



University of Zimbabwe
Faculty of Science
Department of Physics

THE AGROCLIMATIC POTENTIAL OF FUEL CROPS IN ZIMBABWE

By
Alois Tsiga

A thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Agricultural Meteorology

June 2007

“The scientist does not search for the truth. The truth finds the scientist.”

(Ponomarev L.I., 1988: *The Quantum Dice*)

DEDICATION

To my guardian angels, Cecilia and Benson.

Jah Bless.

ABSTRACT

The main objective of this thesis was to assess the agro-climatic potential of fuel crops (typically sorghum) in Zimbabwe using a revised map of solar radiation received at the surface. To achieve this objective climatic data, principally, maximum and minimum temperatures, and surface solar radiation were collected and analyzed.

Values of solar radiation data gathered from two terrestrial and one satellite source did not agree closely. Satellite estimates of solar radiation were found to be on average, at least 21 % lower than ground based measurements. Values from the Climatic Handbook, updated with more recent records from the Zimbabwe Meteorological Department were used to produce monthly radiation maps using the computer program Surfer.

Potential yields (biomass production) of sweet sorghum (Keller variety) under existing climate conditions were calculated using the Ceres model within the Decision Support System for Agrotechnology Transfer (DSSAT version 4.0) for four stations, representative of different Agroecological Zones of Zimbabwe. A few sensitivity tests were implemented to test the response of the potential yield to changes in environmental conditions, as well as a change in the sorghum variety. Potential yields assessment gave high productivity over Karoi (Natural Region IIa) and Masvingo (Natural Region IV) relative to Harare, and Buffalo Range. The lowest potential yield was found in Buffalo Range. However, while Karoi and Masvingo had high yields but, Masvingo displayed a shorter growing season, that means it has a relatively higher biomass production rate.

From the sensitivity tests, a 2 °C rise in maximum temperature (warmer climate) as well as a reduction in surface solar radiation of 5 MJ/m²/day resulted in a decrease in potential yields. The average potential yield decrease under a temperature modified environment was about 4 % and under reduced surface radiation about 9 %.

The potential yields of sweet sorghum (Keller variety) were compared with those of grain sorghum (Pioneer 8333) for the current climate of Karoi. A comparison of the potential yields of two sorghum varieties, Keller (sweet) and Pioneer 8333 (grain) over the Karoi site did not give significant differences. Notable differences, however, were found in the length of the growing period (LGP); Pioneer displayed a short growing period relative to Keller.

The project illustrates the first part of the methodology required to evaluate the potential and economic benefits of different fuel crops in Zimbabwe. Further studies of alternative crops and varieties, and the costs of fuel production are required.

ACKNOWLEDGEMENT

This thesis was made possible through the assistance of Professor James Milford, my colleague Anywhere “Einstein” Tsokankunku, whose tireless efforts with DSSAT4 were invaluable for my modeling exercise. Also deserving special mention is Mr. Albert Mhanda, head of IS at the Meteorological Service Department who assisted me with database management compatible with the model requirements. I would also want to thank my supervisor, Sebinasi Dzikiti for finding time to go through my project and making the final corrections.

More importantly, my gratitude goes to the sponsors of the MAGM Project, the Flemish Inter-University Council (VLIR) and the Coordinator Mr. B. Chipindu who flawlessly coordinated the MAGM program. Not forgetting the government of Zimbabwe through the Director of Meteorological Services, Dr. A. Makarau (Permanent Representative of Zimbabwe with WMO) who afforded me the opportunity to take study leave to pursue my academic career in Agricultural Meteorology. Also deserving of special mention are the data providers, the Zimbabwe Meteorological Services through their IS unit and International Research Institute (USA-IRI) – Climatic Research Unit, University of East Anglia (UK-CRU) who availed all the data used in the analysis.

My fellow students deserve special mention for all their useful hints and tips. They made the working environment bearable through their humorous comments. Together we were ONE.

Last and not least, my family that had to endure my riotous time table, I am eternally grateful for their patience and understanding.

TABLE OF CONTENTS

DEDICATION.....	iii
ABSTRACT.....	iv
ACKNOWLEDGEMENT.....	v
LIST OF FIGURES.....	xi
ABBREVIATIONS AND SYMBOLS.....	xii
CHAPTER 1: INTRODUCTION.....	1
1.1 The Justification of the Research Project.....	1
1.2 Benefits of the study.....	2
1.3 Objectives of the study.....	3
1.4 Target Area.....	4
1.5 Thesis Layout.....	5
CHAPTER 2: LITERATURE REVIEW.....	6
2.1 Historical background.....	6
2.1.1 Principles of bio-diesel production technology.....	6
2.1.2 Advantages of Bio-diesel:.....	6
2.2 Biomass use: Experience from Other Countries.....	9
2.2.1 Australia.....	9
2.2.2 South Africa.....	9
2.2.3 Brazil.....	10
2.2.4 United States of America.....	10
2.2.5 Canada.....	10
2.2.6 Zimbabwe.....	11
2.2.6.1 Background of <i>Jatropha</i> plant in Zimbabwe.....	11
2.3 Arguments against bio-fuels.....	12
2.4 The Challenge.....	14
2.5 Reasons for Factoring Temperature and Solar Radiation in the Cultivation of Fuel Crops.....	15
2.5.1 Effect of temperature on plant growth and development.....	16
2.5.1.1 Distribution.....	16
2.5.1.2 Photosynthesis.....	16
2.5.1.3 Dry Matter Accumulation.....	17
2.5.1.4 Expansion Growth.....	18
2.5.1.5 Phenological Development.....	18
2.5.1.6 Diurnal Temperature Variation.....	19
2.5.1.7 Freezing Temperatures.....	19
2.5.1.8 Germination and Seedling Growth.....	19
2.5.2 Solar Radiation.....	19
2.6 The Climate of Zimbabwe.....	20
2.6.1 Background.....	20
2.6.2 Temperature.....	21
2.6.3 Solar Radiation.....	21
2.6.4 Rainfall.....	22
2.6.5 Agro-climatic mapping.....	23
2.7 Literature review on Fuel Crops and Bio-fuels.....	24
2.7.1 Sweet Sorghum (<i>Sorghum bicolor</i> (L.) Moench].....	24
2.7.1.1 Plant profile.....	24

2.7.1.2 Why Sweet Sorghum?	24
2.7.1.3 Climate influence on sorghum production	26
2.7.1.4 Ethanol production from sweet sorghum:	27
2.7.2 Components of sweet sorghum stem juice	27
2.7.2.1 Brix degree in sweet Sorghum stem	27
2.7.2.2 Total Sugar Content in Juice of Sweet Sorghum	28
2.7.2.3 Glucose content	28
2.7.3 Sugar Cane (<i>Saccharum officinarum</i>)	29
2.7.3.1 Plant profile	29
2.7.3.2 Cultivation	29
2.7.3.3 Sugarcane Yield	30
2.7.3.4 Water Requirements	31
2.7.3.5 Sugarcane in Zimbabwe	32
2.7.3.6 Propagation	32
2.7.3.7 Harvesting Cane	33
2.7.3.8 Transportation	33
2.7.3.9 Sugarcane for Production of Ethanol	33
2.7.4 <i>Jatropha Curcas</i> Plant	34
2.7.4.1 Plant Profile	34
2.7.4.2 Distribution and habitat	34
2.7.4.3 Climate	35
2.7.4.4 Biophysical limits	35
2.7.4.5 Flowering and fruiting habit	35
2.7.4.6 Crop Yield	35
2.7.4.7 Zimbabwe <i>jatropha</i> experience summarized	37
CHAPTER 3: MATERIALS AND METHODS	38
3.1 Introduction	38
3.2 The climate data and their sources	39
3.2.1 Solar radiation data sources	39
3.2.1.1 Ground-based observations	39
3.2.1.2 Instruments used	40
3.2.1.3 Satellite based solar radiation data	41
3.2.1.4 Errors in satellite estimates	41
3.2.1.5 Comparison of data sources for solar radiation	41
3.2.1.6 Differences in the sources	41
3.2.2 Temperature data	44
3.2 Analysis Methods and Tools	45
3.2.1 Surfer 32 version 6.04	46
3.2.2 Crop Modelling	46
3.2.2.1 DSSAT software package system background	46
3.2.2.2 Minimum Data Set (MDS)	47
3.2.2.3 Introduction to Crop Simulation (ICSim) tool	47
3.2.2.4 Differences and limitations of ICSim relative to DSSAT v4 (XBuild) capabilities (Hoogenboom, 2003)	48
3.2.2.5 Outputs of ICSim	49
3.2.2.6 Data type and sources for computer simulation	49
3.2.2.7 Cultivar coefficients in CSM	49
3.3 Crop simulation methodology	50
CHAPTER 4: RESULTS	51
4.1 Introduction	51
4.2 Solar Radiation Data	51
4.2.1 Comparison of the radiation maps	52

4.2.2 Results for solar radiation sources mapping	54
4.2.2.1 <i>Summary of mapping results</i>	55
4.2.3 Quantitative comparison between satellite and ground based measurements ..	55
4.2.3.1 <i>Summary of radiation comparison</i>	58
4.2.4 Radiation data for modelling	58
4.3 Crop Simulation Results	58
4.3.1 Potential yield of sorghum (<i>Sorghum bicolor</i> , L Moench)	58
4.3.2 Potential yield results comparison	60
4.3.2.1 <i>Inter site yield comparisons</i>	60
4.3.2.2 <i>Results of Yield versus LGP</i>	62
4.4 Sensitivity Tests	66
4.4.1 Sensitivity tests under modified environmental conditions	66
4.4.1.1 <i>Harare Belvedere Site</i>	66
4.4.1.2 <i>Results of potential yield under modified environments</i>	67
4.4.1.3 <i>Buffalo Range Site</i>	68
4.4.1.4 <i>Masvingo Site</i>	68
4.4.1.5 <i>Karoi Site</i>	69
4.4.2 Sensitivity test for different sorghum varieties	71
4.4.2.1 <i>Comparison of potential yields between the two varieties</i>	71
4.4.2.2 <i>Comparison of the length of the growing period between the varieties</i> ...	72
4.4.2.3 <i>Comparison of the growing period under a modified environment</i>	73
4.4.2.4 <i>Results for modified temperature environment</i>	74
4.4.2.5 <i>Summary of results on the differences in potential yield at each site</i> <i>under different environmental conditions:</i>	74
4.5 Conversion Efficiency for Sorghum	76
CHAPTER 5: DISCUSSION	77
5.1 Introduction	77
5.2 Radiation	77
5.2.1 Comparison of radiation sources	77
5.2.2 Solar radiation and crop yield	79
5.3 Potential Yield	81
5.3.1 Introduction	81
5.3.2 Potential yield under existing environmental conditions at different sites	81
5.3.3 Potential Yield under a Modified Environment	81
5.3.4 Potential yield versus length of growing period (LGP)	82
5.4 Sensitivity tests discussion	85
5.4.1 Different varieties compared	85
5.5 Conversion efficiency of biomass yield to bio-ethanol	87
5.5.1 Conversion efficiency of sweet sorghum	87
5.5.2 Potential Yield of Sugar Cane	87
5.5.2.1 <i>Productivity of sugarcane in Zimbabwe</i>	88
5.5.2.2 <i>Comparative Productivity in South Africa</i>	90
5.6 Conversion efficiency to bio-fuel for the different fuel crops	91
5.6.1 Potential Yield of Jatropha	91
5.6.2 Conversion efficiency of the jatropha seed oil to biodiesel	92
5.6.3 Comparison of conversion efficiencies of the different fuel crops	92
5.7 Economics of Bio-Fuel Production	93
5.7.1 Introduction	93
5.7.2 Land Availability	94
5.7.3 Productivity of the fuel crops	94
5.7.4 Fibre Production	94
5.7.5 Energy Balance	95

5.8 A Market for Ethanol	96
<u>5.9 Clean development mechanism (CDM) of the Kyoto Protocol 1997).....</u>	<u>96</u>
CHAPTER 6: CONCLUSION.....	97
6.1 Introduction	97
6.2 Revised radiation maps.....	97
6.3 Simulated potential biomass production.....	97
6.3.1 Sensitivity of sorghum yield to environmental changes.	97
6.4 Recommendations	99
6.5 Future Issues.....	99
REFERENCES.....	100

LIST OF TABLES

Table 2.1 Emissions reduction comparisons of bio-diesel with reference to petroleum diesel
Table 2.2 Comparison of the yield, element use and cost of production for the different fuel crops
Table 2.3: WUE (in gl-1) and Consumptive water Use the crops in Comparison
Table 2.4: Comparison of sugar production among three crops.
Table 2.5: Sugar content of the different sweet sorghum varieties
Table 2.6: FAO sugarcane production rankings
Table 2.7: Crop coefficient (Kc) versus development stages
Table 2.8: Relative jatropha seed yield figures that can be expected for a farming system without irrigation.
Table 2.9: Relative jatropha seed yield figures that can be expected for a farming system with irrigation.
Table 3.1: Summary of data sources
Table 3.2: Mean monthly solar radiation for selected stations.
Table 4.1: The percentage difference between solarimeter measurements and satellite based estimates for selected stations and randomly selected months.
Table 4.2: Typical sites (stations) of the Natural Regions used in the analysis.
Table 4.3: Summary of potential biomass production of the sorghum variety Keller.
Table 4.4: Comparison of highest potential biomass production (yield) with length of growing period (LGP) and planting date.
Table 4.5: Correlation coefficients for LGP against biomass production
Table 4.6 Comparison of productivity rate (PR) at different sites for the highest potential biomass productivities.
Table 4.7: Potential yields of the sorghum varieties Keller (sweet) and Pioneer 8333 (grain)
Table 4.8: Difference in biomass production between the sorghum varieties; Keller and Pioneer 8333
Percentage difference in yields between the two varieties; Keller and Pioneer 8333.
Table 5.1: Comparison of solar radiation data from surface observations and satellite estimates.
Table 5.2: Summary of the sorghum varieties crop coefficients used in DSSAT v4.0.2.0
Table 5.3: Simulated and measured results for sugarcane; South African experiment.
Table 5.4: Potential Productivity of Jatropha according to maturity
Table 5.5: Potential conversion efficiencies of the different fuel crops

LIST OF FIGURES

- Figure 1.1 Location of Zimbabwe in the southern African subcontinent
- Figure 2.1: Response of net photosynthesis to air temperature in C3 and C4 plant
- Figure 2.2: Response of grass dry matter accumulation to day/night temperatures, 15/10, 18/13, 21/16, 27/22, 30/25, 33/28 and 36/31°C.
- Figure 2.3 Dry matter (g m^{-2}) versus Accumulated PAR for sweet sorghum
- Figure 2.4: The mean annual radiation map of Zimbabwe
- Figure 2.5: Sugarcane crop in Hawaii.
- Figure 2.6: *Jatropha curcas* fruits before they are ripe.
- Figure 3.1: Ground based station network for solar radiation measurements.
- Figure 3.2: Map showing the spatial distribution of the temperature stations used in the analysis
- Figure 4.1: Satellite and ground based mean monthly maps of solar radiation for Zimbabwe
- Figure 4.2: Correlation graph of radiation measurements between ground stations for different periods.
- Figure 4.3: Correlation graph of radiation measurements between ground observations and satellite estimates.
- Figure 4.4: Potential biomass yield at different sites under current climate.
- Figure 4.5: Length of growing period (LGP) versus biomass production.
- Figure 4.6: Biomass productivity rate (PR) at different sites under current climatic conditions.
- Figure 4.7: Harare: Potential biomass production under different environmental conditions and different planting dates.
- Figure 4.8: Buffalo Range: Potential biomass production under different environmental conditions and different planting dates.
- Figure 4.9: Masvingo: Potential biomass production under different environmental conditions and different planting dates.
- Figure 4.10: Karoi: Potential biomass production under different environmental conditions and different planting dates.
- Figure 4.11: Comparison of the potential biomass production for Keller and Pioneer 8333.
- Figure 4.12: Comparison of the LGP for Keller and Pioneer 8333 under current environmental conditions.
- Figure 4.13: Comparison of the LGP for Keller and Pioneer 8333 under a modified environment (+ 2 °C, maximum temperature).
- Figure 5.1: Percentage difference of satellite based radiation to ground based measurements.
- Figure 5.2: Mean monthly solar radiation cycle at different sites.
- Figure 5.3: The influence of planting date on yield and length of growing period of sweet sorghum.
- Figure 5.4: Productivity rate (ratio of potential yield to length of growing period) at different sites
- Figure 5.5: Above ground fresh matter composition for sweet sorghum and sugarcane
- Figure 5.6: Variations in the rate of partitioning for the various components
- Figure 5.7 The various energy consumers in the production cycle of sweet sorghum.

ABBREVIATIONS AND SYMBOLS

ARDA – Agricultural Development Authority
CDM – Clean Development Mechanism
CRU – Climate Research Unit
DSSAT - Decision Support System for Agro-technology Transfer
GHGs – Green house gases
IBSNAT - The International Benchmark Sites Network for Agro-technology Transfer
IDC – Industrial Development Corporation
IEA – International Energy Agency
IRI – International Research Institute
IS – Information Systems
Kc – Crop coefficient for evaporation measurements.
LGP – Length of the growing period
MAGM – Masters in Agricultural Meteorology
NOCZIM – National Oil Company of Zimbabwe
PAR – Photosynthetically active radiation
POEDG – Plant Oil and Engine Development Group
REW – Renewable Energy World
TAR – Third Assessment Report
UNFCCC – United Nations Framework Convention on Climate Change
VLIR – Flemish Inter-University Council
WMO – World Meteorological Organization
ZESA – Zimbabwe Electricity Supply Authority

CHAPTER 1: INTRODUCTION

‘Just as the 20th century saw the rise of mineral oil as a major fuel, the 21st century should be the forum for the emergence of a new mixture of energy carriers increasingly dominated by renewable energy sources and among these, leading the way is bio-energy.’ (Best, 2006)

The current era is probably seeing the last decades where fossil fuels are of supremacy without competition, where environmental and climate change issues are high on the international agenda and where energy security has come on the scene as a major driver of change, including in Zimbabwe (target area of study). However, as some social scientists have pointed out, another compelling reason calling for a modern bio-energy philosophy are the billions rural people in the world who are still energy poor and require more affordable, clean and sustainable energy, (Rosillo-Calle *et al.*, 2006). The major advantage is that bio-energy is a locally available energy source with the highest versatility among the renewable energies, that is to say it can be made available in solid, liquid or gaseous forms.

The debate of alternative forms of energy has been doing the scientific circles since the wide scale use of fossil fuel began in the 19th century. The reason behind it is the logic that fossil fuel is a finite resource and hence if human civilization is to be sustainably developed or maintained, it shall require a renewable source of energy. Another argument that is rapidly gaining ground is the ‘Climate Change’ debate, where fossil fuel is being singled out for being the major source of greenhouse gas emissions, particularly CO₂, that are responsible for global warming. Therefore the international thrust is to find ways of partially replacing the mineral fuel with bio-energy, (Rosillo-Calle *et al.*, 2006).

Throughout human history biomass in all its forms, has been the most important source of all our basic needs, often summarized as the six “fs”: food, feed, fuel, feedstock, fibre and fertilizer. Biomass products are also a source of a seventh ‘f’ i.e. finance (IEA, 2002)

1.1 The Justification of the Research Project

Zimbabwe is a developing country whose energy requirements particularly in the transport sector are still on the rise. While the current study is essentially limited to Zimbabwe, the methodologies employed are easily transferable to other regions. In fact, Woods *et al.* (2004) has already conducted some preliminary work in some southern African countries, on the feasibility of utilizing sweet sorghum in conjunction with sugarcane for the production of ethanol and for power generation. While his work was more site specific and inclusive of other factors, the current study is mainly focused on the climatic influences to fuel crop production using the DSSAT4 model.

The current study is timely in that it will shed light and understanding on the key climatic elements that will influence the utilization of bio-energy and its future in Zimbabwe. This study seeks to answer the question, “What is the potential of bio-energy in a particular place and moment?” While bio-energy comes in all the three states of matter i.e. solid, liquid and gas, the focus here shall be mainly on the liquid fuel form that is employed mainly in the transportation industry. The transport industry is among the top economic activities that is responsible for a significant amount of CO₂ emissions and it is one of the sectors that has been targeted by the Kyoto Protocol, to which Zimbabwe is signatory, to find ways of reducing emissions of greenhouse gases (GHGs), (UNFCCC, TAR, 2003)

Zimbabwe, like many other countries that do not have mineral oil reserves, annually spends million of dollars in foreign currency in the importation of this vital commodity. Efforts have already started on research activities aimed at finding alternative fuel sources in order to lessen the financial burden on importing oil. The Zimbabwe Herald Newspaper of 13/09/2006, reported that four parastatals (quasi-independent government bodies), [the Industrial Development Corporation (IDC), the Agricultural Development Authority (ARDA), ZESA Holdings and the National Oil Company of Zimbabwe (NOCZIM)] were seeking approval for the construction of a sugar mill by IDC on land provided by Arda at Chisumbanje. NOCZIM’s interest would be on fuel while ZESA Holdings would focus on the power aspects of the project. Zimbabwe already has a relatively large ethanol plant in the southeast of the country based on sugarcane as a feedstock, capable of producing about 40 million litres of anhydrous ethanol (Woods, 2000). The major disadvantage is that ethanol production competes with crystalline sugar production for the same feedstock. The challenge is to identify other feedstocks that do not compete with or jeopardize food security in the country. Among the possible crops that could be cultivated are sweet sorghum (*Sorghum bicolor*, L. Moench) and the *Jatropha curcas* plant (currently receiving a lot of attention from the Ministry of Science and Technology, Zimbabwe). There are other fuel crops available that are not discussed in this study but can equally be assessed using the same methodology as applied here.

1.2 Benefits of the study

The current study should contribute to three main areas i.e. (1) to increase the body of scientific knowledge that is aimed at understanding the physical principles underlying the growing of fuel crops and hence improve on the breeding and management aspects to maximize on fuel crop production for sustainable bio-fuel production and (2) to assist as a decision support tool for policy makers. Whether to invest in fuel crops or not? Which crop and where? (3) to provide

radiation maps from remote sensing sources (satellite). One of the benefits accruing from this study is the feasibility of using satellite based observations of solar radiation to accurately produce solar radiation maps that can find a range of applications especially in radiation sensitive projects. Satellite based measurements would greatly enhance the spatial and temporal resolution of this parameter than is the case at the present. At present, satellite data on radiation has not yet been calibrated and validated with ground observations in Zimbabwe to be of immediate use in a wide range of possible applications.

Since the government has already embarked on the road of bio-fuel production, any additional data and information particularly on agro-climatic conditions suitable for different energy crops would be useful, particularly for research scientists in agriculture, farmers as well as policy makers.

1.3 Objectives of the study

The objective of this study is to identify climate parameters in Zimbabwe that determine the potential yield of fuel crops. To this end the use of the Decision Support System for Agro-technology Transfer (DSSAT) model is being utilized to simulate potential yield of fuel crops. This crop simulation tool could prove to be useful for a range of other experiments designed to look at crop production be it for food or for fuel.

It would be ideal to come up with an agro-climatic zone map showing the areas that potential investors would need to concentrate on when growing a particular fuel crop, unfortunately this requires more field experiments to verify simulated model results which is outside the scope of this work. However, the preliminary results from this study should provide a 'first guess' for any would be investor, regarding the growing of fuel crops of choice.

Lastly but more importantly, the satellite based solar radiation maps produced were to be compared to ground measurements maps. They should provide food for thought in terms of utilization of remotely sensed data that is currently under utilized in Zimbabwe, especially in view of the scarcity of ground observing stations. A more detailed and accurate map would go a long way in the ongoing research on renewable energy sources e.g. solar energy research. The larger scientific community could also stand to benefit from accurate solar radiation data with a better spatial and temporal resolution than at present.

1.4 Target Area

The author's study area is Zimbabwe (Figure 1.1) and the general climate characteristics of the country will be highlighted in subsequent sections.

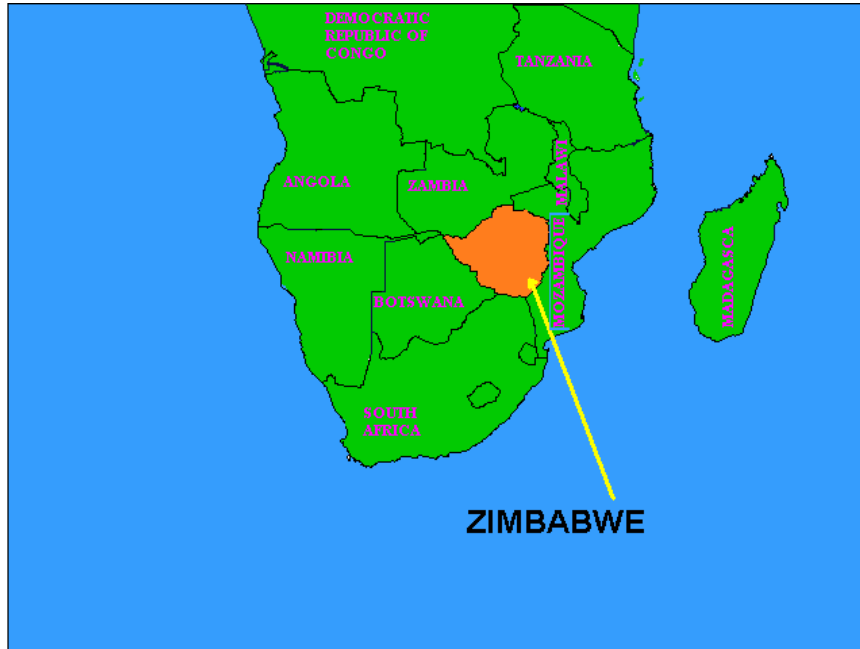


Figure 1.1: *The location of Zimbabwe in the southern African subcontinent*

Zimbabwe is a land locked country whose area is approximately 400 000 km² whose climate can be described as both tropical and extra-tropical. It lies generally between 15° S and 22.5° S and extends from 25° E and 34° E. (Shoko K, 1999; Climate Handbook of Zimbabwe 1980). In a nutshell the climate of Zimbabwe can be described as a tropical 'dry and wet' climate i.e. to say for about seven months it will be dry and the other five months it will be wet. Of course this is a broad simplification of reality when one is interested in the climate of a particular area or locality.

The main factors that control the climate of a locality are determined by 1) its latitude, that in turn determines the amount of solar radiation received at the top of the atmosphere at any time of the year; 2) its position relative to the distribution of land and sea, the latter providing a source of moisture in the form of water vapour and exercising a moderating influence on the diurnal and annual temperature range; 3) its height above sea level, that in turn has a strong bearing on temperature. Other influences that are dependent on 1) and 2) are the general circulation of the atmosphere and its perturbations, ocean currents (warm or cold), nature of underlying surface, vegetative cover and topographical features. The most important large scale circulation features that affect Zimbabwe are the Inter-tropical Convergence Zone (ITCZ)

during the rainy season (November to March), especially the northern half of the country and the mid latitude westerly waves in the dry season (winter; May to July). The intermediate months of August to October (spring) and April (autumn) are transitional periods i.e. when the dominant weather patterns are changing in tandem with the movement of the sun.

This is not an in-depth analysis of the weather and climate of the country but a brief outline of the factors that govern the weather parameters that are the basis of agro-climatic potential of the different fuel crops shall be given in chapter two.

1.5 Thesis Layout

The thesis is structured into basically six chapters including the Introduction (Chapter 1). Chapter 2 dwells on the background to the bio-diesel debate plus the literature review. The history behind it is analyzed in the context of the pros and cons up to present. The different feed-stocks (fuel crops) currently in use the world are analyzed and also the state of the development of the bio-fuel industry in the world, looking at the major players as identified by FAO. Why some countries favor some fuel crops compared to others? Various literatures on the bio-fuel debate as regards the different energy crops are presented, but however, much of the literature used was on sweet sorghum. The last pages of the chapter are devoted to the fuel crops that are being considered for Zimbabwe as potential feedstock material for bio-ethanol or bio-diesel production. The climatic parameters used in the study, namely maximum temperature, minimum temperature, solar radiation and rainfall are then discussed following the crop discussion. Here the purpose is to highlight the significance of weather in the growth and development of fuel crops. This is then followed by a brief overview of the general climate of Zimbabwe, giving a general picture of the spatial as well as temporal distribution of the primary climate parameters. Lastly in this chapter, the agro-ecological zones of Zimbabwe are presented, as an illustration of the link between climate and food crops.

