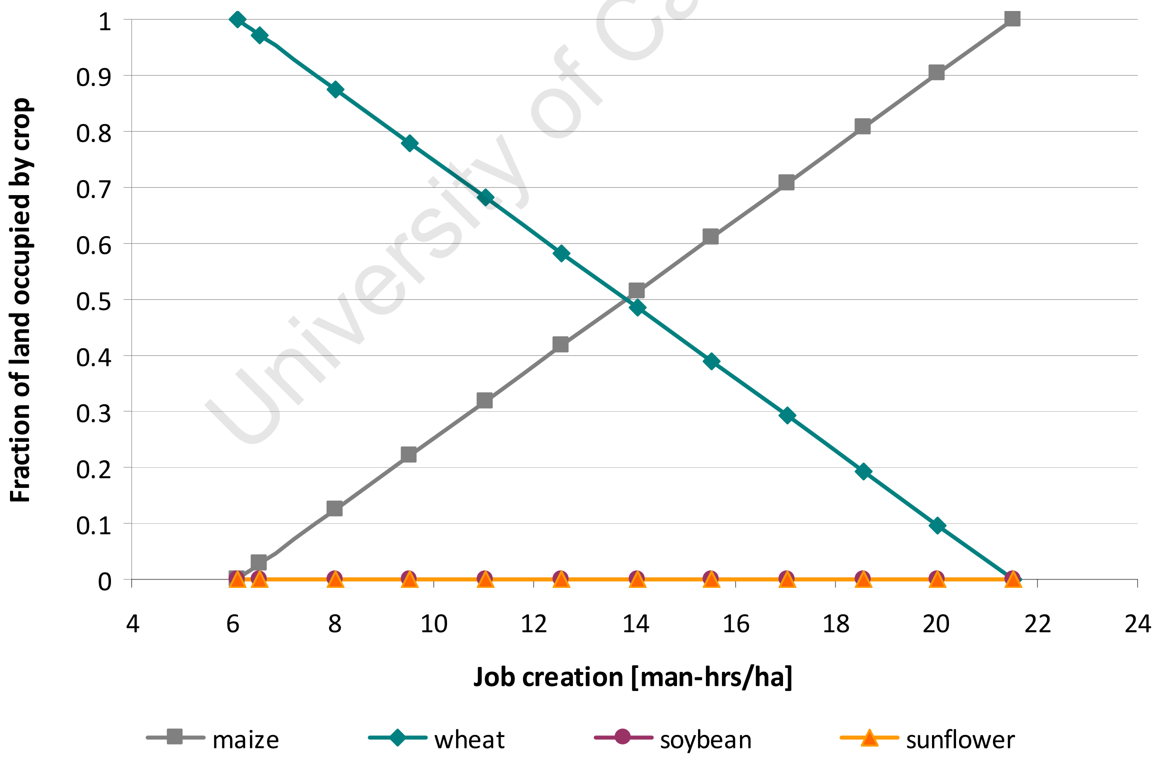


Figure 5. 6: Pareto optimal crop distributions for the four crop scenario

5.3.3.2. Sensitivity analysis

Assumed values of both the fraction of the underutilized land currently in use and the fraction of grain currently sold as second grade were used in the baseline scenarios of this thesis. In this subsection the results are analysed for sensitivity to both of these values. Because of the changing nature of agricultural commodity prices, the sensitivity of the results to changes in these prices is also presented.

Figure 5.7 below shows the sensitivities of the maximum objective values to the fraction of land currently in use for both scenarios. The results show that for both scenarios the maximum values of the objectives are strongly dependant on the fraction of underutilized land currently used; for utilized land fractions between 0.1 and 0.8 the maximum economic gain ranges from R 6,085/ha to R 1,836/ha in the all-crops scenario and from R 6,085/ha to R980/ha in the four-crop scenario. For the same range of unutilized land fractions the maximum job creation ranges from 187 man-hours/ha to 42 man-hours/ha in the all-crops scenario and from 39 man-hours/ha to 9 man-hours/ha in the four-crop scenario.

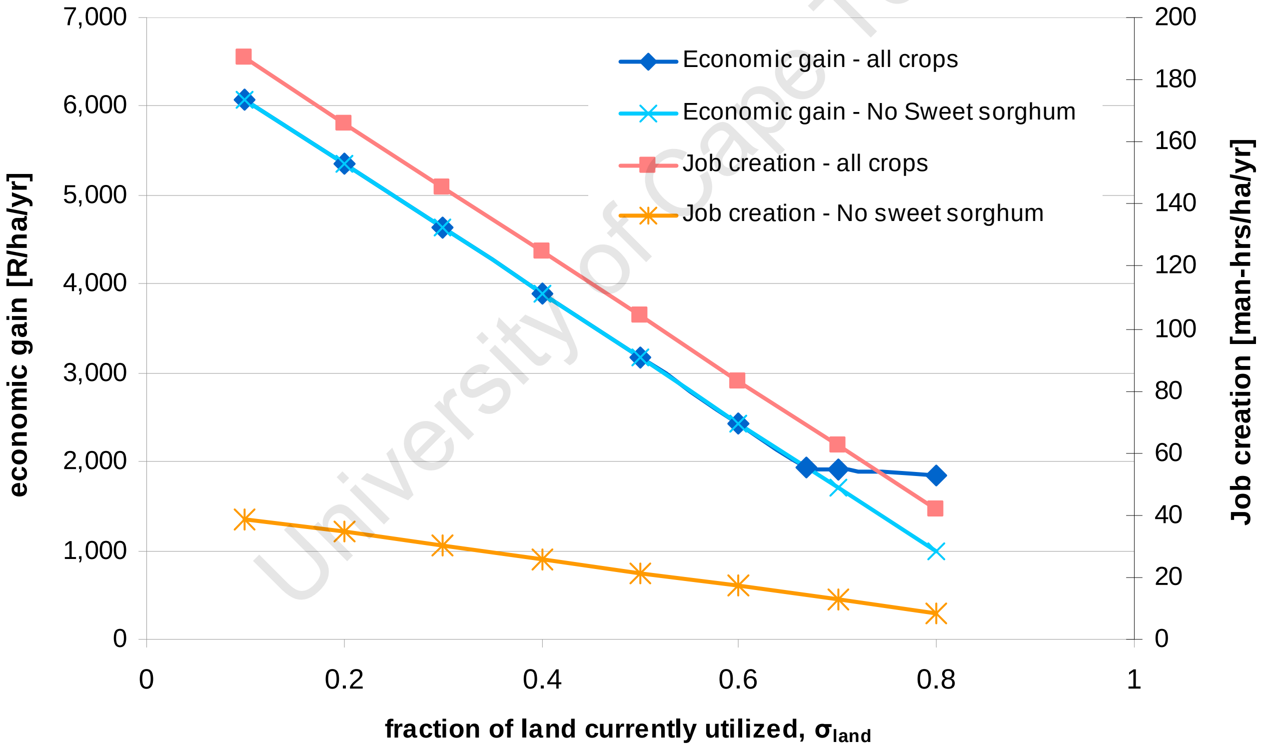


Figure 5. 7: The effect of assumed current land-use fraction on the objectives

Both scenarios show the same decrease of R 729/hectare in the economic gain for every 10% increase in the fraction of land currently utilized from fractions of 0.1 to 0.67. While this sensitivity continues beyond the utilized land fraction of 0.67 in the four-crop scenario, the sensitivity of the all-crops scenario changes to a R 76 /hectare decrease in economic gain for every 10% increase in the underutilized land fraction. This is because at utilized land fractions higher than 0.67 the economic gain achieved by growing sweet sorghum exclusively is larger than that obtained by growing wheat alone; hence the sensitivity observed beyond 0.67 is that of the economic gain from exclusive sweet sorghum production and no longer that of wheat production.

The dependence of the maximum economic gain on the percentage of emerging farmers' grain that is currently sold at second grade prices in the food industry is shown in Figure 5.8 below. The figure shows that a 100% decrease in the percentage of the farmers' grain sold as second grade only results in a 5% decrease in the maximum economic gain. This means that if all of the emerging farmers' grain were to be sold at first grade market prices in the food industry, the maximum economic gain that Maluti-a-Phofung municipality could achieve through biofuels production would only change from R 122.6 million to R 116.5 million per year.

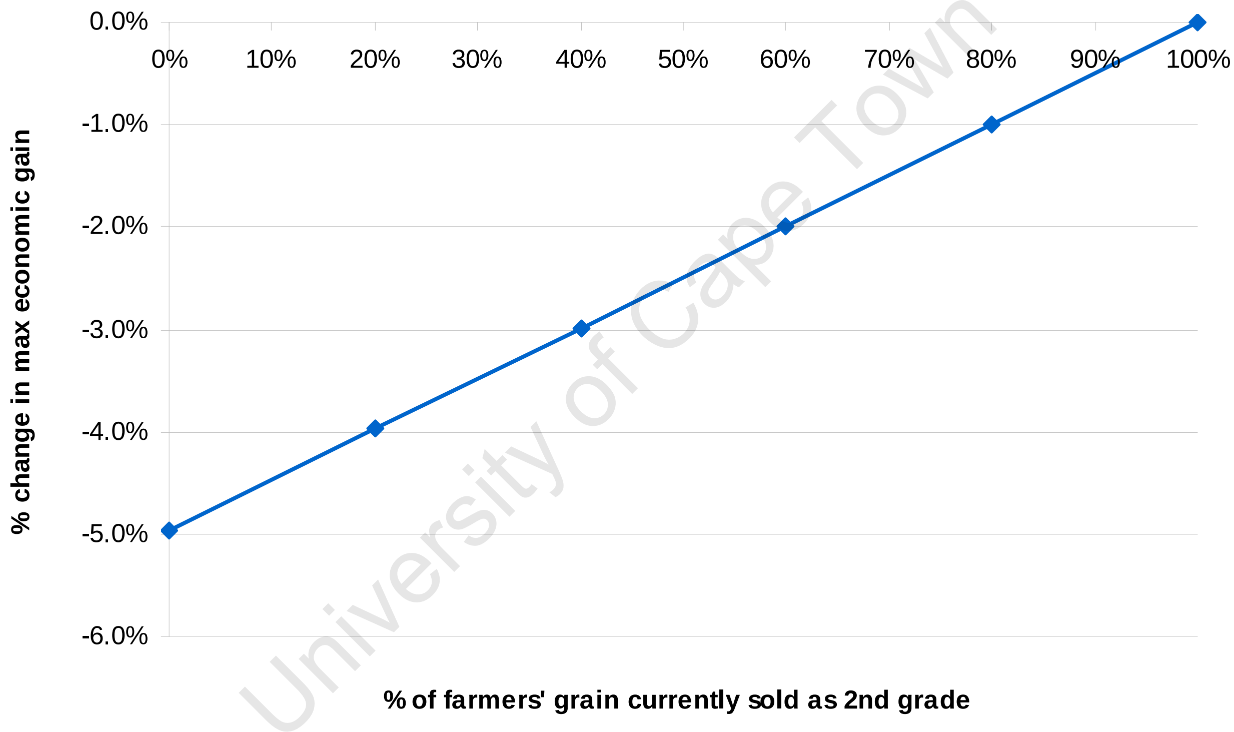


Figure 5. 8: Sensitivity of maximum economic gain to changes in the fraction of grain currently sold as second grade

As with the sensitivity analysis in section 4.3.1.1, the agricultural commodities were grouped into grains, cane and oilseeds for the sensitivity analysis in this subsection.

Only changes in the prices of grains and cane affected the maximum economic gain, while no changes were observed in the maximum economic change as a result of oilseed prices. Figure 5.9 below shows the sensitivity of economic gain to changes in grain and cane prices for the two scenarios. The figure shows that a 1% change in the price of grains results in a corresponding change of 1.7% in the economic gain in the four-crop scenario. In the all-crops scenario the results show that the maximum economic gain is only sensitive to changes in grain prices between 30% and -26%, and any further decrease in grain prices does not have any effect on the economic gain. This is because a 26% decrease in the price of wheat reduces the economic gain to that obtained by growing sweet sorghum exclusively; hence any further decrease in the price of wheat makes it more economical to grow sweet sorghum that it is to grow wheat. The latter effect is also observed when the price of cane increases by more than 17% in the all-crops scenario.

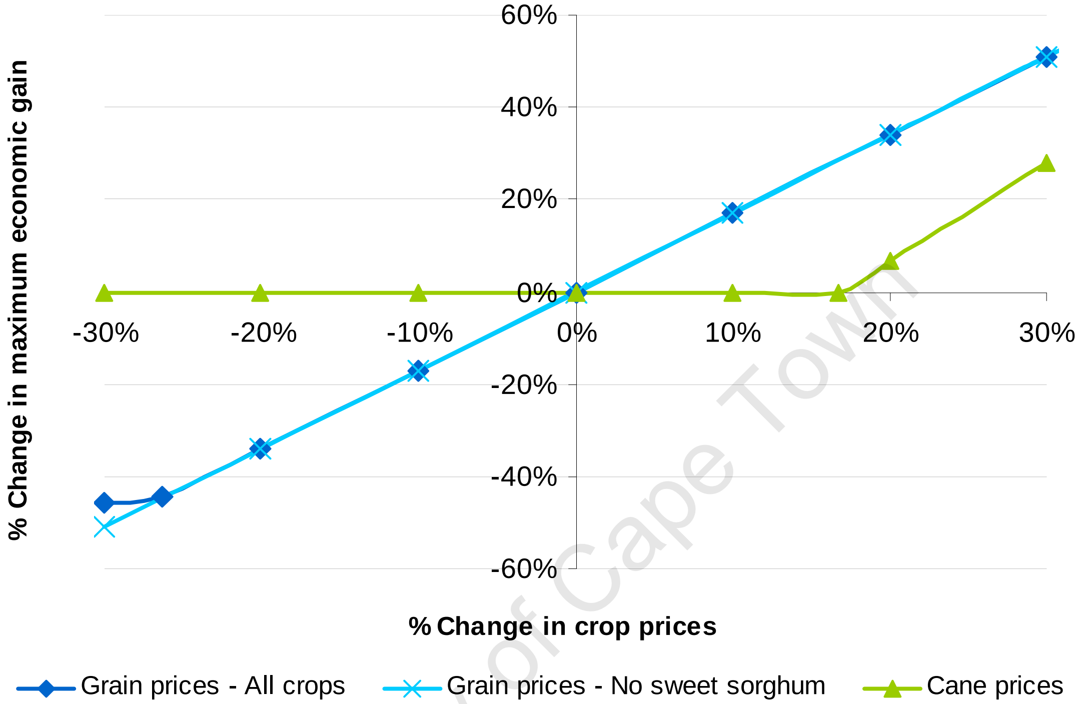


Figure 5. 9: Sensitivity of Economic-gain to changes in commodity prices

5.3.4. Conclusions

The following conclusions can thus be drawn from the case study:

- There are currently about 38,700 hectares of underutilized arable land in Maluti-a-Phofung that can be used for biofuel development in the area. If used efficiently, this land is capable of generating economic revenue ranging between R 7.4 million and R 122.6 million per year, and to create between 237,000 man-hours and 4 million man-hours of agricultural jobs per annum.

- The best biofuel programme in Maluti-a-Phofung requires that only bioethanol energy crops are grown in the underutilized land. Neither a 30% increase in the current oilseed prices nor a 30% decrease in grain and cane prices can make a case for the establishment of a biodiesel plant in Maluti-a-Phofung.

- Of the energy crops currently grown in Maluti-a-Phofung, wheat results in the largest net financial gain for the area while maize creates the largest number of jobs for biofuel production. The inclusion of sweet sorghum in a biofuels programme in Maluti-a-phofung has the potential of creating up to 5 times more jobs in the area than only using the four energy crops familiar to the local farmers.

6. CONCLUSIONS AND RECOMMENDATIONS

This thesis set out to analyse and to compare the land use options offered by different bioenergy crops and technologies available to South Africa for the development of an agriculture-based biofuels industry. In this chapter the findings of the preceding chapters are recalled to determine how well the aims of the study have been met, to draw conclusions in line with the key questions and to make recommendations for further research.

A review of relevant literature revealed that more than half of the global potential of biomass contribution to the energy sector rests in sub-Saharan Africa, and that the extent to which it can be unlocked is greatly dependant on the location, choice of feedstock and method of production. Literature also showed that biofuels are a potential low-carbon energy source, but whether they actually offer the carbon savings depends on how they are produced, and life-cycle assessment methods were found to be the right tools for analysing the sustainability of biofuel supply chains. It was also found that land use change and deforestation for biofuel production strongly influence the success and sustainability of bioenergy systems, and that their effects should always be taken into account in analysing the environmental and social impacts of bioenergy systems from a life-cycle perspective.

The literature review further revealed that while energy modelling can be used to analyse bioenergy systems from an economic viewpoint only and life-cycle assessment tools can be adequately used to analyse their social and environmental aspects, multiobjective optimization is the best method for integrated analysis of all three dimensions.

Chapter 3 then described the system under study in detail, together with the developed multiobjective optimization model. This model simultaneously maximises three objectives; economic gain by the processing plant, direct job creation and greenhouse gas emissions avoided by using the biofuels, all at minimal use of agricultural land. These objectives were chosen as the most outstanding economic, social and environmental objectives respectively for the establishment of a biofuels industry in South Africa.

First presented in chapter 4 are the results of energy balance analyses of the different biofuel supply chains. The results showed that the South African production of maize grain ethanol, wheat grain ethanol, sugarcane ethanol, sweet sorghum ethanol, soybean biodiesel, sunflower biodiesel and canola biodiesel all result in net energy gains. Sugarcane ethanol was found to have the highest effectiveness of biofuel production with a Net Energy Balance of 73 GJ/ha/yr and the highest return on energy input of 3.72, while maize grain ethanol was the poorest in both cases with 6 GJ/ha/yr and 1.20 respectively. The main reason for the poor performance of maize grain ethanol was found to be the large quantities of coal and electricity required for steam generation and DDGS drying during processing.

For both starch-based ethanol and biodiesel, the largest contribution of post-harvest energy inputs is from the fossil energy used in processing the crops, hence the use of renewable energy sources for powering all biofuel plants should be strongly emphasised in future work.

Chapter 4 also presented the environmental effects of land use change for biofuels production. The results showed that bringing land that has not been cultivated for a period of two years to agricultural production results in a carbon debt of about 13,900 kgCO_2/ha, which the biofuels can only repay if their production avoid the emission of greenhouse gases in each subsequent year. In terms of ability to repay this debt, sugarcane ethanol was found to have the highest ability with a repayment period of only 3 years; while maize grain ethanol and sweet sorghum ethanol would not be able repay the debt under the assumptions of this study. In the case of sweet sorghum ethanol, this is due to the assumption of large transport distances associated with the distant location of currently existing sugar mills. The use of sweet sorghum ethanol was found to be able to avoid greenhouse gas emissions only if the sorghum is grown within return transportation distances of 442 km of the processing plant. As in the energy balance analysis, the poor performance by maize grain ethanol here was found to be the fossil energy used in processing, which would have to be replaced by a less greenhouse gas intensive way of providing industrial heat if greenhouse gas emissions are to be avoided.

Presented last in chapter 4 were the results of the multiobjective model. Here scenarios of no targeted national market penetration and a national market penetration target of 2% biodiesel and 8% bioethanol were analysed and the following findings were presented:

- It was found that sugarcane is the most preferable crop for maximising all three objectives wherever it can grow throughout the country, in the absence of a national market penetration target. In the Western Cape areas where sugarcane cannot grow, canola is the most preferred for maximising avoided greenhouse gas emissions and job creation. For maximising economic gain in these areas, however, canola is only better than wheat but it is actually more economical to leave the land uncultivated. In the areas outside the Western Cape where sugarcane cannot grow sweet sorghum is the most preferred for maximizing both economic gain and job creation, while sunflower and canola are the most preferred and second most preferred crops respectively for maximizing avoided greenhouse gas emissions.

- The results further revealed that in the absence of a market penetration target trade-offs are required between avoided greenhouse gas emissions and economic gain or job creation, and these can be achieved by varying the fractions of sweet sorghum, sunflower and canola grown. Under these conditions, an estimated 47 kg of CO_2-eqt emissions are avoided freely per hectare as economic gain and job creation are maximised but any additional kilogram of CO_2-eqt emissions avoided thereafter comes at a cost of R4.50 and 0.2 man-hours.

- In the presence of a national market penetration of 2% biodiesel and 8% bioethanol the three objectives are maximized by three distinct crop combinations. Economic gain is maximized by growing as much sugarcane as possible for ethanol production and as much canola as possible where sugarcane cannot be grown and then supplementing them with maize and sunflower respectively to achieve the required ratio. Job creation is maximised by the same distribution except that sweet sorghum instead of maize supplements sugarcane. Avoided greenhouse gas emissions, on the other hand, is maximized by growing as much sugarcane as possible for ethanol production and then balancing between sunflower for biodiesel production and wheat for ethanol production to achieve the desired proportion. In terms of the quantities of biofuels produced from each hectare, the crop combination that maximises job creation was found to give the highest value, followed by the combination that maximises economic gain.

- These varying crop combinations imply that trade-offs are indeed required between these three objectives. The results showed that the trade-off curve in the presence of a market penetration is essentially made up of three segments; in the first segment the trade-off is between sweet sorghum and maize for ethanol production, in the second segment sunflower and canola compete for biodiesel production whilst in the last segment the trade-off is between sweet sorghum and wheat for ethanol production. It was observed that moving from the first segment to the last increases the greenhouse gas emissions avoided while reducing economic gain and job creation.

- Analysis of the sensitivity of these results to changes in fuel prices, grain prices, cane prices and oilseed prices showed that economic gain in the presence of a national market target is sensitive to changes in all these prices, while in the absence of a market target the economic gain is only sensitive to changes in the first three.

While the qualitative findings of this modelling exercise are believed to be precise, the quantitative results can be improved by using crop yields, agricultural practices and land suitabilities of crops specific to the actual areas, most of which are in the former homelands, where the underutilized land to be used for biofuel production lies.

In chapter 5 was presented a case study of Maluti-a-Phofung where the use of multiobjective optimization modelling for supporting decision-making regarding biofuels, specifically at local government level, was demonstrated. The analysis showed that the area of Maluti-a-Phofung fits all the criteria of the National Industrial Biofuels Strategy of South Africa perfectly, in terms of its history, economic situation and availability of underutilized arable land. Integrated development planning, which is steered by the local municipal office but also involves other stakeholders in Maluti-a-Phofung, was found to be the right tool for deciding the areas' approach in developing a local biofuels programme. The analysis also showed that local economic development and poverty eradication through job creation would be the two major objectives to be achieved by such a programme.

Two scenarios were modelled in this case study; a scenario involving only the four crops familiar to the local farmers, namely maize, wheat, soybean and sunflower (four crop scenario), and a scenario where the farmers are willing to include sweet sorghum in the programme (all crops scenario). A biodiesel plant would be established in the area for biodiesel production while bioethanol crops would be sent to the nearest processing plants outside the bounds of the municipality.

The case study results showed that, in both scenarios, growing wheat for ethanol production would result in maximum financial gain for the municipal area as a whole, while maize and sweet sorghum would result in maximum job creation in the four crop scenario and in the all crops scenario respectively. This confirms the need for tradeoffs between these two objectives, which would involve varying the area fractions of the two crops that maximise the objectives in both scenarios. The trade-off curves also illustrated that while 6.1 man-hours of labour come with maximising economic gain in both scenarios, any additional man-hour created thereafter would come at a cost of R11.30 and R193.00 to the municipality in the all-crops scenario and in the four crop scenario respectively. With all this information available, it would then be up to the decision-makers to pick the scenario and the crop combination that best represent the interests of the people of Maluti-a-Phofung.

6.1. Responding to the key questions

A summary of the answers to the key questions is presented in this section:

- The values of the return on energy input for maize grain ethanol, wheat grain ethanol, sugarcane ethanol, sweet sorghum ethanol, soybean biodiesel, sunflower biodiesel and canola biodiesel are 1.20, 1.32, 3.72, 1.67, 1.66, 1.83 and 1.63 respectively.

- When land that has not been cultivated for a period of two years is suddenly brought to agricultural biofuel production a carbon debt of about 13,900 kgCO_2/ha is created. It would take 80 years, 3 years, 32 years, 21 years and 29 years for wheat grain ethanol, sugarcane ethanol, soybean biodiesel, sunflower biodiesel and canola biodiesel respectively to repay this debt, while maize grain ethanol and sweet sorghum ethanol would not be able repay the debt.

- Sugarcane is the best crop for maximising economic gain, avoided greenhouse gas emissions and job creation wherever it can grow. In areas where it cannot grow, sweet sorghum is the best for maximising economic gain and job creation, while sunflower is the best for maximising avoided emissions.

- Three scenarios maximize benefits of land use for B2 and E8 market penetration: The first scenario involves sugarcane, canola, maize and sunflower; the second scenario involves sugarcane, canola, sweet sorghum and sunflower; the third scenario involves sugarcane, sunflower and wheat.

- All the crop combinations show sensitivity to changes in fuel prices, grain prices and cane price, and no sensitivity to changes in oilseed prices in the absence of a market penetration target. In the presence of a penetration target changes to all the commodity prices influence the optimum crop distributions.

From these findings it can thus be concluded that the objectives of this thesis have been met.

6.2. Recommendations for future work

The following are recommendations arising both from the conclusions in the previous subsection and the thesis as a whole for further research:

- The use of renewable energy sources for powering all biofuel plants should be strongly emphasised in future work

- Crop yields, agricultural practices and land suitabilities of crops specific to the actual areas of the country where the underutilized land to be used for biofuel production lies should be used in the model for a more accurate quantitative analysis

- The objective equations and system boundaries of the national level model be revised to incorporate farm economic benefits as modelled in the case study

- The multiobjective model should be broadened to incorporate other objectives like water usage and plant capital costs which can also influence the choice of energy crops to be grown for biofuel production

- The ability of the meat industry to absorb the oilmeal from the biodiesel processing plant should be incorporated in future work.

7. REFERENCES

AMIGUN, B., MULLER-LANGER, F. & VON BLOTTNITZ, H. (2008) Predicting the costs of biodiesel production in Africa: learning from Germany. *Energy for Sustainble Development,* Volume XII**,** No 1.

AMIGUN, B. & VON BLOTTNITZ, H. (2005) Size Optimization of a Biodiesel Processing Plant. Cape Town, Department of Chemical Engineering, University of Cape Town.

ARC (2008) Cultivar recommendations for the winter rainfall region [online]. Available:http://www.arc.org.za, [Accessed

ARON, J., EBERHARD, A. A. & GANDAR, M. V. (1991) Fuelwood deficits in rural South Africa. *Biomass and Biodiversity,* 1**,** 2.

BACCHIET, P., FEDELI, A. & PAOLI, M. (1992) Biomass production and their use. *Acts of the Congress, Biomass for Energy.* Coltano, Italy. 84-87

BAER, S. G., KITCHEN, D. J., BLAIR, J. M. & RICE, W. (2002) Changes in ecosystem structure and function along a chronosequence of restored grasslands. *Ecological Applications,* 12**,** 6:1688-1701.

BALA, B. K. (1997) Computer modelling of the rural energy system and CO2 emissions for Bangladesh. *Energy,* 22:999-1003.

BALLOD, J. (2008) Personal Communication. Phuthaditjhaba.

BALOLE, T. V. (2001) Strategies to Improve yield and Quality of Sweet Sorghum as a cash Crop for Small Scale Farmers in Botswana. *Department of Plant Production and Soil Science.* Pretoria, University of Pretoria. Doctor of Philosophy,

BANKS, D. I., GRIFFIN, N. J., SHACKLETON, S. E. & MAVRANDONIS, J. M. (1996) Wood supply and demand around two rural settlements in semi-arid savanna, South Africa. *Biomass and Bioenergy,* 11:319-331.

BECKER, J. & BARRY, S. (2006) Optimization of Bioenergy Supply Chains in a South African context. Cape Town, University of Cape Town.

BENDER, M. (1999) Economic Feasibility for Community-Scale Cooperatives for biodiesel. The Land Institute. Website: http://www.landinstitute.org/vnews/display.v/ART/1999/01/18/3e4e6b418401

BERNDES, G., HOOGWIJK, M. & VAN DEN BROEK, R. (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass and Bioenergy,* 25:1-28.

BFAP (2007) Modelling the impacts of macroeconomic variables on the South African biofuel industry. Pretoria.

BODANSKY, D. (2004) International Climate-Efforts Beyond 2012: A survey of approaches. Arlington, Pew Centre on Global Climate Change.

BUCHANAN, G. (2006) Bioeconomic Innovations. IN USDA (Ed.) *Newsroom: Transcripts and Speeches.* http://www.ree.usda.gov/news/speech120406.shtml

BUCHOLTZ, T. S., VOLK, T. A. & LUZADIS, V. A. (2007) A participatory systems approach to modeling social, economic, and ecological components of bioenergy. *Energy Policy,* 35:6084-6094.

BUSINESS TRUST & DPLG (2007) Nodal Economic Profiling Project - Maloti-a-phofung, Free State.

COOPERATIVE EXTENSION SERVICE UK (2008) Sweet Sorghum for Syrup. *New Crop Opportunities Centre newsletter.* Kentucky.

CORMIO, C., DICORATO, M., MINOIA, A. & TROVATO, M. (2003) A regional energy planning methodology including renewable energy sources and environmental constraint. *Renewable and Sustainable Energy,* 7**,** 99-130.

DALZELL, J. M. (2000) *Food industry and the environment in the European Union: practical issuies and cost implications,* Gaithersburg, Aspen Publishers.

DAVIDSON, O. (2006) Energy Policy. IN WINKLER, H. (Ed.) *Energy policies for sustainable development in South Africa: Options for the future.* Cape Town, Energy Research Center, University of Cape Town.

DE BEER, J., WORRELL, E. & BLOCK, K. (1998) *Annual Revision Energy Environment,* 23:123-205.

DE MUSGROVE, A. R. (1984) A linear programming analysis of liquid-fuel production and use options for Australia. *Energy,* 9:281-302.

DEAT (2004) National Spatial Biodiversity Assessment. IN DEAT (Ed.) *Biomes of South Africa.* Pretoria, Department of Environment and Tourism, South Africa. http://soer.deat.gov.za/Themes.aspx?m=268

DEAT (2005) South Africa hails the coming into force of the Kyoto Protocol [online]. Available:http://www.info.gov.za/speeches/2005/05022114151002.htm, [Accessed 01/09/2008]
DELUCCHI, M. A. & LIPMAN, T. (2003) A Lifecycle Emissions Model (LEM): Lifecycle Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity use, Heating and Cooking Fuels, and Materials. Davis, Institute of Transportation Studies, University of California. UCD-ITS-RR-03-17A:
DERMIBAS, A. H. & DERMIBAS, I. (2007) Importance of rural bioenergy for developing countries. *Energy Conversion and Management,* 48:2386-2398.
DME (2003) White Paper on Renewable Energy. Pretoria.
DME (2007) Biofuels Industrial Strategy of the Republic of South Africa. Pretoria.
DME (2008) [online]. Available:http://www.dme.gov.za [Accessed 02/March/2008]
DOA (2006) Trends in the Agricultural Sector. Pretoria.
DOA (2007) Abstract of Agricultural Statistics. Pretoria.
DOPPEGIETER, J. & DU TOIT, J. (1999) National energy modelling initiatives in South Africa. *Journal of energy in South Africa,* 10**,** 1.
EIA (2006) Annual Energy Outlook 2006. Website: http://www.eia.doe.gov/oiaf/aeo/
ELSAYED, M. A., MATTHEWS, R. & MORTIMER, N. D. (2003) Carbon and Energy Balances for a range of Biofuel options. *Report No: B/B6/00784REP/URN 03/836.* Sheffield, Sheffield Hallam University.
ERC (2007) Overview of research focus areas [online]. Available:http:www.erc.uct.ac.za/research.htm, [Accessed 01/June/2007]
ETHANOL AFRICA (2007) Bioethanol Engineering and Technology [online]. Available:http://www.ethanol-africa.com, [Accessed 11/06/2007]
EUCAR (2004) Well-to-wheels analysis of future automotive fuels and powertrains in the European context. IN KODERA, K. (Ed.) *Analysis of allocation methods of bioethanol LCA.* Amsterdam, Leiden University.
EUROPEAN BIOMASS ASSOCIATION (2009) Biomass [online]. Available:http://www.aebiom.org/article.php3?id_article=62, [Accessed 19/03/2009]
FAO-AGLL (2003) Land Suitability Maps for Rainfed Cropping [online]. Available:http://www.fao.org/ag/agl/agll/cropsuit.asp?crop=wwhe&inputlevel=i&search=Display+map+%21, [Accessed 04/02/2008]
FAO (2005) Fertilizer use by crop in South Africa. Rome.
FARGOINE, J., HILL, J., TILMAN, D., POLASKY, S. & HAWTHORNE, P. (2008) Land Clearing and the Biofuel Carbon Debt. *Science,* 319**,** 1235. DOI: 10. 1126/science. 1152747
FERGUSON, A. R. B. (1999) Sugarcane and Energy. Manchester, The Optimum population Trust, UK. http://www.members.aol.com/optjournal/sugar.doc
FERRELL, J. E., WRIGHT, L. L. & TUSKAN, G. A. (1995) Research to develop improved production methods for woody and herbaceous biomass crops. IN JANICK, J. (Ed.) *Perspectives on new crops and new uses.* Alenxandria, VA, ASHS Press.
FPM (2004).
FSSA (2008) Agricultural Lime sales in South Africa, 1994-2007 [online]. Available:http://www.fssa.co.za [Accessed 20/February/2008]
GERMISHUIS, H. (2006) Republic of South Africa Biofuels Annual Report 2006. *Global Agriculture Information.* Pretoria, USDA Foreign Agricultural Service. SF6021:
GNANSOUNOU, E., DAURIUT, A. & WYMAN, C. E. (2005) Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of Northern China. *Bioresource Technology,* 96:985-1002.
GRABOSKI, M. (2002) Fossil Energy Use in the Manufacture of Corn Ethanol. St. Louis, National Corn Growers Association.
GRAIN SA (2007) [online]. Available:http://www.grainsa.co.za, [Accessed 11 June 2007]
GRAIN SA (2008) [online]. Available:http://www.grainsa.co.za [Accessed 29/Feb/2008]
GRASSI, G. (2001) Sweet Sorghum: One of the best food-feed-energy crop. Brussels, Latin America Thematic Network LAMNET.
GROHNHEIT, P. E. (1991) Economic Interpretation of the EFOM model. Butterworth, Heinemann Ltd.
GRUNWALD, M. (2008) The Clean Energy Scam. *Time Magazine.* 171, 15: 26-30
HALL, D. O., ROSILLO-CALLE, F., WILLIAMS, R. H. & WOODS, J. (1993) Biomass for energy supply prospects. IN MARRISON, C. & LARSON, E. (Eds.) *A preliminary Analysis of the biomass Energy production*

potential in Africa in 2025, considering projected land needs for food production. Biomass and Bioenergy. 10, 6: 337-351
HALLAM, L. (2007) Sweet sorghum on trial in Australia [online]. [Accessed
HAMELINEK, C. N. (2004) *Outlook for Advanced Biofuels,* Utrecht, University of Utrecht.
HARDY, M. B., HANEKOM, D. & LANGENHOVEN, W. (2004) Yield and quality of Canola as affected by cultivar and Nitrogen content [online]. Available:http://www.proteinresearch.net [Accessed 08/Feb/2008]
HENNING, D. (1997) MODEST-an energy system optimisation model applicable to local utilities and countries. *Energy,* 22**,** 12:1135-1150.
HILL, J., NELSON, E., TILMAN, D., POLASKY, S. & TIFFANY, D. (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *PNAS,* 103:11206-11210.
HOBBS, B. F. & MEIER, P. (2000) *Energy Decisions and the environment: A guide to the use of Multicriteria Methods,* Massachusetts, USA, Kluwer Academic Publishers.
HOHNE, N. & MOLTMANN, S. (2007) Implications of proposals for future international climate policy after 2012 on Sweden. Germany, Ecofys GmbH.
HOVELIUS, K. & HANSSON, P.-A. (1999) Energy-and exergy analysis of rapeseel oil methyl ester (RME) production under Swedish conditions. *Biomass and Bioenergy,* 17:279-290.
HWANG, C. L. & MASUD, A. (1979) Multiple Objective Decision making Methods and Applications: A state of the art survey. IN MAVROTAS, G. (Ed.) *Generation of efficient solutions in Multiobjective Mathematical programming problems using GAMS: Effective implementation of the e-constraint method.* GAMS. http://www.gams.com
ICRISAT (2006) Sweet Sorghum: Food, Feed, Fodder and Fuel Crop.
IDP (2007) Maluti-a-phofung Local Municipality Integrated Development Plan - 2007/2008 IDP Cycle. Maluti-a-phofung, Free State.
IDP (2008) Maluti-a-phofung Reviewed Integrated Development Plan (IDP) for 2008/2009. Maluti-a-phofung, Free State.
IMCSA (2006) BUSINESS NEWS: Rail infrastructure continues to shrink [online]. Available:http://www.southafrica.info, [Accessed 15th February 2009]
INIYAN, S. & SUMATHY, K. (2000) An optimal renewable energy model for various end-users. *Energy,* 25:563-575.
IPCC (2007) The Physical Science Basis - Contribution of Working Group I to the Fourth Assessment Report of the IPCC. IN IPCC (Ed.) *Climate Change 2007.* www.ipcc.ch
ISO 14041 (1998) Environmental management - Life cycle assessment - Goal and scope definition and Inventory analysis. IN KODERA, K. (Ed.) *Analysis of allocation methods of biofuel LCA.* Amsterdam, Vrije University.
ISO (1997) Environmental management-Life cycle assessment-principles and framework 40140. Geneva, International Standards Organization.
JEBARAJ, S. & INIYAN, S. (2006) A review of energy models. *Renewable and Sustainable Energy Reviews,* 10:281-311.
KALLIVROUSSIS, L., NATSIS, A. & PAPADAKIS, G. (2002) The Energy Balance of Sunflower Production fo Biodiesel in Greece. *Biosystems Engineering,* 81**,** 3:347-354.
KAREKEZI, S. (2001) Renewables in Africa - Meeting the Energy needs of the poor. IN BUCHOLTZ, T. S., VOLK, T. A. & LUZADIS, V. A. (Eds.) *A participatory systems approach to modeling social, economic and ecological components of bioenergy.* Energy Policy. 35, 6084-6094
KASSLER, P. (1994) Energy for development. IN MARRISON, C. & LARSON, E. (Eds.) *A preliminary analysis of the biomass energy production potential in Africa in 2025 considering projected land needs for food production.* Biomass and Bioenergy. 10, 5: 337-351
KHOSA, T. (2007) Farmer enjoys sweet fruits of her labour. *City Press.*
KIMMINS, J. P. (1997) Predicting sustainability of forest bioenergy production in the face of changing paradigms. *Biomass and Bioenergy,* 13:201-212.
KUMAR, A., BHATTAHARYA, S. C. & PHAM, H. L. (2002) Greenhouse gas mitigation potential of biomas energy technologies in Vietnam using the long range energy alternative planning system model. *Energy,* 28:627-654.
KUMAR, S. (2008) Southern Online Bio Technologies Ltd. [online]. Available:www. sol.net.in [Accessed
KWAJA LOUNGE SUITS (2008) Personal Communication. Phuthaditjhaba.

LANGTON, M. I. (2004) Methods and Techniques of sugarcane harvesting. *School of Bioresources Engineering and Environmental Hydrology.* Pietermaritzburg, University of Natal. Bachelor of Science in Agriculture,

LEHTILA, A. & PIRILA, P. (1996) Reducing energy related emissions: using an energy systems optimization model to support policy planning in Finland. *Energy Policy,* 24:805-819.

LEMMER, W. (2006) Bio-Ethanol Production in the Western Cape: Value Adding to Winter Cereal through Ethanol, DDGS and CO2-production. Elsenburgh, Department of Agriculture: Western Cape.

LEPATI, M. (2008) Personal Communication. Local farmer, Phuthaditjhaba

LETETE, T. & GUMA, M. (2008) Energy Research Centre website information report. Cape Town, Energy Research Centre, University of Cape Town.

LIM, Y. I., FLOQUET, P. & JOULIA, X. (1999) Multiobjective Optimization in Terms of Economics and Potential Environment Impact for Process Design and Analysis in a Chemical Simulator. *Ind. Eng. Chem. Res.,* 38:4729-4741.

MACAPHASA, L. (2008) Personal Communication. Phuthaditjhaba.

MACEDO, I. C., SEABRA, J. E. A. & SILVA, J. E. A. R. (2008) Greenhouse gases emissions in the production and use of ethanol from sugarcane in Brazil. *Biomass and Bioenergy*. http://dx.doi.org/10.1016/j.biombioe.2007.12.006

MACEDO, I. D. C. (1997) Greenhouse Gas Emissions and Energy Balances in Bio-ethanol Production and utilization in Brazil. *Biomass and Bioenergy,* 14**,** 1:77-81.

MAJAKE, P. (2008) Personal Communication. Phuthaditjhaba, Thabo Mofutsanyana agricultural office.

MAKOELE, L. (2008) Personal Communication. Phuthaditjhaba.

MARRISON, C. I. & LARSON, E. D. (1996) A preliminary Analysis of the biomass Energy production potential in Africa in 2025, considering projected land needs for food production. *Biomass and Bioenergy,* 10**,** 6:337-351.

MAVROTAS, G. (2007) Generation of efficient solutions in Multiobjective Mathematical Programming problems using GAMS: Effective implementation of the e-constraint method. Website: http://www.gams.com/

MCLAUGHLIN, S., BOUTON, J., BRANSBY, D., CONGER, B., OCUMPAUGH, W., PARRISH, D., TALIAFERRO, C., VOGEL, K. & WULLSCHLEGER, S. (1999) Developing switchgrass as a bioenergy crop. IN JANICK, J. (Ed.) *Perspectives on new crops and new uses.* Alenxandria, VA, ASHS Press.