Chapter 3 is devoted to materials and methods used in the current research effort. The data sources and their suitability for the present study are discussed. The chapter is divided into two parts, one part is looking at the more frequently observed weather parameters of rainfall and temperature and the second part is looking at the less observed but very important parameter of solar radiation. Two methods of radiation observations are analyzed; ground based observations and remotely sensed data from satellite (geostationary). The main tools used to analyze the data are discussed next, namely the computer based Surfer Program and the DSSAT Cropping Simulation Model. Chapter 4 will concentrate on the results obtained. Discussion of the results is done in Chapter 5 and finally the conclusions and recommendations arising from the findings are given in Chapter 6

CHAPTER 2: LITERATURE REVIEW

2.1 Historical background

The concept of bio-fuel dates back to 1885 when Dr. Rudolf Diesel built the first diesel engine with the full intention of running it on a vegetative source (fuel crops). Diesel presented an engine powered by peanut oil in 1900 at the Paris World Expo. In 1912 he stated " *..the use of vegetable oils for engine fuels may seem insignificant today. But such oils may in the course of time become as important as petroleum and the coal tar products of present time.*"

2.1.1 Principles of bio-diesel production technology

Bio-diesel can be produced at room temperature and atmospheric pressure. The reaction takes place when vegetable oil is mixed with alcohol in the presence of a catalyst to form bio-diesel and glycerol. The preferred alcohols are methanol and ethanol. The catalyst may be a strong acid such as sulphuric acid or a strong base such as sodium hydroxide or potassium hydroxide. The base is preferred because it is easy to handle and the rate of reaction is high and the amount of oil converted to bio-diesel is also high. The rate of reaction is affected by other factors such as temperature, stirring and oil acidity.

The proportional ingredients of the bio-diesel are as follows: One litre of vegetable oil, 150 – 200 ml of methanol (or ethanol) and 3.5 g of sodium hydroxide. First, sodium hydroxide is dissolved in alcohol to form a solution. Second the solution is mixed with oil for the reaction to take place. The ingredients will produce about 1.15 litres of bio-diesel. If methanol is used, a closed container (reactor) is necessary to protect the operator from methanol poisoning. Any amount of water in the ingredients (alcohol or oil) reduces the yield of bio-diesel and should be avoided (Kibahozi, 2005).

The form in which bio-diesel is used is denoted as BXX where XX is the percentage of bio-diesel in a mixture, for example B100 is pure bio-diesel and B20 contains 20% bio-diesel and 80% petroleum diesel. Most vehicle engines can use bio-diesel of B20 percentage mixture but unfortunately, not all diesel engines can use B100, because pure bio-diesel may damage certain elastomers and natural rubber used in the fuel pump parts and hoses (Kibahozi, 2005).

2.1.2 Advantages of Bio-diesel:

Bio-diesel is renewable, with net zero carbon dioxide emission (Kibahozi, 2005). Other emissions are also lower compared to petroleum diesel as shown in Table 2.1 below. The negative or positive sign indicates the percentage decrease/ increase in emission compared to emissions from burning of petroleum diesel. Bio-fuel is an umbrella term used to describe all

fuels derived from organic matter. The two most common bio-fuels are bio-ethanol, a substitute for gasoline, and bio-diesel, a substitute for diesel. Both are seen by climate change scientists as complimentary ways of cutting greenhouse gas emissions quickly with minimal modification to the existing vehicle and fuel infrastructure. The course of action for mitigation of climate change is to stabilize and reduce concentrations of greenhouse gases. Bio-diesel, as a fuel produced from vegetable oil, is one of the mitigation options that can be used by countries to mitigate climate change and provide sustainable development (Kibahozi, 2005).

Table 2.1 Emissions reduction comparisons of bio-diesel with reference to petroleum diesel Source: www.biodiesel.org

Emission Type	*B100	**B20
Total Unburned Hydrocarbons	-10 to -67%	-20%
Carbon monoxide	-10 to -48%	-12%
Particulate matter	- 24 to -47%	-12%
Soot	-50 to -52%	
NOx	+8 to +12%	
Sulfates	-100%	-20%
PAH (polycyclic aromatic hydrocarbons) {average reduction across all compounds measured}	-80%	-13%
Ozone potential of speciated Hydrocarbons	-50%	-10%
<u>NOTE:</u> Range variability depends on type of engine; turbulent engine is more efficient than direct injection engine. *100 % pure bio-diesel **20 % bio-diesel and 80 % petroleum diesel		

- Bio-diesel molecules contain oxygen atoms that improve combustion efficiency (Blassnegger, 2003; Wolfgang, 2003). On the other hand, bio-diesel increases nitrogen oxide emissions. The emissions can be reduced by using the oxidation type catalytic converter (Kibahozi, 2005).
- It is essentially non-toxic (one tenth the toxicity of salt!) and biodegradable.
- Healthwise, it does not contain toxic and carcinogenic aromatics (benzene, toluene and xylene), hence bio-diesel emissions show decreased levels of polycyclic aromatic hydrocarbons (PAH) and nitrated polycyclic aromatic hydrocarbons (nPAH), which have been identified as potential cancer causing compounds.
- Contains very little amount of sulphur. Sulphur dioxide is a compound that causes respiratory diseases.
- For countries without fuel source, it is a foreign currency saver.
- Economic stability can be found through use of own fuel source as international oil cartel determines the tune for the price of oil.

- Employment opportunities are boosted, resulting in poverty alleviation
- Qualifies for Clean Development Mechanism (CDM)* under the Kyoto Protocol (Kibahozi, 2005).
- Technically it has properties similar to petroleum diesel; hence no engine modifications are required. Power output at B100 just less by 5%, hardly noticeable
- It has higher flash point, i.e. temperature at which it ignites. It is therefore safer to transport and store than petroleum diesel.
- Bio-diesel has better lubricating properties than diesel, hence longer engine-lifetime (Wolfgang, 2003).

Bio-ethanol is produced by processing starchy or sugar-rich crops such as sweet sorghum, sugar cane, wheat or maize. In the case of starchy crops, the starch is converted into sugars using enzymes. The resulting highly pure ethanol can be blended with petrol to various percentages.

Footnote: *CDM – This is one of the mechanism by which countries with emission quota reduction targets can employ by paying another country (developing) to adopt clean technology with the emission reduction being ascribed to the developed country. The Kyoto Protocol was crafted by the United Nations Framework Convention on Climate Change (UNFCCC) in Japan in 1997. This document was the first international attempt to place legally binding limits on greenhouse gas emissions from developed countries.

Sugar cane and sweet sorghum are grown specifically for fuel in a number of countries. A variety of other lignocellulose materials including sugar cane stalks can contribute to the process, and the residues used as fertilizer on the fields. According to REW, (2000) using one ton of bio-ethanol instead of fossil fuel reduces the emission of CO₂ into the atmosphere by 2.3 tons. The assumption is that CO₂ is simply cycled during the whole growth and consumption process. Needless to say, the significance of the CO₂ reduction lies in the principle rather than the actual figure that it might not fully reflect the assumptions inherent in the calculations.

Long-term viability of agricultural fuel crops also depends on maintaining the physical quality of the soils, and the plant nutrition. The different feed-stocks have different nutritional requirements and the cost of producing a unit quantity of bio-ethanol also differs. A comparative table for element use and cost per cubic metre of bio-ethanol produced for some feed-stocks is shown below (Table 2.2). However comparative figures for *Jatropha* are not available.

Table 2.2 Comparison of the yield, element use and cost of production for some fuel crops (Source: REW, 2000)

Crop	Sugar yield t/ha	Element use, kg/t yield			Bioethanol Cost US\$/m ³
		N	P ₂ O ₅	K ₂ O	
Sugar cane	8 - 12	1	0.1	2	260
Sugar beet	6 – 8	5	1 – 2	5 – 6	590
Sweet sorghum	7 – 12	0.9	0.9	1.3	200 -300
Maize	5 – 8	10	4	5	300 - 420

It appears from the Table 2.2 above that sweet sorghum together with sugarcane have relatively low production costs (US\$ 200-300 per cubic metre) compared to sugar beet and maize. The main advantage that sweet sorghum has over sugarcane is that it has higher water use efficiency. But it must be borne in mind that production costs are also related to the level of development in a country. Different technologies of production could result in different costs.

2.2 Biomass use: Experience from Other Countries

In addition to crops grown specifically for fuel there is a wide range of commercial uses of biomass by-products to produce power on the medium scale. In some cases the benefit from energy as a by-product may materially improve the viability of growing a fuel crop.

2.2.1 Australia

In Australia, like in Triangle Ltd. (Zimbabwe) bagasse from sugar mills is the raw material for power generation. For example, from one mill in Queensland, 120 kiloton/year of bagasse is produced, and burnt in a generating plant with a capacity of 22MW. Of this, about 8 MW is used on site, and the rest exported to the local electricity grid (REW, 2002). Since this process has already been proven, its further exploitation could substantially boost the power generation capacity of the country (Zimbabwe).

2.2.2 South Africa

The South African transport energy sector is apparently shifting towards more utilization of bio-fuel, with newspaper reports talking of ‘...government to make a decision on whether or not to force oil companies refining crude oil in SA to add ethanol to their petrol later this year,’ (Bain, 2006).

There is debate in South Africa on which raw material would be the most efficient when it comes to feed-stock for bio-ethanol plants. Some people argue maize would be the most cost effective feedstock while others are in favour of sugar cane. The argument is that sugar cane involves a simpler process than maize. The role of carbon trading no matter which crop was used as feedstock appears to be taking centre stage in any projects involving bio-fuels and fuel crops in South Africa.

2.2.3 Brazil

Currently Brazil is the largest producer of sugarcane and consequently has the highest percentage of vehicles running on bio-ethanol, estimated at 45 %. Walter *et al.*, (2006), reported that in 2004, 42 % of Brazilian primary energy supply was covered by renewables, with a contribution of 13.6 % of sugar cane products (alcohol and bagasse).

According to the report, the country fulfills the main required conditions regarding large-scale production of biomass, such as land availability, adequate weather conditions, little constraints regarding labour and the domain both of biomass production and biomass conversion technologies in the agricultural and in the industrial sites. Estimated savings due to avoided oil imports were about US\$52.1 billion (January 2003) from 1975 to 2002 (Goldemberg *et al.*, 2004).

Use of land devoted to sugarcane growing in Brazil is less than 2 % (5.5 million hectares) and it is well accepted that large-scale sugarcane plantations in Brazil has not affected food production and even a substantial enlargement of the alcohol production would be possible without serious constraints (Walter *et al.*, 2006). The Brazilian experience in bio-fuels production indicates that it is possible to produce such fuels in a sustainable way and at low cost.

2.2.4 United States of America

The United States of America has the world's fastest growing fuel ethanol market. In 2004 it was approximately 14 billion litres while production was about 13 billion litres, hence the ready market for surplus ethanol produced elsewhere like Brazil. Most of the bio-ethanol in the USA is produced from maize but research into other possible sources is being carried out in the face of the growing argument against causing starvation in poorer countries that rely on food imports (New Scientist, 2006; Arthur, 1997).

2.2.5 Canada

Canada is regarded as leader in Bio-Oil technology and Bio-Oil development. One of the leading Canadian companies on Bio-Oil technology, Lignol Innovations of British Columbia anticipates commercial production of ethanol from woody fibre using its process in 2006 (Bradley, 2006). Lignol claims it will have the lowest production cost for ethanol. Bio-Oil from

pyrolysis of wood is brown, free-flowing liquid comprised highly oxygenated compounds and has a density of 1.2 kg/litre. With fast pyrolysis biomass waste is heated rapidly in the absence of oxygen, vaporized and then condensed into liquid fuel. Its heating value is 40 % of diesel by weight and 55 % by volume. It can be stored, pumped and transported like petroleum products and can be combusted directly in boilers, gas turbines and slow to medium speed diesels for heat and power (Bradley, 2006).

2.2.6 Zimbabwe

The country already boasts of an ethanol plant based on sugarcane as a stock-feed in the southeast run by Triangle Ltd. However, of late the competition with crystalline sugar and a dwindling market for the product had forced production levels to decrease (Woods, 2000). The focus in Zimbabwe at present is the *Jatropha curcas* plant as a source of bio-diesel. The government through the Ministry of Science and Technology is directing research efforts aimed at establishing plantations where the jatropha plant can be grown. Currently, large scale processing plants have yet to be established for the production of bio-diesel from jatropha seed oil. The development of the bio-fuel industry is at an experimental stage. The results of this project should augment national efforts aimed at enhancing bio-fuel production from fuel crops including *Jatropha curcas* plant. An expansion of the agricultural base to include fuel crop cultivation is being seen as a national priority (Muropa, 2002)

2.2.6.1 Background of Jatropha plant in Zimbabwe

Jatropha curcas plant is mainly grown in Mutoko and Mhondoro as a hedge. The plant does well in warm conditions with temperatures above 20°C and up to 28°C. It is not sensitive to day-length and has low rainfall requirements, but it responds to higher rainfall under hot climatic conditions as well (Industrial Development Corporation of Zimbabwe, 2000). Research work has been conducted on *Jatropha* growing at a number of sites for example at Art Farm under the auspices of Plant Oil & Engine Development Group (POEDG) in 1992. Sites were chosen due their differences in agro-climate and the range was from natural region 2a to natural region 5 (Masvingo, Beitbridge, Kadoma and Mid-Sabi) with a view to ascertaining the best plant spacing and possible seed yields. Fertilizer application at 400kg per hectare was selectively applied at some sites.

The following results were obtained (Source: Industrial Development Corporation of Zimbabwe, 2000):

- Masvingo trial germinated badly, about 60 %
- The average growth rate was 35-40 % better in warmer Mid-Sabi than at Art Farm near Harare.

- At Art farm (near Harare), there was no response to fertilizer application unlike that at Mid-Sabi. (unexplained).
- At Art Farm, wider spacing gave higher yields (2 tons/ha) than close spacing (0.5 ton/ha)
- Fruits are picked one or two years earlier from vegetative propagation than from seed planting.

Apart from production of bio-diesel, jatropha oil and its associated by-products can be used in a variety of ways:

- a) Jatropha oil is an excellent substitute of palm kernel oil, which is currently being imported.
- b) Jatropha oil is high in Oleic Acid and hence can be converted into a liquid soap as a pesticide (www.jatrophacurcas.org).
- c) It can be sulphated and sulphited to produce fat liquoring agents for the tanning industry.
- d) The oil has been used in its basic form as a pesticide to fight against armyworm, termites, harvester ants etc.
- e) Soap is a bi-product in the production of bio-diesel.
- f) Pharmaceutical uses - In the Phillipines they use it to stop diarrhoea, in Nigeria the leaves are used as wound dressing and in Cameron, they use the leaves as a cure for fever, jaundice and rheumatism (IDC., 2000).
- g) The press cake is valuable as organic manure since it has nitrogen content of 3.2 – 3.8 % which is similar to that of chicken manure (IDC., 2000).
- h) Plants can be used as hedge to demarcate boundaries for homesteads.

Despite there being trials planted, few research results have been published in Zimbabwe on different bio-fuel feed-stocks, comparing their commercial economic viability and sustainability. Sugarcane has been the only bio-ethanol feedstock to be used practically in a liquid bio-energy industry setup (Woods, 2000). The author is of the opinion that given the sensitivity of food security to changes in crop production systems, the main thrust on any research efforts should be biased towards non-food feedstock so as to avoid competition that might impact negatively on national food reserves. Currently efforts are directed at the *Jatropha Curcas* plant. However sweet sorghum and sugarcane could also be viable options. This study will also form part of the research literature of comparative studies of the different bio-fuel feed-stocks (fuel crops) that can possibly be exploited.

2.3 Arguments against bio-fuels

Despite the advantages associated with the production and utilization of bio-fuels, there are arguments that have been advanced mainly by environmentalists worried about the negative

impacts of the cultivation of fuel crops particularly in virgin forests. The main argument is that the remaining rainforests in such places as Brazil and Borneo will be cleared in order to grow fuel crops, which will lead to loss of biodiversity. Worst of all, some argue that bio-fuels will barely slow down global warming if the technology behind them does not improve (New Scientist, 2006). Since the time of Rudolph Diesel, bio-fuels have not received much attention until the oil crisis of the 1970s, when some countries like Brazil returned to bio-fuels. According to a study published by the Worldwatch Institute (2006); for Brazil to produce 10 % of its entire fuel consumption requires just 3 % of its agricultural land. However in other countries the numbers do not add up. The same Worldwatch study estimated that to meet a 10 % fuel target, the US would require 30 % of its agricultural land and for Europe up to 72 %. The basis of the argument against bio-fuels assumes that all countries are economically and technologically advanced to the same level. For instance not only do Brazilians drive far less than their European counterparts but their fertile land and favourable climate mean their crop yields are higher, and their population density is lower. Therefore, it is necessary for individual countries to assess their own capability and limitations when considering investment in the bio-fuel industry. It is obvious some countries will become net exporters of bio-fuel while others will be importers depending on their national priorities. Other countries like China, Cuba, and Hungary including Zimbabwe have plans for bio-fuels but the first stage should be assessment of the economic viability of different feed-stocks.

The environmental benefits of bio-ethanol from cultivation to final production of bio-fuel needs to be assessed carefully. Cultivating a crop demands large quantities of fertilizer and pesticides, which themselves have environmental and energy costs (www.newscientist.com, 2005). Several research studies have tried to balance the fossil fuel bio-fuel equation comparing emissions at every stage of production from seed to engine. Farell, (2006) estimated that bio-ethanol would produce 13 % less GHG than an equivalent amount of gasoline. However, Farell arrived at this figure by assuming the leftover biomass from making the bio-ethanol is used as a dry fuel in a furnace or fed to animals. However not all bio-ethanol refineries do this; in Triangle Ltd. in the SE of Zimbabwe, the bagasse from production of crystalline sugar from sugar cane is used to generate electricity. Given these research findings, institutions or the bio-fuel industry should at the very onset factor in the utility of the by-product of making bio-fuel so as to optimize on its economic viability rather than create another waste disposal problem.

Another argument is based on the envisioned slump in grain diverted to bio-ethanol production that would precipitate a rise in world grain price. This would be particularly true of those systems that use maize as a feedstock like the USA. The issue of availability of land is also country specific judging from the country report from Brazil.

The argument being posed by those opposed to the pro bio-fuel debate is that the booming demand for bio-fuels is having dangerous environmental and social impacts in the major

countries of cultivation such as Brazil, Indonesia, Malaysia, Borneo and New Guinea. However, for Zimbabwe, land availability should not present such problems.

The arguments presented so far are mainly to do with environmental costs not the science and technology per se. It would suffice to say that every case has its own merits and demerits. The issues raised are not applicable to every situation; one needs to take into consideration the different backgrounds of the countries involved. A case in point is the country report from Brazil on the availability of land and the argument that cultivation of sugarcane for bio-ethanol will cause a deficit in production of food crops (New Scientist, 2006). While it might be true some people might engage in practices that are not beneficial to the ordinary person, if properly managed, fuel crop cultivation could actually be of financial benefit to the poorer communities.

A future possible solution to the fuel crop versus food crop competition could be to produce bio-ethanol without using food crops, and focusing instead on converting cellulose-rich organic matter into ethanol. Cellulose feed stocks could deliver twice as much ethanol per hectare as maize according to Bradley (2006) and the Canadian company Lignol Innovations appears to be leading in this endeavour.

2.4 The Challenge

During the 1970-2000 period, part of the sugar crop in Zimbabwe was processed into ethanol for blending with mineral petrol, but eventually the demand for domestic and export crystalline sugar outweighed the supply and the price of mineral fuel had dropped and both militated against the further development of the bio-fuel industry. The challenge is to jump-start the bio-fuel project now as current fuel shortages impact negatively on the economy. These days the government is encouraging farmers to grow *Jatropha Curcas* plants for bio-diesel production. However, the case for the other alternate fuel crops being cultivated for bio-fuel has not been investigated thoroughly. A study undertaken by Woods J. et al., (1996) on the integration of sweet sorghum with sugarcane in existing sugar industries in semi-arid areas of Zimbabwe, showed good promise for bio-energy production i.e. the production of ethanol and electricity in a Combined Heat and Power system (CHP).

The current study should add to this knowledge bank, providing a foundation in terms of agro-climatic information for the potential production of fuel crops of choice. The establishment of plantations requires agro-climatic zoning, among other factors, as a prerequisite to tap the potential of these crops to the full. On the other hand, complimentary to the cultivation of the crops is the processing of the feedstock to produce the bio-fuel, which means that processing plants will have to be established to produce the bio-diesel.

To the author's knowledge, little research has been undertaken in Zimbabwe to investigate the different agro-climatic conditions that favour the maximization of production of the different types of fuel crops. The efforts of this research are therefore primarily designed to add to this knowledge. The aim is to classify the agro-climatic zones of the country in terms of their suitability for the cultivation commercially, of the different fuel crops, (*sugar cane, sweet sorghum, and jatropha curcas plant*).

2.5 Reasons for Factoring Temperature and Solar Radiation in the Cultivation of Fuel Crops

“Weather has significant impact on crop growth and development. It is a key component that controls agricultural production,” Hoogenboom (2000). In some cases, it has been stated that as much as 80% of the variability of agricultural production is due to the variability of weather conditions, especially rain-fed production systems.

The critical agro-meteorological variables associated with agricultural production are precipitation, air temperature and solar radiation. Air temperature is the main weather variable that regulates the vegetative and reproductive development (Hodges, 1991). Solar radiation provides the energy for the processes that drive photosynthesis, affecting carbohydrate partitioning and biomass accumulation of the individual plant components (Boote and Loomis, 1991).

Growing a crop is an exercise in energy transformation. In order to achieve this transformation, it is necessary for the crop to carry out the following three processes in sequence:

- Interception of incident solar radiation by the leaf canopy;
- Conversion of the intercepted radiant energy to chemical potential energy, (the latter conveniently expressed in terms of plant dry matter).
- Conversion of the dry matter produced between the harvested parts and the rest of the plant.

The yield (Y) of a crop over a given period of time can be expressed by the equation (2.1) (Walker *et al.*, 1989);

$$Y = Q \times I \times E \times H \quad 2.1$$

Where:-

Q is the total quantity of incident solar radiation by the leaf canopy;

I is the fraction of Q which is intercepted by the canopy.

E is the overall photosynthetic efficiency of the crop (i.e. the efficiency of conversion of radiant to chemical potential energy), commonly expressed in terms of the total plant dry matter produced per unit of intercepted radiant energy.

H is the fraction of the dry matter produced that is allocated to the harvested parts. This is really the harvest index of the crop stand, although it should be emphasized that it is normally expressed in terms of above-ground production, excluding the root system.

Walker, *et al.*, (1989) quoting Watson (1940) said that variation in I accounts for most of the differences in yield between sites and seasons in temperate regions, because E and H are relatively constant in the absence of severe stress (drought, disease). What has been established is that in certain crops, notably grasses, there is limited scope for improvement of yield by variation in I and H and that increased production can come only from increases in E.

2.5.1 Effect of temperature on plant growth and development

Ambient temperature affects natural species distribution (apart from managed agriculture).

2.5.1.1 Distribution

C4 grasses like sweet sorghum are best adapted to warmer temperatures prevailing in warm lowland areas of the tropics like in Zimbabwe. However, species, ecotypes, and cultivars of C4 grasses differ in their temperature responses Jones (1992). These genotype differences are evident in tolerance to freezing and chilling and high temperatures.

2.5.1.2 Photosynthesis

C4 grasses have higher optimum temperature for photosynthesis than C3 grasses such as wheat, barley, oats and most temperate forage grasses. For example, according to Jones (1992), Vong and Murata (1977) found that the optimum temperature for wheat photosynthesis is 18 °C while that of maize, grain sorghum, and millet is 30 °C (Figure 2.1)(Jones, 1983).

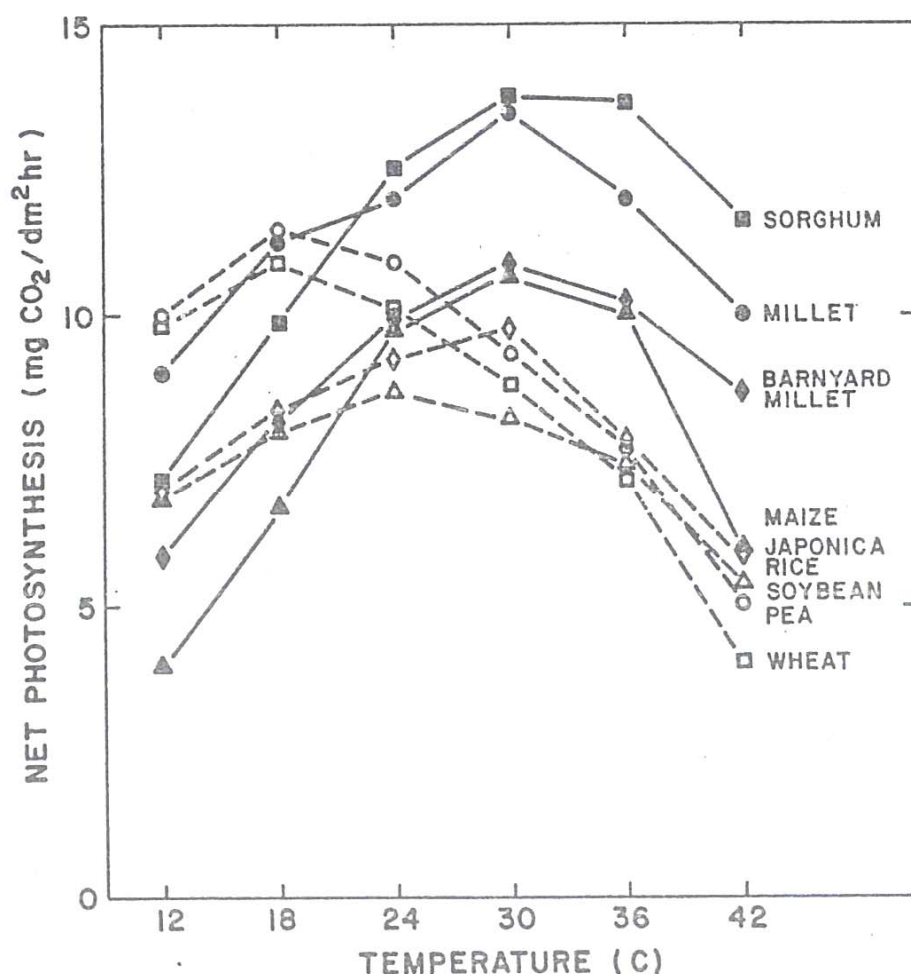


Figure 2.1: Response of net photosynthesis to air temperature in C3 and C4 plant. (Vong and Murata 1977); (Source: Jones, H G., 1992)

2.5.1.3 Dry Matter Accumulation

Experiments conducted in growth chambers and temperature-controlled greenhouses in general indicated that the optimum mean daily air temperature for C4 grass dry matter accumulation is about 30-35°C. Growth is severely reduced above about 40°C and below about 20°C.

The effect of temperature on dry matter accumulation is similar, though not identical, to its effect on photosynthesis. At suboptimal temperatures the relative photosynthesis rate is usually higher than the relative rate of dry matter accumulation. For example, the minimum temperature for maize and C4 grass net photosynthesis is usually less than 10°C but the minimum temperature for dry matter accumulation is about 10°C, Jones (1992). In sugarcane, maximum stalk production is obtained at a mean temperature of 30°C; however, maximum sucrose storage occurs at lower mean temperatures. Increase in tiller number and tiller weight contributes to the growth of most grasses. For most grasses the optimum temperature for tiller numbers is lower

than for tiller size, a reflection of the availability of non structural carbohydrates in the parent tiller at lower temperatures (Jones, 1992).

2.5.1.4 Expansion Growth

Leaf and stem growth are very sensitive to temperature. When water and nutrients are adequately supplied, sugarcane stalk elongation is highly correlated with air temperature. However, the relationship between the elongation and temperature is affected by other factors. Jones (1992) suggested that cane often grows more rapidly at a given temperature in spring than in autumn, probably due to differences in mineral nutrition, soil moisture and crop age (Clements, 1980; Stender, 1924; Sun and Chow, 1949).