MCLAUGHLIN, S. & WALSH, M. E. (1998) Evaluating Environmental Consequences of Producing herbaceous Crops for Bioenergy. *Biomass and Bioenergy,* 14**,** 4:317-324.

MESSNER, S. & SCHRATTENHOLZER, L. (2000) MESSAGE-MACRO: Linking energy supply model with a macroeconomic module and solving it iteratively. *Energy,* 25:267-282.

MEYERS, A. (2008) Personal Communication. Phuthaditjaba, Thabo Mofutsanyana district agricultural office.

MILLER, S. C. (2005) Overdue for a Paradigm Shift [online]. Available:http://bioconversion.blogspot.com/2005_08_01_archive.html, [Accessed 04/05/2007]

MITTELBACH, M. & REMSCHMIDT, C. (2004) Biodiesel - The Comprehensive Handbook. IN STEPHENSON, A. (Ed.) *The Sustainability of Biofuels using life cycle analysis techniques.* Cambridge, university of Cambridge.

MOLOI, S. (2008) Personal Communication. Phuthaditjhaba.

MONTI, A. & VENTURI, G. (2003) Comparison of the energy performance of fibre sorghum, sweet sorghum and wheat monocultures in northern Italy. *European Journal of Agronomy,* 19:35-43.

MOTHEKHE, M. (2008) Personal Communication. Phuthaditjhaba, Maluti-a-Phofung Municipal IDP office.

MUNASINGHE, M. (2007) *Making Development More Sustainable: Sustainomics Framework and Practical Applications,* Colombo 5, Sri Lanka, Munasinghe Institute for Development Press.

MUNICIPAL DEMARCATION BOARD (2008) Maluti a phofung local municipality (FS194). www.demarcation.org.za

MURRAY, N. (2008) Personal Communication. Cape Town.

NAGEL, J. (2000) Determination of an economic energy supply structure based on biomass using mixed-integer linear optimization model. *Ecological Engineering,* 16:91-102.

NAKATA, T. (2004) Energy economic models and the environment. *Progress in Energy and Combustion Science,* 30:417-475.

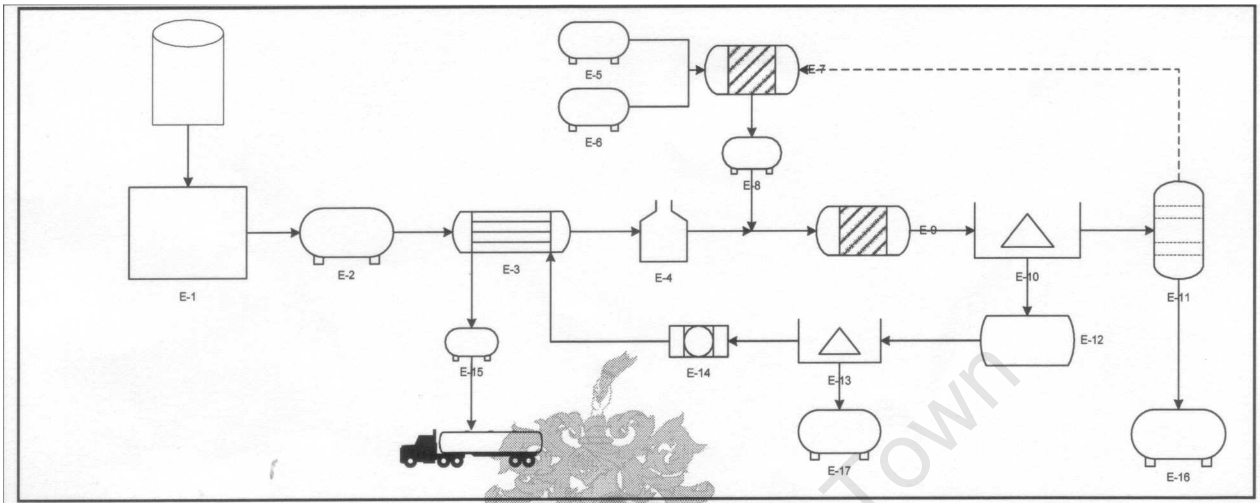
NATIONAL BIOFUELS STUDY (2006) An Investigation into the Feasibility of Establishing a Biofuels Industry in the Republic of South Africa.
NATIONAL BIOFUELS TASK TEAM (2006) National Biofuels Study: An Investigation into the Feasibility of Establishing a Biofuels Industry in the Republic of South Africa. Pretoria.
NEL, A. A. (2001) Determinants of sunflower seed quality for processing. *Department of Plant Production and Soil Science.* Pretoria, University of Pretoria. PhD in Plant Production: Agronomy,
NGUYEN, M. H. & PRINCE, R. G. H. (1996) A simple rule for Bioenergy conversion plant size optimization: Bioethanol from sugarcane and sweet sorghum. *Biomass and Bioenergy,* 10**,** 5/6:361-365.
NOLTE, M. (2007) Commercial Biodiesel Production in South Africa: A preliminary economic feasibility study. *Department of Chemical Engineering.* Stellenbosch, University of Stellenbosch. Master of Science in Engineering,
NTHOLENG, T. (2008) Personal Communication. Phuthaditjhaba.
OFFICE OF ENERGY EFFICIENCY (2008) Bison Transport - Winnipeg, Manitoba. IN COSTKILLER.NET (Ed.) *Bison Transport - Winnipeg, Manitoba.* Canada. http://costkiller.net/tribune/cost-saving-tips-bison-transport.htm
OMETTO, A. R., ROMA, W. N. L. & ORTEGA, E. (2004) Emergy Life Cycle Assessment of fuel ethanol in Brazil. IN ORTEGA, E. & ULGIATI, S. (Eds.) *IV Biennial International Workshop "Advances in Energy Studies".* Unicamp, Campinas, Brazil. 389-399
PRASAD, G. & VISAGIE, E. (2005) Renewable energy technologies for poverty alleviation: Initial assessment report-South Afria. *RET-GNESD.* Cape Town, Energy Research Centre.
PROTEIN RESEARCH FOUNDATION (2008) Price averages: Canola and lupins [online]. [Accessed
RAGAUSKAS, A. J., WILLIAMS, C. K., DAVIDSON, B. H., BRITOVSEK, G., CAIRNEY, J., ECKERT, C. A., FREDERICK, W. J. J., HALLET, J. P., LEAK, D. J., LIOTTA, C. L., MIELENZ, J. R., MURPHY, R., TEMPLER, R. & TSCHAPLINSKI, T. (2006) The Path Forward for Biofuels and Biomaterials. *Science,* 311**,** 5760:484-489.
REDDY, B. V. S. (2007) Ethanol from Sweet sorghum does not compromise food security [online]. Available:http://www.scienceinafrica.co.za, [Accessed 10 July 2007]
RICHARDS, I. R. (2000) Energy balances in the growth of oilseed rape for biodiesel and of wheat for bioethanol. *Levington Agriculture Report.* Ipswich, BABFO.
ROOS, A. & RAKOS, C. (2000) The limits of modelling. Experiences with bioenergy in practice-could models have predicted this outcome. *Biomass and Bioenergy,* 18:331-340.
S&T2 CONSULTANTS INC. (2003) Addition of Wheat Ethanol to GHGenius. IN KODERA, K. (Ed.) *Analysis of Allocation methods of bioethanol LCA.* Amsterdam, Vrije University.
SASA (2008) [online]. Available:http://www.sugar.org.za, [Accessed 02 Februrary 2008]
SCHALKWYK, M. (2008) Government outlines vision, strategic direction and framework for climate change policy [online]. Available:http://www.info.gov.za/speeches/2008/08072816451001.htm, [Accessed 23/03/2009]
SCHOEMAN, J. L. & VAN DER WALT, M. (2006) Overview of land Suitability for biofuel crops. Pretoria, Agricultural Research Council.
SEARCHINGER, T., HEIMLICH, R., HOUGHTON, R. A., DONG, F., ELOBEID, A., FABIOSA, J., TOKGOZ, S., HAYES, D. & YU, T.-H. (2008) Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-use Change. *Science,* 319**,** 1238. DOI: 10.1126/Science. 1151861
SHAPOURI, H. & GALLAGHER, P. (2005) USDA's 2002 Ethanol Cost-of-Production Survery. IN USDA (Ed.) *Agricultural Economic Report.*
SHEEHAN, J., CAMOBRECO, V., DUFFIELD, J., GRABOSKI, M. & SHAPOURI, H. (1998) Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. Colorado, U. S. D. A and U. S. D. E.
SHURSON, J., SPIEHS, M., WHITNEY, M. & KNOTT, J. (2004) Nutritional and value added benefits of feeding maize DDGS or other dry-mill co-products to swine.
SMEETS, M. W., FAAIJ, A. P. C., LEWANDOWSKI, I. M. & TURKENBURG, W. C. (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science,* 33:56-106.
SNYMAN, H. A. (2005) Short-term influence of fire in a semi-arid grassland on (2): Root distribution, seasonal root production and root / shoot ratio. *Grassroots: Newsletter of the Grassland Society of South Africa.* Vol. 5, No. 3:
SOSULSKI, K. & SOSULSKI, F. W. (1993) Enzyme-Aided vs. Two-Stage processing of Canola: Technology, Product Quality and Cost Evaluation. *Journal of American Oil Chemists' Society,* 70**,** 9:825-829.

STATSSA (2005) Abstract of Agricultural Statistics 2004. Pretoria.
STEPHENSON, A. (2007) The Sustainability of biofuels using Life Cycle Analysis techniques. *Chemical Engineering Department.* Cambridge, University of Cambridge. Certificate of postgraduate study, 101
STEUER, R. E. & SUN, M. (1995) The Parameter of space investigation method of multiple objective nonlinear programming: A computation investigation. IN LIM, Y. I., FLOQUET, P. & JOULIA, X. (Eds.) *Multiobjective optimization in Terms of Economics and potential environment impact for process design and analysis in a chemical simulator.* Ind. Eng. Chem. Res. 38,
TAURUS AND TAMASA FURNUTURE (2008) Personal Communication. Phuthaditjhaba.
TESFAMARIAM, E. H. (2004) Modelling the soil water balance of canola Brassica napus L (Hyola 60). *Department of Plant Production and Soil Science.* Pretoria, University of Pretoria. MSc (Agric) in irrigation,
THABO MOFUTSANYANA DISTRICT DOA (2008) Municipality Land Distribution. Maloti-a-phofung, Free State.
THAMAHANE, M. & NHLAPHO, S. (2008) Personal Communication. Phuthaditjhaba, Maluti-a-phofung LED Municipal office.
THEKA, E. (2002) A life cycle assessment of ethanol produced from sugarcane molasses. *Department of Chemical Engineering.* Cape Town, University of Cape Town. MSc, 115
TILMAN, D., HILL, J. & LEHMAN, C. (2006) Carbon-Negative Biofuels from Low-Input High-Diversity Grassland Biomass. *Science,* 314**,** 1598. DOI: 10. 1126/science. 1133306
TNAU (2007) Sweet Sorghum Production Technology. Coimbatore.
TSENG, P., LEE, J. & FRILEY, P. (2005) A hydrogen economy: Opportunities and challenges. *Energy,* 30**,** 3:6-13.
TYLUTKI, T. P. (2006) Distillers grains in cattle diets: Opportunity or challenges. *Matrix: magazine of the Animal Feed Manufacturers Association.* 15, 4: 18-25
UGARTE, D. L. T. (2005) The Contribution of Bioenergy to a New Energy Paradigm. *EuroChoices,* 4**,** 3:06-13.
UNCTAD (2008) Biofuel production technologies: status, prospects and implications for trade and development. Geneva, United Nations.
VIGON, B. W., TOLLE, D. A., CORNABY, B. W., C, L. H., HARRISON, C. L., BOGUSKI, T. L., HUNT, R. G. & SELLERS, J. D. (1993) Life-cycle Assessment inventory guidelines and principles. Cincinnati, U.S. Environmental Protection Agency. EPA/600/R-92/245:
VON BLOTTNITZ, H. & CURRAN, M. A. (2007) A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. *Journal of Cleaner production,* 15**,** 607-619.
WEST, T. O. & MARLAND, G. (2002) A Synthesis of carbon sequestration, carbon emission, and net carbon flux in agriculture: comparing tillage practices in the United States. *Agriculture, Ecosystems and Environment,* 91:217-232.
WIENESE, A. (1999) Co-generation in the South African sugar Industry. *Processing South African Sugar Technology Association* 73.
WIENESE, A. & PURCHASE, B. S. (2004) Renewable Energy: An opportunity for the South African Sugar Industry? *Processing South African Sugar Technology Association,* 78.
WILLIAMS, R. H. (1995) The prospects for renewable energy. *Siemens Review.* Erlangen, MCD Verlag.
WORLD ENERGY COUNCIL (2007) Global Energy scenarios to 2050 and beyond. Website: http://www.worldenergy.org/wec-geis/edc/scenario.asp
Climate Analysis Indicators Tool (CAIT), Excel version 3.0.WORLD RESOURCES INSTITUTE (2005). Washington DC. Available: http://cait.wri.org
WRIGHT, L. L. (1994) Production status of woody and herbaceous crops. *Biomass and Bioenergy,* 6:191-209.
YAMAMOTO, H., YAMAJI, K. & FUJINO, J. (2000) Scenario analysis of bioenergy resources and CO2 emissions with a global land use and energy model. *Applied Energy,* 66:325-337.

APPENDICES

APPENDIX A: Biodiesel Processing plant description

Figure A1 below shows a flow diagram of the biodiesel processing plant used in this thesis. This plant consists of a 20ton/hr hexane extractor, a containerized plant, a glycerol purifier and storage tanks for additional feedstock and product.



SEBP Plant: Equipment List

E1	Hexane extractor	E10	Centrifuge (contaminated biodiesel & crude glycerol)
E2	External Crude vegetable oil storage	E11	BK-95 glycerol purifier
E3	Heat Exchanger 35°C	E12	Continuous dry wash system
E4	Burner 60°C	E13	Centrifuge (biodiesel & magnesium waste)
E5	KOH storage	E14	Filter
E6	Methanol storage	E15	Biodiesel buffer storage
E7	Methoxide reactor	E16	External glycerol Storage
E8	Methoxide storage	E17	External magnesium waste storage
E9	Transesterfication reactor (continuous)		

Figure A1: Biodiesel processing plant flow diagram (Nolte, 2007)

APPENDIX B: Country Maps

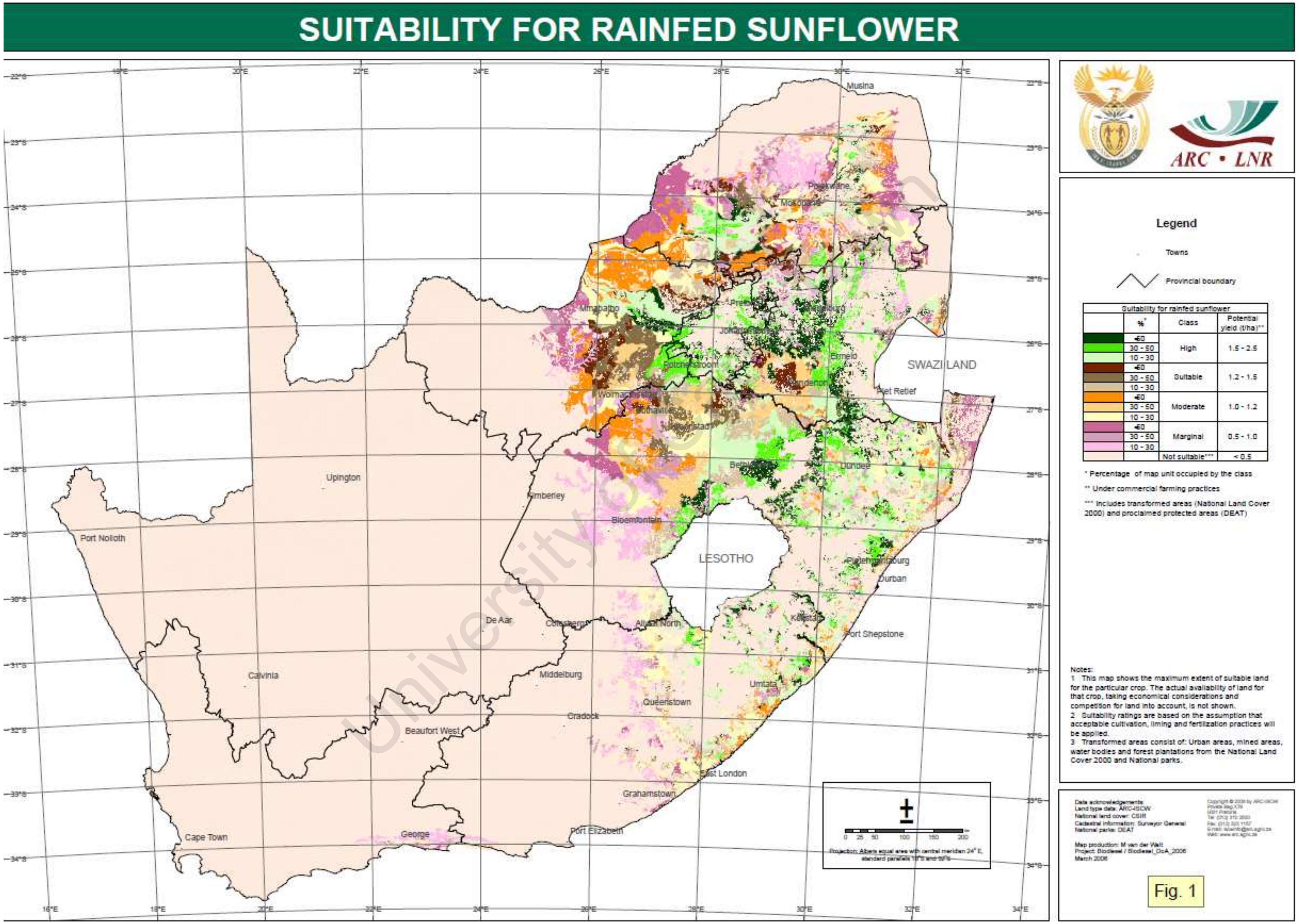


Figure A2: Land suitability for rainfed sunflower (Schoeman and van der Walt, 2006)

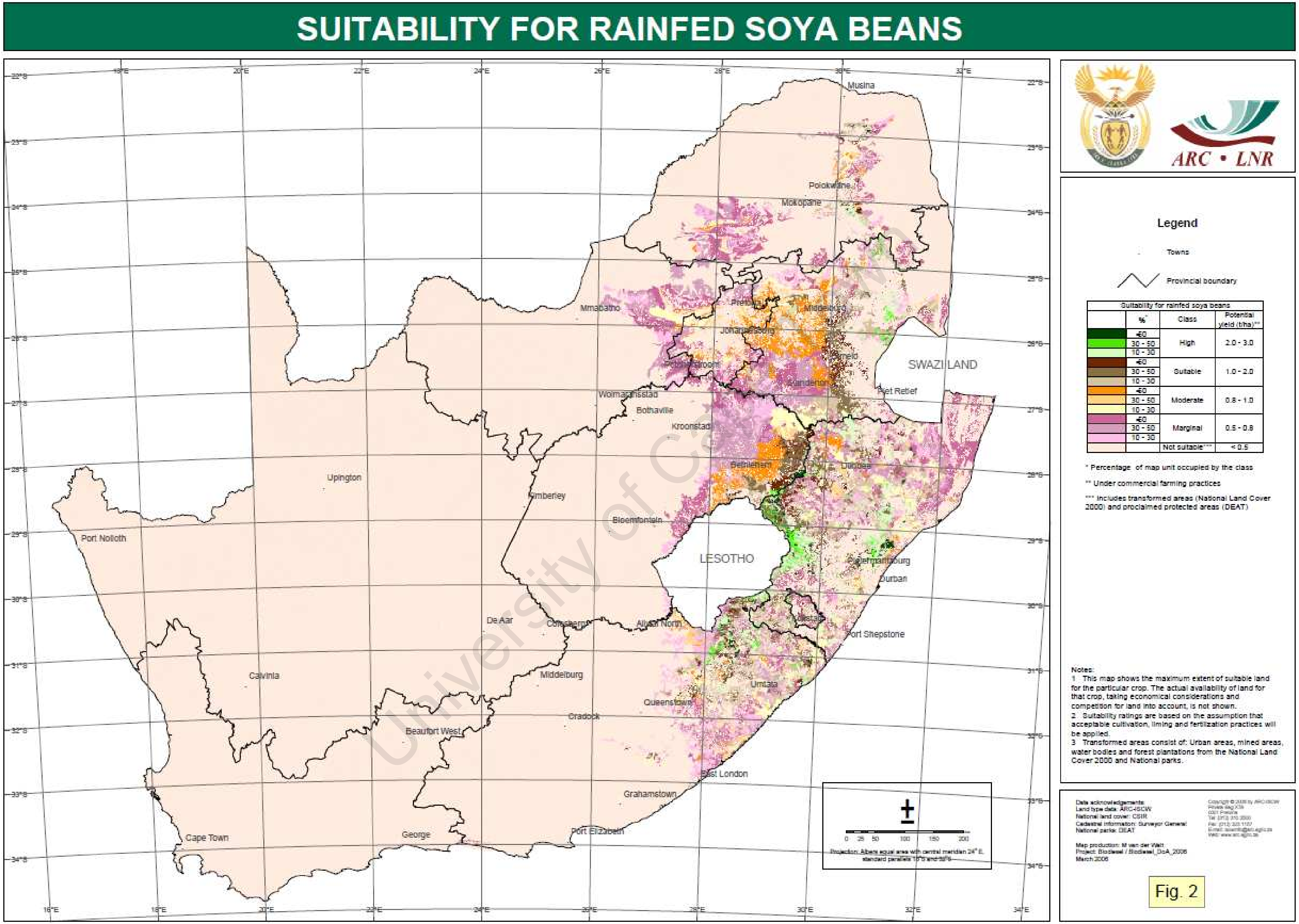


Figure A3: Area suitability of rainfed soybean (Schoeman and van der Walt, 2006)

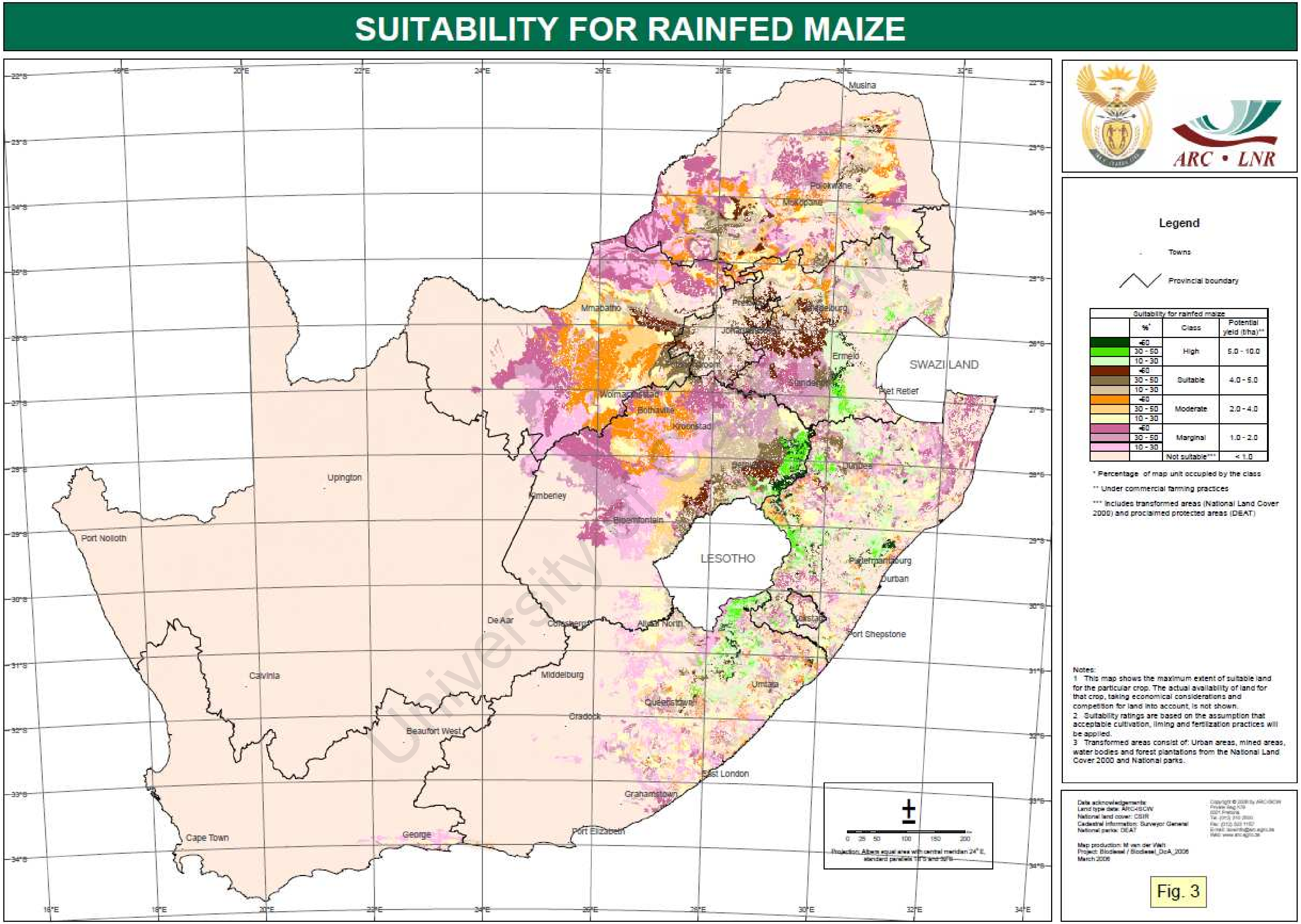


Figure A4: Area suitability of rainfed maize (Schoeman and van der Walt, 2006)

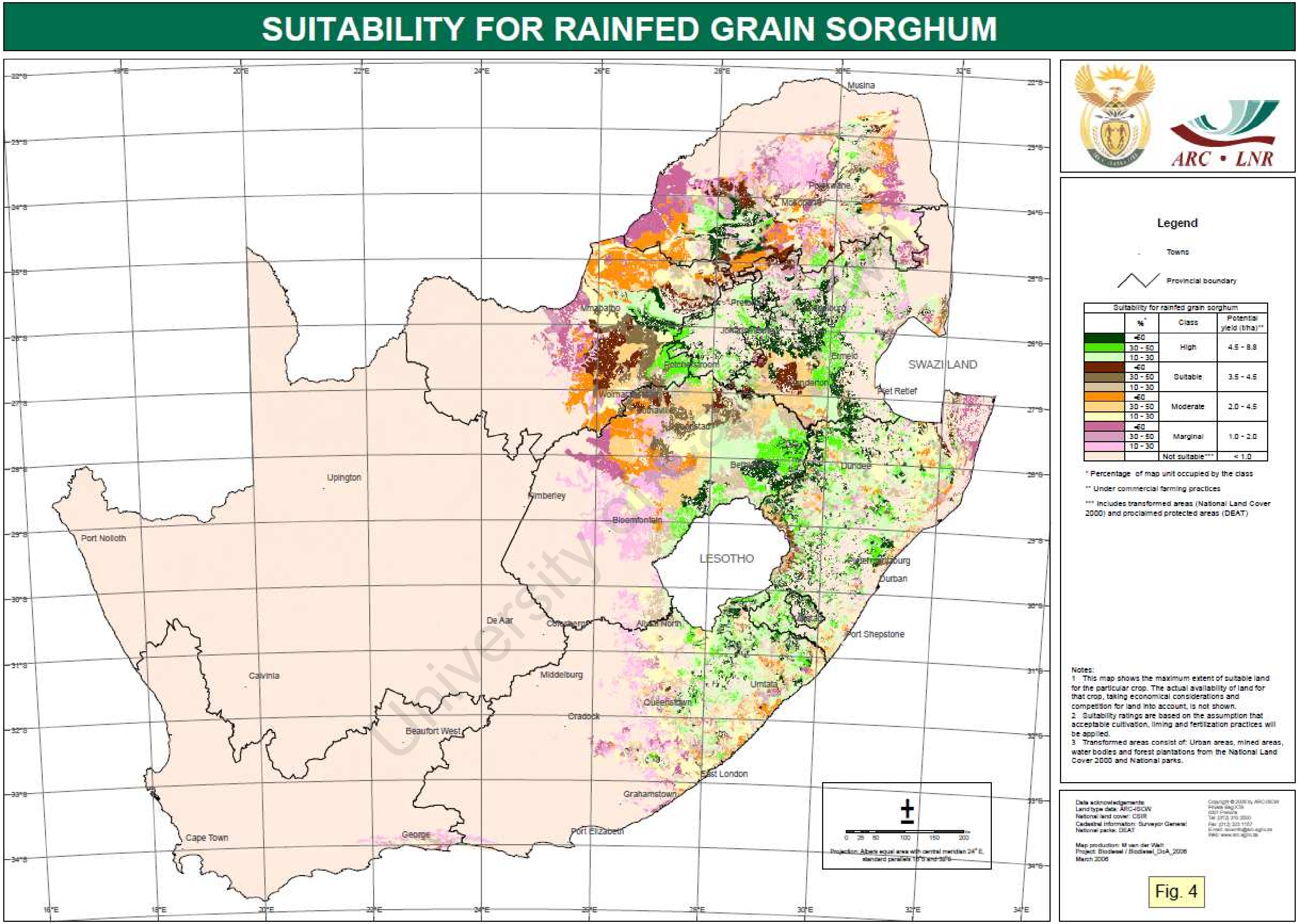


Figure A5: Area suitability of sorghums (Schoeman and van der Walt, 2006)

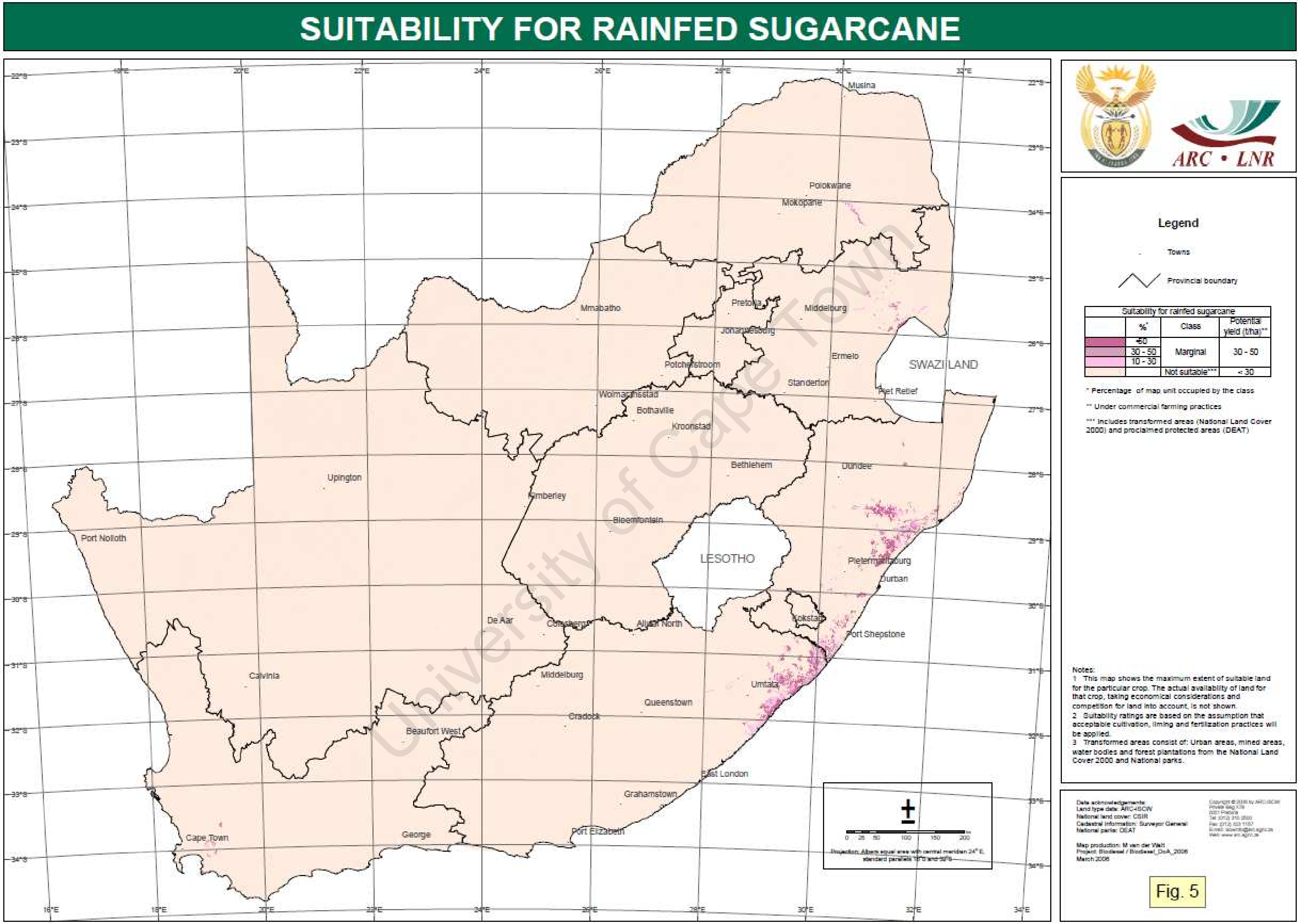


Figure A6: Area suitability of rainfed sugarcane (Schoeman and van der Walt, 2006)

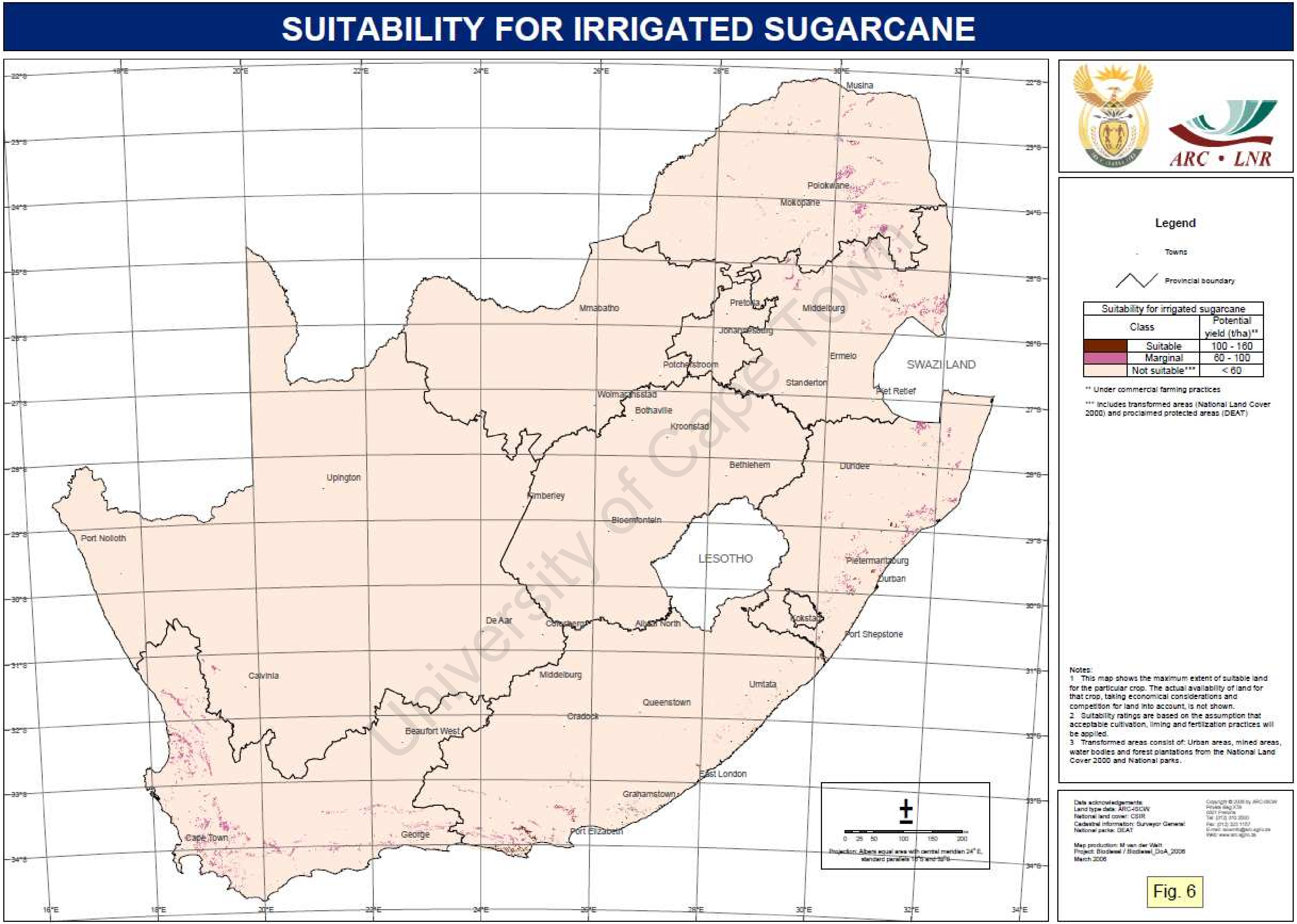


Figure A7: Area suitability of irrigated sugarcane (Schoeman and van der Walt, 2006)

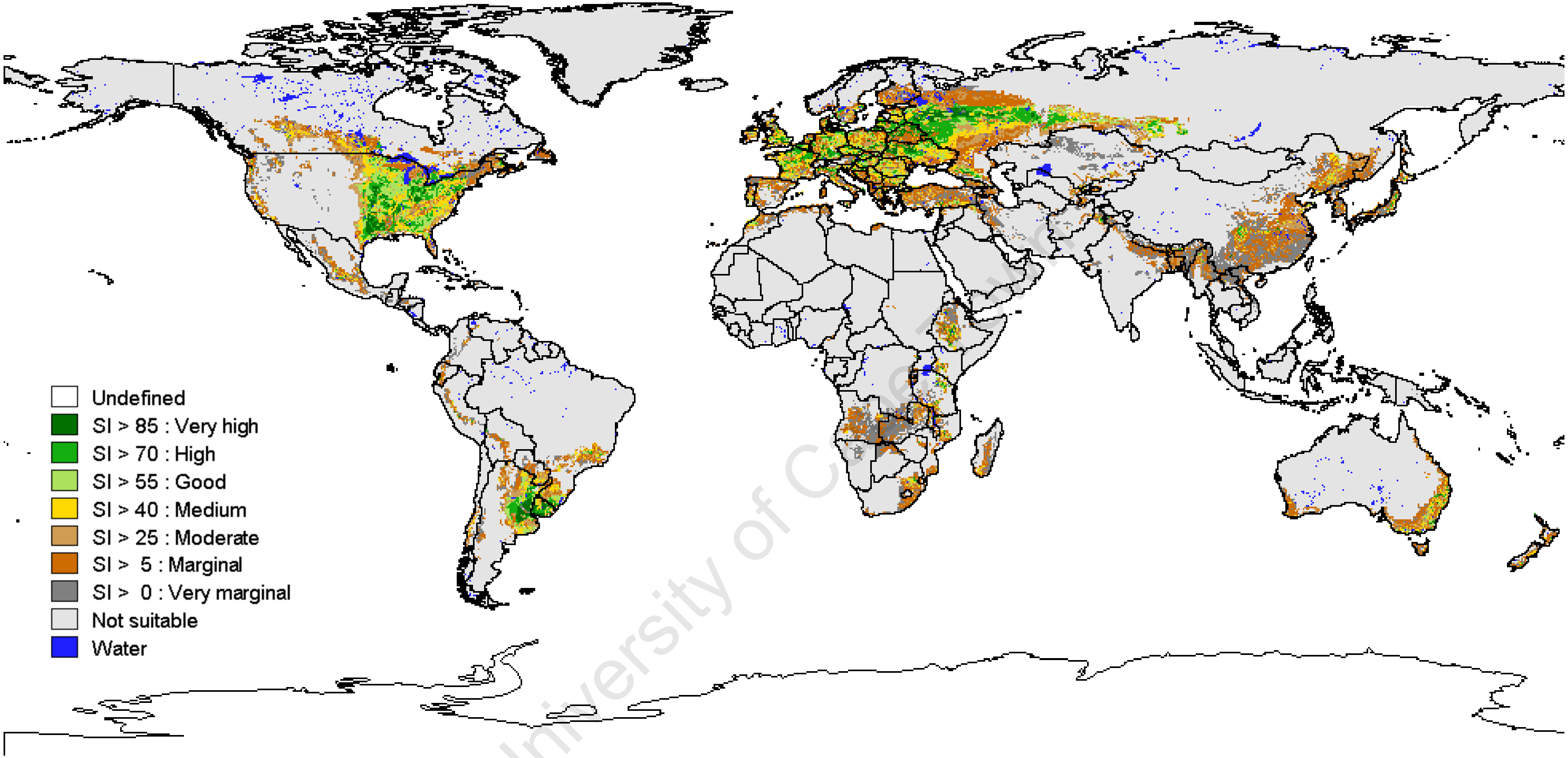


Figure A8: Area suitability of rainfed wheat (FAO-AGLL, 2003)