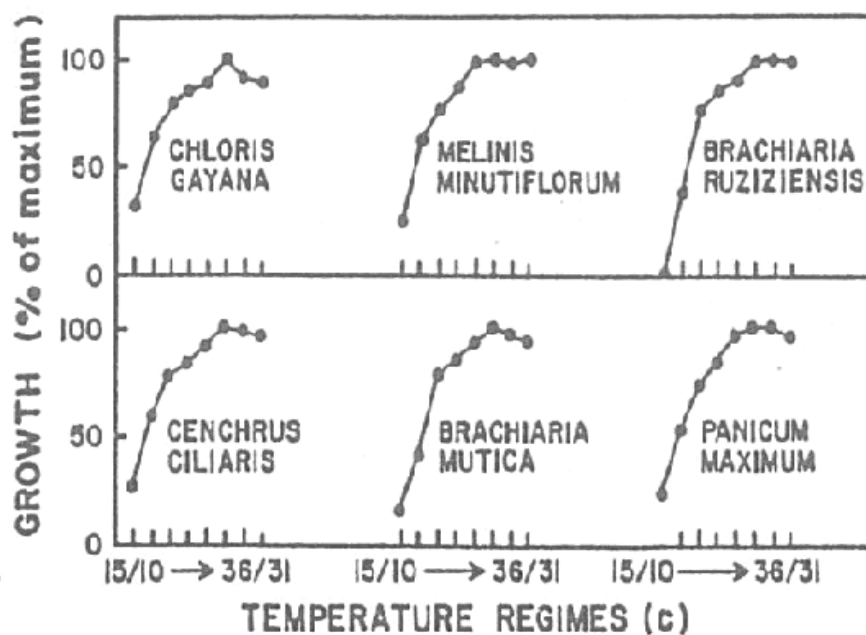


Figure 2.2: Response of grass dry matter accumulation to day/night temperatures, 15/10, 18/13, 21/16, 27/22, 30/25, 33/28 and 36/31 °C. From Sweeney and Hopkins (1975). (Source: Jones, H G., 1992)

2.5.1.5 Phenological Development

The phenological development of plants is accelerated by warm temperatures and delayed by cool temperatures. For example, high temperatures after anthesis shorten the grain filling period of grain sorghum and can reduce both seed weight and number (Balasko and Smith, 1971; Peters et al., 1971). The effect of temperature on the growth stages has been quantified using several indices like the “growing degree-day” (GDD) that is most common. The daily value of GDD is the difference between the daily mean temperature and a threshold temperature. A GDD index is obtained by summing daily GDD from planting to some stage of development. The

equation can be written thus: $GDD = \sum(T_m - T_c)$; where T_m is the mean temperature for the day and T_c is the threshold temperature for the crop in degrees celcius.

2.5.1.6 Diurnal Temperature Variation

Albert, *et al.*, (1988) reported that for sugarcane grown at equal mean temperatures, diurnal temperature variation resulted in higher growth rates than constant temperatures. Other researchers like Ivory and Whiteman (1978) found out that at sub-optimal mean temperatures equal day/night temperatures give the highest growth rates. However, at optimum or supra-optimum mean temperatures, the highest growth rates occur when the day temperatures are about 10°C higher than night temperatures. They concluded that at sub-optimal temperatures a reduction in night temperatures causes more reduction in net photosynthesis than in dark respiration. At optimum and supra-optimum temperatures the reverse is true.

2.5.1.7 Freezing Temperatures

C4 grasses are more susceptible to frost. Freezing temperatures severely damage tissues and frequently kill the entire plant (Jones, 1992).

2.5.1.8 Germination and Seedling Growth

One of the most severe effects of high temperature on C4 grass growth is its inhibition of germination and early growth. The high midday light intensities found in the tropics and subtropics often cause temperatures of bare surface soils to exceed 50°C

2.5.2 Solar Radiation

It has been shown through experimentation that for many crops plant biomass is proportional to accumulated intercepted solar radiation. Figure 2.3, shows the relationship between radiation (ΣPAR) accumulated from emergence to harvest and total sweet sorghum dry biomass produced (Monteith, 1977).

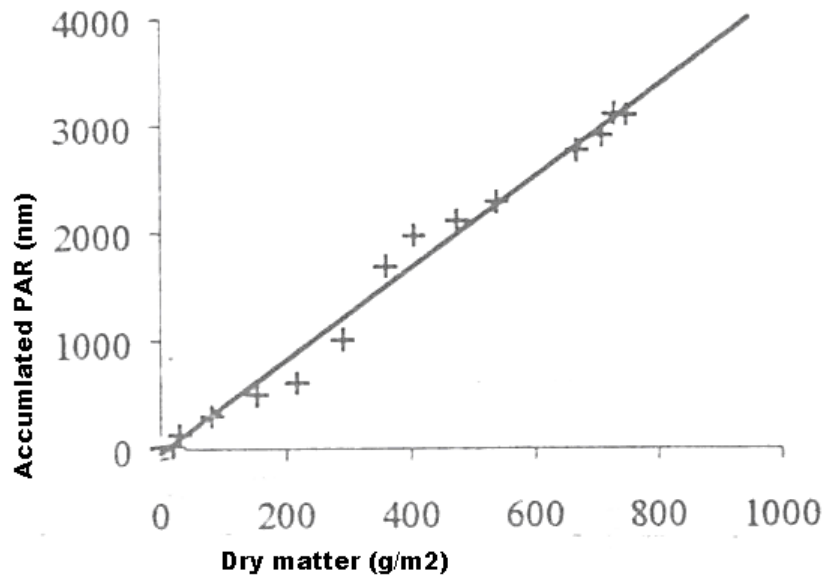


Figure 2.3: Dry matter (gm^{-2}) versus Accumulated PAR for sweet sorghum (Monteith, 1997)

In conclusion, it can be seen from these figures that the weather parameters of temperature and solar radiation play a pivotal role in the final yield of a crop. Therefore an accurate climatic record of temperature and radiation is imperative for maximization of crop productivity through application of these climatic data. An understanding of how they affect plant growth, development and partitioning is necessary to develop crop models that produce results closer to the ground truth. Climate information of at least 30 years (continuous daily observation) with a good spatial distribution will be required in crop model simulation exercises as well as agro-climatic mapping. The climate of a particular place will therefore be invaluable for assessing its suitability to produce fuel crops.

2.6 The Climate of Zimbabwe

2.6.1 Background

Brief overviews of some of the parameters of the climate of Zimbabwe that are directly pertinent to the current study are given. Crop growth requires sufficiently high levels of temperature and solar radiation for photosynthesis and therefore net carbon assimilation. In the previous chapter, the influence of temperature and radiation on growth and photosynthesis and the need for these climate information and data in strategic crop production was highlighted. The most important or rather primary weather inputs into a crop model are maximum and minimum temperature, solar radiation and rainfall.

Good crop management if economically viable can control factors like water, nutrients, humidity and management of pests and diseases. Monthly average maps of temperature and

radiation are the main focus in this section. They will be discussed in order to characterize the spatial and temporal distribution of the parameters in Zimbabwe, because it is known that inter-annual variation in climatic growth factors can have a strong influence on crop growth particularly in annual crops with short growth periods like sorghum (Woods, 2000). This will assist in the understanding of preferred planting and harvesting dates for optimum crop yield for the fuel crops (sweet sorghum) being studied through the Cropping Simulation Model (CSM) tool in DSSAT4.

Productivity is defined in terms of useful products or outputs that can be derived per given unit mass or unit area, in this case – bio-fuel in the form of bio-diesel or bio-ethanol produced per hectare. However, it is first necessary to establish the fundamental climate factors, which define the potential productivity of the fuel crops, sweet sorghum, sugarcane, and jatropha, which is important for defining the ultimate efficiency of the agricultural system. The long-term averages for temperature and solar radiation were calculated using Excel and the contour maps were drawn with the computer program Surfer 32.

2.6.2 Temperature

Temperature is a critical consideration determining agricultural production in any locality. It determines date of planting through control of the germination process via the soil temperature. Some seeds will not germinate if the soil temperature is above a certain threshold (Jones, 1992). Temperature determines the duration of the growing period, from which concept of growing degree-days is derived by agriculturalists. It could safely be said that, besides water availability, temperature governs the length of the growing season. There are a number of formats in which temperature is depicted for use in agricultural practices:

- 1) The observed values of minimum temperature as a baseline for agronomic practices.
- 2) The observed maximum temperature for assessing the upper threshold in crop growth and development.
- 3) The calculated average temperature as a mathematical mean: $T_{\text{mean}} = (T_{\text{max}} + T_{\text{min}})/2$
- 4) The thermal time as given by the ‘degree-days’ formula: $GDD = \sum (T_{\text{mean}} - T_{\text{base}})$ for $T_{\text{base}} < \text{or} = T_{\text{mean}} < \text{or} = T_o$; where GDD (°Cday) is accumulated growing degree days, T_{base} is the threshold temperature for development to occur and T_o is the optimum temperature. $\sum$ is the summation of days between germination and maturity of the crop.

In this particular study, the temperature component is included in the subroutines of the DSSAT Cropping Simulation Model in the growth and development stages of the crop.

2.6.3 Solar Radiation

The fundamental determinant of biomass productivity is the amount of sunlight falling on the leaves of the plant (Woods, 2000). The annual average radiation spatial pattern for Zimbabwe

(Figure 2.4) shows that the SE of the country and the Zambezi valley receive relatively high solar energy compared to the rest of the country. Despite the latitudinal control of radiation received at the top of the atmosphere, the insolation at the surface is governed by the prevailing weather conditions. The influence of cloud cover is quite significant during the rainy season whereby the cloudiness results in a marked drop in the amount of radiation received.

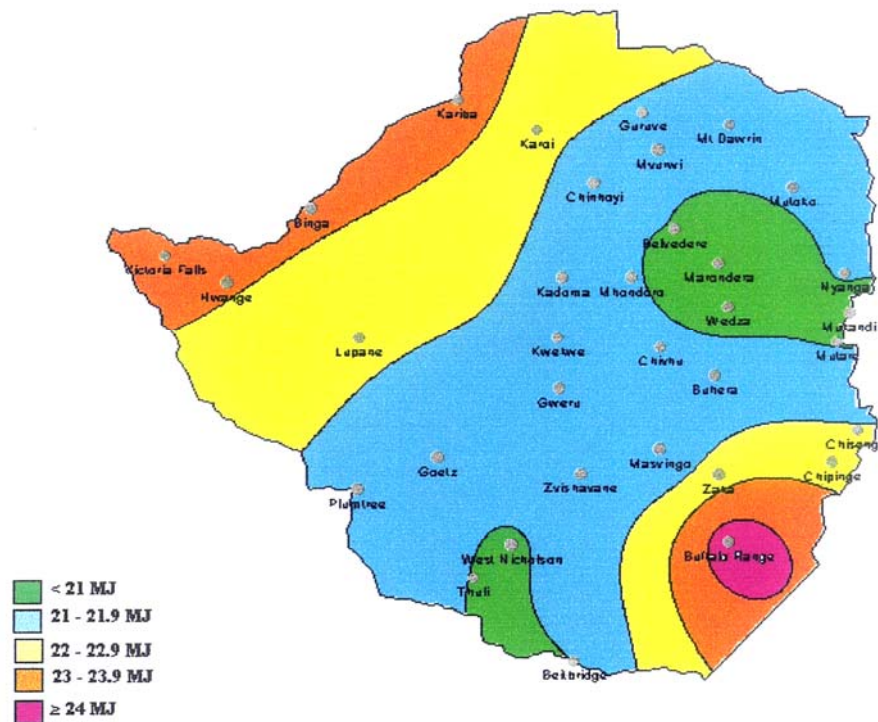


FIGURE 2.4: *The mean annual radiation map of Zimbabwe* (Source: Shoko, 1999)

2.6.4 Rainfall

The climate of Zimbabwe is characterized by a rainy season of about five months (approximately November to March). Apart from rather variable transition months, the rest of the year has little or no rain (Climate Handbook of Zimbabwe, 1980). The mountainous Eastern Highlands can and do receive some rain in the form of drizzle though even in the winter months due to the influence of orography. In winter the dominant weather feature is the incursion of a cool and moist maritime air-mass emanating from the Mozambique Channel from mobile highs of the subtropical high pressure belt that frequently traverse the southern African subcontinent.

The average annual rainfall for the whole country is about 675 mm, ranging between about 300 mm in low lying Limpopo Valley to as much as 3000 mm in the Eastern Highlands. There is a general increase of rainfall from south to north and this gradient is distorted by the even stronger

association between the elevation and rainfall, with rainfall much more at high elevations than in low lying areas.

While it is important to know the rainfall characteristics of any locality for crop cultivation, water is one of those parameters that can be managed by man through the use of irrigation systems if there is a deficit and through drainage if there is too much. However, even this management system shall require information regarding the rainfall pattern of an area for planning purposes. In this thesis, rainfall is one of the primary weather elements included in the Crop Modelling System (CMS) of DSSAT4. However, water availability is considered to be non-limiting when it comes to the calculation of potential total above ground biomass. It is assumed that there will be sufficient irrigation to give the potential yield. Therefore it is only being considered mainly in its role as water for crop use. Its seasonal and annual variation shall not be dwelt on in the present discussion.

Crop models can use the relationship between water use and photosynthesis to limit crop growth when soil water falls below threshold levels i.e. the crop becomes water stressed. However, in CERES crop model, as used in DSSAT4, the relationship between the crop growth and water stress is a simple “on/off” switch, with no photosynthesis allowed to occur at all below threshold levels and full photosynthesis allowed to occur above the threshold (Woods, 2000).

2.6.5 Agro-climatic mapping

In this study, the simulation of potential yield (above ground biomass) per site is being linked simply to the Natural Regions as they apply to Zimbabwe. This is not to assume the whole region shall expect similar productivities as it has been found out that yields do differ from site to site due to differences in local climate, management practices, crop genotype and crop variety.

2.7 Literature review on Fuel Crops and Bio-fuels

2.7.1 Sweet Sorghum (*Sorghum bicolor* (L.) Moench]

2.7.1.1 Plant profile

Sweet sorghum is a tropical, annual grass (domesticated in Ethiopia) that can be grown in the countries with moderate climate without frost during the vegetative period Stricevic *et al.* (1997). Sweet sorghum presents high genotype variability in terms of end-products from lingo-cellulosic fibers to soluble sugars. (Wei *et al.*, 1997).

It has a number of biological advantages over other fuel crops in that it has water-logging resistance, is drought tolerant and also exhibits saline-alkali tolerance (Wei *et al.* 1997). It can also do well in infertile soils. Chinese experience has shown that it does well in regions with GDD between 1500 to 2500, GDD (defined as accumulated growing degree days). Unfortunately the base temperature (T_{base}) was not given. The pH was also found to be between 5 and 8 in most of the areas where it was grown. The sugar productivity realized ranged between 2.25-3.75 kg of sugar juice of brix degrees* Bx 38-40° per hectare during the 1977 trial period (Wei, *et al.*, 1997). Biomass productivity of sweet sorghum was found to be between 6000 to 9000 kg/ha. In terms of grain productivity, it ranged between 2250-4500 kg/ha.

Sweet sorghum [*Sorghum bicolor* (L.) Moench] is the only crop that provides grain and stem that can be used for sugar, alcohol, syrup, jaggery, fodder, fuel, bedding, roofing, fencing, paper and chewing (Nallathambi, 1998; Nimbkar, 1998). Sweet sorghums have also been widely used for the production of forage and silage for animal feed.

[Footnote: *brix degree is the unit used to measure total available fermentable sugars.]

2.7.1.2 Why Sweet Sorghum?

Sorghum particularly sweet sorghum with its multiple diversified components (starch, sugar, lingo-cellulosic) appears a very promising crop for the food, feed, energy chemical markets which can be used in the following markets, heat market, power/ heat market (cogeneration), transport market (bio-ethanol) and food feed markets (Grassi, 1997). Among the cultivated

crops of the grass family, sweet sorghum has the highest dry matter accumulation rate (Zelitch, 1973) estimated at an average of $50 \text{ gm}^{-2} \text{ day}^{-1}$ for a number of world sites. Its efficiency for converting light energy is also better than that of sugarcane (Heichel, 1976). In a study carried out to assess the productivity of sweet sorghum under Mediterranean Climate (Marcello *et al.*, 1997), results showed that under potential conditions, in comparison with other crops sweet sorghum produces the highest biomass and consumes the same amount of water as other summer crops with identical cycle length (length of growing period). Sweet sorghum also efficiently transforms absorbed radiation into dry matter ($\text{RUE} = 3.7 \text{ kg of dry matter per MJ}$) and consumes less water during the transpiration process for equal weight of biomass produced ($\text{WUE} = 5.2 \text{ g l}^{-1}$) (Marcello *et al.*, 1997).

The RUE values (g/MJ) found for the following specific crops were;

- Soybean = 1.72 ± 0.10
- Sunflower = 2.05 ± 0.11
- Grain sorghum = 3.39 ± 0.07
- Sugarcane = 3.6

(source: Varlet –Grancher as quoted by Marcello *et al.*, 1997)

Therefore it would suffice to say, under potential conditions, compared to other crops, sweet sorghum produces the highest absolute quantity of biomass per unit land surface (up to 32 t/ha of dry matter, Marcello *et al.*, 1997). It also consumes the same amount of consumptive water (550mm , Marcello *et al.*, 1997) as other crops with identical growth seasonal cycle length. It transforms the absorbed radiation into dry matter at a higher efficiency of $\text{RUE} = 3.7 \text{ kg of dry matter per MJ}$, (Marcello M. *et al.*, 1997) than other C4 crops [3.4 kg/MJ for grain sorghum]. Sweet sorghum also, has the highest biomass water use efficiency ($\text{WUE} = 5.2 \text{ g l}^{-1}$) among the various crops studied (Marcello *et al.*, 1997. (Table 3.2).

Table 2.3: Water Use Efficiency (WUE) and consumptive water use for different crops. (Source: Marcello *et al.*, 1997)

	Soybean	Grain sorghum	Sunflower	Sweet sorghum
WUE (g l^{-1})	2.8	3.7	3.6	5.2
Consumptive water (l)	344	545	400	550

There are two types of sorghum, that is, grain sorghum and sweet sorghum that can be used for bio-ethanol production, the only difference being in the amount of sugars in the stalk. Sweet sorghum in general has a higher biomass productivity compared to grain sorghum. Differences could be due to past evolutionary selection pressure. Grain sorghum favored shorter plant

stature and increased grain yield through increased partitioning of total biomass to panicle without significant improvement in dry matter production. Grain sorghum has higher efficiency in demobilizing assimilates from leaves and stalk to grain in contrast, sweet sorghum promotes higher dry matter production and increase in the extractable stalk sugars without significant gains in grain yield.

Both sugar and grain can be produced which means potential productivity of arable land can be given full play. Sweet sorghum is a well known C4 plant with a high biomass production. Sugar juice in stalk is up to about 40 % of biomass can be used to produce alcohol. This translates to more than 6106 l/ha under optimum conditions.

Table 2.4: Comparison of sugar production among three crops. (Source: Marcello *et al.*, 1997)

Variety	Growing time (days)	Sugar production (%)
Sugarcane	240	7.0
Sugar beet	170	10.0
Sweet sorghum	150	4.70

2.7.1.3 Climate influence on sorghum production

The experimental results of Junfeng (1997) reveal that climate is an important consideration in the production of sweet sorghum. Therefore the temperature, radiation, and rainfall characteristics of a region need to be assessed for their potential in sweet sorghum production. For Zimbabwe, it is imperative to know the effect of the parameters to the biomass productivity of sweet sorghum if it is to be utilized in a bio-ethanol industry.

In separate but related experiments carried out in Germany over a period of ten years (1985-1995); looking at the sustainability of the sweet sorghum crop for energy production in Europe, Bassam and Jakob (1997) reported that the biomass growth rate was determined in the periods in which the temperature was higher than 10 °C and the most productive growth rate stage has been ascertained when temperatures reached 17 °C and above. As in the Mediterranean and Hungary, (Marcello *et al.*, 1997; Hunkar, 1997) temperature was by far the most deciding and critical growth factor of all climatic parameters. Their findings concluded that the major problem for a wide introduction of sweet sorghum in the Middle and Northern Europe is the insufficient cold tolerance in the early growth stages. Such a problem is not a major constraint over most parts of Zimbabwe, where temperatures rarely go down to sub-zero levels for a greater part of the year.

In India, research on bio-ethanol and other related by products, from sweet sorghum has been going on since the early 1970s. Complete development of indigenous technology for fermentation of sweet sorghum juice, solar distillation of ethanol and finally its use as a cooking and lighting fuel in new and improved stoves and lanterns was carried out. Sweet sorghum bagasse was also tested in an existing paper mill to assess its suitability for paper manufacture. These various possible uses of sweet sorghum apart from ethanol production render it a suitable and economically viable crop in developing countries like Zimbabwe where other needs could be satisfied as well

2.7.1.4 Ethanol production from sweet sorghum:

In the final analysis, the viability of sweet sorghum as a feedstock for ethanol production will depend on the utility of the by products of the production process. In this regard knowledge of the various components of the sweet sorghum plant would be necessary to facilitate full exploitation of this promising plant.

2.7.2 Components of sweet sorghum stem juice

The stem juice of sweet sorghum is rich in fermentative sugar and is a desirable alcoholic fermentation material. The sugar content is commonly expressed with juice brix degree, but the relation between sugar content and brix degree has not been determined very clearly (Junfeng, 1997). In addition to fermentative sugar, other kinds of sugars are also found in the stem juice of sweet sorghum. The acquirement of the contents of different sugars is beneficial to the enhancement of alcohol production rate. There are also some ammonia acids and minerals in the juice, measuring their contents enable better use sweet sorghum with multi-purpose.

The research carried out by Junfeng, (1997), determined the sugar content and brix degree of different varieties in different growth stages. These varieties are yet to be tried in Zimbabwe. The results gave a scientific basis for the arrangement in the varieties and their sowing dates, so as to prolong the fermentation period and increase the efficiency of the alcoholic fermentation processing system. Therefore, the study by Junfeng (1997) had a practical instructive meaning for sweet sorghum breeding as well as for cultivation and for fermentation.

2.7.2.1 Brix degree in sweet Sorghum stem

The research shows that the brix degree of juice in sweet sorghum stem is lower before heading stage. After that, with the grain forming, the brix degree increases towards its maximum at harvest stage. Therefore, the recommendation from these results is that sweet sorghum should be harvested at the grain maturing stage in which both high sugar content and grain yield can be obtained.

2.7.2.2 Total Sugar Content in Juice of Sweet Sorghum

There are plenty of sugars in the juice of sweet sorghum stem. However, how many kinds of sugars exist in the juice is still a question to be answered. The test by enthrone spectrophotometry shows the following kinds of sugars are also found in the juice of sweet sorghum, stem: *xylose, ribose, arabinose, fructose, sorbose, galactose, mannose, sucrose glucose, polyglucose and glucoses* (Jungfeng, 1997).

2.7.2.3 Glucose content

Glucose is the primary material of plant photosynthesis. For C₄ species, besides the Calvin cycle of glucose formation, there is also a four-carbon pathway for CO₂ fixation in mesophyll cells, therefore they have great potential for CO₂ assimilation.

Sweet sorghum is a C₄ crop, with lower CO₂ compensation point, higher light saturation point and weak photorespiration, and consequently has a higher biological yield. Table 3.4 shows the sucrose content of the tested varieties relative to glucose and fructose (Junfeng, 1997).

Table 2.5 Comparison of the sugar content of different varieties of sweet sorghum.
(Source Junfeng, 1997)

Variety	Percentage sugar content (%)		
	Glucose	Fructose	Sucrose
Rio	1.62	1.30	7.19
Shennong No. 2	2.26	1.86	5.0
6 AX1022	2.28	1.86	5.5
Jitian	3.5	2.67	4.45
Longshil	1.86	1.63	7.91

Similar experiments carried out in the United States by Glen *et al.*, (1991) established that sweet sorghum can produce large quantities of both readily fermentable carbohydrate, and fibre for conversion via enzymatic hydrolysis, per unit land area. In fact, on the average, sweet sorghum produces more carbohydrate per unit land area than maize in the drought-prone southeastern Piedmont of the United States (Glen *et al.*, 1991). Unlike maize, sweet sorghum does not concentrate carbohydrates in grain, but stores them in the stalk.

2.7.3 Sugar Cane (*Saccharum officinarum*)

2.7.3.1 Plant profile

Sugar cane is a tall tropical southeast Asian grass (*Saccharum officinarum*) having thick, solid, tough stems that are a chief commercial source of sugar (Columbia University Press Encyclopedia). It is a perennial species of the family Gramineae (grass family), probably cultivated in Asia from prehistoric times (Albert *et al.*, 1998). Sugarcane somewhat resembles maize and sorghum, with a large terminal panicle and a noded stalk. It is a C4 plant. Part of a sugarcane plantation from Hawaii (Figure 2.5).



Figure 2.5 *Saccharum officinarum* grown in Hawaii

2.7.3.2 Cultivation

Most of the rain-fed and irrigated commercial crop is grown between 35°N and S of the equator. The crop flourishes under a long, warm growing season with a high incidence of radiation and adequate moisture, followed by a dry, sunny and fairly cool but frost-free ripening and harvesting period.

Sugarcane cultivation requires a tropical or subtropical climate, with a minimum of 600 mm of annual rainfall. Optimum temperature for sprouting of stem cuttings is 32° to 38°C. Optimum

growth is achieved with mean daily temperatures between 22° and 30°C. Minimum temperature for active growth is approximately 20°C. For ripening, however, relatively lower temperatures in the range 10°C to 20°C are desirable, since this has a noticeable influence on the reduction of vegetative growth rate and the enrichment of sucrose in the cane. It is one of the most efficient photosynthesizers in the plant kingdom, able to convert up to 2 % of incident solar energy into biomass. In prime growing regions, such as Hawaii, sugarcane can produce 20 kg for each square metre exposed to the sun. A summary of the major sugarcane producers in the world is given in the FAO rankings of 2005 (Table 2.6)

Table 2.6: FAO sugarcane production rankings for 2005. (Source: FAO Commodity Ranking; www.fao.int)

RANK	COUNTRY	PRODUCTION *(int \$1000)	PRODUCTION **(Mt)
1	Brazil	8 725 914	420 121 000
2	India	4 825 286	232 320 000
3	China	1 819 452	88 730 000
4	Thailand	1 029 610	49 572 000
5	Pakistan	981 260	47 244 000
6	Mexico	937 277	45 126 500
7	Colombia	827 669	39 849 240
8	Australia	794 369	38 246 000
9	Phillipines	643 870	31 000 000
10	United States of America	535 948	25 803 960
11	Indonesia	529 635	25 500 000
12	South Africa	451 230	21 725 100

*(int \$1000) = calculated based on 1999-2001 international prices

** (MT) = Metric tones based on official figures

2.7.3.3 Sugarcane Yield

A long growing season is essential for high yields. The normal length of the total growing period varies between 9 months with harvest before winter frost to 24 months in Hawaii, but is generally 12 months.

Sugar yield depends on cane tonnage, sugar content of the cane and on the cane quality. It is important that the cane is harvested at the most suitable moment when the economic optimum of the recoverable sugar per area is reached. Cane tonnage at harvest can vary between 50 and 150 ton/ha or more, which depends particularly on the length of the total growing period and

whether it is a plant or a ratoon crop. Cane yields produced under rain-fed conditions can vary greatly. Good yields in the humid tropics and subtropics with irrigation can yield up to 150 ton/ha cane. The water utilization efficiency for harvested yield (WUE) for cane containing about 80 % moisture is 5 to 8 kg/m³ and for sucrose containing 0.6 to 1.0 kg kg/m³, both with the highest values for good ratoon crops in the subtropics.

The flowering of sugarcane is controlled by day-length, but it is also influenced by water and nitrogen supply. Flowering has a deleterious effect on sucrose content, hence flowering should be prevented or non-flowering varieties should be used. Towards maturity, vegetative growth is reduced and sugar content of the cane increases greatly. Sugar content at harvest is usually between 10 and 12 % of the fresh cane weight, but under experimental conditions 18% or more has been observed. Sugar content seems to decrease slightly with increased cane yields. Luxurious growth should be avoided during cane ripening. With respect to juice purity, low minimum temperatures positively affect this several weeks before harvest.

2.7.3.4 Water Requirements

Adequate available soil moisture throughout the growing period is important for obtaining maximum yields because growth is directly proportional to the water transpired. Depending on climate, water requirement of sugarcane are 1500 to 2500 mm evenly distributed over the growing season.

The crop coefficient (Kc) values, relating to reference evapotranspiration (Eto) for the different growth stages are presented in the following table 3.6

Table 2.7 Crop coefficient (Kc) versus development stage (Source: Kwanayi, 2002)

Development stages	days	Kc coefficients*
Planting to 0.25 full canopy	30 - 60	0.45 – 0.6
0.25 to 0.5 full canopy	30 - 40	0.75 – 0.85
0.50 to 0.75 full canopy	15 - 25	0.90 – 1.00
0.75 to full canopy	45 - 55	1.00 – 1.20
Peak use	180 - 330	1.05 – 1.30
Early senescence	30 - 150	0.80 – 1.05
Ripening	30 – 60	0.60 – 0.75

* Kc values depend on minimum relative humidity and wind velocity.

Sugarcane does not require a special type of soil. Best soils are those that are more than 1 metre deep but rooting depth of up to 5 m is possible. The soil should preferably be well-aerated (after heavy rain the pore space filled with air >10 to 12 %) and have a total available water content of 15% or more. The optimum soil pH is about 6.5 but sugarcane will grow in soils with pH in the range of 5 to 8.5.

Sugarcane has a high nitrogen and potassium needs and relatively low phosphate requirements, or 100 to 200 kg/ha N, 20 to 90 kg/ha P and 125 to 160kg/ha K for a yield of 100 ton/ha cane.

Row spacing varies usually between 1.1 and 1.4 m; number of sets per ha depends on the number of buds per sett and may vary between 21000 and 35 000.

Sugarcane is moderately sensitive to salinity and decreases in yield due to increasing salinity.

2.7.3.5 Sugarcane in Zimbabwe

In Zimbabwe sugarcane is mainly grown in the Lowveld, in the southeast of the country, where temperatures are suitable for its cultivation. However, due to the low rainfall received in the area, irrigation is the main source of water. It is postulated in this study that in terms of biophysical limitations, sugarcane can also be successfully grown in the Zambezi valley that almost has similar climatic conditions as the Lowveld but with significantly more annual rainfall. According to sugarcane production guidelines (Kwanayi et al.,2002) sugarcane has a long growing season of about 12 months, with a high water requirement of about 1500 mm/year. In terms of temperature, it thrives under high temperatures (Tmin 16 – 21°C and Tmax 27 – 38°C). Different genotypes can vary in their requirements but not to a great deal and some of the seed cane varieties certified by Zimbabwe Sugar Association (ZSA) include N14, N10 and NCO 376.

Planting is also timed to take advantage of the weather conditions, although theoretically it can be done throughout the year but ideally in the late summer months (August to November). The period from March/April is also suitable due to low weed pressure characteristic of the period. The crop results in high sucrose yield because the well-grown cane is dried off when conditions are best suited for ripening. Sugarcane planted from May to June is generally slow growing due to the very low temperature characteristic of the period (Kwanayi, et al.,2002). There are 203 harvesting days for the year and for Zimbabwe yield levels are in the range 90 – 120 ton/ha (dry matter) with a sugar content of about 12%.

2.7.3.6 Propagation

Sugarcane is propagated from cuttings rather than from seeds, although certain types still produce seeds, modern methods of stem cuttings have become the most common method of reproduction. It takes about 8 – 10 months to produce seed cane and one would require about 5 – 8 tonnes seed cane to plant one hectare. Propagation of the crop is done with cuttings (setts) with shoots 25 – 30 cm long.

Each cutting must contain at least one bud, and the cuttings are usually planted by hand. Once planted, a stand of cane can be harvested several times; after each harvest, the cane sends up new stalks, called ratoons. Usually, each successive harvest gives a smaller yield, and eventually the declining yields justify replanting. Depending on agricultural practice, 2 to 10 harvests may be possible between each planting.

2.7.3.7 Harvesting Cane

Sugar cane is harvested by hand or mechanically. Hand harvesting accounts for more than half of the world's production, and is especially dominant in the developing world. When harvested by hand, the field is first set on fire. The fire spreads very rapidly, burning away the leaves, but leaving the water-rich stalks and roots unharmed. Harvesters then cut the standing cane just above the ground with knives (Woods, 2000).

The juice is concentrated by evaporation into dark, sticky sugar. Refined sugar, less nourishing as food, is obtained by precipitating out the non-sugar components. Almost pure sucrose is the main commercial product. By products obtained from sugarcane include molasses, rum, alcohol, fuel, livestock feed, and from the stalk residue, paper and wallboard.

2.7.3.8 Transportation

Time between burning of cane and milling should be < 72 hours because sucrose decreases with time due to fermentation.

2.7.3.9 Sugarcane for Production of Ethanol

Interest in the use of sugarcane for the production of ethanol is on the rise, in light of high oil and gasoline prices. Brazil has successfully adopted its fuel economy to replace much of its gasoline consumption with ethanol consumption. Maize is predominantly used in the United States for the production of ethanol. Sugarcane, however, is many times more efficient for the production of ethanol. However, as far as Zimbabwe is concerned, while there is already some plans for using sugarcane to produce ethanol, the competition for sugar crystal supply might render it less attractive for ethanol production than other stock-feeds like jatropha, sweet sorghum or sunflower.

2.7.4 *Jatropha Curcas* Plant

2.7.4.1 Plant Profile

Jatropha curcas is a drought-resistant perennial plant, growing well in marginal or rather poor soils. It is easy to establish, grows relatively quickly and can produce seeds for 50 years. It belongs to the family Euphorbiaceae Synonyms: *Curcas purgans*. The common English name is physic nut (www.jatrophaworld.com); Shona (Zimbabwe) – Jirimono. Figure 2.6 shows jatropha fruits before they ripen.



Figure 2.6: *Jatropha Curcas* plant fruits (source: www.D1)

2.7.4.2 Distribution and habitat

It is still uncertain where exactly the centre of origin is, but it is believed to be Mexico and Central America. It was introduced to Africa and Asia and but is now cultivated world-wide (www.jatrophacurcas.org). This highly drought-resistant species is adapted to arid and semi-arid conditions. The current distribution shows that introduction has been most successful in the drier regions of the tropics with annual rainfall of 300-1000 mm. It occurs mainly at lower altitudes (0-500 m) in areas with average annual temperatures well above 20°C but can grow at higher altitudes and tolerates slight frost. It grows on well-drained soils with good aeration and is well adapted to marginal soils with low nutrient content.

2.7.4.3 Climate

Regarding climate, *Jatropha curcas* is found in the tropics and subtropics and likes heat, which means it does well in warmer areas (www.jatrophacurcas.org). It can withstand severe heat. Mean annual temperature: 20-28 °C, Mean annual rainfall: 300-1000 mm or more. However, it also does relatively well even in lower temperatures and can withstand a light frost but not for prolonged periods. When it is cold it will drop its leaves. The older the tree the better its tolerance level. Black frost will almost certainly kill young plants and severely damage older plants. The water requirement of the jatropha plant is extremely low and it can stand long periods of drought by shedding most of its leaves to reduce transpiration loss (Finealt Engineering, 2006).

2.7.4.4 Biophysical limits

Jatropha is a highly adaptable species, but its strength as a crop comes from its ability to grow on very poor and dry sites. It is not sensitive to day length and is well adapted to alkaline soils. It does well in low lying areas, warm temperatures and average rainfall; It can thrive on the poorest stony soil. It can grow even in the crevices of rocks. The leaves are shed during the winter months and form mulch around the base of the plant. The organic matter from shed leaves enhance earth-worm activity in the soil around the root-zone of the plants, which improves the fertility of the soil. It is found to be growing in some parts of Zimbabwe, rugged in nature and can survive with minimum inputs and it is easy to propagate.

2.7.4.5 Flowering and fruiting habit

The trees are deciduous, shedding the leaves in the dry season. Flowering occurs during the wet season and two flowering peaks are often seen. In permanently humid regions, flowering occurs throughout the year. The seeds mature about three months after flowering. Early growth is fast and with good rainfall conditions nursery plants may bear fruits after the first rainy season, direct sown plants after the second rainy season. The flowers are pollinated by insects especially honey bees. Fruits are produced in winter when the shrub is leafless, or it may produce several crops during the year if soil moisture is good and temperatures are sufficiently high. Each inflorescence yields a bunch of approximately 10 or more ovoid fruits. A three, bi-valved cocci is formed after the seeds mature and the fleshy exocarp dries. The seeds become mature when the capsule changes from green to yellow, after two to four months (Rosillo-Calle, *et al.*, 2006)

2.7.4.6 Crop Yield

Jatropha plant produces seeds with an oil content of about 37 %. The oil can be combusted as fuel without being refined. It burns with clear smoke-free flame. It has been tested successfully as fuel for simple diesel engine. (www.jatrophaworld.org).

A good crop can be obtained with little effort. Depending on soil quality and rainfall, oil can be extracted from the jatropha nuts after two to five years. The annual nut yield ranges from 0.5 to 12 tons. The kernels consist of oil to about 60 percent; this can be transformed into biodiesel fuel through esterification.

It is difficult to estimate unequivocally the yield of a plant that is able to grow in very different conditions. Yield is a function of water, nutrients, heat and the age of the plant and other factors. Many different methods of establishment, farming and harvesting are possible. Yield can be enhanced with right balance of cost, yield, labour and finally cost per metric ton (Mt). Seed production ranges from about 2 tons per hectare per year to over 12.5t/ha/year, after five years of growth. Although not clearly specified, this range in production may be attributable to low and high rainfall areas. An example of the difference in potential seed production that can be expected of two farming systems (without irrigation and with irrigation) is illustrated in Table 2.8 and 2.9.

Table 2.8 *Jatropha* potential seed production (ton/ha) figures that can be expected for a farming system without irrigation (Source: www.jatrophaworld.org).

Mt/Ha (metric ton per hectare)			
DRY			
	LOW	NORMAL	HIGH
Year 1	0.10	0.25	0.40
Year 2	0.50	1.00	1.50
Year 3	0.75	1.25	1.75
Year 4	0.90	1.75	2.25
Year 5	1.10	2.00	2.75

Table 2.9 *Jatropha* potential seed production expected for a farming system with irrigation

MT/HA (metric ton per hectare)			
IRRIGATED			
	LOW	NORMAL	HIGH
Year 1	0.75	1.25	2.50
Year 2	1.00	1.50	3.00
Year 3	4.25	5.00	5.00
Year 4	5.25	6.25	8.00
Year 5	5.25	8.00	12.50

2.7.4.7 Zimbabwe *jatropha* experience summarized

In Zimbabwe, the bio-diesel project using feedstock from the *jatropha* plant is managed by Finealt Engineering. It has been determined that the local seed has oil content of about 35 – 40 % and one ton can yield up to 250 litres of oil. So far the limited research described in section 2.3.4 has been the only recorded effort in Zimbabwe directed at the *Jatropha curcas* plant. The results of the experiments, certainly require further research, for example why there was poor germination at Masvingo, why there was a lack of response to fertilizer application at Art Farm. The relationship between growth rate and temperature as depicted by the different rates between Art Farm and Mid-Sabi needs to be investigated with possible application of crop models. At present, the author is not aware of any modeling effort that has been directed at the productivity of *Jatropha*. Hopefully the current study will demonstrate the possibility of applying modeling to cultivation of *Jatropha* in Zimbabwe, so that its potential yield in terms of bio-diesel can be compared to other bio-fuel yields from fuel crops like sweet sorghum and sugarcane.

CHAPTER 3: MATERIALS AND METHODS

3.1 Introduction

The chapter is divided into two parts; the materials and methods used in the solar radiation analysis and the materials and methods of the modeling process. It was found prudent to give a separate treatment to the weather element of radiation because of its importance to a number of applications. Mean monthly maps of solar radiation using satellite data have been prepared, and then compared with those from the Climate Handbook of Zimbabwe (1980) that used ground based solarimeter measurements. The most appropriate data for the modeling process is daily data, and it was selected from ground measurements of selected meteorological stations.

The second part of the chapter is mainly concerned with the simulation of potential yield in terms of above ground biomass using DSSAT4 model. The main tool used in assessing the crop yield is the computer based Cropping Simulation Model tool (CSM) in the Decision Support System in Agro-technology Transfer (DSSAT v4.0). The model uses daily climatic data in its simulation of crop growth, development and finally yields. The model structure will be discussed later on in this chapter, but the model does not cover all the crops under review in this study. The *Jatropha curcas* plant is not included among the crops that the model has been designed to simulate, this is primarily due to the fact that it is a new crop in the bio-fuel production scenario and research work is ongoing in a number of countries. Since more crop models are envisaged to be included in DSSAT in the future, perhaps jatropha will eventually be included in the suite of the crop models currently in use in DSSAT. Future efforts could be directed that way in Zimbabwe where cultivation of jatropha is being encouraged by the government. The simulation of sugarcane is included in the DSSAT v4, but as legacy models, because it is still run in the previous DSSAT version 3.5, that is a DOS version. The only relevant crop, which is fully functional in the DSSAT v4 CSM system, is sorghum. Although the initial work in DSSAT4 has concentrated on grain sorghum varieties, the sweet sorghum varieties are easily incorporated through manipulation (changing) of the crop coefficients that determine the different development stages of a crop in the model.

3.2 The climate data and their sources

Choice of climatic data used in this study was governed primarily by the model requirements of the Decision Support System in Agro-technology Transfer (DSSAT version 4.0.2.0) that in turn were determined by the weather elements influencing crop growth, development and yield. While it is recognized that more weather or climate parameters should be included in the model simulations, most data is not readily available, therefore the International Benchmark Standards Network for Agro-technological Transfer (IBSNAT) group chose to describe a generalized minimum data set (MDS) to be used for running the crop simulation models (Hoogenboom *et al.*, 2003). This standard includes a minimum data set for weather consisting of maximum and minimum air temperature, solar radiation and precipitation. Table 3.1. gives a summary of the climate data and their sources used in this analysis.

Table 3.1: Summary of climate data sources

Parameter	No. of stations used	Period	Total no. of years	Source of data
Monthly rainfall (mm)	60	1971 to 2000	30	Meteorological Services Dept. (Zimbabwe)
Solar radiation ($\text{MJm}^{-2}\text{d}^{-1}$)	20	1951 to 1970	20	Climate Handbook of Zimbabwe
Monthly maximum and minimum temperature ($^{\circ}\text{C}$)	23	1971 to 2000	30	Meteorological Services Dept. (Zimbabwe)
Daily solar radiation ($\text{MJm}^{-2}\text{d}^{-1}$)	4	1991 to 2000	10	Meteorological Services Dept. (Zimbabwe)
Daily rainfall (mm)	4	1991 to 2000	10	Meteorological Services Dept. (Zimbabwe)
Daily maximum and minimum temperature ($^{\circ}\text{C}$)	4	1991 to 2000	10	Meteorological Services Dept. (Zimbabwe)
Solar radiation (Wm^{-2})	Grid resolution: 0.5 x 0.5 (lat, lon)	1961 to 1990	30	Climate Research Unit (CRU), University of East Anglia, (united Kingdom)

3.2.1 Solar radiation data sources

3.2.1.1 Ground-based observations

The record for ground based observed solar radiation data is not as expansive as the observed temperature or rainfall data. To begin with, the record is shorter and secondly the number of observation stations is relatively few. The most unfortunate issue on solar radiation is that, there were more observing stations in the first half of the twentieth century (> 20 stations), while the current station network is less than ten stations. As a result the period chosen for ground based

solar radiation data is rather ‘old’ (1951 to 1971) for the climatic characterization of solar radiation for Zimbabwe, because this was the time when there was still a wide coverage of solar radiation measuring stations

(Figure 3.1). As can be seen from Figure 3.1, there are quite large data gaps for areas over the northwest of the country and the interpolation methods used to fill in the missing values have their own shortcomings especially in mountainous areas as opposed to flat plains.

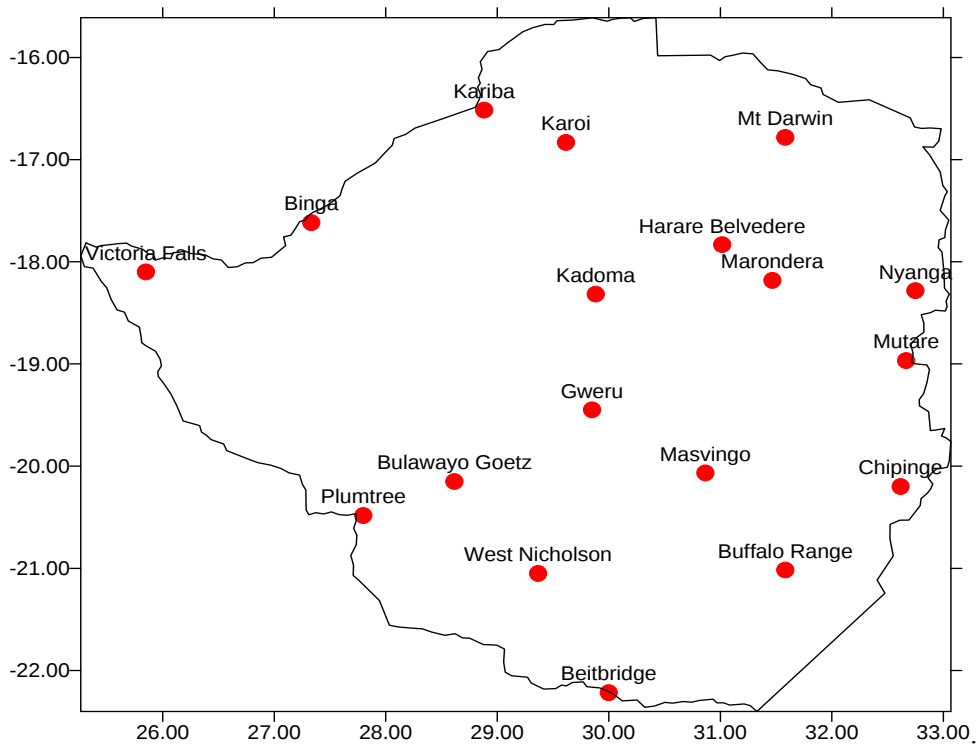


FIGURE 3.1: Ground based station network for solar radiation measurements

(Source: Zimbabwe Meteorological Services Department)

3.2.1.2 Instruments used

Moll pyranometers installed at Bulawayo and Harare provided records of both global and diffuse solar radiation. Global radiation refers to the total receipt regardless of source, whereas diffuse refers to the radiation scattered by the atmosphere and any particulate matter held in suspension such as haze or clouds, but excluding direct radiation from the sun. These Moll pyranometers were calibrated against world standards, so they formed the national standards for a secondary network of Gunn-Bellani spherical pyranometers which respond to global radiation but are of lower accuracy (Climate Handbook of Zimbabwe, 1980). The network of instruments used to measure solar radiation for the period 1990 to 2000 used in the model simulation is called Sonego solarimeters.

3.2.1.3 Satellite based solar radiation data

The satellite data used in this study was significantly lower (>20%) on average compared to solarimeter measurements and some of the errors for underestimation could arise from the model assumptions in the estimation of the solar radiation (Pinker and Lazlo, 1992; Beyer, *et al.*, 1995; Bonomo and Brignoli, 1994). However, it would require a separate study to comprehensively validate the satellite data for the whole of Zimbabwe. Despite the underestimation drawback, the data has a more detailed spatial signature than the ground based observation purely because of its superior resolution (0.5° by 0.5°).

3.2.1.4 Errors in satellite estimates

Satellite measurements, although they have distinct advantages over ground based observations in terms of spatial and temporal resolution, they do suffer from instrument calibration errors that require correction procedures namely (Gautier *et al.*, 1980):-

- Correction for the satellite angle
- Corrections for cloud cover
- Instrument calibration
- Correction for the sun angle

In addition, the data needs to be validated with ground observations.

3.2.1.5 Comparison of data sources for solar radiation

From the afore-going discussion on the data sources of solar radiation, the next step is an assessment of the best source to use in the analysis. The solar radiation datasets are in two time-scales, monthly and daily data. The monthly data are from two sources and a comparison is made between them to assess the better dataset to be used in the final analysis. The computer program *Surfer32* is used to produce contour maps for each month. The result of this analysis gives the spatial and temporary variations of the parameter in the country that forms the basis of assessing the potential of a locality for the production of a particular crop. The daily data set is extracted from surface observations archived at the Zimbabwe Meteorological Services Department and is primarily used in the crop simulation modeling process. The principal crop simulation tool CSM in the DSSAT4 requires solar radiation at daily time steps.

3.2.1.6 Differences in the sources

The radiation data used in this analysis was from essentially three sources. The Zimbabwe Meteorological Services Department provided two data sources; the Climate Handbook of Zimbabwe (1980) for the period 1951 to 1970 and archived daily data for the period 1991 to 2000 from the Data Processing Unit in the Information Systems (IS) branch. Satellite based

solar radiation data was sourced from the University of East Anglia - Climate Research Unit (UEA - CRU), United Kingdom database, for the period 1961 to 1990 (Table 3.1).

One thing to note on the radiation data is that all the sources have different periods, thus making it less than ideal for comparison purposes. However, since the data is averaged over the respective period, it is assumed that differences arising from the different periods analyzed should be minimal by virtue of the conservative nature of the parameter, all other things being equal. Unlike rainfall whose variability has been the basis of several studies, average solar radiation is relatively unchanged over the time periods being considered here.

The comparison of site specific radiation values was done by approximating the grid reference of a station (latitude, longitude) to the nearest satellite grid point value. Since the satellite measurements were in watts per square metre (Watts/m^2), they were converted to $\text{MJ/m}^2/\text{day}$ by multiplying with a constant factor (i.e. $[24 \times 60 \times 60]/10^6$) to make them comparable to ground observations. The mean monthly radiation figures for selected months and stations are shown in Table 3.2.

The choice of months used in the comparison analysis was based on the Zimbabwean seasons; January and February are representative of the wet season (summer) and June, July are typical of the dry season (winter); March and October represent the transition period from summer to winter and winter to summer respectively.

TABLE 3.2 : Mean monthly solar radiation for selected stations: (a)

BEITBRIDGE ($\text{MJm}^{-2}\text{d}^{-1}$)			
Instrument	Sonago solarimeter	Moll pyranometer	Satellite
Period	1991 - 2000	1951 - 1971	1961 -1990
January	25.18	24.60	17.20
February	22.55	23.50	16.20
March	23.50	21.20	15.90
June	16.00	13.70	13.10
July	16.80	15.20	14.00
October	24.42	21.30	17.90

(b)

MOUNT DARWIN ($\text{MJm}^{-2}\text{d}^{-1}$)			
Instrument	Sonago solarimeter	Moll pyranometer	Satellite

<i>Period</i>	1990 - 2000	1951 - 1971	1961 -1990
January	22.82	21.50	15.00
February	22.75	21.20	14.80
March	22.88	21.60	15.00
June	17.85	16.90	13.30
July	18.73	17.90	13.90
October	25.17	23.00	17.70

(c)

KAROI (MJm⁻²d⁻¹)			
<i>Instrument</i>	Sonago solarimeter	Moll pyranometer	Satellite
<i>Period</i>	1990 - 2000	1951 - 1971	1961 -1990
January	23.16	20.60	14.90
February	22.75	20.40	14.80
March	23.93	21.70	15.50
June	19.74	16.90	13.80
July	20.92	18.20	14.70
October	27.30	23.50	17.90

(d)

HARARE BELVEDERE (MJm⁻²d⁻¹)			
<i>Instrument</i>	Sonago solarimeter	Moll pyranometer	Satellite
<i>Period</i>	1990 - 2000	1951 - 1971	1961 -1990
January	19.17	20.80	15.50
February	17.43	20.60	15.20
March	19.07	21.50	15.40
June	15.85	16.40	13.20
July	15.99	17.90	14.10
October	22.71	23.60	17.60

(e)

GWERU (MJm⁻²d⁻¹)			
<i>Instrument</i>	Sonago solarimeter	Moll pyranometer	Satellite

Period	1990 - 2000	1951 - 1971	1961 -1990
January	23.02	22.40	16.70
February	24.21	21.60	16.00
March	23.78	21.60	15.90
June	19.56	16.10	13.10
July	17.70	17.70	14.00
October	23.1	23.10	17.50

(f)

MASVINGO (MJm⁻²d⁻¹)			
Instrument	Sonago solarimeter	Moll pyranometer	Satellite
Period	1990 - 2000	1951 - 1971	1961 -1990
January	23.18	22.40	17.20
February	23.55	22.10	16.20
March	22.34	21.80	15.70
June	16.75	15.40	12.70
July	17.02	16.80	13.30
October	24.06	21.50	17.10

3.2.2 Temperature data

The temperature data used in this study was sourced from the Zimbabwe Meteorological Services Department. The dataset has data at two time steps. There is monthly data that has been analyzed to produce monthly contour maps of maximum temperature using the Surfer32 computer program. The number of stations used in the temperature analysis was 20 (Figure 3.3) and the climate period was 1971 to 2000.

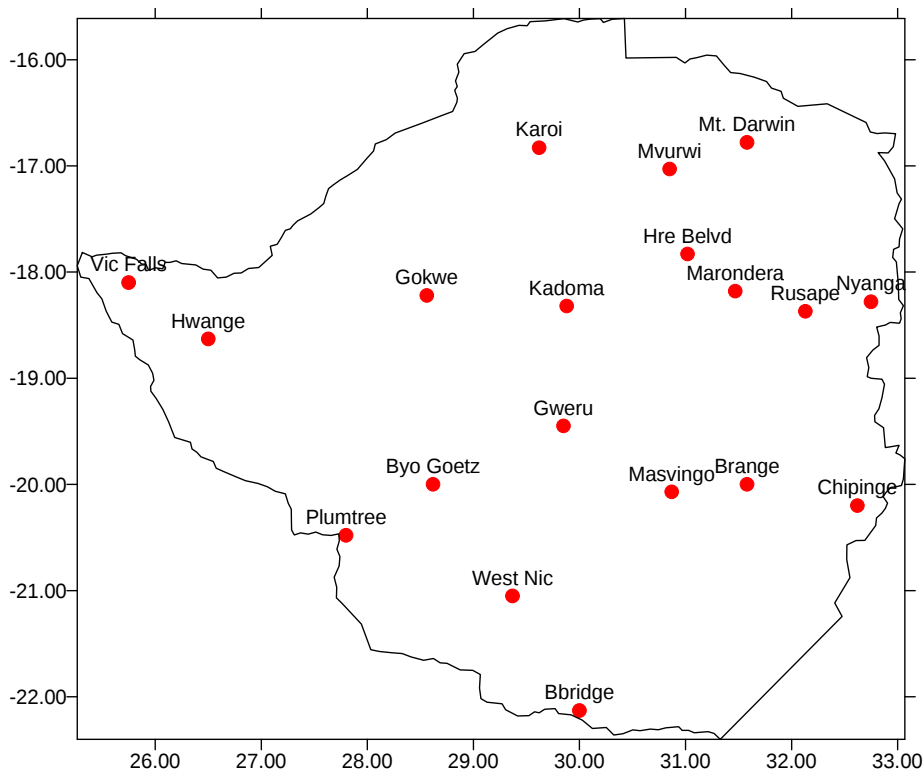


Figure 3.3 Map showing the stations used in the temperature analysis

The choice of the period was governed by availability of data and also that the period covers the most recent climate pattern observed over the country. Preliminary climate change studies on temperature have suggested that a warming trend is discernible in some Zimbabwean stations' time series (New *et al.*, 2006); hence it would only be more appropriate to use the latest information unlike the radiation data. The current data period (1971 to 2000) is more continuous with fewer data gaps than earlier periods.

The second level of the temperature data is daily time series. However, the daily data was only sourced for a few sample stations that will be used for site-specific case studies. The crop simulation model (CSM) requires among its weather parameters, daily or monthly data. The CSM gives yield in terms of weight of above ground biomass per hectare. However, for a better comparison of the different fuel crop yield potential, the final potential yield for sweet sorghum and sugarcane is converted to litres of ethanol per unit area (hectare), while the potential yield for *Jatropha curcas* is given as mass of oil (kg) per hectare.

3.2 Analysis Methods and Tools

The data analysis was tackled using two principal tools:-

- Surfer 32 for surface mapping of climate parameters
- DSSAT4 CSM tool for crop simulation

3.2.1 Surfer 32 version 6.04

Surfer (Win32) is a product of Golden Software Inc. (1996); it is a data management system specifically for surface mapping using interpolation techniques. The spatial interpolation of agro-climatic data aims at estimating the value of rainfall, temperature or any other parameter at a given site based on the observations at neighbouring locations. Some of the interpolation techniques employed are generic and are described in the climate database FAOCLIM-2, which is a Climate Database for the entire world. The Agro-meteorology Group of the Food and Agricultural Organization of the United Nations (FAO) developed the FAOCLIM-2 software (Coordinator, Agro-meteorology Group; agromet@fao.org).