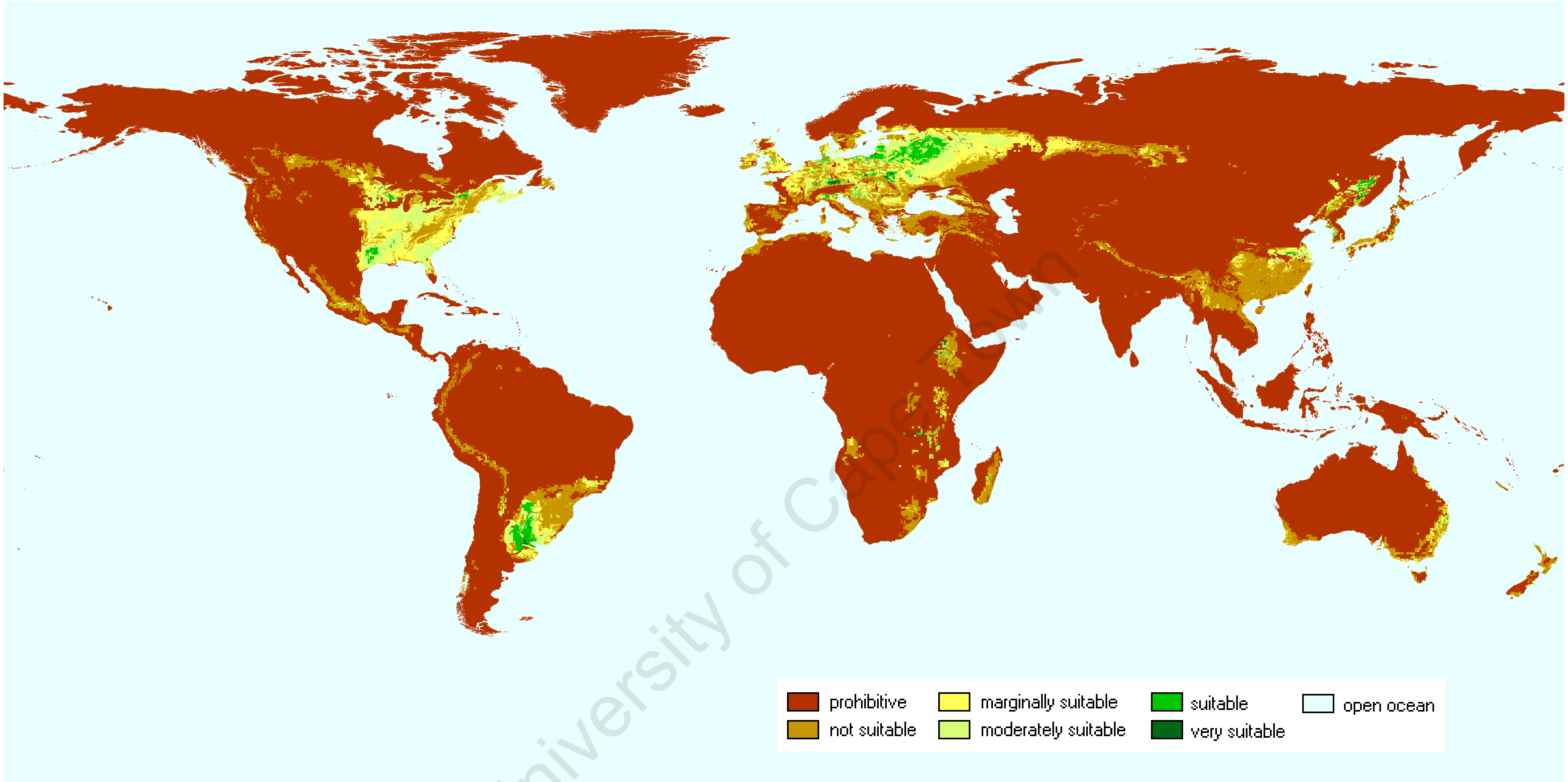


Figure A9: Area suitability of rainfed canola (FAO-AGLL, 2003)

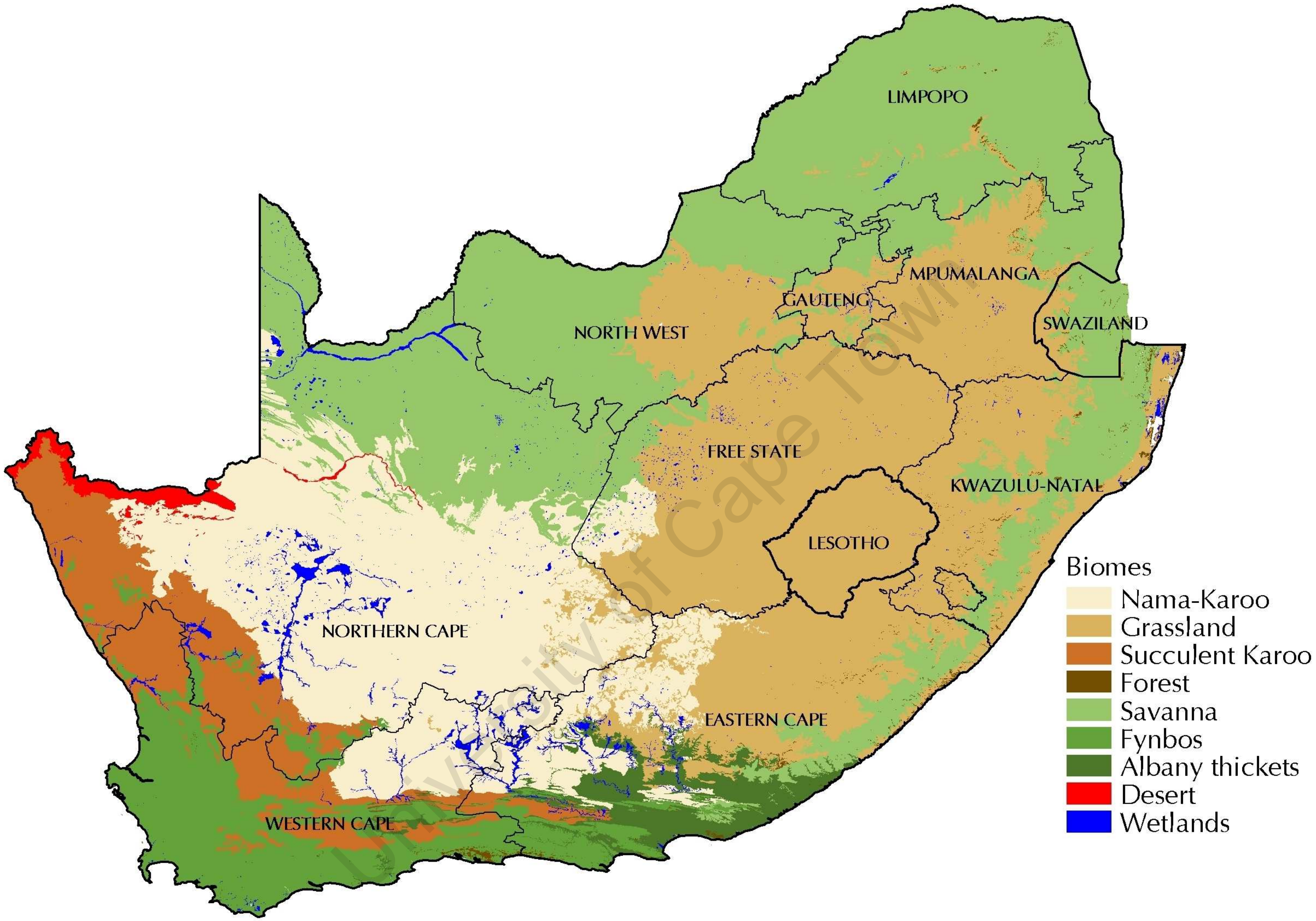


Figure A10: Biomes of South Africa (DEAT, 2004)

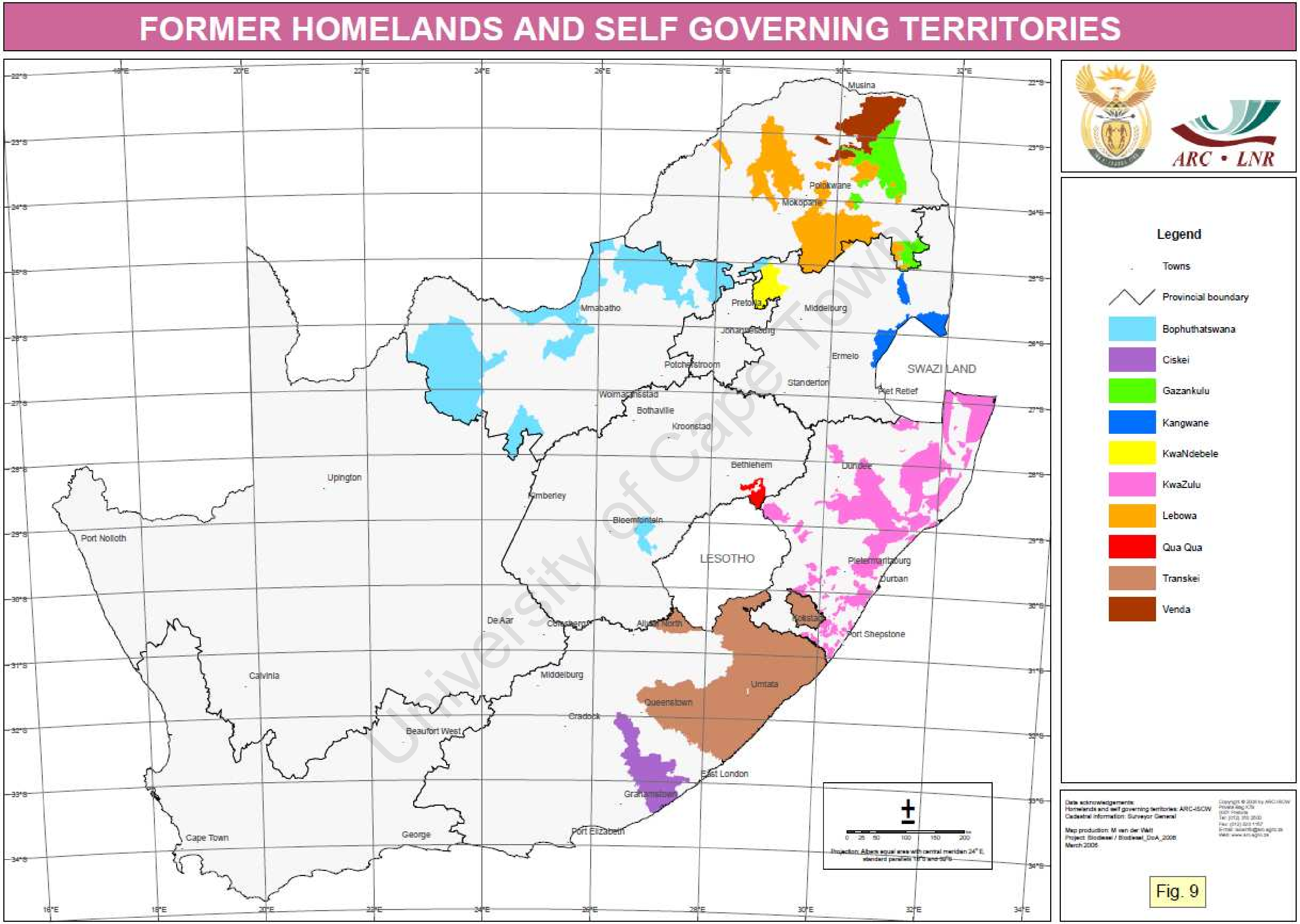


Figure A11: Former homelands of South Africa (Schoeman and van der Walt, 2006)

APPENDIX C: Derivations of Objective equations

1. Economic Gain Objective

National Model

If we define $i \in I$ = {Biodiesel, Bioethanol}

$j \in J$ = { Maize, Wheat, Sugarcane, Sweet sorghum, Soybean, Sunflower, Canola}

then for each bioenergy crop *j* the value added, in R/ha can be expressed as:

$$Value\ Added_j = \sum_i [(Biofuel\ revenue_{i,j} + By\text{-}product\ revenue_{i,j} + Co\text{-}generated\ Electricity\ revenue_{i,j}) - (Raw\ material\ cost_{i,j} + processing\ cost_{i,j})] \quad (1).$$

If we further define

y_{ij} = Yield of biofuel *i* produced from bioenergy crop *j* [litres/hectare/yr]

$y_{biodiesel,maize} = y_{biodiesel,wheat} = y_{biodiesel,sugarcane} = y_{biodiesel,sweet-sorghum} = 0$

$y_{bioethanol,soybean} = y_{bioethanol,sunflower} = y_{bioethanol,canola} = 0$

$C_{Byproduct,j}$ = Selling price of by-product of bioenergy crop *j* [R/kg]

C_{elec} = Price of electricity [R/kWh]

C_{market_j} = Market price of crop *j* [R/tonne]

$C_{process_j}$ = All post-harvest costs of processing crop *j* [R/litre]

$\phi_{Byproduct,j}$ = Amount of by-product produced per litre of biofuel from crop *j* [kg/litre]

ϕ_j = tonnes of crop *j* required to produce a litre of biofuel [tonne/litre]

ϕ_{elec_j} = Amount of by-product produced per litre of biofuel from crop *j* [kWh/litre].

then value added, V_j of each crop becomes:

$$V_j = \sum_i y_{ij} * \left[\left(C_i + \phi_{Byproduct,j} * C_{Byproduct,j} + \phi_{elec,j} * C_{elec} \right) - \left(\phi_j * C_{market,,j} + C_{process,j} \right) \right] \quad (2).$$

If x_j = fraction of land occupied by bioenergy crop *j*, then the overall value added, V(x), is given by the sum of the value added values of all the crops as shown in the equation below:

$$V(x) = \sum_i \sum_j x_j y_{ij} * \left[\left(C_i + \phi_{Byproduct,j} * C_{Byproduct,j} + \phi_{elec,j} * C_{elec} \right) - \left(\phi_j * C_{market,,j} + C_{process,j} \right) \right]. \quad (3)$$

Case Study Model

For the Maluti-a-Phofung case study value added is defined as:

$$Value\ Added_{total} = (Profit_{biofuel} - Profit_{No\_biofuel})_{oilseeds} + (Profit_{biofuel} - Profit_{No\_biofuel})_{grains} + (Profit_{biofuel} - Profit_{No\_biofuel})_{s\_sorghum} \quad (4)$$

<u>Oilseeds</u>: If the value added by each oilseed *j*, $(Profit_{biofuel} - Profit_{No\_biofuel})_{oilseed,j}$, is represented by $V_{oilseed,j}$ then,

$$V_j = (AgricP_{biofue,j} + ProcessP_j) - AgricP_{NO-biofuel,j} \quad (5)$$

Where $AgricP_{biofue,j}$ = profit from agriculture in the presence of biofuel programme

$ProcessP_j$ = profit of the biodiesel processing plant as expressed by equation (2)

$AgricP_{NO-biofuel,j}$ = Profit from agriculture in the absence of the biofuel programme.

If we further define

σ_{land} = Fraction of the underutilized land that is currently being cultivated

P_j = Farmers' profit from selling crop *j* at market price = $AgricP_j / (Ø_{jj} * y_{ij})$ [R/tonne]

then Vj for every oilseed *j* can be expressed as:

$$V_j = ProcessP_j + AgricP_{biofue,j} - \sigma_{land} AgricP_{biofuel,j} \quad (6)$$

$$= y_{biodiesel,j} * \left[\left(C_{biodiesel} + \phi_{Byproduct,j} * C_{Byproduct,j} + \phi_{elec,j} * C_{elec} \right) - \left(\phi_j * C_{market,j} + C_{process,j} \right) \right] + AgricP_{biofuel,j} - \sigma_{land} * AgricP_{biofuel,j} \quad (7)$$

$$= y_{biodiesel,j} * \left[\left(C_{biodiesel} + \phi_{Byproduct,j} * C_{Byproduct,j} \right) - \left(\phi_j * C_{market,j} + C_{process,j} \right) + (1 - \sigma_{land}) * \phi_j * P_j \right] \quad (8)$$

The term for co-generated electricity has been removed in the latter because it is not applicable to biodiesel processes.

<u>Grains</u>: Because no processing of grains occurs within Maluti-a-Phofung, the value added by each grain *j*, $(Profit_{biofuel} - Profit_{No\_biofuel})_{grain,j}$, represented by $V_{grain,j}$ is therefore:

$$V_j = AgricP_{biofue,j} - AgricP_{NO-biofuel,j} - Cost_{Transportation,j} \quad (9)$$

If we define the fraction of the farmers' grain currently sold at 2nd grade market prices as g_2, then the value added for each grain *j* becomes:

$$V_j = y_{ethanol,j} * \left[\phi_j * P_j - \sigma_{land} * \left((1-g_2) * \phi_j * P_j - g_2 * \phi_j * P_{2,j}\right) - \delta_j\right] \tag{10}$$

$$= y_{ethanol,j} * \left[\phi_j * \left(P_j - \sigma_{land} * \left((1-g_2) * P_j + g_2 * P_{2,j}\right)\right) - \delta_j\right] \tag{11}$$

Where $P_{2,j}$ = Profit made by farmers from selling crop *j* at 2nd grade market price [R/tonne]

δ_j = Cost of transporting crop *j* to processing plant [R/litre].

<u>Sweet sorghum</u>: For sweet sorghum the value added is defined as:

$$V_{s\_sorghum} = AgricP_{biofuel,s\_sorghum} + GrainC_{biofuel,s\_sorghum} - AgricP_{NO-biofuel,s\_sorghum} - Cost_{Transportation,s-sorghun} \tag{12}$$

Where: $GrainC_{biofuel,s\_sorghum}$ = Revenue from sales of sorghum grain in presence of biofuel programme.

But because for sweet sorghum $AgricP_{NO-biofuel,s\_sorghum} = \sigma_{land} * \phi_{Byproduct,s\_sorghum} * P_{Byproduct,s\_sorghum}$, then value added can be expressed as:

$$V_{s\_sorghum} = y_{ethanol,s\_sorghum} * \begin{bmatrix} \phi_{s\_sorghum} P_{s-sorghum} + \phi_{Byproduct,s\_sorghum} C_{Byproduct,s\_sorghum} \\ - \sigma_{land} * \phi_{Byproduct,s\_sorghum} * P_{Byproducts,s\_sorghum} - \delta_{s\_sorghum} \end{bmatrix} \tag{13}$$

$$= y_{ethanol,s\_sorghum} * \left[\phi_{s\_sorghum} P_{s-sorghum} + \phi_{BP,s\_sorghum}\left(C_{BP,s\_sorghum} - \sigma_{land} P_{BP,s\_sorghum}\right) - \delta_{s\_sorghum}\right] \tag{14}$$

The overall value added combining value additions from all oilseeds, grains and sweet sorghum can thus be expressed as:

$$V(x) = x_j \begin{bmatrix} y_{biodiesel,j} \sum_{j \in B}\left(C_{biodiesel} + \phi_{BP,j} C_{BP,j} - \left(\phi_j C_{market,j} + C_{process,j}\right) + \left(1 - \sigma_{land}\right)\phi_j P_j\right) + \\ y_{bioethanol,j} \begin{bmatrix} \sum_{j \in S} \phi_j \left(P_j - \sigma_{land}\left(g_2 P_{2,j} + (1-g_2) P_j\right)\right) + \\ \phi_{s\_sorghum} P_{s-sorghum} + \phi_{BP,s\_sorghum}\left(C_{BP,s\_sorghum} - \sigma_{land} P_{BP,s\_sorghum}\right) - \delta_j \end{bmatrix} \end{bmatrix} \tag{15}$$

2. Avoided Greenhouse gas emissions Objective

From section 3.4.2 the avoided greenhouse gas emissions are defined as:

Avoided GHG emissions = GHG emissions$_{\text{-Replaced products}}$ – GHG emissions$_{\text{-Biofuel production}}$.