Surfer is used to generate surface maps of monthly maximum temperature, as well as monthly maps of solar radiation from the datasets collected. The maps are used in conjunction with relevant literature to qualitatively assess the suitability of the Zimbabwean climate to the cultivation of the different fuel crops. Kriging and minimum curvature are the methods of interpolation that are employed by the Surfer program. Kriging is a linear regression prediction using data of the same attributes as that being estimated (Bogaert, *et al.*, 1995). Cokriging on the other hand is the linear regression that uses data defined on different attributes.

3.2.2 Crop Modelling

Computer models, in general are mathematical representation of the real world system (Tsuji, *et al.*, 1998). A model might include many assumptions, especially when information that describes the interactions of the system is inadequate or does not exist. In reality, it is impossible to include all the interactions between the environment and the modeled system in a model. Primary weather inputs for a computer simulation model are air temperature, solar radiation and rainfall. Secondary inputs are wind speed, relative humidity, soil temperature and dew point.

3.2.2.1 DSSAT software package system background

IBSNAT, i.e. the International Benchmark Sites Network for Agro-technology Transfer was a network consisting of a contractor (University of Hawaii), its subcontractors and many global collaborators. Together they created a network of national, regional, and international agricultural research for the transfer of agro-technology among the global partners in both developed and lesser developed countries. From 1982 to 1987, the program was under the auspices of the USAID. ICASA was established in 1994 as a non-profit corporation in Honolulu in Hawaii. The International Consortium for Agricultural Systems (ICASA); developed the Decision Support System for Agro-technology Transfer (DSSAT) (Hoogenboom *et al.*, 2003).

3.2.2.2 Minimum Data Set (MDS)

IBSNAT project defined a minimum data standard (MDS) for crop model applications (DSSAT4 volume 1 with reference to work by ICRISAT, 1984; IBSNAT, 1990). This standard includes a minimum data set for weather consisting of maximum and minimum air temperature, solar radiation and precipitation.

The model version that is employed in this study is DSSAT v4.0 that is an upgrade of the DSSAT v3.5 system, which was released in 1999. One of the most important changes and improvements in DSSAT v4 is that it has been completely redesigned and is now MS Windows based. Below is a summary of the most relevant components of DSSAT4 that are used in this analysis

DSSAT v4.0: (Source:–Hoogeboom *et al.*, 2003) includes:-

- ❑ More than 18 different crops simulated with CSM, including maize, wheat, rice, barley, sorghum, millet, soybean, peanut, dry bean, chickpea, cowpea, faba bean, velvet bean, potato, tomato, bell pepper, cabbage, bahia and brachiaria and bare fallow
- ❑ The DSSAT v3.5 legacy models, including cassava, sunflower, sugarcane, taro, tanager, and pineapple.
- ❑ A New Weather Data Manager WeatherMan for entering, analyzing and generating weather and climate data.
- ❑ The Introductory Simulation Tool ICSim for simple simulations and application of models as a teaching tool.

The list above is by no means exhaustive. One of the most important tools available in DSSAT v4 is a Crop Management Data Tool called XBuild, for entering and editing of experimental data. It is the simulation tool that is employed when crop modeling is done in conjunction with field experiments for validation purposes. In this study, the ICSim tool is employed in the simulation of crop yield. This tool was developed in response to training needs identified at a training workshop in Egypt on the use of DSSAT. In this case, it was chosen because of its simplicity and ease of use since no field experimental data is available that would have warranted the use of the XBuild tool.

3.2.2.3 Introduction to Crop Simulation (ICSim) tool

ICSim is a MS Windows application that is used as an add-on to DSSAT v4. ICSim makes use of the DSSAT directory structure and communication protocol that designates the location of all programs and data files used in DSSAT. The Visual Basic version 6 program was developed as part of a US-Egyptian cooperative project (Hoogemboom, *et al* 2003). A more comprehensive Windows based tool (XBuild) has been developed that will provide access to all the

functionality of the crop models. The crop simulation tool for DSSAT (XBuild) allows users to specify any combination of several crops for purposes of validation (comparing with observed data), seasonal analysis, crop rotations and spatial analysis that are available in DSSAT v4. A full documentation of the tools available in DSSAT v4 is found in “Tsuji *et al.*, 1994 and Hoogenboom *et al.*, 1999 volume 4.” The main capabilities of crop simulation models of DSSAT v4 software package allows users to specify weather, soil and main practices to simulate crop growth and yield using any of the crop models and data sets available in DSSAT v4.

3.2.2.4 Differences and limitations of ICSim relative to DSSAT v4 (XBuild) capabilities (Hoogenboom, 2003)

- The difference between XBuild and ICSim is that ICSim creates its own working directory (called \DSSAT4\ICSim) for all management files and all outputs of crop models.
- ICSim provides capabilities to set up simulation runs for any number of crop models in DSSAT4, single season simulations only. It does not allow for users to simulate for a number of years to estimate the effects of weather variability on crop production.
- Results of ICSim are not linked with some experimental measurements for validation.
- ICSim simulates crop, soil and management conditions specified by the user using the crop models operating in the water and nitrogen limitation mode (i.e. with the soil water and nitrogen balances switched on). Also automatically simulates potential yield.
- In ICSim, soil, water and nitrogen initial conditions are set in a simple way on the first screen.
- Initial residue for simulation done with ICSim is assumed to be 1000kg/ha and cannot be changed by user.
- In the Environmental Modification Screen, users can only specify one modification. This modification is aimed to start on the date specified in the corresponding box on the screen; that is defaulted to be the planting date. Once activated the environmental modification remains in effect throughout the season.
- ICSim does not allow for pest damage to be imposed on the crops.
- ICSim does not provide users with access to seasonal, sequence or spatial analysis programs in DSSAT v4, nor does it provide users with access to other important utilities, such as WeatherMan (Hoogenboom *et al.*, 2003)

The reason for choosing ICSim was because my study did not include field experiments to verify model results. Therefore the results presented here are primarily simulated results that might or might not be closely linked to experimental results. Furthermore, not all the available results were discussed, only potential biomass production and length of growing season were analyzed with respect to different climatic (environmental) conditions.

3.2.2.5 *Outputs of ICSim*

3.2.2.5.1 *Overview.Out*

Overview.Out provides an overview of the input conditions and simulated crop performance. However as already stated, results are not linked to experimental measurements for validation.

- ✓ The first section in this file presents information that uniquely describes the simulated results data set. This includes the Experimental Name, treatment number, crop, planting date, population and row spacing, soil initial conditions etc.
- ✓ The second section in Overview.Out contains a summary of soil characteristics and cultivar coefficients.
- ✓ The next section deals with crop and soil status at the main development stages, followed by a comparison of simulated and measured data for major variables.
- ✓ Followed by information on simulated stress factors and weather summary during the development phases, as appropriate for the crop.

3.2.2.5.2 *Summary.Out*

The section in Summary.Out of ICSim contains one line summary of the main development events, water and nitrogen variables, and yield components. Furthermore it has two more lines of information on (1) scenario with water and nitrogen limitation (2) potential yield with water and nitrogen balances turned off.

3.2.2.6 *Data type and sources for computer simulation*

The weather data required to run the ICSim model included, daily maximum and minimum temperature (°C), daily solar radiation (MJ/m²/day) and daily rainfall (mm). This data had to be in a specific format, Excel or text, and in this case Excel was chosen since it was the original working datasheet and was therefore easier to manipulate into the required format for input into DSSAT4 weather files.

3.2.2.7 *Cultivar coefficients in CSM*

The CSM CERES-Sorghum crop model is designed to simulate grain varieties only. There are 55 grain sorghum varieties that have so far been incorporated into the DSSAT4 CSM sorghum crop model. However, one can add-on a variety for simulation by the same model by changing the crop coefficients. The crop coefficients are the ‘drivers’ of the growth and development of a particular cultivar. For the purposes of this study, the sweet sorghum variety Keller was added to the list of varieties, making the total list 56. The Keller variety has demonstrated a comparably high potential yield in field experiments in Zimbabwe (Woods, 2000) and Europe (Daliannis, 1997). In order to test the sensitivity of the model to different sorghum varieties, the Keller (sweet variety) was compared to a grain variety, Pioneer 8333 at one of the test sites, Karoi.

3.3 Crop simulation methodology

The crop simulation was done for four sites, namely Karoi, Harare Belvedere, Masvingo and Buffalo Range, using the weather data available, other stations were not chosen due to data gaps for the period 1990 to 2000. Solar radiation is not available for some Zimbabwe stations, hence the need to change to other modes of observation like satellite based observation (remote sensing) that would provide a more reliable spatial and temporal resolution of the parameter.

Since the aim of the crop simulation exercise was to get an idea of the potential yield of the fuel crop, in this case sweet sorghum, under the given environmental conditions, the daily data for the ten year period (1991 to 2000) was averaged to produce the average daily data for one Julian year of 365 days. In order to satisfy the crop simulation to proceed without interruption through a complete growing season, the data was entered twice as if it was data for two consecutive years. However, the potential and actual yields of sugarcane for this work were derived from literature and statistics from the Triangle Ltd. Company in the southeast of the Zimbabwe where the bulk of sugar cane is grown in the country. There are two main reasons why simulation runs for sugar cane cultivation at the four sites mentioned above were not done; one was that field data is already available (albeit for one area) from the long experience of growing sugar cane in the SE of Zimbabwe plus research work (Woods et al., 2000) that has been done in the area. Secondly, the current DSSAT v4 crop models do not include sugarcane explicitly but it is a 'legacy model' that is only available in the DSSAT v3.5 crop models and it is run in DOS (still under development to migrate to DSSAT v4).

The incorporation of a jatropha model into the DSSAT CSM is yet to be implemented. Therefore it could not be simulated.

CHAPTER 4: RESULTS

4.1 Introduction

The first part of the chapter, examines the results of the analysis of the different sources of solar radiation. In the second part, the results of the DSSAT - CSM crop simulation for sweet sorghum are analyzed, in terms of the potential yield (above ground biomass). The assessment of the potential yield is carried out primarily under existing climatic conditions. Furthermore, two sensitivity tests are carried out under modified environments (i.e. maximum temperature rise of 2°C and a 5 MJ/m²/day reduction in solar radiation) to gauge the effect of the modifications on the potential yield. A third sensitivity test is done through a comparison between two sorghum varieties, a grain cultivar, Pioneer 8333 and the sweet sorghum cultivar, Keller. The varieties comparison is mainly useful from a breeding point of view, to assess characteristics that could be useful in gene manipulation to come up with a super variety which can deliver both high sucrose content and high grain yield. The future potential productivity of sorghum might eventually be judged from its capacity to deliver both sucrose for ethanol production and grain for food.

4.2 Solar Radiation Data

Knowledge of the solar radiation pattern is useful for identifying potential areas for the cultivation of fuel crops particularly sweet sorghum because of its influence on the plant photosynthesis as already discussed in chapter two. One of the challenges we face in Zimbabwe is an adequate solar radiation observation network. Currently, there are less than 10 stations that routinely measure radiation around the country compared to more than 20 in 1970; consequently

any interpolation method based on the present data coverage is bound to be fraught with inaccuracies. This limitation in a good spatial coverage of radiation data impacts negatively on applications requiring such data i.e. recent accurate radiation maps. In this study, satellite based observations are used as one of the possible sources of solar radiation data. However, this data needs to be validated against ground based observations and in the current study it was used as it is.

4.2.1 Comparison of the radiation maps

Figure 4.1 below shows two radiation maps produced for each month for selected months. The left pane map is from radiation data sourced from ground based measurements and the right pane is for radiation sourced from satellite observations. The period of the data sources is different (see Table 3.1); the ground observations' period was from 1951 to 1971 and the satellite observations are for the period 1961 to 1990. Ground and satellite based radiation maps' units are $\text{MJm}^{-2}\text{d}^{-1}$.

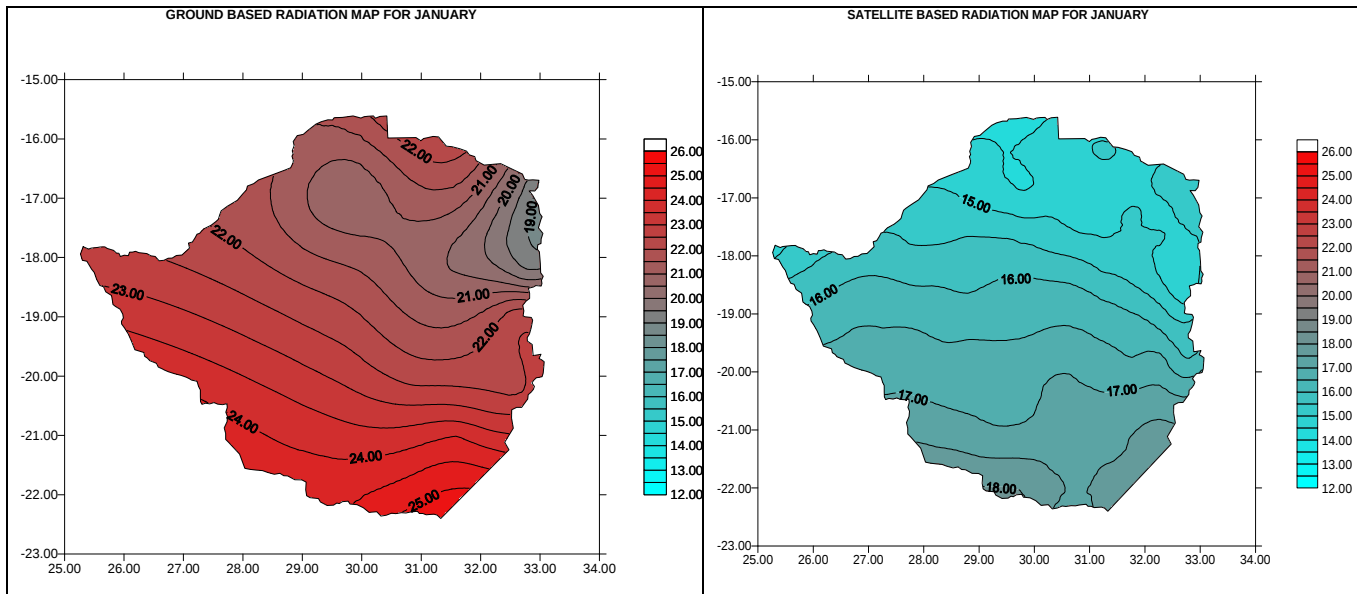


Figure 4.1a: January solar radiation from ground based observations (left pane) and satellite based estimates (right pane)

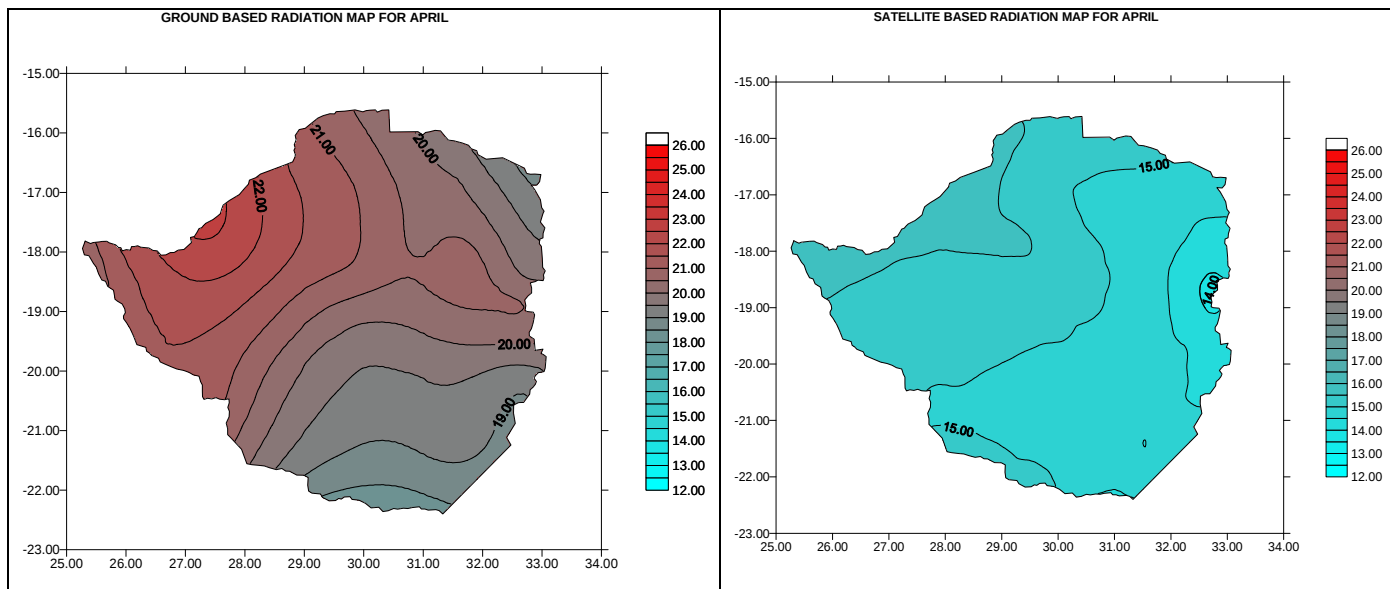


Figure 4.1b: Radiation maps for April: ground based observations (left pane) and satellite based estimates (right pane)

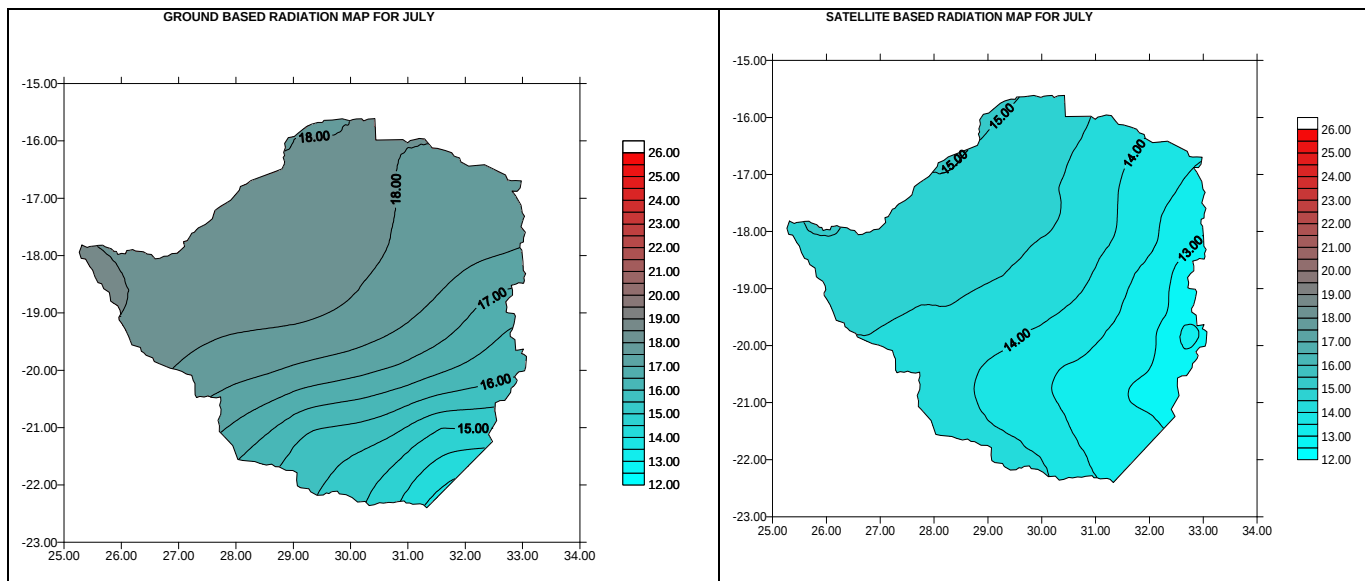


Figure 4.1c: Radiation maps for July: ground based observations (left pane) and satellite based estimates (right pane)

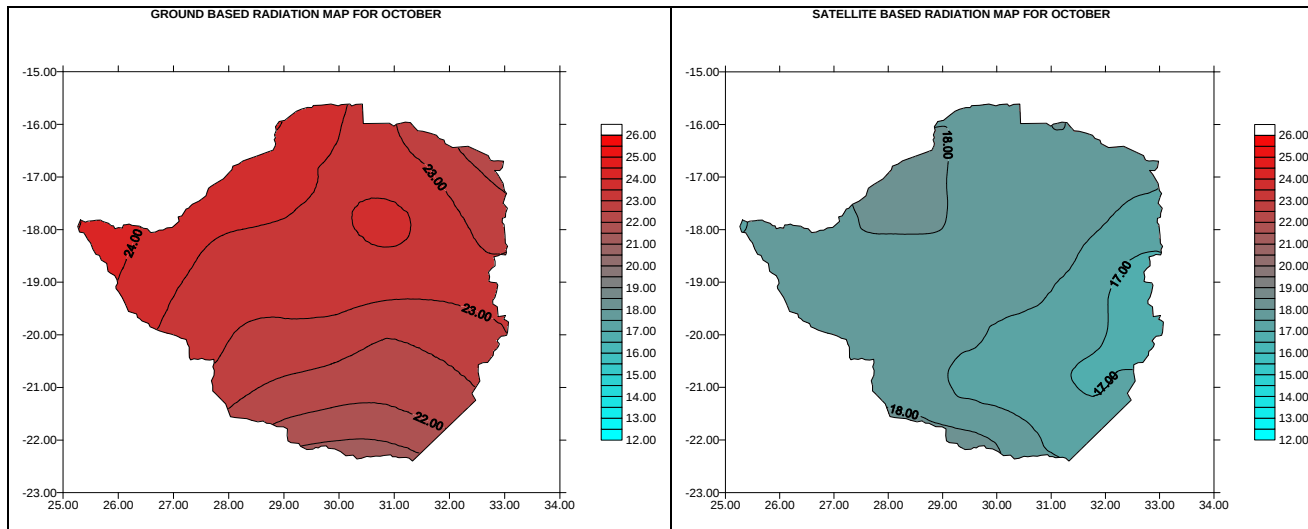


Figure 4.1d: Solar radiation maps for October: ground based observations (left pane) and satellite based estimates (right pane)

4.2.2 Results for solar radiation sources mapping

The radiation comparison was done for four selected months which are typical of the seasons of Zimbabwe. The comparison of the two sources of radiation data through the radiation maps reveals differences that are summarized in subsequent sections.

January

During this period, the ground based radiation map shows that the mean radiation ranges between about 18-25 ($\text{MJ/m}^2/\text{day}$) with an increasing trend from NE to SW. Satellite measured data map shows a range of about 14-18 ($\text{MJ/m}^2/\text{day}$) with an increasing trend from N to S. The contour pattern broadly defines lower radiation values over the north-northeastern sector with relatively high values in the south of the country. This pattern reflects the general weather systems prevailing during this time of the year. Cloudy conditions predominate over northern parts of the country relative to southern areas due to the influence of the Inter-tropical Convergence Zone (ITCZ).

April

The radiation pattern changes during this period with the radiation minima shifting to the east of the country for satellite observations and to the south for ground based measurements but there is a general agreement about higher values over the northwestern sector. Furthermore the ground based radiation range for April is somewhat reduced, ranging between about 18-22 ($\text{MJ/m}^2/\text{day}$) and the satellite observations range is correspondingly reduced to 14-16 ($\text{MJ/m}^2/\text{day}$).

July

Noteworthy during this period is the considerable overlap of the ranges from the two radiation sources, unlike in the other months. The spatial pattern is in fairly good agreement for both maps. Ground based data ranges between 14-18 (MJ/m²/day) and for satellite observations between 13-16 (MJ/m²/day). The trend of values increases from E-SE going towards the NW. July is typical of the winter period with predominantly clear skies. The radiation pattern depicted during this month is indicative of the strong influence cloud cover has on the spatial distribution of surface solar radiation. During July there is a prevalence of low level cloud incursions from mobile high pressure systems situated to the SE of the subcontinent.

October

There is considerable difference between the two radiation maps during this period. Not only is there is no discernible overlap in the measured radiation from the two sources; but the ground based observations show radiation values in excess of 20 (MJ/m²/day) throughout the country, while satellite estimates have little range between 17 and 18 (MJ/m²/day). Compared to other analyzed months, the range between the minima and maxima radiation values is considerably less in October.

4.2.2.1 Summary of mapping results

On the whole, the maps are showing that ground based observations of surface solar radiation has more spatial variability than satellite based measurements. The lack of overlap in the contour ranges for the two sources (except in winter) suggest the need to assess the precision and accuracy of satellite observations. Despite this drawback, the fairly good agreement in the general spatial pattern is indicative of the potential of satellite information for future use on surface solar radiation mapping. The satellite data has the additional advantage of being readily available and has a higher resolution than the current ground based measurements.

4.2.3 Quantitative comparison between satellite and ground based measurements

Initially, a comparison of ground based observations of solar radiation (grn_data) was done using regression method (Figure 4.2). The correlation coefficient (R^2) is 0.9269, for the period 1951-1970 data set versus the 1990-2000 data set. This suggests a strong linear relationship between the two data sets. Therefore it is possible to use either data set for a comparison with satellite based estimates. However, an average of the two data sets was calculated and used to compare with satellite based observational data.

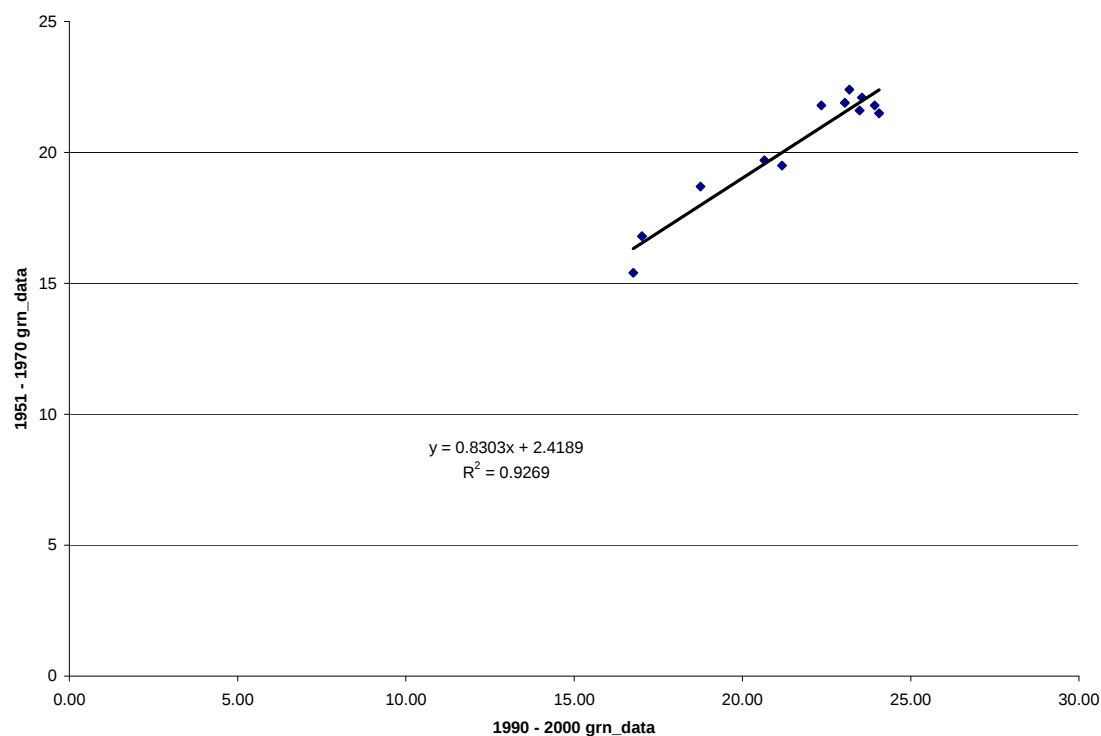


Figure 4.2: Linear correlation graph of ground based observation for different periods (1951 – 1970 and 1990 – 2000).

The comparison of the ground based observational data against the satellite estimates of solar radiation is shown in Figure 4.3.

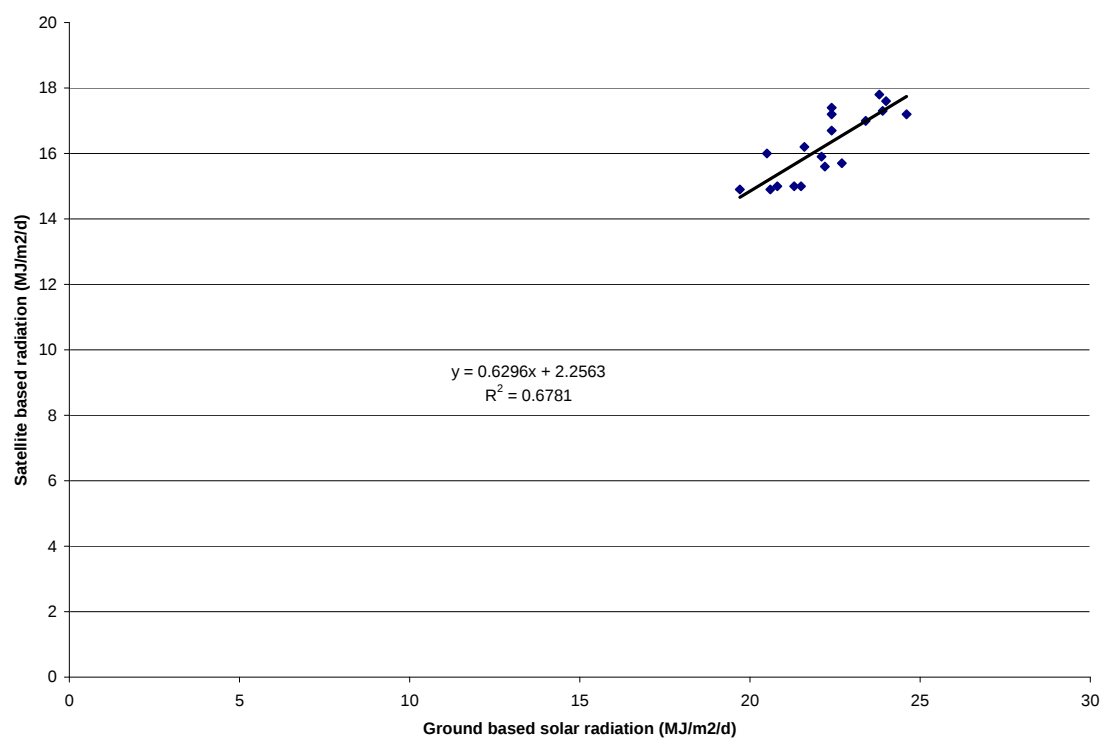


Figure 4.3: Linear correlation graph of ground based solar radiation against corresponding satellite estimates

The regression of the two data sets indicates that the linear relationship as depicted by R^2 ($R^2 = 0.6781$) is weaker than in Figure 4.2. Furthermore the results of the percentage differences found between the two radiation sources for selected sites are given below (Table 4.1). Quite large differences were found between solarimeter based measurements (ground observations) and satellite estimated values in absolute terms, when comparing site-specific data. Satellite values were lower than ground-based observation by more than 20 % on average (Table 4.1).

Table 4.1: The percentage difference between solarimeter measurements and satellite based estimates for selected stations and randomly selected months.

Station	January (%)	February (%)	March (%)	June (%)	July (%)	October (%)	Average (%)
Beitbridge	-31	-30	-29	-12	-12	-22	-22
Hre_Belvedere	-25	-20	-24	-18	-17	-24	-21
Gweru	-26	-30	-30	-27	-25	-29	-28
Masvingo	-25	-29	-29	-21	-21	-25	-25
Mt Darwin	-32	-33	-33	-23	-24	-26	-29
Karoi	-32	-31	-32	-25	-25	-30	-29

On average, Harare, (Belvedere) had the lowest percentage difference (21 %) while the largest differences are observed in Mount Darwin and Karoi, coincidentally both sites are situated over the northern parts of the country. Equally noticeable in the monthly figures is the lower differences (%) in winter (June, July) particularly over Beitbridge with the lowest difference of 12 %. This relatively smaller difference is observed at most sites except Gweru and Karoi. The Gweru results could possibly reflect the prevalence of low level cloud associated with ‘guti’ incursions from the SE. The effect of cloud cover on radiation was also found experimentally by Gautier *et al.*, (1980). In their (Gautier *et al.*, 1980) calculations, however, they had discovered that the satellite estimates tended to overestimate rather than underestimate as was found in the present study. Differences of site and calibration procedures could also come into play but the important point I have observed in the preceding results is that clear skies (particularly winter time) tend to reduce the difference between the two sources of radiation data.

Future research efforts could be directed at coming up with an improved model to calculate surface solar radiation from satellite data for Zimbabwe. As already demonstrated (Gautier *et al.*, 1980; Farzin Aghdasi, 1990, unpublished), processing of satellite imagery involves geometrical correction for the camera’s viewing angle, correction of the pixel brightness values for the sun angle, and accounting for the atmospheric transmissivity. The correction

methodologies need to be assessed for the Zimbabwe region where such large differences exist between surface observation and satellite based data.

4.2.3.1 Summary of radiation comparison

Quantitative assessments of the two data sets has revealed that satellite estimates are on average lower than ground measurements by >20%, with slightly less difference margin in winter (Figure 4.2), at least for most of the stations used in the analysis.

The results confirm in percentage terms the difference found in the mapping comparisons. Therefore, the use of the satellite data in this thesis shall be limited to the radiation mapping comparisons.

4.2.4 Radiation data for modelling

In this study, ground based solar radiation data is used in the modeling exercise, because it approximates (in magnitude) other datasets found in literature sources on experiments done in the SE of Zimbabwe (Woods, *et al.*, 2004).

In addition, a sensitivity run on the effect of reducing solar radiation by about 25% (-5 MJ/m²/day) was also incorporated to test yield potential response to variations in solar radiation, be it from climate variability or measurement errors.

4.3 Crop Simulation Results

The purpose of this second component of the research is to compare the potential productivity of sweet sorghum (Keller variety) as a fuel crop under existing climate for different sites. Four stations (sites) data were analyzed, typically representing three Natural Regions of Zimbabwe (table 4.2). The potential productivities of sugarcane and jatropha were not simulated with local data but are from literature sources and are discussed in the next chapter.

Table 4.2: Typical sites (stations) of the Natural Regions used in the analysis

Station data analyzed	Natural Region
Karoi	IIa
Harare Belvedere	IIa
Masvingo	IV
Buffalo Range	V

4.3.1 Potential yield of sorghum (*Sorghum bicolor*, L Moench)

Literature has shown that sorghum is one of the most productive crop species. This high productivity results from a combination of high light and nutrient use efficiencies and the ability

of sorghum to extract relatively high fractions of these resources when environmental conditions become limiting (Woods, 2000; Daliannis, 1997; Kulkarni *et al.*, 1997).

The simulation results' main output of interest to the objectives of the study is potential yield (above ground biomass) under existing environmental conditions. The model results give the potential yield in kilograms per hectare (kg/ha) of total above ground biomass. In addition the simulated results of the potential yields under two different climatic scenarios are also given.

The results of the potential yield (above ground biomass) in the three scenarios are given in Table 4.3; where y1 = biomass production under existing environmental conditions; y2 = biomass production under a modified environment (daily maximum temperature data increased by two degrees centigrade); y3 = potential yield under a modified environment (the daily radiation reduced by 5 MJm⁻² (about 25 %); y1-y2 = difference in yield between existing climate and a 2°C rise in maximum temperature; y1-y3 = difference in yield between existing climate and a 5 MJ/m²/day reduction in surface radiation.

Table 4.3: Summary of potential yield of sweet sorghum (Keller cultivar) at different sites under different environmental conditions

KAROI	Existing climate	+ 2degC	-5 MJ/m2				
Planting date	y1 (kg/ha)	y2 (kg/ha)	y3 (kg/ha)	y1-y2	%diff	y1-y3	%diff
jan	12803	12310	11862	493	4	941	7
marc	12774	12513	11660	261	2	1114	9
may	10924	10205	9914	719	7	1010	9
jul	11202	10692	10592	510	5	610	5
sept	11832	11472	11008	360	3	824	7
nov	12149	11587	11139	562	5	1010	8
MASVINGO							
jan	12803	12184	11694	619	5	1109	9
mar	10668	11000	9555	-332	-3	1113	10
may	9463	9019	8723	444	5	740	8
jul	10820	10345	10086	475	4	734	7
sept	11457	11066	10549	391	3	908	8
nov	12352	11224	11086	1128	9	1266	10
HARARE							

jan	12301	12015	10983	286	2	1318	11
marc	10056	10473	9023	-417	-4	1033	10
may	9901	9402	9068	499	5	833	8
jul	10849	10568	9806	281	3	1043	10
sept	11301	11025	10024	276	2	1277	11
nov	11598	11299	10240	299	3	1359	12
BUFALLO RANGE							
jan	10515	9783	9557	732	7	958	9
marc	11480	10988	9873	492	4	1607	14
may	10242	10085	9170	157	2	1072	10
jul	10028	9771	9399	257	3	629	6
sept	9910	9213	9161	697	7	749	8
nov	10130	9536	9500	594	6	630	6

4.3.2 Potential yield results comparison

The comparison of potential yields at the various sites was done in two ways; inter-site and intra-site comparisons.

4.3.2.1 Inter site yield comparisons

The simulated potential yields at the different sites under different environments are given in Table 4.1. Below is the potential yield comparison for the different sites under existing climatic conditions (Figure 4.4).

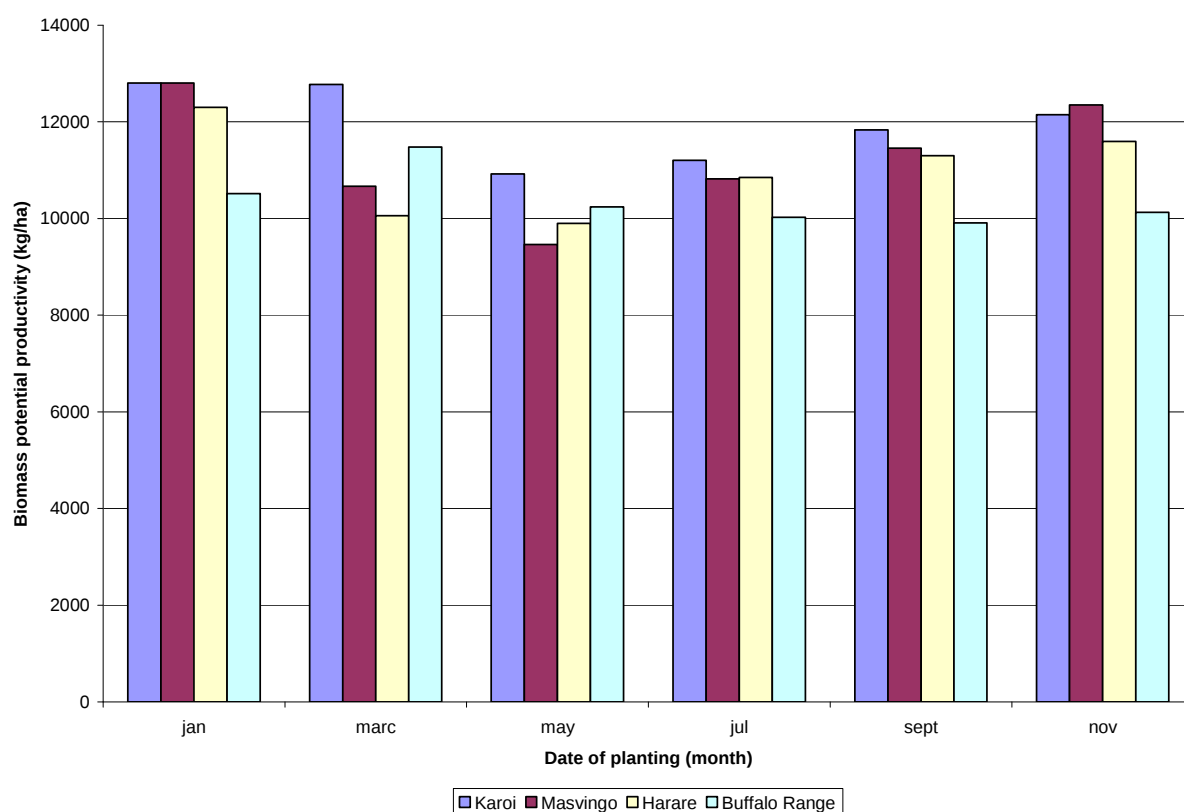


Figure 4.4 Potential yields at different sites under existing climate with different planting dates.

(a) Yield versus Date of Planting (DOP)

Slightly higher yields are obtained for all sites when the sweet sorghum crop is planted in January or November except in Buffalo Range that attains the highest yield for a crop planted in March. Incidentally, Karoi yield for a March crop is also quite high comparable to January. There is a general trend across all sites that lower yields are obtained for a crop planted in winter (i.e. May and July). Biomass production is highest over Karoi for crops planted in January, March, May, July, and September except in November and the productivity is above 10000 kg/ha. On the other hand, Masvingo site while displaying relatively high productivities comparable with Karoi's for most planting dates (> 10000 kg/ha) has the lowest biomass production in May (< 10000 kg/ha).

(b) Yield versus site

Karoi site obtained the highest biomass productivity for crops planted in January and March and also for the other simulated scenarios. It is only matched by Masvingo for January and November (slightly higher) crops. The major difference is that yields over Masvingo decrease quite markedly during the winter period. This could be attributed to relatively low mean daily temperatures experienced over the region during the winter months. Lower temperatures do not encourage vigorous vegetative growth compared to higher temperatures (within the crop tolerance limits).

(c) Potential biomass productivity versus length of growing period (LGP) and planting date (DOP).

Above ground biomass is correlated with the length of the growing period (LGP) in most crop development and growth processes (Woods, 2000). In this analysis potential yields (above ground biomass) are compared with the length of the growing period (LGP) and the date of planting. (Table 4.4)

Table 4.4: Comparison of the highest potential yield for each site with length of growing period and planting date: Yield 1= yield under existing climatic conditions and Yield 2 = under a 2°C degree increase in maximum temperature

Station	Region	Yield 1 + LGP + DOP			Yield 2 + LGP + DOP		
		Keller (kg/ha)	LGP (days)	Date of planting	Keller (kg/ha)	LGP (days)	Date of planting
Karoi	Ila	12803	185	Jan	12513	167	Mar
Harare	Ila	12301	182	Jan	12015	160	Jan

Masvingo	IV	12803	154	Jan	12184	137	Jan
Buffalo	V	10515	139	Jan	10988	126	Mar
Range							

4.3.2.2 Results of Yield versus LGP

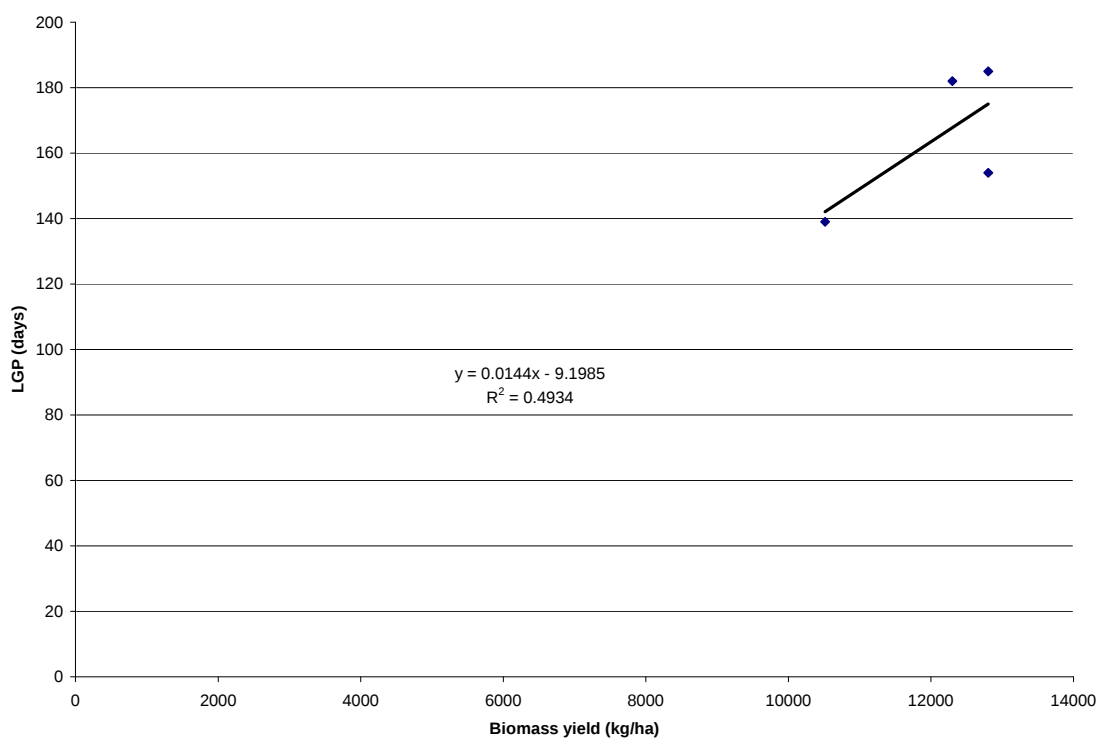


Figure 4.5: Length of growing period versus potential biomass productivity for all sites for a crop planted in January.

The correlation coefficient (R^2) between biomass production and length of growing period is only 0.4934 (Figure 4.5). It appears there is a weak linear correlation between the two quantities. For example when a comparison between Karoi and Masvingo is made of biomass versus LGP, in yield 1 (under existing climatic conditions), Karoi's yield of 12803 kg/ha are produced in 185 days (LGP) but in Masvingo, the same yield is produced in a shorter growing period, 139 days, giving a difference of 46 days (one and half months!). Similarly in yield 2 (under a warmer climate), the Harare site yield of 12015 kg/ha is produced in 160 days but the Masvingo site produces a higher yield (12184 kg/ha) in a shorter growing period (137 days). These results tend to confirm the low correlation coefficient. This means other factors should be considered when one is planning to grow sweet sorghum in any particular site. The same results are found when individual sites' biomass productivities are correlated with their LGPs, for the different planting dates, the coefficients (R^2) are very low (Table 4.5).

Table 4.5 Correlation coefficients for LGP versus potential biomass for Keller (sweet sorghum variety)

Site	Regression equation	Coefficient (R^2)
Karoi	$Y = 0.079x + 104.57$	0.0494
Masvingo	$Y = -0.0188x + 75.697$	0.1415
Harare	$Y = -0.0116x + 238.87$	0.0468
Buffalo Range	$Y = 0.0302x - 33.681$	0.4445

Another way the author compared the results was by reducing them to an arbitrary productivity rate (PR) given as:

$$PR = \text{Yield} / \text{LGP} \quad 4.1$$

(PR = arbitrary ratio used as a comparison tool for present discussion only)

Table 4.6 shows the productivity rates (PR) for the different sites. By reducing the yield data and length of growing period data into one (PR) value it becomes easier to compare the potential of each site to produce the fuel crop, (in this case sweet sorghum.), under its uniquely different environmental conditions. The potential rate (PR) combines both yield and length of growing period both of which are influenced by environmental conditions.

Table 4.6: Comparison of PR values for highest biomass production at the different sites regardless of planting dates.

Station	Region	Biomass under existing climate (PR units of kg/ha/day)	Biomass under warmer climate (PR units of kg/ha/day)
		Keller variety	Keller variety
Karoi	Ila	69.2	74.9
Harare	Ila	79.9	75.1
Masvingo	IV	83.1	88.9
Buffalo Range	V	75.6	87.2

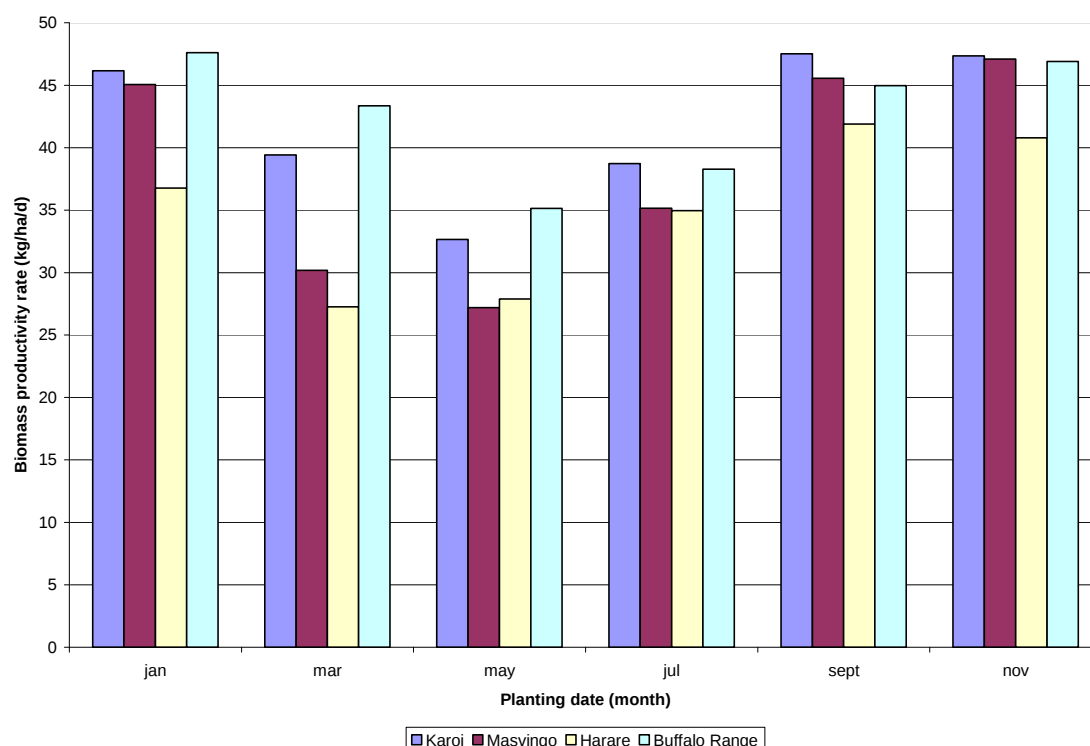


Figure 4.6: Biomass productivity rate (PR) at different sites under existing climatic conditions with varied planting dates.

The results of the productivity rate (PR) displayed in Figure 4.6 reveal that for the crop planted in January; Buffalo Range has the highest rate (> 45 kg/ha/day), followed by Karoi, then Masvingo and lastly Harare (about 37 kg/ha/day). This rank sequence is repeated for the March crop but with lower rates; Buffalo Range tops the PR range at about 43 kg/ha/day and Harare with the lowest rate of 27 kg/ha/day. In May, the top two positions are unchanged but Harare has a higher rate than Masvingo. For July, the Karoi rate tops Buffalo Range and there is little difference between the Harare and Masvingo productivity rates. The crops planted in September and November have an identical sequence; Karoi has the highest rate, followed by Masvingo, Buffalo Range and Harare has the lowest rate of the four. It can also be concluded that generally the productivity rates for May and July are lower than for the other planting dates with the highest rates being realized in January, September and November. The explanation behind the different productivity rates can be attributed to the temporal variation in received radiation for each site. While Buffalo Range receives relatively higher solar radiation in January than the rest of the stations, during the winter month; May, July, and even September, it has the lowest radiation received. This is due to the latitudinal difference of between stations. Of the four stations, Buffalo Range is the most southerly, followed by Masvingo and then Harare. Karoi is the most northerly, which could explain its higher productivity rate for May, July, September and November. Site comparisons of productivity rate (PR) indicate that for some stations, there

is strong correlation e.g. Masvingo and Karoi have a correlation coefficient, $R^2 = 0.9227$, while a comparison of the PR values for Buffalo Range and Harare give a low coefficient; $R^2 = 0.3932$. Stations with a strong linear correlation would tend to suggest that they belong to the same agro-climate regime for the production of sorghum. However, the PR results are not directly related to the total above ground biomass, for example Buffalo Range displays a high productivity rate, but has the lowest total above ground biomass (Table 4.6). The reason behind this discrepancy could also be explained through the different radiation characteristics for each site.

4.4 Sensitivity Tests

4.4.1 Sensitivity tests under modified environmental conditions

There is a general decrease in potential yield across the sites under modified environmental conditions (Table 4.3). In the first scenario, when the maximum temperature is increased by 2 °C; simulating a climate change scenario of a warmer environment, (New *et al.*, 2006), the potential yield decreases by an average of about 4 % across the board regardless of planting date except over Harare and Masvingo (DOP = March). Similarly for the second scenario of a 25 % decrease in solar radiation, the potential yield decreases by about 9 %, approximately double the percentage decrease due to a warmer climate. The reason for using a 25 % decrease in solar radiation was based on the average decrease in solar radiation as measured by satellite. A 25 % decrease scenario was motivated by the need to assess the yield margin that would result from using satellite based solar radiation data as it is instead of using ground based data.

In the following sections, results from each site are analyzed separately.

4.4.1.1 Harare Belvedere Site

In this analysis, the results of potential yields of Keller (sweet sorghum variety) under different environmental conditions and different planting dates are combined (Figure 4.7) for the Harare site.

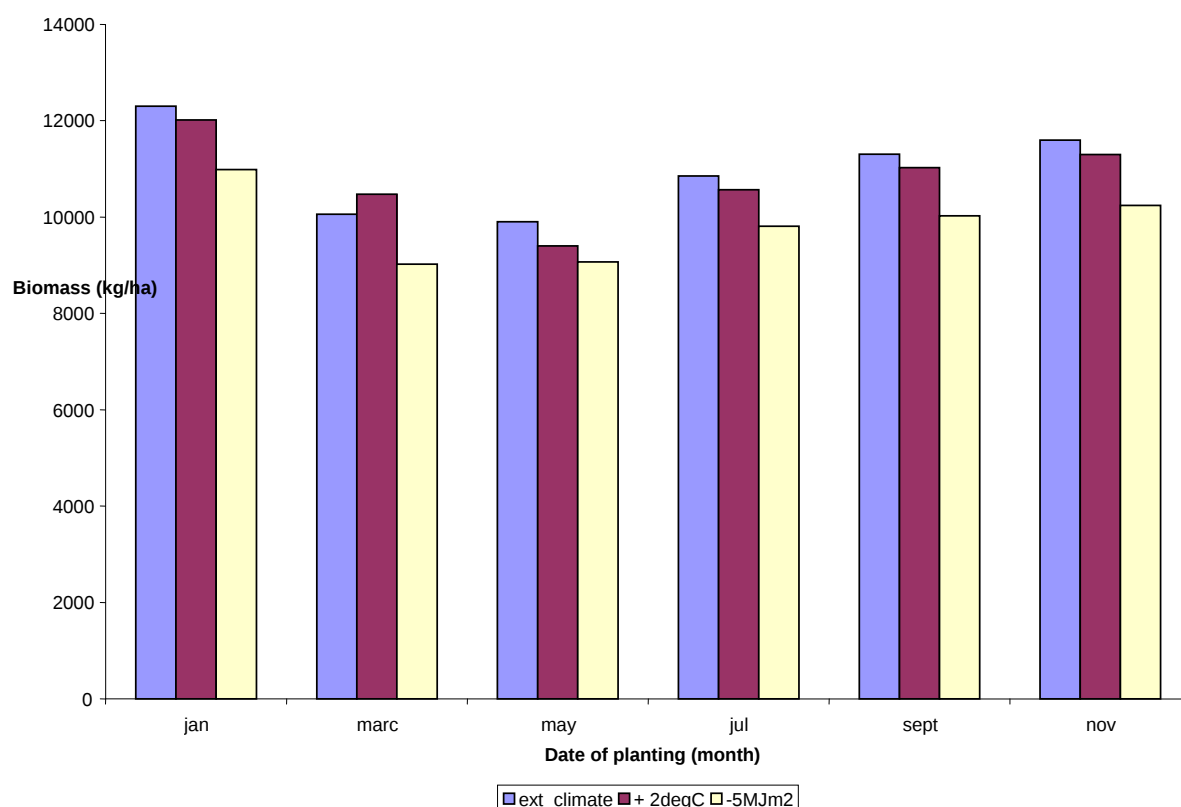


Figure 4.7 Potential biomass productivity of the Keller sweet sorghum variety under different environmental conditions at Harare; maximum temperature increased by 2 °C and solar radiation decreased by 5MJm⁻²

4.4.1.2 Results of potential yield under modified environments

The simulations of potential yield generally decrease under both reduced solar radiation and increased maximum temperature with the exception of the crop planted in March. The increase in temperature boasted its yield to slightly higher (+ 4 %) than can be obtained under existing climatic conditions. This is probably because of the added advantage of a warmer winter conducive to a more vigorous vegetative growth, but still the yield is lower than the yields for a crop planted in January or November. Field experiments would be necessary to validate the results.