If G(x) represents the overall avoided greenhouse gas emissions objective in kgCO2-eqt, then the avoided greenhouse gas emissions for each crop *j*, can be expressed as:

$$G_j = \lfloor E_{biofuel,j} + E_{ALL-Byproduct,j} \rfloor - \lfloor E_{Agric,j} + E_{Process,j} \rfloor \quad (16)$$

Where $E_{biofuel,j}$ = Life-cycle emissions of the replaced fossil fuel

$E_{ALL-Byproduct,j}$ = Life-cycle emissions of the products replaced by the by-products from crop *j*

$E_{Agric,j}$ = Life-cycle emissions of all agricultural activities involved in growing crop *j*

$E_{Process,j}$ = Life-cycle emissions of all post-harvest activities involved in processing crop *j*

If we then define

E_i = emission factor associated with replaced fossil fuel [kg CO_2-eqt/litre]

$E_{Byproduct,j}$ = Emission factor associated with replaced by-products [kg CO_2-eqt/kg by-product]

E_{elec} = Emission factor associated with replaced Eskom electricity [kg CO_2-eqt/GJ]

Then the avoided greenhouse gas emissions become:

$$G_j = \sum_i y_{ij} * \lfloor E_i + \phi_{Byproduct,j} * E_{Byproduct,j} + \phi_{elec,j} * E_{elec} \rfloor - \lfloor E_{Agric,j} + E_{Process,j} \rfloor \quad (17)$$

The life-cycle emissions of all agricultural activities involved in growing crop *j*, $E_{Agric,j}$, is the sum of emissions from each of the sources in Table A.1 below. If we define the agricultural emission factor φ_{agric_j} in kg CO_2-eqt/ha/yr as:

$$\varphi_{agric_j} = \sum_{\forall\, Agric\ sources} Amount_{source_j} \cdot E_{source}$$

Then the avoided greenhouse gas emissions can be expressed as:

$$G_j = \sum_i y_{ij} * \lfloor E_i + \phi_{Byproduct,j} * E_{Byproduct,j} + \phi_{elec,j} * E_{elec} \rfloor - \lfloor \varphi_{agric,j} + E_{Process,j} \rfloor$$

Table A.1: Sources of emissions in agricultural operations

Source	Units	
	Amount	**E (Emission factor)**
Seed	kg/ha	Kg CO_2-eqt/kg
Diesel	GJ/ha	Kg CO_2-eqt/GJ
Nitrogen	kg/ha	Kg CO_2-eqt/kg
P_2O_5	kg/ha	Kg CO_2-eqt/kg
K_2O	kg/ha	Kg CO_2-eqt/kg
Lime	kg/ha	Kg CO_2-eqt/kg
Herbicides	kg/ha	Kg CO_2-eqt/kg
Pesticides	kg/ha	Kg CO_2-eqt/kg
Fungicides	kg/ha	Kg CO_2-eqt/kg
Trash burning	kg trash/ha	Kg CO_2-eqt/kg trash
Agricultural machinery	kg steel/ha	Kg CO_2-eqt/kg steel
Agricultural labour	Persons/ha	Kg CO_2-eqt/person

Also the life-cycle emissions of all post-harvest activities involved in processing crop *j*, $E_{Process,j}$, is the sum of the emissions from process chemicals, process energy , crop transportation, labour, facility steel and facility concrete. If we define and

$\varphi_{process_{ijk}}$, = the post-harvest emission factor [kgCO2 -eqt/litre]

E_{chem_k} = emission factor of chemicals used in processing plant *k* [kgCO_2-eqt/litre biofuel]

E_{energy_k} = emission factor of fossil energy used in plant *k* [kgCO_2-eqt/litre biofuel]

E_{trans_j} = emission factor associated with transportation of crop *j* [kg CO_2-eqt/ton crop]

$E_{BFtrans_i}$ = emission factor of transporting biofuel *i* [kg CO_2-eqt/litre biofuel]

E_{labour} = emission factor associated with human labour [kg CO_2-eqt/person]

E_{steel} = emission factor associated with steel [kg CO_2-eqt/kg steel]

$E_{concrete}$ = emission factor associated with concrete [kg CO_2-eqt/kg concrete]

δ_{labour_k} = labour requirements of processing technology k [persons/litre biofuel]

$\emptyset_{steel_k}$ = steel requirements of processing technology k [kg steel/litre]

$\emptyset_{concrete_k}$ = concrete requirements of processing technology k [kg/litre]

Then

$$\varphi_{process_{ijk}} = \left(E_{chem_k} + E_{energy_k} + \emptyset_j E_{trans_j} + E_{BFtrans_i} + \delta_{labour_k} E_{labour} + \emptyset_{steel_k} E_{steel} + \emptyset_{concrete_k} E_{concrete}\right) \cdot \gamma_{jk} \tag{18}$$

where $k \in K$ = {grain-processing, cane-processing, oilseed-processing} and γ_{jk} is a dimensionless matrix that matches the bioenergy crops to the correct processing technologies given by:

$$\gamma_{jk} = \begin{bmatrix} & \text{maize} & \text{wheat} & \text{sugarcane} & \text{s\_sorghum} & \text{soybean} & \text{sunflower} & \text{canola} \\ \text{Grain processing} & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ \text{Cane processing} & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ \text{Oilseed processing} & 0 & 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix}$$

The avoided greenhouse gas emissions for each crop *j* can thus be expressed as:

$$G_j = \sum_i \left[y_{ij} * \left(E_i + \phi_{Byproduct,j} * E_{Byproduct,j} + \phi_{elec,j} * E_{elec}\right) - \left(\varphi_{agric,j} + y_{ij} * \sum_k \varphi_{Process,ijk}\right)\right] \tag{19}$$

The overall avoided greenhouse gas emissions are therefore the sum of the avoided greenhouse gas emissions of the individual crops as shown in the following equation:

$$G(x) = \sum_i \sum_j x_j * \left[y_{ij} * \left(E_i + \phi_{Byproduct,j} * E_{Byproduct,j} + \phi_{elec,j} * E_{elec}\right) - \left(\varphi_{agric,j} + y_{ij} * \sum_k \varphi_{Process,ijk}\right)\right] \tag{20}$$

3. Job creation Objective

National Model

Job creation here is defined as:

Job-creation = Agricultural Jobs$_{\text{-Permanent}}$ + Agricultural jobs$_{\text{-Temporary}}$ + Processing Jobs

For each biofuel, *j*, the number of permanent agricultural jobs, *Agricultural Jobs$_{\text{-Permanent},j}$*, can be expressed as:

$$\text{Agricultural Jobs}_{\text{-Permanent},j} = h * W_{p\_agr,j} * S_j$$

Where:

$h = 8$, is the number of working hours per day

$W_{p\_agr,j}$ = Number of permanent agricultural workers required per ha of j grown

S_j = Length of farming season for crop j [days/yr]

If we further define

$L_{t\_agr,j}$ = Temporary agricultural labour required for growing crop j [man-hours/ha]

$L_{pro,k}$ = Labour requirements of processing technology *k* [man-hours/litre]

Then the Job creation objective, $Z(x)_j$, for each crop *j* becomes:

$$Z_j = \sum_i \left[h * W_{p\_agr,j} * S_j + L_{t\_agr,j} + y_{ij} \sum_k \gamma_{jk} L_{pro,k} \right] \tag{21}$$

The overall Job creation objective is therefore:

$$Z(x) = \sum_i \sum_j x_j \left[h \cdot W_{p\_agr,j} \cdot S_j + L_{t\_agr,j} + y_{ij} \sum_k \gamma_{jk} L_{pro,k} \right] \tag{22}$$

Case Study Model

For the Maluti-a-Phofung case study, only the jobs brought about by utilizing the currently unutilized land are included in the objective equation. Thus a factor of $(1-\sigma_{land})$ is included for the agricultural jobs in the Job creation equation for the case study as shown below:

$$Z(x) = \sum_i \sum_j x_j \left[(1-\sigma_{land})(h \cdot W_{p\_agr,j} \cdot S_j + L_{t\_agr,j}) + y_{ij} \sum_k \gamma_{jk} L_{pro,k} \right] \tag{23}$$

APPENDIX D: Calculation of B2:E8 ratio

National consumption of Diesel and Petrol (2007)				
Petrol	11,558,000,000	litres/annum	405	PJ/annum
Diesel	9,757,000,000	litres/annum	357	PJ/annum
8% of Petrol	924,640,000		32.36	PJ/annum
2% of Diesel	780,560,000		7.14	PJ/annum
B2:E8 Market penetration				
8% Bioethanol	1,522,220,132	litres/annum	32.36	PJ/annum
2% Biodiesel	216,888,066	litres/annum	7.14	PJ/annum
RATIO [Bioethanol/biodiesel]	**7.018 vol/vol**		**4.531 J/J**	

The following calorific values were used in the above calculation:

Petrol	35.0 MJ/litre
Diesel	36.6 MJ/litre
Bioethanol	21.26 MJ/litre
Biodiesel	32.93 MJ/litre

APPENDIX E: Gams code for the 3-objective model

```
SETS
        i biofuels /bioethanol, biodiesel/
        j bioenergy crops /maize, wheat,wheat_w, sugarcane,Sugarcane_w, sweet_sorghum, soybean,
sunflower, canola, canola_w/
        s GHG gasses emitted on farm /Carbon_dioxide, Methane, Nitrous_oxide/
        t bioenergy processing technology /Grain_processing, Stalk_processing, Transesterification/
        K number of objective functions /1*3/
        KM1(K) constrained objective functions according to the å-constraint method /2,3/
ALIAS    (K,KK,LK)

PARAMETERS
        dir(K) direction of the objective functions (1 for max and -1 for min)
        /1  1
         2  1
         3  1/;

PARAMETERS
        E(i) Energy contained in a litre of biofuel i in GJ per litre
        /bioethanol     0.02126
         biodiesel      0.03293/

        Litre_ton(j) Litres of biofuel produced per ton of crop
        /maize          421
         wheat          358.08
         wheat_w        358.08
         sugarcane      78.61
         sugarcane_w    78.61
         sweet_sorghum  65.8208
         soybean        204.50
         sunflower      431.72
         canola         454.44
         canola_w       454.44/

        Litre_ton2(j) Net Litres of biofuel sold per ton of crop
        /maize          421
         wheat          358.08
         wheat_w        358.08
         sugarcane      78.61
         sugarcane_w    78.61
         sweet_sorghum  65.8208
         soybean        202.3
         sunflower      427.16
         canola         449.64
         canola_w       449.64/;

table
       y_mass(i,j) yield of bioenergy crop j in tons per ha
                   maize   wheat  wheat_w  sugarcane sugarcane_w   sweet_sorghum  soybean  sunflower
canola  canola_w
        bioethanol     3.031   2.805    2.805   57.98      57.98        31.884       0       0       0       0
        biodiesel        0       0        0       0          0             0       1.120    0.948    1.141    1.141 ;
```

```
parameter y(i,j)  yield of bioenergy crop j in litres per ha;
        y(i,j)= Litre_ton(j) * y_mass(i,j);

parameters
        E_dummy(i) dummy parameter for bioethanol
        /bioethanol    1
         biodiesel     0/
        D_dummy(i) dummy parameter for biodiesel
        /bioethanol    0
         biodiesel     1/

        Maize_(j) dummy parameter for maize
        /maize         1
         wheat         0
         wheat_w       0
         sugarcane     0
         sugarcane_w   0
         sweet_sorghum 0
         soybean       0
         sunflower     0
         canola        0
         canola_w      0/
        Wheat_(j) dummy parameter for wheat
        /maize         0
         wheat         1
         wheat_w       0
         sugarcane     0
         sugarcane_w   0
         sweet_sorghum 0
         soybean       0
         sunflower     0
         canola        0
         canola_w      0/
       Wheat_w_(j) dummy parameter for wheat_w
        /maize         0
         wheat         0
         wheat_w       1
         sugarcane     0
         sugarcane_w   0
         sweet_sorghum 0
         soybean       0
         sunflower     0
         canola        0
         canola_w      0/
        sugarcane_(j) dummy parameter for sugarcane
        /maize         0
         wheat         0
         wheat_w       0
         sugarcane     1
         sugarcane_w   0
         sweet_sorghum 0
         soybean       0
```

```
 sunflower     0
 canola        0
 canola_w      0/
 sugarcane_w_(j) dummy parameter for sugarcane_w
/maize         0
 wheat         0
 wheat_w       0
 sugarcane     0
 sugarcane_w   1
 sweet_sorghum 0
 soybean       0
 sunflower     0
 canola        0
 canola_w      0/
Sweetsorghum_(j) dummy parameter for sweet sorghum
/maize         0
 wheat         0
 wheat_w       0
 sugarcane     0
 sugarcane_w   0
 sweet_sorghum 1
 soybean       0
 sunflower     0
 canola        0
 canola_w      0/
soybean_(j) dummy parameter for soybean
/maize         0
 wheat         0
 wheat_w       0
 sugarcane     0
 sugarcane_w   0
 sweet_sorghum 0
 soybean       1
 sunflower     0
 canola        0
 canola_w      0/
sunflower_(j) dummy parameter for sunflower
/maize         0
 wheat         0
 wheat_w       0
 sugarcane     0
 sugarcane_w   0
 sweet_sorghum 0
 soybean       0
 sunflower     1
 canola        0
 canola_w      0/
Canola_(j) dummy parameter for canola
/maize         0
 wheat         0
 wheat_w       0
 sugarcane     0
 sugarcane_w   0
```

```
 sweet_sorghum  0
 soybean        0
 sunflower      0
 canola         1
 canola_w       0/
 Canola_w_(j) dummy parameter for canola_w
/maize          0
 wheat          0
 wheat_w        0
 sugarcane      0
 sugarcane_w    0
 sweet_sorghum  0
 soybean        0
 sunflower      0
 canola         0
 canola_w       1/;

parameters
  Amt_BP_mass(j) kg of by-product per ton of energy crop (grain for sweet sorghum)
  /maize          318.316
   wheat          430.694
   wheat_w        430.694
   sugarcane      0
   sugarcane_w    0
   sweet_sorghum  47.193
   soybean        779
   sunflower      620
   canola         600
   canola_w       600/

  Amt_Elec(j) quantity of excess electricity sold in kWh per litre
  /maize          0
   wheat          0
   wheat_w        0
   sugarcane      0.21
   sugarcane_w    0.21
   sweet_sorghum  0.1572
   soybean        0
   sunflower      0
   canola         0
   canola_w       0/

  C_p_market(j) Market(purchase)price of energy crop j in ZAR per tonne
  /maize          1805
   wheat          3706
   wheat_w        3706
   sugarcane      207.54
   sugarcane_w    207.54
   sweet_sorghum  207.54
   soybean        4550
   sunflower      4935
   canola         3500
   canola_w       3500/
```

```
        C_process(j) Processing cost of energy crop j in ZAR per litre
        /maize          3.02
         wheat          3.11
         wheat_w        3.11
         sugarcane      2.42
         sugarcane_w    2.42
         sweet_sorghum  3.48
         soybean        3.86
         sunflower      2.74
         canola         2.67
         canola_w       2.67/

        C_BP(j) Selling price of by-product from crop j in ZAR per kg by-product
        /maize          2.78
         wheat          2.69
         wheat_w        2.69
         sugarcane      0
         sugarcane_w    0
         sweet_sorghum  1.534
         soybean        4.09
         sunflower      2.95
         canola         2.43
         canola_w       2.43/

        SP(i) Selling price of biofuel i in ZAR per litre(verify these values one last time)
        /bioethanol     7.01
         biodiesel      6.92/

        RHS(K) right hand side of the constrained obj.functions in e-constraint
        MAXOBJ(K) maximum value from the payoff table
        MINOBJ(K) minimum value from the payoff table
        w(k) indicator parameters for the objective functions
        PAYOFF(K,KK) payoff table entries;

* necessary initial values for the parameters
        MAXOBJ(K) = 1;
        MINOBJ(K) = 0;
        PAYOFF(K,KK) = 0;

parameters
*Avoided CO2 emission parameters
        Amt_DSL(j) kg of Diesel used per ha in agricultural activities of j
        /maize          71.75
         wheat          64.5
         wheat_w        64.5
         sugarcane      74.26
         sugarcane_w    74.26
         sweet_sorghum  155.119
         soybean        65.47
         sunflower      62.4
         canola         62.5
         canola_w       62.5/
```

```
Amt_N2(j) kg of N2 used per ha of j grown
/maize          52.3
 wheat          30
 wheat_w         30
 sugarcane      92
 sugarcane_w    92
 sweet_sorghum  120
 soybean        2.8
 sunflower      12.8
 canola         57.5
 canola_w       57.5/

Amt_P2O5(j) kg of P2O5 used per ha of j grown
/maize          28.5
 wheat          40
 wheat_w         40
 sugarcane      57
 sugarcane_w    57
 sweet_sorghum  40
 soybean        10
 sunflower      17.9
 canola         68.8
 canola_w       68.8/

Amt_K2O(j) kg of K2O used per ha of j grown
/maize          5.7
 wheat          4
 wheat_w         4
 sugarcane      133
 sugarcane_w    133
 sweet_sorghum  40
 soybean        3.2
 sunflower      1.7
 canola         65.2
 canola_w       65.2/

Amt_Herb(j) kg of Herbicide used per ha of j grown
/maize          2.2
 wheat          4.935
 wheat_w         4.935
 sugarcane      2.2
 sugarcane_w    2.2
 sweet_sorghum  3.0
 soybean        0
 sunflower      2.5
 canola         1.02
 canola_w       1.02/

Amt_Ins(j) kg of Insecticide used per ha of j grown
/maize          0.08
 wheat          1.07
 wheat_w         1.07
```

```
 sugarcane      0.16
 sugarcane_w    0.16
 sweet_sorghum  9.0
 soybean        1.2
 sunflower      0
 canola         0.036
 canola_w       0.036/

Amt_Fungi(j) kg of Fungicide used per ha of j grown
/maize          0.0
 wheat          2.0
 wheat_w        2.0
 sugarcane      0.0
 sugarcane_w    0.0
 sweet_sorghum  0.0
 soybean        0.0
 sunflower      0.0
 canola         0.0
 canola_w       0.0/

Amt_Trash(j) kg of trash burned per ha of j grown
/maize          0
 wheat          0
 wheat_w        0
 sugarcane      5705
 sugarcane_w    5705
 sweet_sorghum  0
 soybean        0
 sunflower      0
 canola         0
 canola_w       0/

Amt_Agrsteel(j) kg of steel in agricultural implements per ha of j grown
/maize          23.022
 wheat          23.022
 wheat_w        23.022
 sugarcane      33.462
 sugarcane_w    33.462
 sweet_sorghum  23.02
 soybean        20.8
 sunflower      20.8
 canola         20.8
 canola_w       20.8/

Agr_labor(j) Agricultural labour requirements per ha of j grown
/maize          0.00848
 wheat          0.00848
 wheat_w        0.00848
 sugarcane      0.0767
 sugarcane_w    0.0767
 sweet_sorghum  0.00848
 soybean        0.00848
 sunflower      0.00848
```

canola 0.00848
canola_w 0.00848/

Amt_Seed(j) kg of seed required per ha of j grown
/maize 12.5
wheat 120
wheat_w 120
sugarcane 1
sugarcane_w 1
sweet_sorghum 7.250
soybean 76.1
sunflower 3.5
canola 4.5
canola_w 4.5/

Em_fuel_eqt(i) CO2-eqt emissions of biofuels per GJ of fuel i burnt
/bioethanol 81.8
biodiesel 88.26/

Em_BP(j) CO2-eqt emissions of by-product of j per litre biofuel sold
/maize 0.812
wheat 1.438
wheat_w 1.438
sugarcane 0.202
sugarcane_w 0.202
sweet_sorghum 0.606
soybean 3.274
sunflower 1.238
canola 1.067
canola_w 1.067/

Em_Seed(j) CO2-eqt emissions per kg seed of j used
/maize 3.85
wheat 0.4033
wheat_w 0.4033
sugarcane 27.07
sugarcane_w 27.07
sweet_sorghum 3.15
soybean 0.92
sunflower 2.77
canola 0.32
canola_w 0.32/

*Technology dependant parameters
Em_chem(t) CO2-eqt emissions of chemicals used in technology t per litre of biofuel (grain assumed equal to stalk)
/Grain_processing 0.023
Stalk_processing 0.023
Transesterification 0.067/

Em_crop_trans(j) CO2-eqt emissions from transporting a tonne of crop j
/maize 26.77
wheat 21.97

```
 wheat_w       21.97
 sugarcane     4.13
 sugarcane_w   4.13
 sweet_sorghum  77.21
 soybean       10.17
 sunflower     10.17
 canola        10.17
 canola_w      10.17/

Em_bf_trans(i) CO2-eqt emissions from transporting a litre of biofuel i
/Bioethanol          0.0276
 Biodiesel           0.0276/

Tech_labor(t) Post agriculture labour requirements in persons per litre of biofuel
/Grain_processing      0.00000042
 Stalk_processing      0.00000154
 Transesterification   0.00000302/

Amt_techsteel(t) kg of steel used in constructing processing plant t per litre
/Grain_processing      0.00067
 Stalk_processing      0.0015
 Transesterification   0.0011/

Amt_concrete(t) kg of concrete used in constructing processing plant t per litre
/Grain_processing      0.0062
 Stalk_processing      0.0051
 Transesterification   0.0088/;

table
Em_Energy(t,j) CO2-eqt emissions of FF Energy used in technology t per litre
                   maize   wheat   wheat_w  sugarcane   sugarcane_w   sweet_sorghum  soybean
sunflower   canola  canola_w
Grain_processing      670.12   569.97  569.97      0          0       0            0          0        0
0
Stalk_processing        0       0       0          0          0       0            0          0        0        0
Transesterification     0       0       0          0          0       0          144.8      144.8    144.8
144.8;

parameters
Season(j) length of cropping season for crop j in days
/maize         150
 wheat         180
 wheat_w       180
 sugarcane     365
 sugarcane_w   365
 sweet_sorghum  150
 soybean       150
 sunflower     150
 canola        180
 canola_w      180 /

Agr_labor_temp(j) Temporary labour required for harvesting crop j in man-hours per ha
/maize        32.88
```

```
        wheat          0
        wheat          0
        sugarcane      121.0
        sugarcane_w    121.0
        sweet_sorghum  197.7
        soybean        0
        sunflower      0
        canola         0
        canola_w       0/

        Tech_labor_MAP(t) Technology labour requirements in man-hours per litre
        /Grain_processing       0.00131
         Stalk_processing       0.00556
         Transesterification    0.00252/;

table
        T_filter(t,j) Technology filter
                         maize   wheat  wheat_w  sugarcane sugarcane_w   sweet_sorghum  soybean
sunflower  canola  canola_w
        Grain_processing       1      1      1        0          0        0       0        0        0       0
        Stalk_processing       0      0      0        1          1        1       0        0        0       0
        Transesterification    0      0      0        0          0        0       1        1        1       1;

scalars
        Em_N2 CO2-eqt emissions per kg of N2 fertilizer /9.08/
        Em_P2O5 CO2-eqt emissions per kg of P2O5 fertilizer /1.728/
        Em_K2O CO2-eqt emissions per kg of K2O fertilizer /0.882/
        Amt_lime kg of lime required per ha per annum (100-150) /194/
        Em_lime CO2-eqt emission per kg of lime used /0.6494/
        Em_Herb CO2-eqt emissions per kg of herbicide /32.43/
        Em_Ins CO2-eqt emissions per kg of insecticide /37.55/
        Em_Fungi CO2-eqt emissions per kg of fungicide /35.43/
        Em_Trash CO2-eqt emissions per kg of trash burned /0.083/
        Em_Steel CO2-eqt emissions per kg steel produced /11.17/
        Em_labour National CO2-eqt emissions per capita /9.52/
        Em_Concrete CO2-eqt emissions per kg concrete produced /0.82/
        Em_DSL  CO2-eqt emissions per GJ diesel fuel /88.26/
        Diesel_Energy Energy of petroleum diesel in GJ per kg /0.04337/
        C_elec cost of electricity in ZAR per kWh /0.2403/
        h number of agricultural working hours per day /8/
        BP_r fractional price increase of oilcake /1/
        BP_r2 fractional price increase of sorghum grain /1/;

parameter A_BP(j) Amount of by-product in kg of j per litre of biofuel;
        A_BP(j) = Amt_BP_mass(j)/Litre_ton2(j);
parameter C_p(j) Total cost of producing biofuel from crop j in ZAR per litre;
        C_p(j) = C_p_market(j)/Litre_ton2(j)+ C_process(j);
parameter A_DSL(j) GJ of diesel used per ha in agricultural activities of j;
        A_DSL(j) = Amt_DSL(j)*Diesel_Energy;
parameter Em_AGR(j) Aggregated agricultural emissions factor of j;
        Em_AGR(j) =
A_DSL(j)*Em_DSL+Amt_N2(j)*Em_N2+Amt_P2O5(j)*Em_P2O5+Amt_K2O(j)*Em_K2O+Amt_lim
```

```
e*Em_lime+Amt_Herb(j)*Em_Herb+Amt_Ins(j)*Em_Ins+Amt_Fungi(j)*Em_Fungi+Amt_Trash(j)*Em_Trash+Amt_Agrsteel(j)*Em_Steel+Agr_labor(j)*Em_labour+Amt_Seed(j)*Em_Seed(j);
parameter Em_PRO(i,j,t) Aggregated processing emissions factor of j;
        Em_PRO(i,j,t) =
(Em_chem(t)+Em_Energy(t,j)/Litre_ton2(j)+Em_crop_trans(j)/Litre_ton2(j)+Em_bf_trans(i)+Tech_labor(t)*Em_labour+Amt_techsteel(t)*Em_Steel+Amt_concrete(t)*Em_Concrete)*T_filter(t,j);

parameter coef_OBJ(K,i,j) Objective function coefficient;
        coef_OBJ('1',i,j) = y(i,j)*(SP(i)+A_BP(j)*C_BP(j)+Amt_Elec(j)*C_elec-C_p(j));
        coef_OBJ('2',i,j) = y(i,j)*(E(i)*Em_fuel_eqt(i)+ Em_BP(j))-
(Em_AGR(j)+sum((t),(y(i,j)*Em_PRO(i,j,t))));
        coef_OBJ('3',i,j) = h*Agr_labor(j)*Season(j)+ Agr_labor_temp(j)+
y(i,j)*sum((t),(T_filter(t,j)*Tech_labor_MAP(t)));

scalars
        r B2-E8 demand ratio of bioethanol vs biodiesel /4.5/
        E_Ethanol Energy content of bioethanol in MJ per litre /21.26/
        E_Diesel Energy content of biodiesel in MJ per litre /32.93/
        land_w_c Western Cape land constraint constant /0.016/
        land_o_c Rest of the country land constraint constant /0.984/
        maize_c maize constraint constant /0.813/
        wheat_c wheat constraint constant /0.61/
        wheat_w_c wheat constraint constant /0.016/
        sugar_c sugarcane constraint constant /0.045/
        sugar_w_c sugarcane_w constraint constant /0.014/
        sorghum_c sweet sorghum constraint constant /0.984/
        soybean_c soybean constraint constant /0.573/
        sunflower_c sunlower constraint constant /0.883/
        canola_c canola constraint constant /0.315/
        canola_w_c canola constraint constant /0.016/

* the following scalars are for the implementation of the e-constraint method
        g2, g3 counter for grid points per objective function 2 and 3
        numg2 number of intervals per objective function 2 /5 /
        numg3 number of intervals per objective function 3 /5 /
        totcounter total counter of generated points
        jk counter used in the lexicographic optimization for the payoff table
        kopt auxiliary parameter ;

 POSITIVE VARIABLES
        SL(k) slack for max obj or surplus for min obj variables for e-constraint
        x(i,j) percentage of land used to grow crop j ;

 FREE VARIABLES
        Z(K) objective function variables
        OBJ auxiliary variable for the objective function during the construction of the payoff table
        A_OBJVAL auxiliary variable for the objective function of the å-constraint method ;

 EQUATIONS
        land_w western cape land availability constraint
        land_o other land availability constraint
        demand demand ratio constraint of diesel vs petrol
        science_E To assure that only sugar crops are grown for bioethanol
```

```
        science_D to assure that only oils are grown for biodiesel
        maize_suitability maize suitability constraint
        wheat_suitability wheat suitability constraint
        wheat_w_suitability wheat_w suitability constraint
        sugarcane_suitability sugarcane suitability constraint
        sugarcane_w_suitability sugarcane_w suitability constraint
        s_sorghum_suitability sweet sorghum suitability constraint
        soybean_suitability soybean suitability constraint
        sunflower_suitability sunflower suitability constraint
        canola_suitability canola suitability constraint
        canola_w_suitability canola suitability constraint

        OBJF(K) k-th objective function
        CON_OBJ(K) constrained objective functions
        AUGM_OBJ augmented objective function in order to avoid weakly efficient solutions
        ALLOBJ all the objective functions in one expression;

land_w.. sum((i,j), x(i,j)*sugarcane_w_(j))+ sum((i,j), x(i,j)*canola_w_(j))+ sum((i,j),
x(i,j)*wheat_w_(j)) =e= land_w_c;
land_o.. sum((i,j), x(i,j)*maize_(j))+ sum((i,j), x(i,j)*wheat_(j))+ sum((i,j), x(i,j)*sugarcane_(j))+
sum((i,j), x(i,j)*sweetsorghum_(j))+ sum((i,j), x(i,j)*soybean_(j))+ sum((i,j), x(i,j)*sunflower_(j))+
sum((i,j), x(i,j)*canola_(j))=e= land_o_c;
demand.. sum((i,j), x(i,j)*y(i,j)*E_dummy(i)) =e= r*sum((i,j), x(i,j)*y(i,j)*D_dummy(i));
science_E.. sum((i,j), x(i,j)*E_dummy(i)*soybean_(j))+ sum((i,j), x(i,j)*E_dummy(i)*sunflower_(j))+
sum((i,j), x(i,j)*E_dummy(i)*canola_(j))+sum((i,j), x(i,j)*E_dummy(i)*canola_w_(j)) =e= 0;
science_D.. sum((i,j), x(i,j)*D_dummy(i)*maize_(j))+ sum((i,j), x(i,j)*D_dummy(i)*wheat_(j))+
sum((i,j), x(i,j)*D_dummy(i)*wheat_w_(j))+ sum((i,j), x(i,j)*D_dummy(i)*sugarcane_(j))+ sum((i,j),
x(i,j)*D_dummy(i)*sugarcane_w_(j))+ sum((i,j), x(i,j)*D_dummy(i)*sweetsorghum_(j)) =e= 0 ;
maize_suitability.. sum((i,j), x(i,j)*E_dummy(i)*maize_(j)) =l= maize_c;
wheat_suitability.. sum((i,j), x(i,j)*E_dummy(i)*wheat_(j)) =l= wheat_c;
wheat_w_suitability.. sum((i,j), x(i,j)*E_dummy(i)*wheat_w_(j)) =l= wheat_w_c;
sugarcane_suitability.. sum((i,j), x(i,j)*E_dummy(i)*sugarcane_(j)) =l= sugar_c;
sugarcane_w_suitability.. sum((i,j), x(i,j)*E_dummy(i)*sugarcane_w_(j)) =l= sugar_w_c;
s_sorghum_suitability.. sum((i,j), x(i,j)*E_dummy(i)*sweetsorghum_(j)) =l= sorghum_c;
soybean_suitability.. sum((i,j), x(i,j)*D_dummy(i)*soybean_(j)) =l= soybean_c;
sunflower_suitability.. sum((i,j), x(i,j)*D_dummy(i)*sunflower_(j)) =l= sunflower_c;
canola_suitability.. sum((i,j), x(i,j)*D_dummy(i)*canola_(j)) =l= canola_c;
canola_w_suitability.. sum((i,j), x(i,j)*D_dummy(i)*canola_w_(j)) =l= canola_w_c;

OBJF(K).. sum((i,j), x(i,j)*Coef_OBJ(K,i,j))=e= z(K) ;

CON_OBJ(K).. Z(K) - dir(K)*SL(K) =E= RHS(K) ;
AUGM_OBJ.. dir('1')*Z('1')+10**(-3)*SUM(K$KM1(K),SL(K)/(MAXOBJ(K)-MINOBJ(K)))=E=
A_OBJVAL ;
* the augmented objective function is used in the å-constraint method
* we optimize the first objective function and put the others as constraints
* the second term is for avoiding weakly efficient points
 ALLOBJ.. sum(K, w(K)*dir(K)*z(K))=e=obj ;
* allobj is for the construction of the payoff matrix

$ontext
 explanation: for a max objective the corresponding constraint in the
 å-constraint method is obj(k)>=rhs(k) ==> obj(k)-s(k)=rhs(k)
```

```
 Accordingly for a min objective the corresponding constraint in the
 å-constraint method is obj(k)<=rhs(k) ==> obj(k)+s(k)=rhs(k)
 Consequently the only thing that differs in the two cases is the sign of s(k)
 this is accomplished through the dir(k) parameter
$offtext

 MODEL PGEN /ALL/ ;
 OPTION ITERLIM = 100000;
 option bratio = 0.25;

$ontext
 the rhs(k) parameter can be used to set reservation values
 reservation value is an upper bound for minimization objectives
 and a lower bound for maximization objectives
 i.e. objfunc <= res_val for minimization and objfunc >= res_val for maximization
 these bounds are inactive by setting rhs(k)=-dir(k)*10**9 which means
 +INF for upper bound and -INF for lower bound
$offtext

 rhs('1')=-dir('1')*10**9;
 rhs('2')=-dir('2')*10**9;
 rhs('3')=-dir('3')*0;

 FILE payofile1 /march09.doc/;
 PUT payofile1 ;
 PUT 'PAYOFF TABLE'/ ;

$ontext
 lexicographic optimization for payoff table, loop for the payoff table
the optimizations are lexicographic optimizations in order to secure the efficiency
of the produced extreme solutions
the lk set and the jk parameters are used in order to optimize first the proper
objective function in lexicographic optimizations
$offtext
parameter F(i,j) checking the flow ratio of biodiesel vs bioethanol;

 loop(lk,
        for (jk=1 to card(lk),
            if (ord(lk)+jk-1 > card(lk),
              kopt=ord(lk)+jk-1-card(lk);
            else
               kopt=ord(lk)+jk-1
                     );
            w(kk)=0;
* select the objective function to optimize
            w(kk)$(ord(kk)=kopt)=1;
            solve PGEN using LP maximizing obj ;
            payoff(lk,kk)$(ord(kk)=kopt)=z.l(kk)$(ord(kk)=kopt);
* freeze the value of the last objective optimized
            z.fx(kk)$(ord(kk)=kopt)=z.l(kk)$(ord(kk)=kopt);
               );
        loop(kk,
               put payoff(lk,kk):10:2
```

```
            );

* release the fixed values of the objective functions for the new loop of optimizations
        put /;
        z.up(kk)=10**9 ;
        z.lo(kk)=-10**9 ;
    );

 MINOBJ(KK)=SMIN(K,PAYOFF(K,KK));
 MAXOBJ(KK)=SMAX(K,PAYOFF(K,KK));

 putclose payofile1;
 FILE payofile /march09_1.doc/;
 PUT payofile ;
 PUT ' PAYOFF          TABLE'/
 loop (k,
        loop(kk, put payoff(k,kk):12:2);
        put /;
     );

 putclose payofile;
 payofile.ap=1;
 PUT ' ' /;
 option bratio = 0;
* option bratio=0 is for exploiting previous basis information in consecutive solve statements
 totcounter=0
 put '      z1           z2           z3 '/;
 for (g2=0 to numg2,
        RHS('2') = (dir('2')+1)/2*MINOBJ('2')-(dir('2')-1)/2*MAXOBJ('2') +
dir('2')*(g2/numg2)*(MAXOBJ('2')- MINOBJ('2'));
        for (g3=0 to numg3,
                RHS('3') = (dir('3')+1)/2*MINOBJ('3')-(dir('3')-1)/2*MAXOBJ('3') + dir('3')*(g3/numg3) *
(MAXOBJ('3')-MINOBJ('3'));
        SOLVE PGEN USING LP MAXIMIZING A_OBJVAL ;
        loop((i,j), put j.tl, @20, i.tl, @32, x.l(i,j):6:5 /);
        totcounter=totcounter+1;
        if (PGEN.modelstat=4 or PGEN.modelstat=9 or PGEN.modelstat=10,
          PUT totcounter:4:0,' infeasible '/;
* force it to exit the loop if infeasible
* if g3=0 at infeasibility means that you must also exit the g2 loop
           if (g3=0, g2=numg2);
           g3=numg3;
           Else
           PUT totcounter:4:0, Z.L('1'):12:2 ;
           loop(km1,
              put Z.L(km1):12:2 ;
              );
           put / ;

           );
        );
    );
 putclose payofile;
```

APPENDIX F: Transportation distance calculations

Oilseed transportation distance

STATSSA,2007: There are 284 local municipalities countrywide occupying an area of 1220813 km^2:

284	municipalities	
1,220,813	km2 national area	
4,299	km2/municipality	
73.98	km average local municipal diameter	**Oilseed transportation distance**

Maize transportation distance

Data from *ETHANOL AFRICA & ARC-LAND SUITABILITY REPORT*

7	Bioethanol plants within maize growing areas [Ethanol Africa plants only]
20,828,000	ha of nationally suitable land for maize
208,280	km2 of nationally suitable area for maize
29,754	km2/plant
194.64	km average maize transportation diameter

Wheat transportation distance

Data from ETHANOL AFRICA & ARC-LAND SUITABILITY REPORT

8	Bioethanol plants [7 Ethanol Africa plants & 1 Western Cape plant]
16,039,000	ha of nationally suitable land for grains
160,390	km2 suitable area
20,049	km2/plant
159.77	km average wheat transportation diameter

Sweet sorghum transportation distance

Data from ARC-LAND SUITABILITY REPORT & SASA

1,161,526	ha, area in sugar growing areas where mills are clustered
25,203,000	ha of nationally suitable land for sweet sorghum
24,041,475	ha: S-Sorghum suitable area far from sugar mills
240,415	km2/plant
553.27	km average sweet sorghum transportation diameter

APPENDIX G: Energy Coefficients and Emission factors

Steel Energy Coefficient

Energy consumption in Iron & steel production South Africa in PJ [2000 data]		
143.2	Commercial coal	
59.7	Coke oven gas	
53.7	Coke oven coke	
87.5	electricity	
8.9	fuel oil	
10	Hydrogen rich gas	
0	natural gas	
363,000,000	**GJ total**	[From: DME, 2002, Energy outlook]
8,622,000	**tons total**	[From SAISI website]
42.10	**GJ/ton [MJ/kg]**	Steel Energy coefficient

Concrete Energy Coefficient

Cement & Brick production [2000 data]		
Mass per brick	2.4	kg/brick
No of bricks produced per year	978,000,000	From: Stats SA 2001
Mass of brick produced per year	2,347,200	tonnes/yr
Mass of cement produced per year	8,715,000	tonnes/yr
Total Cement & bricks	**11,062,200**	**tonnes/yr**
Energy Consumption in PJ		
	32.7	Coal
	20.5	Electricity
	3.4	Fuel oil
	6.5	Hydrogen rich gas
	63,100,000	**GJ total** [DME, 2002, Energy outlook]
	5.70	**GJ/ton [MJ/kg]**

Labour Energy Coefficient

Per Capita Energy consumption 2004 in PJ		
3,573.34	Coal	
94.15	Natural gas	
1,016.66	Crude oil	
145.90	Nuclear	
4,830,060,000	**GJ Non-Renewable**	[From: DME, 2004 Energy Planning]
44,820,000	2001 Population	
107.77	**GJ/person**	

Emission Factor Table

Emission Source	Units	Direct	Indirect	Total Emissions	Total Emissions	
				Native units	Value	Units
Fuel/Energy						
TRAIN	kg CO2/ton-km	0.02	0.12	0.14	**0.14**	kg CO2/ton-km
CRUDE OIL		20.0		20	**73.33**	kg CO2/ GJ
Petrol (Gasoline)	kg C/GJ	18.9	3.41	22.31	**81.80**	kg CO2/ GJ
Diesel	kg C/GJ	20.2	3.87	24.07	**88.26**	kg CO2/ GJ
Fuel Oil	kg C/GJ	21.1	4.95	26.05	**95.52**	kg CO2/ GJ
Natural Gas	kg C/GJ	15.3	9.53	24.83	**91.04**	kg CO2/ GJ
Coal	kg C/GJ	25.8	0.42	26.22	**96.15**	kg CO2/ GJ
Coke Oven gas	kg C/GJ	12.1	0.42	12.52	**45.91**	kg CO2/ GJ
Coke oven coke	kg C/GJ	29.2	0.42	29.62	**108.61**	kg CO2/ GJ
Electricity	kg CO2 / kwh		0.98	0.98	**271.84**	kg CO2/ GJ
Agrochemicals						
Nitrogen	kg C/Mg	1,461.43	1,014.85	2,476.28	**9.08**	kg CO2/ kg
P2O5	kg C/Mg		471.16	471.16	**1.73**	kg CO2/ kg
K2O	kg C/Mg		240.54	240.54	**0.88**	kg CO2/ kg
Lime	kg C/Mg	120.00	57.10	177.10	**0.65**	kg CO2/ kg
Herbicides	kg C/Mg		8,844.08	8,844.08	**32.43**	kg CO2/ kg
Insecticides	kg C/Mg		10,240.01	10,240.01	**37.55**	kg CO2/ kg
Fungicides	kg C/Mg		9,661.79	9,661.79	**35.43**	kg CO2/ kg
Trash burning (t dry matter burnt)	kg CO2eqt/kg	0.08		0.08	**0.08**	kg CO2/ kg
Machinery & Buildings						
Cement	kg CO2/ kg		0.82	0.82	**0.82**	kg CO2/ kg
Carbon Steel	kg CO2/ kg		11.17	11.17	**11.17**	kg CO2/ kg
Stainless Steel	kg CO2/ kg		11.17	11.17	**11.17**	kg CO2/ kg
Processing chemicals						
Grain milling & fermentation chemicals	kg CO2/ton bdiesl				**0.02**	kg CO2/ litre EtOH
Cane crushing & fermentation chemicals	kg CO2/ton cane		1.8	1.80	**0.02**	kg CO2/ litre EtOH
Transesterification chemicals	kg CO2/ton bdiesl		75.67	75.67	**0.07**	kg CO2/ litre bdsl
Processing Energy requirements						
Grain milling & fermentation	kg CO2/litre EtOH		1.59	1.59	**1.59**	kg CO2/litre EtOH
Oilseed crushing & transesterification	kg CO2/kg seed		144.84	144.84	**144.84**	kg CO2/ ton seed
Transportation						
Maize	kg CO2/tonne	26.77		26.77	**26.77**	kg CO2/tonne
Wheat	kg CO2/tonne	21.97		21.97	**21.97**	kg CO2/tonne