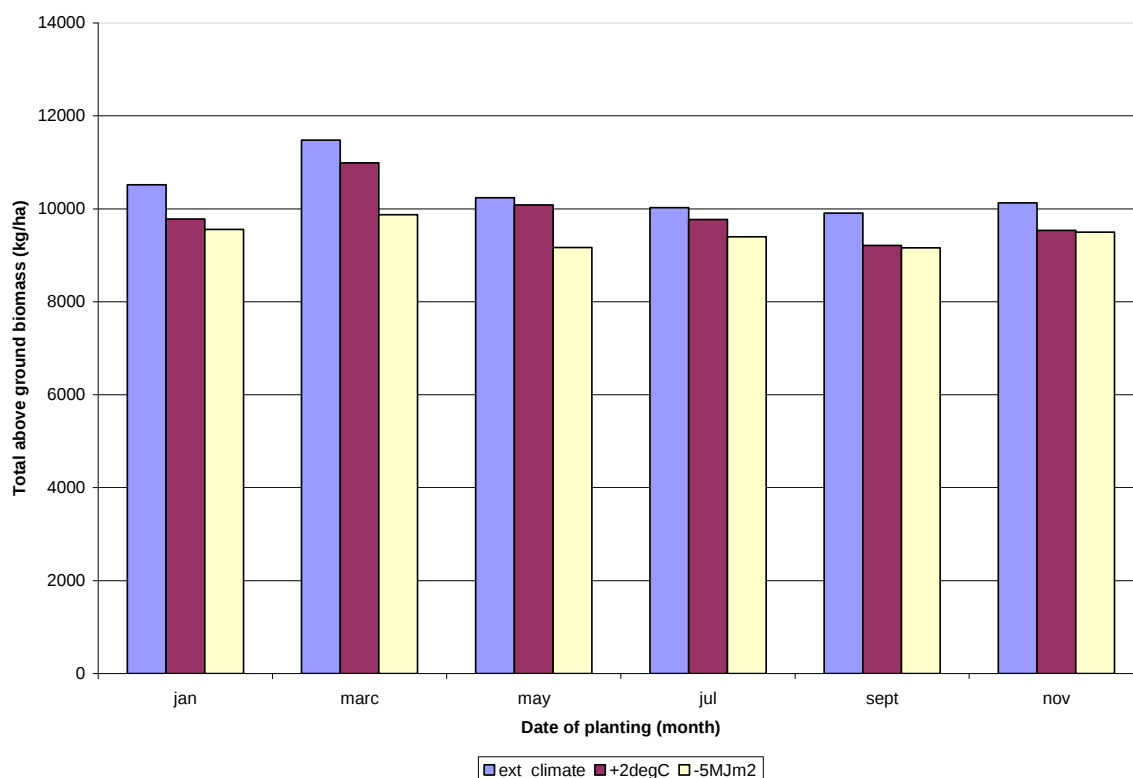


Figure 4.8 Potential biomass productivity of the Keller sweet sorghum variety under different environmental conditions at Buffalo Range; maximum temperature increased by 2 °C and solar radiation decreased by 5MJm⁻²

4.4.1.3 Buffalo Range Site

The results for the Buffalo Range site (Figure 4.8) show a similar trend to the results obtained over Harare. The potential yield decreases under the modified environments, more so with a reduction in received solar radiation. However, biomass productivity for Buffalo Range is generally +/- 10000 kg/ha whereas for Harare, its biomass is more than 10000 kg/ha for January, September and November.

4.4.1.4 Masvingo Site

Figure 4.9 shows the variations in potential biomass yield due to different environmental conditions for Masvingo in Region IV. The climate of the region is characterized by moderate rainfall (500 – 1000 mm) with summer temperatures mainly in the upper twenties (degrees celcius). However, in winter, frequent incursions of a cool and moist air-mass from the Mozambique channel) affect the area resulting in low cloud with drizzle at times (guti). During these ‘guti’ episodes daytime temperatures can be depressed quite considerably unlike places like Karoi which are hardly affected by guti incursions.

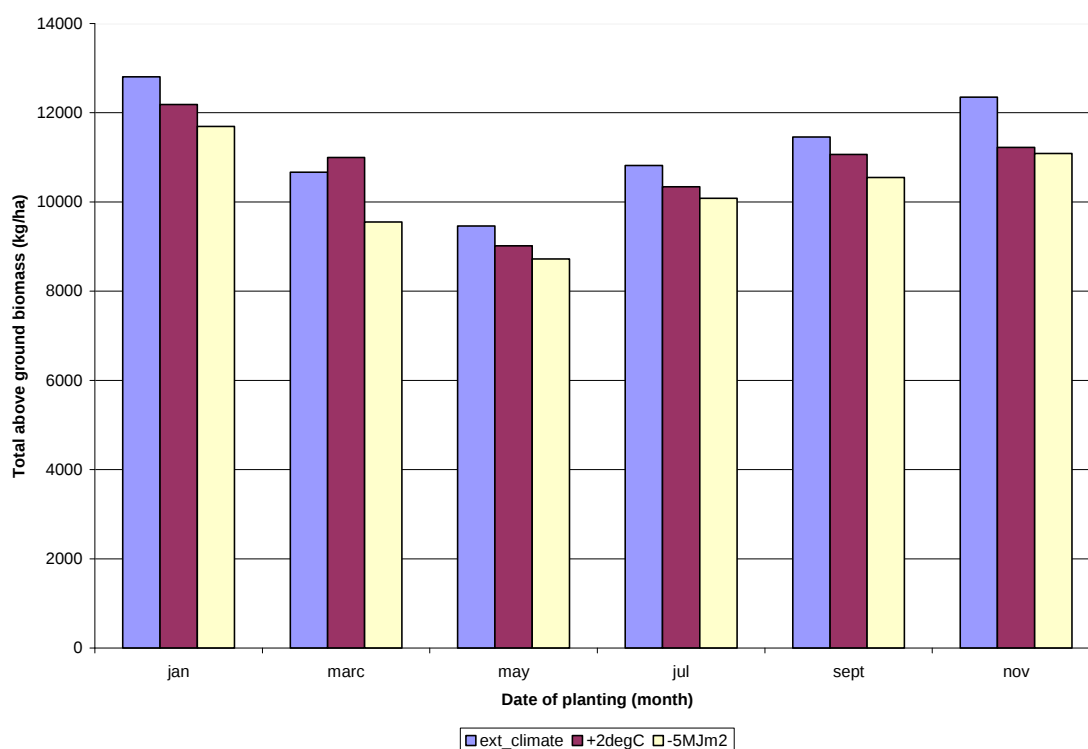


Figure 4.9 Potential yields of sweet sorghum (Keller) under different environments over Masvingo; existing climate; warmer conditions (+ 2°C rise in max temperature); and a 5 MJm⁻² reduction in solar radiation.

Under existing climatic conditions, the highest yield is about 12800 kg/ha for a crop planted in January, with the lowest yield of about 9500 kg/ha obtainable from a crop planted in May. Essentially the variation in yield trend follows what has been observed over other sites; modifying the environment through a temperature increase or a reduction in radiation causes a general decrease in potential yield. The only exception occurs under a temperature increase for a crop planted in March; biomass productivity is higher by about 3% than under the existing climate (Table 4.3). A similar response in potential biomass yield (March crop) was found over the Harare site.

4.4.1.5 Karoi Site

The Karoi site is used as a test site not only for the potential yields of the sweet sorghum variety Keller but also for the grain sorghum variety Pioneer 8333. The sorghum varieties found in the DSSAT4 model are all grain varieties and Keller was the only sweet variety that was added (by author) to the sorghum varieties for simulation. The addition of Keller was achieved by inserting the variety and its crop coefficients in the sorghum file in DSSAT. Crop coefficients were obtained from Woods (personal communication) that he used in trials he did in the SE of Zimbabwe (Woods, 2000).

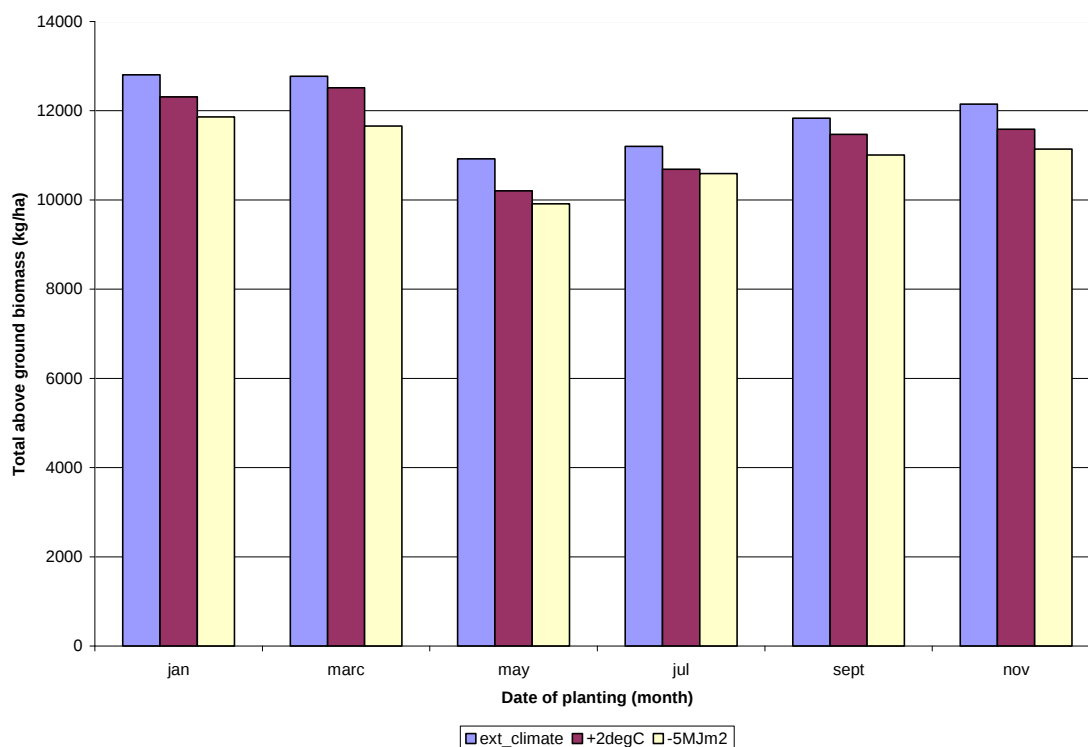


Figure 4.10 Potential yields of (Keller) sweet sorghum under different environmental conditions over Karoi; existing climate; warmer conditions (+ 2°C rise in max temperature); and a 5 MJm⁻² reduction in solar radiation.

Results of potential yields trends over Karoi (Figure 4.10) are different from those simulated over Buffalo Range. Generally the biomass over Karoi is much higher (> or close to 12 t/ha for planting date of January, March, September and November) than over Buffalo Range. Unlike the Masvingo and Harare sites which display an increase in productivity under a temperature modification scenario, for a crop planted in March, a decrease in yield is observed at Karoi. However, the January crop gave very similar biomass production at values greater than 12 t/ha. Biomass production for crops planted in May and July are lower than January, March, September and November crops. This could be attributed to the higher average temperatures experienced in summer relative to the winter averages. The minimum temperatures could also be too low for vigorous vegetative growth, but further research would be necessary to verify the assumption.

In order to compare the potential yield difference between varieties, the sorghum grain Pioneer (8333) yields are computed as in the sweet variety Keller.

4.4.2 Sensitivity test for different sorghum varieties

4.4.2.1 Comparison of potential yields between the two varieties

The results obtained for the potential yields of the two varieties are shown in Table 4.7.

Table 4.7 Potential biomass of the sorghum varieties Keller (sweet) and Pioneer 8333 (grain)

Planting date	Biomass production under existing climatic conditions		Biomass production under a higher maximum temperature		Biomass production under decreased radiation	
	KY1	PY1	KY2	PY2	KY3	PY3
jan	12803	12624	12310	12187	11862	11750
mar	12774	13419	12513	13029	11660	12160
may	10924	10650	10205	10644	9914	10015
jul	11202	11443	10692	11166	10592	10826
sept	11832	11904	11472	11385	11008	11090
nov	12149	11826	11587	11586	11139	11244

Key:

- KY = potential yield of Keller variety under scenarios 1, 2, 3.
- PY = potential yield of Pioneer 8333 variety under scenarios 1, 2, 3.

Table 4.8: Differences in biomass production between the sorghum varieties; KY is Keller (sweet sorghum) yield and PY is Pioneer 8333 (grain sorghum)

Planting date	Difference in biomass production under existing climate	Difference in biomass production under a warmer climate	Difference in biomass production under decreased radiation
	KY1 – PY1	KY2 – PY2	KY3 – PY3
Jan	479	123	112
Mar	-645	-516	-500
May	274	-439	-101
Jul	-241	-474	-234
Sept	-72	87	-82
Nov	323	1	-105

Figure 4.11 shows that there is a strong linear relationship in potential yields between the two varieties under current environmental conditions ($R^2 = 0.8619$). A further test on whether there is a significant difference (95 % significant level) in potential yield between Keller variety and Pioneer 8333, gives a z-score of 0.4602 and allowing for either tail of the

probability density function, it becomes 0.9204, which implies that the differences in yields are not significant. Even the z-score under a warmer climate (+ 2C rise in maximum temperature) is 0.2946. This appears to confirm the results obtained above, i.e. any differences found are most likely caused by chance and therefore not significant.

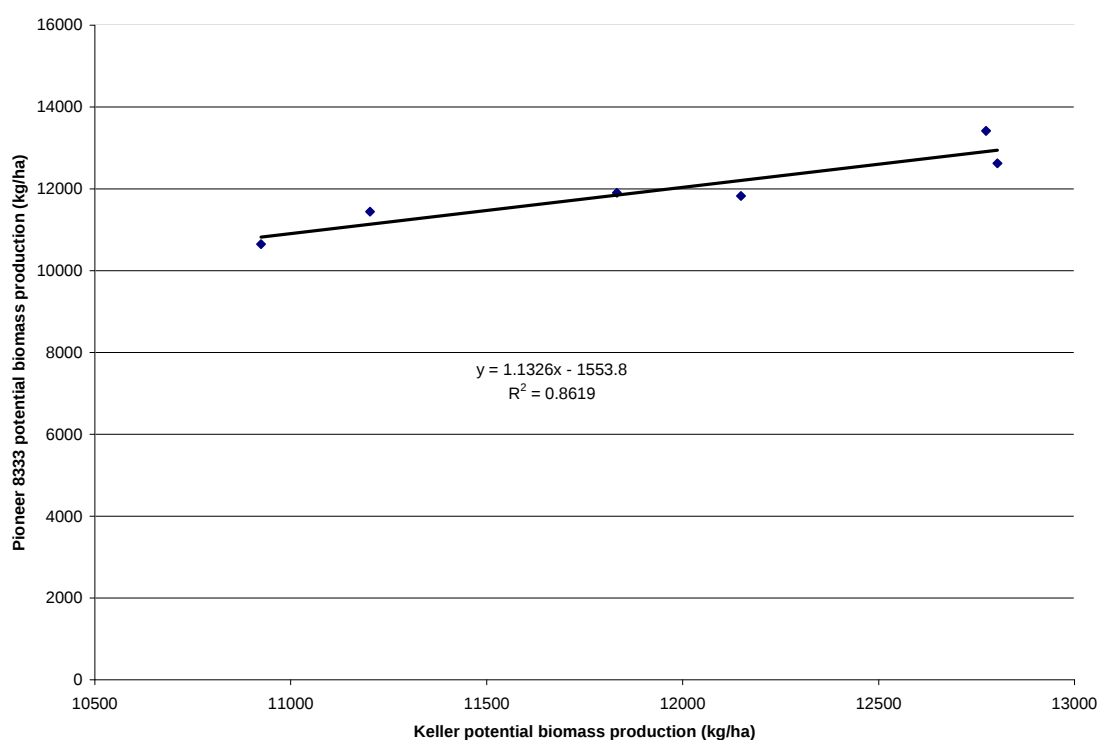


Figure 4.11: Comparison of potential yields of Keller and Pioneer under existing climatic conditions for Karoi site.

From the difference in potential yields between the two varieties under existing climatic conditions, no clear cut generalizations can be made. The Keller variety has a higher yield for a crop planted in January, May and November. However, the same does not hold true in the in scenarios 2 and 3. The only conclusion to be drawn from these results is that there is no significant difference in potential biomass production between the two sorghum varieties.

4.4.2.2 Comparison of the length of the growing period between the varieties

Normally a longer growing period should result in higher biomass production when compared to a shorter period, assuming the photosynthesis efficiencies are the same. Figure 4.12 gives a comparison of the growing periods between the two sorghum varieties under existing environmental conditions.

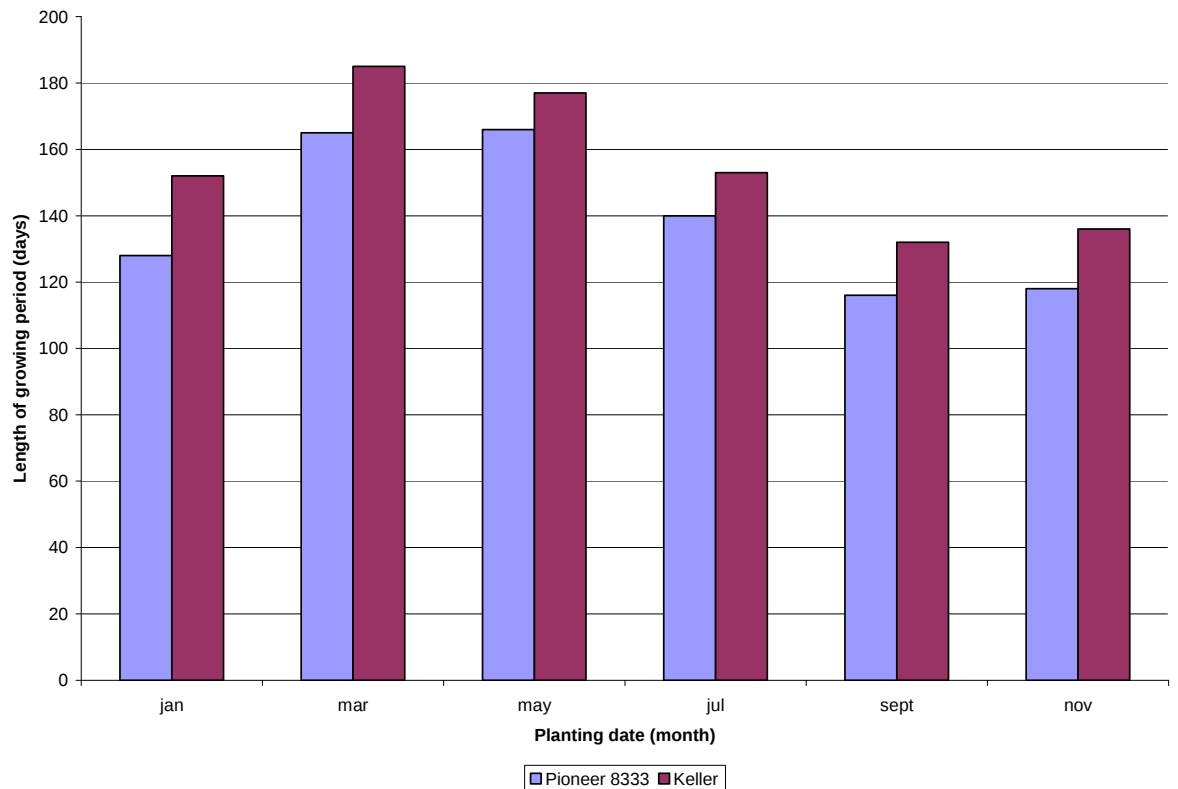


Figure 4.12 Comparison of LGP between Pioneer and Keller under existing climate at Karoi.

Figure 4.12 clearly shows that the sweet sorghum variety Keller has longer growing period than the grain sorghum variety Pioneer 8333 under current climatic conditions in the Karoi area, although the potential biomass production does not differ significantly.

4.4.2.3 Comparison of the growing period under a modified environment

An assessment is made on the influence on the growing period under a warmer climate (2 °C rise in maximum temperature) for the two varieties under consideration. There is no change in the relative difference in LGPs for the varieties as depicted by Figure 4.13

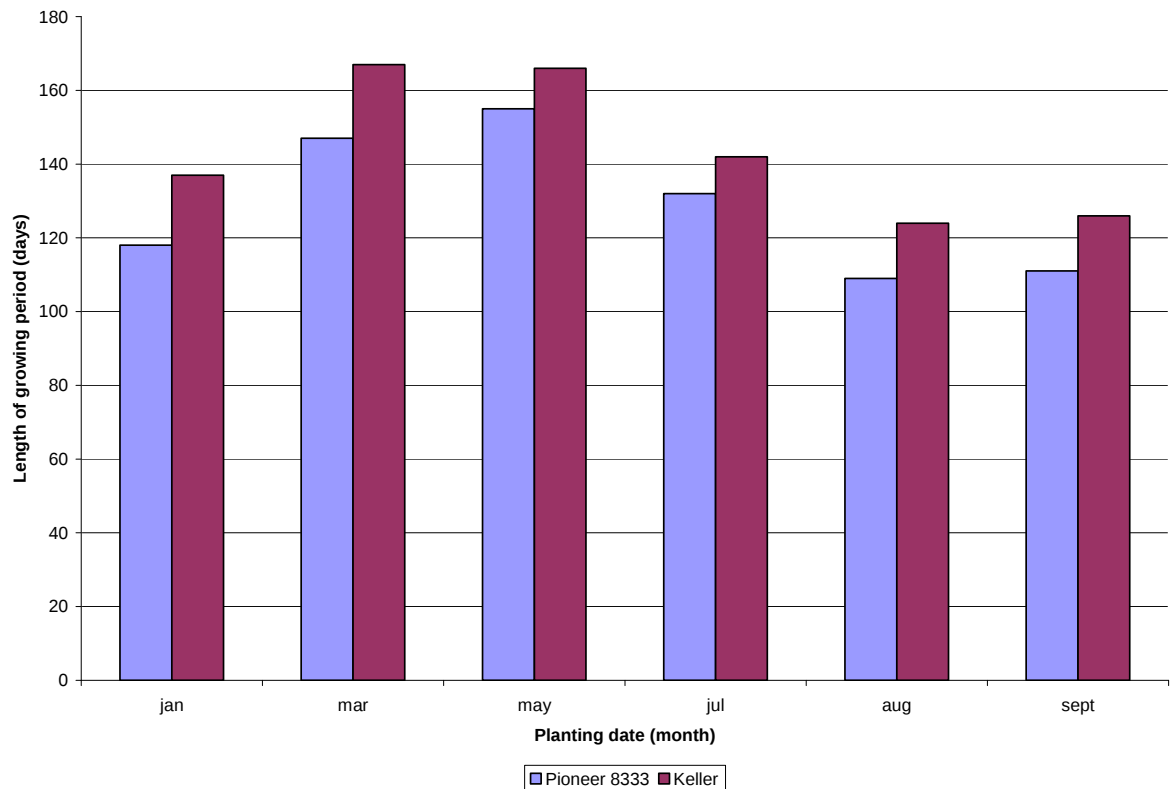


Figure 4.13 LGP comparisons under a two degree rise in maximum temperature

In conclusion, it would appear from the simulations of the two sorghum varieties, Keller and Pioneer that the sweet sorghum variety has a longer growing period compared to the grain variety under all the environmental conditions simulated.

4.4.2.4 Results for modified temperature environment

Essentially, the temperature modification of the environment does not appear to affect the yields of the two varieties. Biomass obtained after planting in January, and March are marginally higher for both varieties, but there is no significant difference as already found out in the statistics given above. With such minor differences in the potential yields, it becomes imperative to consider the cost of production under the different scenarios in order to differentiate between the optimum planting dates and final yield.

4.4.2.5 Summary of results on the differences in potential yield at each site under different environmental conditions:

- ❑ In terms of potential yield between the sorghum grain variety (Pioneer) and sweet sorghum variety (Keller), there is no distinct difference between the two under existing environmental conditions.
- ❑ The potential productivity of both varieties decrease when the environment is modified either through the maximum temperature being increased by 2 °C or when there is a 5 MJ/m²/day decrease in surface solar radiation.

- ❑ Keller variety takes longer to mature but does not show a corresponding increase in potential yield.
- ❑ Crops planted in the summer months (November, January and March) generally show higher productivities compared to those planted in the early or mid winter months (May and July).
- ❑ The lowest potential biomass yield is about 9000 kg/ha, under any environmental condition.
- ❑ Changes in the environmental weather parameters had little effect on the comparative potential yields between the Keller and Pioneer variety according to the simulation results obtained in this study for the Karoi site.

4.5 Conversion Efficiency for Sorghum

The ultimate aim of this project is to assess the productivity of fuel crops in terms of the amount of bio-fuel (ethanol) produced from either unit biomass or from unit land area. Woods, (1998) in previous field experiments done in the southeast of Zimbabwe, came up with a mathematical formula adapted from Dallianis (1997) in computing the theoretical ethanol yield from sweet sorghum, as follows:

$$\text{EtOH (lha}^{-1}\text{)} = [\text{Total sugar content (\%)} \text{ in fresh weight}] \times [6.5 \text{ (conversion factor)}] \times [0.85 \text{ (conversion efficiency)}] \times [\text{total biomass (t/ha of fresh matter)}]$$

For example taking the Karoi potential yield of a total biomass of about 12.8 t/ha for a crop planted in January and assuming a sugar content percentage of 13 % (Mahohoma personal communication), the equivalent ethanol produced is calculated thus:

$$13 \times 6.5 \times 0.85 \times 12.8 = 919.36 \text{ litres (EtOH) per hectare} \quad 4.2$$

CHAPTER 5: DISCUSSION

5.1 Introduction

In this chapter the results obtained in chapter five are discussed with respect to the aims and objectives of the thesis. A brief overview of the economics of bio-fuel production is given at the end of the chapter based on some literature sources since this aspect was not part of the thesis. The viability of bio-fuel production will ultimately depend on a positive cost-benefit analysis that makes economic sense.

5.2 Radiation

The results obtained in this research about satellite estimates of solar radiation confirm the potential of this source to eventually be a reliable source of surface solar radiation data. Although only monthly radiation data was used in the analysis, daily data is also available upon request from the European Space Agency (ESA). What is required is validation of these satellite data so that they can be used more confidently for any of the various applications alluded to earlier. One of the outputs of the present work is mean monthly radiation maps from remotely sensed data (satellite). However, this effort was not so successful because of the large discrepancies found between satellite observations and ground based measurements (Table 4.2).

5.2.1 Comparison of radiation sources.

There were two sources of solar radiation measurements used in the analysis. The first source was from the Climate Handbook of Zimbabwe (1980) and the instruments used to measure the radiation were Gunni-Bellani spherical pyranometers calibrated against Moll pyranometers that are of higher accuracy. This data was used in the derivation of mean monthly maps using Surfer computer program. The daily radiation dataset that was used in the weather data files of DSSAT4 in conjunction with temperature and rainfall data, was measured using the Sonago solarimeter network currently installed at the about eight stations around the country. These datasets were sourced from the Meteorological Services Department of Zimbabwe.

Since the datasets from ground measurements were based on different observed periods, a comparison was done between them to ascertain their spatial and temporal consistency. The results of the comparison of the two data sources from ground-based instruments showed insignificant differences as indicated earlier (Table 5.1).

Table 5.1: Comparison of solar radiation data from surface observations for different periods and satellite observations: A:- surface data for 1990-2000 period; B:- surface data for 1951-1970; C:- satellite data for period 1961-1990

Station	(A)Ground based reference: 1990-2000 (MJ/m ² /d)	(B)Ground based: 1951-1970 (MJ/m ² /d)	Comparison B/A X 100 (%)	(C)Satellite estimates: 1961-1990 (MJ/m ² /d)	Comparison C/A X 100 (%)
<i>Beit-bridge</i>	21.41	19.92	93	15.72	73
<i>Mount Darwin</i>	21.70	20.35	94	14.95	69
<i>Karoi</i>	22.97	20.22	88	15.27	66
<i>Harare Belvedere</i>	18.37	20.13	110*	15.08	82
<i>Gweru</i>	22.76	20.42	90	15.53	68
<i>Masvingo</i>	21.15	20.00	95	15.37	73

With the exception of Harare Belvedere (**B/A** = 110 %), the ground based data for the period 1951 to 1971 was slightly lower than for the period 1990 to 2000 for all sites. The differences could possibly reflect a decrease in the mean cloud cover of the latter period to the earlier period or differences in instrumentation. The final outcome of this study is little affected from using either dataset. The earlier period data (1951-1971) was used solely for the production of mean monthly solar radiation maps for comparison with satellite based estimated averages. The averages for the period (1990-2000) were used in the DSSAT-CSM crop modeling exercise. The WeatherMan tool in DSSAT v4.0.2.0 is used for entering and analyzing data. The fairly large differences found between satellite estimates and ground based measurements, rendered the data (satellite) less useful for the modeling exercise, and was only used in the monthly comparisons. The simulated potential yield results of a modified environment under a 5 MJ/m²/day reduction gives the approximate results one would obtain using current satellite estimates (an average 25 % decrease was used, but actual average percentage decrease obtained from Table 5.1 (C/A X 100 %) is 28.2 %). The results reflect the sensitivity of potential yield to errors in radiation measurements.