Sugarcane	kg CO2/tonne	4.13		4.13	**4.13**	kg CO2/tonne
Sweet sorghum	kg CO2/tonne	77.21		77.21	**77.21**	kg CO2/tonne
Soybean	kg CO2/tonne	10.17		10.17	**10.17**	kg CO2/tonne
Sunflower	kg CO2/tonne	10.17		10.17	**10.17**	kg CO2/tonne
Canola	kg CO2/tonne	10.17		10.17	**10.17**	kg CO2/tonne
Grain ethanol transportation	kg CO2/tonne EtOH	34.89		34.89	**0.03**	kg CO2/litre EtOH
Cane ethanol tranportation	kg CO2/tonne EtOH	34.89		34.89	**0.03**	kg CO2/litre EtOH
Biodiesel transportation	kg CO2/ton bdiesl	34.89		34.89	**0.03**	kg CO2/litre biodsl
Labour	kg CO2/person		9.52	9.52	**9.52**	kg CO2/person
Seed						
Maize	kg C/kg seed		1.05	1.05	**3.85**	kg CO2/kg seed
Wheat	kg C/kg seed		0.11	0.11	**0.4033**	kg CO2/kg seed
Sugarcane	kg CO2/tonne cane		0.37	0.37	**27.07**	kg CO2/ha
Sweet sorghum	kg C/kg seed		0.86	0.86	**3.15**	kg CO2/kg seed
Soybean	kg C/kg seed		0.25	0.25	**0.92**	kg CO2/kg seed
Sunflower	kg C/kg seed				**2.77**	kg CO2/kg seed
Canola	kg CO2/kg seed		0.32	0.32	**0.32**	kg CO2/kg seed
OUTPUTS (Replacement products)						
Maize DDGS	kg CO2/litre		0.81	0.81	**0.81**	kg CO2/litre
Wheat DDGS	kg CO2/litre		1.44	1.44	**1.44**	kg CO2/litre
Sugarcane electricity	kg CO2/litre		0.20	0.20	**0.20**	kg CO2/litre
Sorghum grain & electricity	kg CO2/litre		0.61	0.61	**0.61**	kg CO2/litre
Soybean meal & glycerol	kg CO2/litre		3.27	3.27	**3.27**	kg CO2/litre
Sunflower meal & glycerol	kg CO2/litre		1.24	1.24	**1.24**	kg CO2/litre
Canola meal & glycerol	kg CO2/litre		1.07	1.07	**1.07**	kg CO2/litre
Glycerol	kg CO2/kg		4.76	4.76	**4.76**	kg CO2/kg

Key:

(yellow)	From JRC, 2006, IN Macedo, 2008
(light blue)	From
(green)	From IPCC
(orange)	From West

APPENDIX H: Transportation and Processing cost calculations

Truck Transportation Cost Calculations

TRUCK TRANSPORTATION COSTS						
10	ton	Truck Size				
10.2	R/km	[From: Randburg Truck hire]				
2,700	R/day	[From: Randburg Truck hire]				
50	km/hr	Average truck speed				
1	hrs required to load & offload					
NB: Total annual cost is the sum of the daily rate charge and the excess km charge						
	Maize	**Wheat**	**Sugarcane**	**Soybean**	**Sunflower**	**Canola**
return trips required /yr = plant capacity/(truck size* litres biofuel/ton crop)	25,748	30,272.21	159,018	11,119.93	5,267.33	5,003.97
Million km travelled/yr	5.01	4.83	4.77	0.82	0.39	0.37
Million R/yr (excess km only)	**51.12**	**49.33**	**48.66**	**8.39**	**3.97**	**3.78**
driving hrs required per return trip	3.89	3.20	0.6	1.48	1.48	1.48
Total hrs required per return trip	4.89	4.20	1.6	2.48	2.48	2.48
No of trips/day (calculated)	1.64	1.91	5.00	3.23	3.23	3.23
No of trips/day	1	1	5	3	3	3
No of days required/yr (calculated)	25,748.22	30,272.21	31,803.54	3,706.64	1,755.78	1,667.99
No of DAYS required/yr	25,749	30273	31,804	3,707	1,756	1,668
Million R/yr (daily charge only)	**69.52**	**81.74**	**85.87**	**10.0089**	**4.74**	**4.5**
TOTAL ANNUAL COST, Million R/yr	**120.64**	**131.07**	**134.53**	**18.40**	**8.72**	**8.28**

Rail Transportation Costs

SA'S RAIL FREIGHT DATA [2006] From: http://www.southafrica.info		
Number of electric locomotives	1,914	60.5%
number of diesel locomotives	1,249	39.5%

SPOORNET CHARGE RATES [R/ton] From: Nolte, 2007			
ITEM	**250km**	**500km**	**1000km**
Crops	91.25	140.62	230
Biofuel	161.35	274.55	408.5

Processing Costs (A)

	SWEET SORGHUM processing		**SUGARCANE processing**		**MAIZE processing**		**WHEAT processing**	
Plant Capacity	125.00	Million litres/yr	125.00	Million litres/yr	108.40	Million litres/yr	108.40	Million litres/yr
	Annual cost (Million R/yr)	**Rand/litre**	**Annual cost (Million R/yr)**	**Rand/litre**	**Annual cost (Million R/yr)**	**Rand/litre**	**Annual cost (Million R/yr)**	**Rand/litre**
variable Costs								
Energy/extraction cost	0		73.712		73.712	0.68	73.712	0.68
Chemicals etc	12.32	0.10	56.368	0.10	56.368	0.52	56.368	0.52
Labour	10	0.08	11.924	0.08	11.924	0.11	11.924	0.11
Water	2.5	0.02	2.168	0.02	2.168	0.02	2.168	0.02
Transport costs	282.984	2.26	134.458	1.20	134.458	1.24	144.888	1.34
Maintenance & insurance	30	0.24	3.252	0.24	3.252	0.03	3.252	0.03
Subtotal	**337.804**	**2.70**	**281.882**	**1.64**	**281.882**	**2.60**	**292.312**	**2.70**
Fixed costs								
Depreciation (6.7% fixed cap)	44.338	0.35	20.596	0.35	20.596	0.19	20.596	0.19
Capital charges	36.562	0.29	14.634	0.29	14.634	0.14	14.634	0.14
Working capital costs	7.941	0.06	6.504	0.06	6.504	0.06	6.504	0.06
Admin (25% of overheads)	8.750	0.07	3.252	0.07	3.252	0.03	3.252	0.03
Subtotal	**97.591**	**0.781**	**44.986**	**0.781**	**44.986**	**0.415**	**44.986**	**0.415**
Total	**435.40**	**3.48**	**326.87**	**2.42**	**326.87**	**3.02**	**337.30**	**3.11**

Processing Costs (B)

	SOYBEAN processing		SUNFLOWER processing		CANOLA processing	
Plant Capacity	46.53	Million litres/yr	46.53	Million litres/yr	46.53	Million litres/yr
	Annual cost (Million R/yr)	**Rand/litre**	**Annual cost (Million R/yr)**	**Rand/litre**	**Annual cost (Million R/yr)**	**Rand/litre**
variable Costs						
Energy/extraction cost	30.164	1.34	14.288	0.64	13.574	0.60
Chemicals etc	13.66	0.61	13.7	0.61	13.66	0.61
Labour	1.992	0.09	1.992	0.09	1.992	0.09
Water	0.013	0.00	0.013	0.00	0.013	0.00
Transport costs	21.595	0.96	11.911	0.53	11.474	0.51
Maintenance & insurance	5.399	0.24	5.399	0.24	5.399	0.24
Subtotal	**72.823**	**3.24**	**47.303**	**2.10**	**46.112**	**2.05**
Fixed costs						
Depreciation (6.7% fixed cap)	7.713	0.34	7.713	0.34	7.713	0.34
Capital charges	3.252	0.14	3.252	0.14	3.252	0.14
Working capital costs	2.325	0.10	2.535	0.11	2.288	0.10
Admin (25% of overheads)	0.813	0.04	0.813	0.04	0.813	0.04
Subtotal	**14.103**	**0.627**	**14.313**	**0.636**	**14.066**	0.63
Total	**86.93**	**3.86**	**61.62**	**2.74**	**60.18**	**2.67**

APPENDIX I: Avoided GHG emissions calculations

Avoided GHG emissions Table

			Maize Ethanol			**Wheat Ethanol**			**Sugarcane Ethanol**		
	EF		*Activity value*		*Emissions*	*Activity value*		*Emissions*	*Activity value*		*Emissions*
Seeds	1		48.125	kg CO2/ha	48.125	48.4		48.400	27.07		27.07
Fuel	88.26	kgCO2/GJ	3.11	GJ/ha	274.638	2.80	GJ/ha	246.820	3.22	GJ/ha	284.26
N	9.08	kgCO2/kg	52.25	kg/ha	474.415	30	kg/ha	272.391	92.00	kg/ha	835.33
P2O5	1.728	kgCO2/kg	28.5	kg/ha	49.236	40	kg/ha	69.103	57.00	kg/ha	98.47
K2O	0.8820	kgCO2/kg	5.7	kg/ha	5.027	4	kg/ha	3.528	133.00	kg/ha	117.31
Lime	0.6494	kgCO2/kg	194	kg/ha	125.979	194	kg/ha	125.979	194	kg/ha	125.98
Herbicides	32.43	kgCO2/kg	2.23	kg/ha	72.315	4.94	kg/ha	160.034	2.20	kg/ha	71.34
Insecticides	37.55	kgCO2/kg	0.08	kg/ha	3.004	1.07	kg/ha	40.175	0.16	kg/ha	6.01
Fungicides	35.43		0		0.000	1.95	kg/ha	69.082	0		0.00
Trash	0.0830	kgCO2/kg	0	kg/ha	0.000	0	kg/ha	0.000	5705.00	kg/ha	473.52
Equipment (steel)	11.171	kgCO2/kg	23.02	kg steel/ha	257.179	23.022	kg steel/ha	257.179	33.462	kg steel/ha	373.81
Labour	9.520	kgCO2/person	0.0085	person/ha	0.081	0.008	person/ha	0.081	0.0767	person/ha	0.73
				kgCO2/ha	**1,310**		**kgCO2/ha**	**1,293**		**kgCO2/ha**	**2,413.82**
Chemicals	1	kgCO2/litre	0.02	per litre	0.023	0.02		0.023	0.023		0.02
Energy	1		1.59	per litre	1.5917	1.59		1.592	0.000		0.00
Crop trans	1	kgCO2/tonne	0.064	per litre	0.064	0.061	tonne/litre	0.061	0.052	tonne/litre	0.05
Biofuel trans	0.0276	kgCO2/litre	1.000	per litre	0.028	1.000		0.028	1.000		0.03
Labour	9.52	kgCO2/person	0.000	person/litre	0.00000	0.000	person/litre	0.000	0.000	person/litre	0.00
steel	11.17	kgCO2/kg	0.001	kg/litre	0.0074	0.001	kg/litre	0.007	0.002	kg/litre	0.02
concrete	0.82	kgCO2/kg	0.006	kg/litre	0.0051	0.006	kg/litre	0.005	0.005	kg/litre	0.00
				kgCO2/litre	**1.718**		**kgCO2/litre**	**1.716**		**kgCO2/litre**	**0.12**
				kgCO2/ha	**2193**		**kgCO2/ha**	**1724**		**kgCO2/ha**	**566.87**
total				**kgCO2/ha**	**3,503**		**kgCO2/ha**	**3,016**		**kgCO2/ha**	**2,981**
Avoided GHG Emissions											
Biofuel	1	GJ/litre	81.80	kgCO2/GJ	1.74	81.80	kgCO2/GJ	1.74	81.80	kgCO2/GJ	1.74
Byproduct	1		0.81	kgCO2/litre	0.81	1.44	kgCO2/litre	1.44	0.20	kgCO2/litre	0.20
				kgCO2/litre	**2.55**		kgCO2/litre	**3.18**		kgCO2/litre	**1.94**
				kgCO2/ha	**3,255.20**		kgCO2/ha	**3,191**		kgCO2/ha	**8,845**
NET AVOIDED GHG EMISSIONS			**kgCO2/ha**		**-247**	**kgCO2/ha**		**175**	**kgCO2/ha**		**5,864**

Avoided GHG emissions Table continued

Sweet sorghum ethanol			Soybean biodiesel			Sunflower biodiesel			Canola biodiesel		
Activity value		*Emissions*	*Activity value*		*Emissions*	*Activity value*		*Emissions*	*Activity value*		*Emissions*
22.86		22.86	69.76		69.76	9.71		9.71	1.42		1.42
6.73	GJ/ha	593.75	2.84	GJ/ha	250.58	2.70	GJ/ha	238.72	2.71	GJ/ha	239.03
120.00	kg/ha	1,089.56	2.80	kg/ha	25.42	12.75	kg/ha	115.77	57.50	kg/ha	522.08
40.00	kg/ha	69.10	10.00	kg/ha	17.28	17.85	kg/ha	30.84	68.75	kg/ha	118.77
40.00	kg/ha	35.28	3.20	kg/ha	2.82	1.70	kg/ha	1.50	65.20	kg/ha	57.51
194.00	kg/ha	125.98	194.00	kg/ha	125.98	194.00	kg/ha	125.98	194.00	kg/ha	125.98
3.00	kg/ha	97.28	0.00	kg/ha	0.00	2.50	kg/ha	81.07	1.02	kg/ha	33.16
9.00	kg/ha	337.92	1.20	kg/ha	45.06	0.00	kg/ha	0.00	0.04	kg/ha	1.35
0.00		0.00	0.00		0.00	0.00		0.00	0.00		0.00
0.00	kg/ha	0.00	0.00	kg/ha	0.00	0.00	kg/ha	0.00	0.00	kg/ha	0.00
23.02	kg steel/ha	257.18	20.83	kg steel/ha	232.71	20.83	kg steel/ha	232.71	20.83	kg steel/ha	232.71
0.01	person/ha	0.08	0.01	person/ha	0.08	0.01	person/ha	0.08	0.01	person/ha	0.08
	kgCO2/ha	**2,629.00**		**kgCO2/ha**	**769.68**		**kgCO2/ha**	**836.37**		**kgCO2/ha**	**1,332.09**
0.02		0.02	0.07	per litre	0.07	0.07	per litre	0.07	0.07	per litre	0.07
0.00		0.00	0.72	per litre	0.72	0.34	per litre	0.34	0.32	per litre	0.32
1.17	tonne/litre	1.17	0.05	per litre	0.05	0.02	per litre	0.02	0.02	per litre	0.02
1.00		0.03	1.00	per litre	0.03	1.00	per litre	0.03	1.00	per litre	0.03
0.00	person/litre	0.00	0.00	person/litre	0.00	0.00	person/litre	0.00	0.00	person/litre	0.00
0.00	kg/litre	0.02	0.00	kg/litre	0.01	0.00	kg/litre	0.01	0.00	kg/litre	0.01
0.01	kg/litre	0.00	0.01	kg/litre	0.01	0.01	kg/litre	0.01	0.01	kg/litre	0.01
	kgCO2/litre	**1.24**		kgCO2/litre	**0.88**		kgCO2/litre	**0.48**		kgCO2/litre	**0.46**
	kgCO2/ha	**2,612.51**		**kgCO2/ha**	**201.45**		**kgCO2/ha**	**194.95**		**kgCO2/ha**	**237.58**
	kgCO2/ha	**5,242**		**kgCO2/ha**	**971**		**kgCO2/ha**	**1,031**		**kgCO2/ha**	**1,570**
81.80	kgCO2/GJ	1.74	88.26	kgCO2/GJ	2.91	88.26	kgCO2/GJ	2.91	88.26	kgCO2/GJ	2.91
0.61	kgCO2/litre	0.61	3.27	kgCO2/litre	3.27	1.24	kgCO2/litre	1.24	1.07	kgCO2/litre	1.07
	kgCO2/litre	**2.34**		kgCO2/litre	**6.18**		kgCO2/litre	**4.14**		kgCO2/litre	**3.97**
	kgCO2/ha	**4,921**		kgCO2/ha	**1,415**		kgCO2/ha	**1,696**		kgCO2/ha	**2,060**
kgCO2/ha		**-321**	**kgCO2/ha**		**444**	**kgCO2/ha**		**665**	**kgCO2/ha**		**490**

APPENDIX J: Estimating Case-Study parameters

Estimating Underutilized land in Maluti-a-Phofung

Arable Emerging farmers' land in Maluti-a-Phofung [Personal communication]			
Farmer	**Total Farm land, ha**	**Arable land on Farm, ha**	**% of arable land**
Shadrack Moloi	118	17	14.41
Lekhotla Makoele	386	173	44.82
Tefo Ntholeng	250	185	74.00
Lepati Macaphasa	506	116	22.92
Average %			**39.04**
Emerging farmers land [From: DPLG, 2007]	95,896	37,435	39.04
Semi-urban state land	10,000	3,904	39.04

2nd Grade Grain prices and profits

[All prices from: GrainSA]	Market price	% of 2nd Grade price to market price	2nd Grade price	Profit
Maize grain [R/ton]	1,805	94.7	1709	498
Wheat grain [R/ton]	3,706	97.0	3,594	2,600
Sorghum grain [R/kg]	1.53		0.50	1.03

Estimating Sweet sorghum cane profits

Sweet sorghum agricultural costs & Profits @ RV price of R207.50					
Production Costs					**Profit [R/ton]**
R/ha	**R/ton**	**In native units**		**Reference**	
1,719.07	53.92			ICRISAT	153.58
2,039.10	63.95	10500	Rupees/ha	Prabu - The Hindu newspaper	143.55
2195.6	68.86	220	US$/ha	ICRISAT2	138.64
	62.24	**Average**			**145.26**

Agricultural Profits in Eastern Freestate, 2006-2008 [From: GrainSA]

	Maize	Wheat	Soybean	Sunflower
1. Lopende koste/Variable cost				
Saad/Seed	388.00	108.00	336.00	153.00
Kunsmis en kalk/Fertiliser & Lime	735.00	494.00	792.00	743.00
Onkruidbeheer/Weed control	174.00	98.00	132.00	22.00
Plaagbeheer/Pest control	112.00	91.00	17.00	209.00
Brandstof/Fuel	484.00	465.00	475.00	694.00
Herstelwerk en onderdele/Repairs & parts	472.00	366.00	493.00	657.00
Oesversekering/Crop insurance				
Seisoensarbeid/Casual labour	18.00	6.00	0.00	11.00
Gereelde arbeid/Permanent labour	395.00	286.00	212.00	313.00
Lisensies & versekering	0.00	0.00	0.00	0.00
Bemarkingskoste/Marketing cost				
Droog,sif& opberging/Drying, cleaning & storage			131.00	72.00
Pakmateriaal/Packaging material		177.82	3.00	0.00
Rente op produksiekrediet/Interest on production credit	288.77		264.45	267.45
Kontrakwerk/Contract work				
Ander koste/Other cost	135.00	235.00	370.00	370.00
Totaal lopende koste/Total variable cost	**3201.77**	**2326.82**	**3225.45**	**3511.45**
2. Kapitaalkoste/Capital cost				
Masjinerie en gereedskap/Machinery & equipment:				
Depresiasie/Depreciation	172.60	172.60	189.86	189.86
Rente/Interest	258.90	258.90	284.79	284.79
Vaste verbeterings/Fixed improvements				
Rente/Interest	0.00	0.00	0.00	0.00
Depresiasie/Depreciation	0.00	0.00	0.00	0.00
Herstel & onderhoud/Repairs & maintenance	36.00	34.00	37.40	37.40
Totaal kapitaalkoste/Total capital costs	**467.50**	**465.50**	**512.05**	**512.05**
Totale koste per ha/Total cost per ha	**3669.27**	**2792.32**	**3737.50**	**4023.50**
Opbrengs/Yield (ton/ha)	3.03	2.81	1.12	0.95
Koste/Cost (R/ton)	**1210.58**	**993.71**	**3337.05**	**4244.20**
Inkomste/Income				
Produsenteprys/Producer price (R/ton)	1805.00	3706.00	4550.00	4935.00
Per ha				
Wins/Verlies/Profit/Loss				
Per ha				
Per ton:	**594.42**	**2712.29**	**1212.95**	**690.80**

Maluti-a-Phofung Case study truck transportation costs

TRUCK TRANSPORTATION COSTS		
10	ton Truck	
10.2	R/km	From: Randburg Truck hire
2700	R/day	From: Randburg Truck hire
50	km/hr	truck speed
1	hrs required to load & offload	
	Maize	**Wheat**
Plant capacity, Million litres/yr	108.4	108.4
Distance to plant, km	145.34	145.34
return trips reqd /yr	25,748	30272.20747
Million km travelled/yr	3.74	4.40
Million R/yr (excess km only)	**38.17**	**44.88**
driving hrs reqd per return trip	2.91	2.9068
Total hrs reqd per return trip	3.91	3.9068
No of trips/day (calc)	2.047711682	2.05
No of trips/day	2	2
No of days reqd/yr (calc)	12,874.11	15,136.10
No of DAYS reqd/yr	12,875	15,137
Million R/yr (day charge only)	**34.76**	**40.87**
TOTAL (Million R/yr)	**72.93**	**85.75**
TOTAL (R/litre)	**0.6728**	**0.7910**

- Transportation distance for sweet sorghum = 621 km
- The freight transportation cost table in Appendix H was used to estimate sweet sorghum transportation costs