Therefore the available ground based observations of surface solar radiation datasets were adequate for the radiation characterization of the country as well as the modeling application. However, future validation of the satellite estimates for Zimbabwe is imperative, because while the old data set might appear reasonably useful now and for this type of limited study, it will not be adequate in applications that require more precision and accuracy. The earth's radiation balance is likely to change under a changing climate scenario; hence there is a need to periodically update the radiation climate database.

Typically when one looks at the radiation variation on a monthly basis, it is noticed that winter months have the least difference between ground based measurements and satellite estimates because of the lack of significant cloud cover (Figure 5.1). The sensitivity of surface solar radiation to cloud types and cover, was also highlighted in the experiments carried out by Gautier *et al.*, (1998).

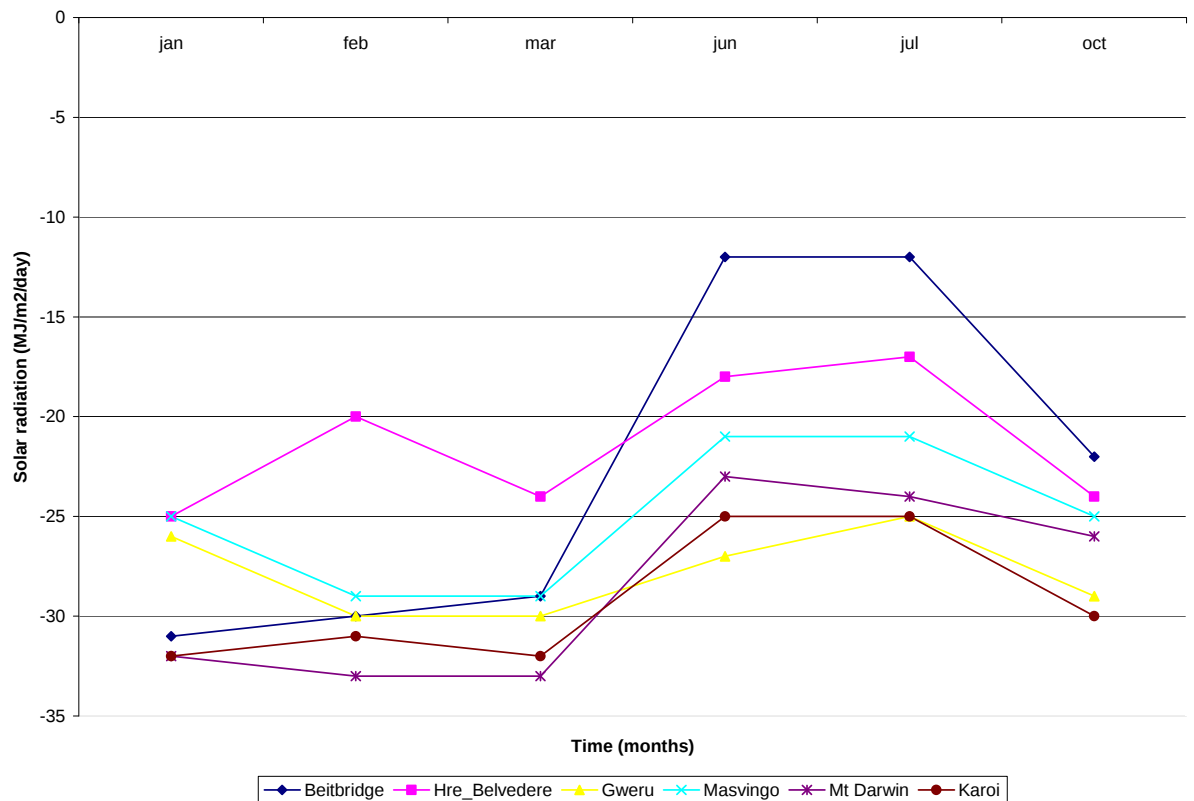


Figure 5.1 Graphical representation of the percentage difference of satellite based radiation to ground based measurements.

This relationship between solar radiation and cloud cover is important for crop modeling as well as climate change studies because of the link between cloud cover and hours of bright sunshine.

5.2.2 Solar radiation and crop yield

Solar radiation at the surface is one of the major determinants of crop yield. When crop leaves absorb sunlight falling on them, the energy gained is used to drive the photosynthesis engine for the generation of plant tissue among other uses. Therefore the period when this energy is required by the crop should coincide with the period of maximum insolation to yield the best results.

The variations in mean monthly radiation for different stations in Zimbabwe were calculated for the period 1991 to 2000 (Figure 5.2). All the radiation curves except the Beitbridge curve depict a sinusoidal curve with two peaks in an annual cycle. One peak, occurred approximately in February and the other peak occurred in October. The radiation minima occurred in June/July. Beitbridge peaks only in December/January because of its latitudinal position ($22^{\circ} 13'S$); the sun is overhead once a year.

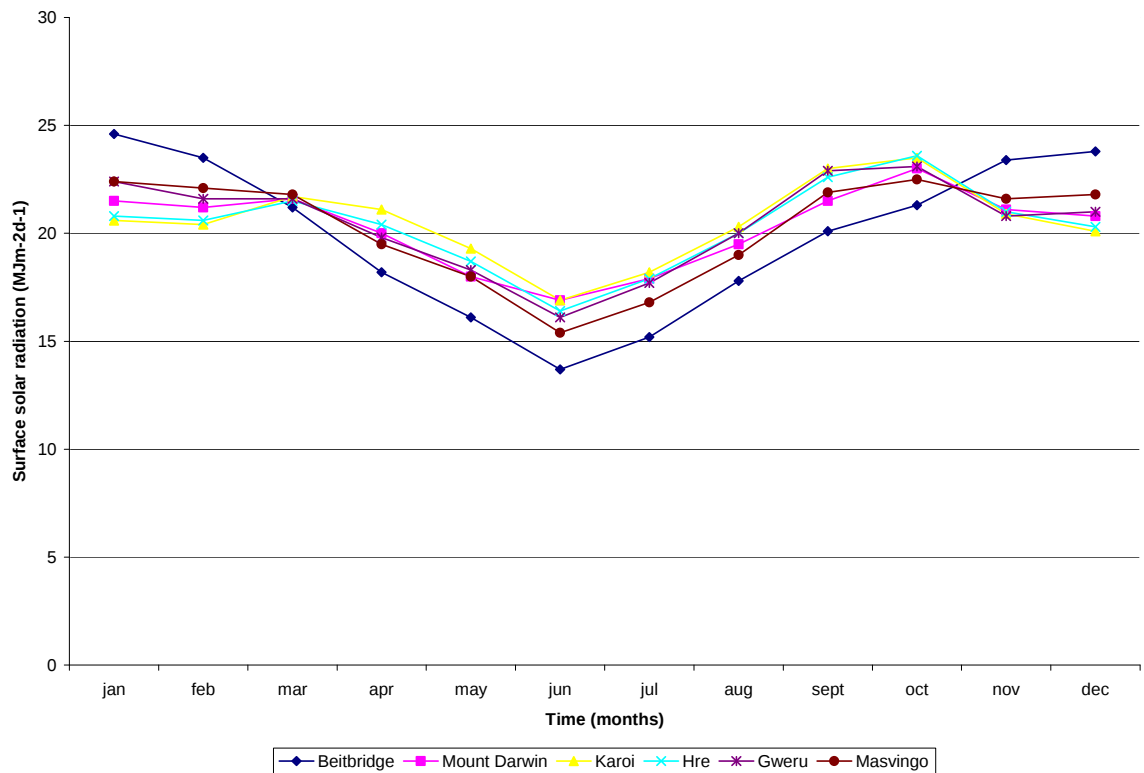


Figure 5.2 Mean monthly solar radiation cycle at different sites

This radiation cycle is important for relatively short season crops, like sorghum that are sensitive to radiation at particular phenological stages (Woods, 2000). In the model simulation exercise involving these data, the results in chapter 4 indicate that the highest potential yield for sorghum was achieved when the crop was planted in January or September. Looking at the radiation trend, it is not difficult to understand why; the crop will grow under plenty of sunshine which is good for vegetative growth. However, if there is a reduction in radiation during this vegetative period due to excessive cloud cover, the biomass productivity will be reduced. Sugarcane on the other hand would not be affected the same way because of relatively long growing period (12 months growth cycle). Therefore radiation information should be taken into account particularly when planning for two crops per year, as would be the case for sweet sorghum to make it competitive with sugarcane. As far as *Jatropha curcas* plant is concerned, research is still going on to establish the relationship between crop yield and radiation

5.3 Potential Yield

5.3.1 Introduction

The simulation of potential yield was done using the Introductory to Cropping Simulation (ICSim) tool of DSSAT4. The Cropping Simulation Model gives two results, (1) the crop yield under the existing climatic conditions and (2) automatically computes the potential yield. For the purposes of this work, the main focus was on potential yield in terms of biomass production and its sensitivity to environmental modifications as well as different varieties (sweet sorghum versus grain sorghum). That means the water and nutrition supply are considered non-limiting, i.e. they are assumed adequate for the needs of the plant throughout the growing period. The designers of the DSSAT4 program had the additional notion of calculating what is known as yield gap when comparing the yields given under the two scenarios described above, but this is not done in the present study since the current focus is on potential yield. Furthermore, simulation was done on two different varieties of sorghum; grain sorghum (Pioneer 8333) and sweet sorghum (Keller). The potential yields obtained under existing climatic conditions are the principal reference yield of all the other simulations.

5.3.2 Potential yield under existing environmental conditions at different sites

In the comparisons of potential yields under existing environmental conditions (Figure 4.3), for the sweet sorghum variety Keller, the highest yield was observed in Karoi and Masvingo (12803 kg/ha), Natural region IIa and Natural Region IV respectively. The lowest potential yield was obtained in Buffalo Range (10505 kg/ha), Natural Region V. Incidentally, Harare (Belvedere) which falls under Natural Region IIa (12301 kg/ha) had a relatively low yield compared to its counterpart within the same region, Karoi. When these potential yield results are combined with the radiation results, it is apparent that the areas with the highest radiation values tend to produce a higher yield. For example Karoi has the highest annual radiation (Figure 5.2) has a correspondingly high potential yield. The only exception is Harare (Belvedere) that has the lowest radiation figures but produce a higher yield than that of Buffalo Range (represented by Beitbridge in Figure 5.2). The influence of temperature on potential yield is an added factor to the influence of radiation. Obviously there is a more complex interaction between temperature and radiation on crop yield that can not be explained through these simple simulations; field experiments are required to verify the results.

5.3.3 Potential Yield under a Modified Environment

The ranking order of relative potential yields of sites from highest to lowest is unchanged even when the environment is altered or modified; Karoi still produces a relatively high yield compared to the other sites under a temperature or radiation modified climate and Buffalo Range produces the lowest result of the four sites.

The conclusion to be drawn from these results is that Natural Region IIa and Natural Region IV have a greater potential of producing sweet sorghum, of the Keller variety, from the sites considered in this study. Further simulations complimented by field experiments are necessary to have a complete assessment of the whole country. Woods *et al.*, (2004) had encouraging results from field trials with the Keller variety over the SE of Zimbabwe.

5.3.4 Potential yield versus length of growing period (LGP)

Normally the length of the growing period should be proportional to the amount of above ground fresh matter produced (Figure 5.3), for the simple reason that there is more time for exposure to sunlight and hence enhanced photosynthesis leading to accumulation of dry matter. However, the results obtained in this study did not produce convincing evidence of this hypothesis. This aspect was borne out by the comparison of the arbitrary comparison tool ‘productivity rate’ (PR). A comparison of the potential yield versus the length of the growing period under existing climate, reveals that the Masvingo site has a shorter growing period (by more than a month!) compared to Karoi for the same yield. This leads to a high productivity rate for Masvingo relative to Karoi, and this aspect is repeated for the other sites as well, particularly Buffalo Range, where the low overall potential yield is compensated by a high productivity rate (Table 4.5)

From these results, depending on the management strategy, a decision to cultivate a certain fuel crop in a suitable location should not just consider the potential yield in isolation but should factor in the length of the growing period. In related studies conducted in the SE of Zimbabwe by Woods (2000), the complex relationship between planting date, yield and length of growing period were captured in Figure 5.3. There is fairly good agreement between the results of this particular study and the work done by Woods (2000).

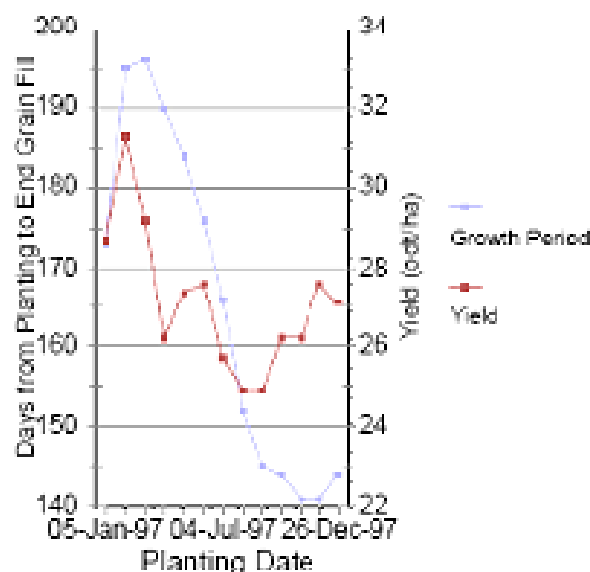


Figure 5.3 The influence of Planting Date on Yield and Length of Growing Period of Sweet Sorghum (Source: Woods, 2000)

Figure 5.4 summaries the productivity rate (PR) for all sites under different environmental conditions. The Masvingo site has the highest PR of the four sites under existing climatic conditions as well as under modified environmental conditions, followed by Karoi then Buffalo Range. Harare has the lowest PR of all sites under any condition. However, most noticeable is that the PR for all sites is highest under a 2°C degree increase in maximum temperature. This implies that temperature influence on PR dominates other factors under consideration here.

Current trends in sorghum crop cultivation in the country have targeted the low rainfall regions of Lowveld and Masvingo as a drought mitigation strategy; in view of these results, Karoi could in future play a bigger role in sorghum production as a cash crop for ethanol production.

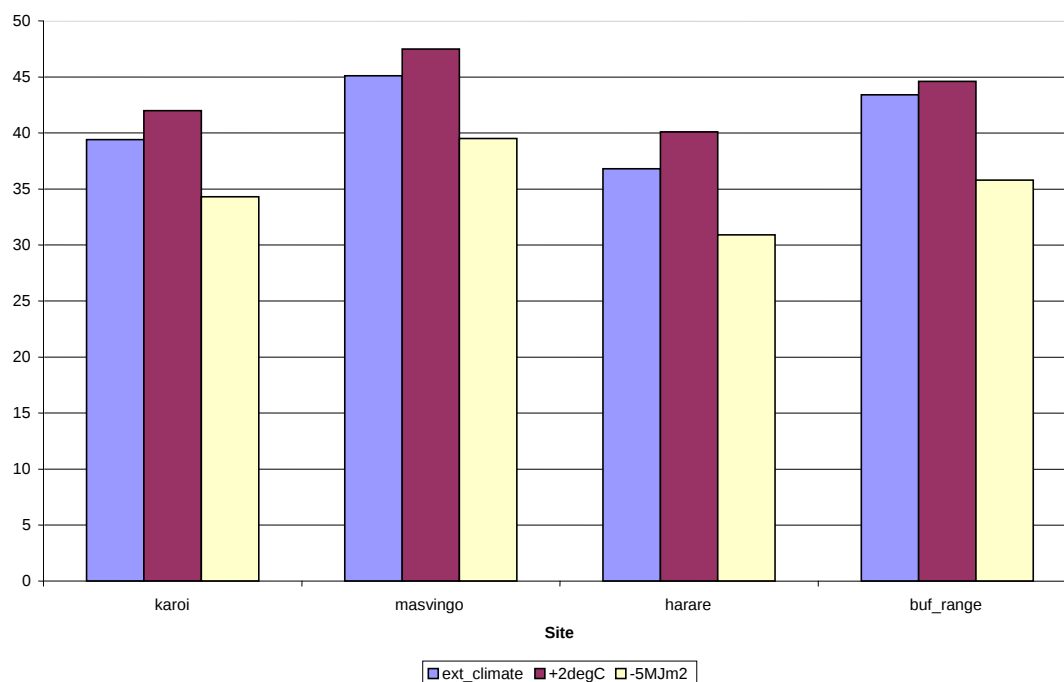


Figure 5.4: Productivity rate (PR) at different sites under different environmental conditions.

From a management point of view the length of the growing period for Keller over Karoi is 5 to 6 months whereas it takes about 3 to 4 months for maturity to be reached over Masvingo site. In view of this information, Masvingo site could be more favourable than Karoi when it comes to comparison of period of maturity in relation to final potential yield. The difference in length of growing period will need to be verified by field experiments before investment into the bio-fuel industry with sweet sorghum as a feedstock is encouraged.

Therefore more information is needed by the farmer to make an informed decision that takes into account all the pertinent variables in the cultivation of a fuel crop. The current discussion is only focusing on the potential yield and the climatic variables but investigations need to be widened, more importantly the cost variable will need to be included in any investment decision on the production of bio-ethanol. Although a brief overview of the economics of production of bio-fuel is given at the end of this chapter, it is not a major theme of this thesis.

5.4 Sensitivity tests discussion

The preceding discussion has focused on the results obtained of potential biomass production under current conditions. However, the figures portrayed have also included potential biomass production obtained under modified environmental conditions (Section 5.2.3). The picture that emerges suggests that potential yield will generally decrease under the modification scenarios considered here. The reasons for the decrease in potential yield can only be assumed without experimental results to validate model simulated results. In the case for temperature, an increase in the maximum temperature can cause a decrease in potential yield if the optimum threshold temperature for the crop has been exceeded. Similarly, a reduction in surface solar radiation reduces the photosynthetic processes and hence reduces carbon assimilation. This information helps researchers who are interested in the future agricultural scenarios under climate change.

5.4.1 Different varieties compared

The sensitivity test on the sorghum varieties compared a sweet variety to a grain variety. The comparison of the potential yields was done for Keller (sweet variety) and Pioneer 8333 (grain variety) for the Karoi site only. It is assumed other sites will produce more or less the same trends in the differences between the varieties.

The comparison of the two sorghum varieties Pioneer 8333 (grain) and Keller (sweet) indicates that the sweet variety has a higher potential yield in Karoi under existing climate conditions except for the crop planted in July. Otherwise, the grain variety gives a higher yield potential under most of the modified environments. However there is no statistically significant difference in the biomass production as found out earlier ($R^2 = 0.8619$ and the z-score is 0.098)

In conclusion, the simulations on varieties suggest that the potential biomass production is independent on the sorghum variety. What is important to note is that during the simulation of the sweet sorghum variety Keller, it was necessary to modify the crop coefficients that drive the crop growth and development within the model. It is through these modifications that much of the difference in potential yield can be explained. Table 5.2 below summaries the main crop coefficients used for the two sorghum varieties.

Table 5.2 Summary of the sorghum varieties crop coefficients used in DSSAT v4.0.2.0
(Hoogenboom *et al.*, 2003; for Pioneer 8333 and Woods, 2000; *personal communication* for Keller)

Variety	P1	P20	P2R	P5	G1	G2	PHINT
<i>Pioneer 8333</i>	325.0	15.50	30.0	540.0	11.0	6.0	49.0
<i>Keller</i>	495.0	11.80	30.0	540.0	0.0	6.0	49.0

Key:

- P1: Thermal time from seeding emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8°C) during which the plant is not responsive to changes in photoperiod.
- P20: Critical photoperiod or the longest day length (hours) at which development occurs at a maximum rate. At values higher than P20, the rate of development is reduced.
- P2R: Extent to which phasic development leading to panicle initiation (expressed in degree day) is delayed for each hour increase in photoperiod above P20.
- P5: Thermal time (degree days above a base temperature 8°C) from beginning of grain filling (3-4 days after flowering) to physiological maturity.
- G1: Scaler for relative leaf size.
- G2: Scaler for the partitioning of assimilates to the panicle (head).
- PHINT: Phylochron interval; interval in thermal time (degree days) between successive leaf tip appearance.

5.5 Conversion efficiency of biomass yield to bio-ethanol

In the final analysis, what is required is the energy carrier in the form of liquid fuel as bio-ethanol or bio-diesel. The current study was comparing the potential of the three fuel crops, sweet sorghum, sugarcane and jatropha.

5.5.1 Conversion efficiency of sweet sorghum

While it has not been possible to simulate potential productivities for all the crops using the available weather data, some estimates are available in literature that have been verified by field trials (Woods, 2000) of the conversion efficiencies of the different fuel crops. It is worth noting that the simulated potential yields for sweet sorghum in this study are less than theoretical yields obtained elsewhere (Woods *et al.*, 2004; Marcello *et al.*, 1997; Grassi, 1996). However, Kulkarni *et al.*, (1997) gave results of yields obtained in China as 5.25 tons/grains/y ha, and 15.7 ton ligno-cell/y ha and 7.3 ton/sugar/y ha; for South Central Europe, the yield was 5 ton grains/y ha 5 ton ligno-cell/y ha and 8ton/sugar/y ha. These results are generally of the same order of magnitude as those obtained in the current simulated potential yields. Woods (2000) used an average sweet sorghum potential yield of 60 ton/ha in calculating the bio-ethanol production, whereas in the simulated results in this study, the highest potential yield was slightly above 12 t/ha. Daliannis (1997) found stem dry matter yields of about 30 t/ha for European countries Greece, south Italy, and south Spain. Kulkarni *et al.*, (1997) also came up with a theoretical yield of about 5 600 liters per hectare for sweet sorghum that is comparable with Woods' estimate.

Another critical point to bear in mind is that the production of ethanol from sugarcane (12 months growing cycle) is about twice that from sweet sorghum based on a 120 days growing cycle. Therefore, for sweet sorghum to compete with sugarcane in terms of productivity, at least two crops will have to be grown in one year.

5.5.2 Potential Yield of Sugar Cane

Unfortunately in this project, it has not been possible to simulate sugarcane potential yields using the DSSAT version 4.0.2.0 because the crop model is still undergoing modifications to change it from the previous DOS version (DSSAT version 3.5) to the Windows version i.e. DSSAT4. Hence, the author relied mainly on data from literature sources particularly work previously done by Woods (2000) in the southeast of Zimbabwe. In addition some data is available from DSSAT v3.5 experimental work done in South Africa. These data should serve to highlight, though marginally, the significant aspects of sugarcane potential yields in Zimbabwe.

5.5.2.1 Productivity of sugarcane in Zimbabwe

The final sugar yield on any project depends on cane tonnage, sugar content of the cane and on the cane quality. It is important that the cane is harvested at the most suitable moment when the economic optimum of recoverable sugar per area is reached. Cane tonnage at harvest can vary between 50 and 150 ton/ha, which depends particularly on the length of the total growing period and on whether it is a ratoon or a plant crop. In Zimbabwe yields of 120 ton/ha are normal but higher yields have been achieved under experimental conditions (personal communication, Triangle Ltd.).

Good yields in the humid tropics where the crop is totally rain fed, range between 70 to 100 ton/ha cane compared to 110 to 150 ton/ha in the dry tropics and subtropics under irrigation (Woods, 2000). The water utilization efficiency for harvested yield for cane containing 80 % moisture is 5 to 8 (kg/m³) and for sucrose containing no moisture 0.6 to 1.0 kg/m³.

Woods, (2000) illustrated the different components and the variation between species of sugarcane and sweet sorghum by analysis of above ground fresh matter composition. Figure 5.5 shows how the fresh weight mass, at harvest, is partitioned between the major products, water, sugars, stem fibre, tops and leaves and dissolved solids. Figure 5.6 shows the variations in the partitioning rate for the components indicated. Most noticeable is the sharp increase in fibre partitioning after the peak in sugar accumulation. This fact is critical when considering the timing of harvesting and crushing the cane for the production of ethanol and use of by products like fibre.

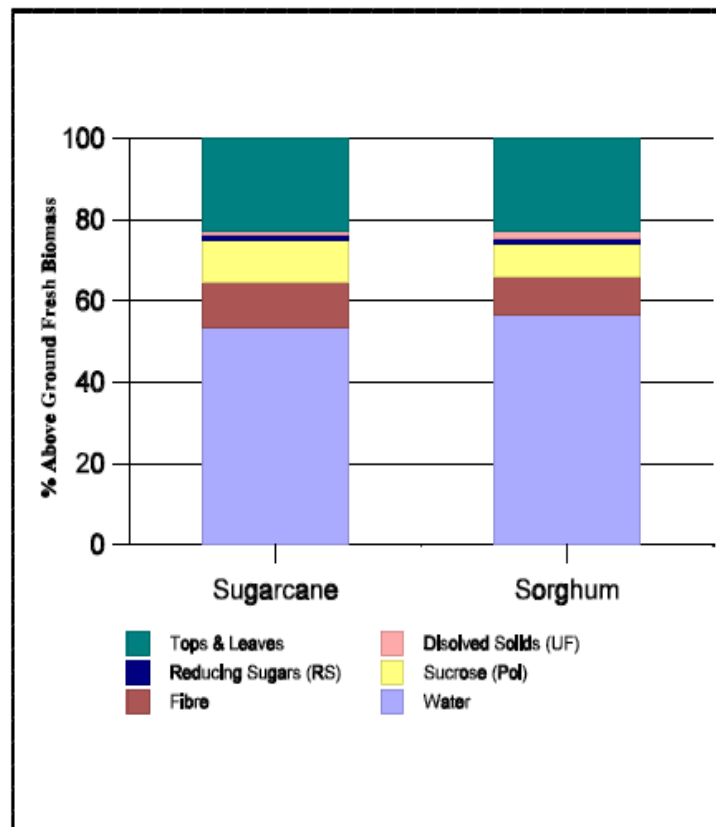


Figure 5.5 Above ground fresh matter composition for sweet sorghum and sugarcane (Source: Woods, 2000)

Woods in his work on sugarcane composition noted that crop quality varied significantly throughout the season as shown by Figure 5.6.

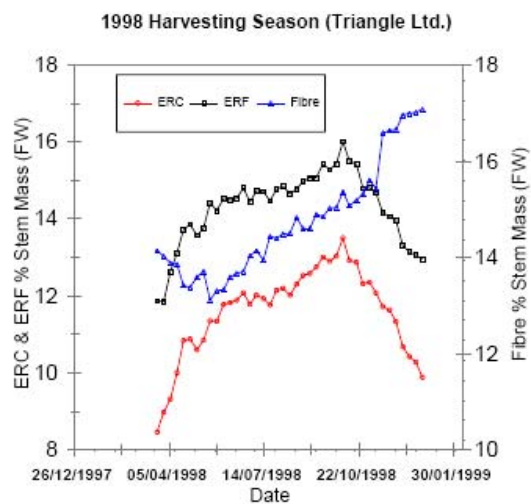


Figure 5.6 Variations in the rate of partitioning for the various components (Source: Woods, 2000)

[ERF is estimated recoverable fermentables; ERC is estimated recoverable crystals]

Figure 5.6 shows the trends in sugar and fibre content of delivered sugarcane stems throughout the harvesting season (1998) at Triangle (Wenman, 1999). The graph information is useful for management purposes; for example when to harvest a sugarcane crop for optimum recoverable fermentables or sugar crystals.

5.5.2.2. Comparative Productivity in South Africa

The results shown in Table 5.3 were extracted from the DSSAT version 3.5 Crop simulation for sugarcane for an experiment carried out in South Africa in 1989.

Table 5.3 Simulated and measured results for a South African experiment

Variable	Predicted	Measured
Sucrose yield (kg/ha)	21531	16800
Harvest Index	55.0	48.0
Biomass yield	57760	-
Leaf Area Index	3.0	2.6

Other details pertaining to above experiment:

- Planting date – June 1, 1989
- Row spacing – 120.0 cm
- Plant density – 13.3 per m²
- Cultivar – NCo 376

5.6 Conversion efficiency to bio-fuel for the different fuel crops

Sugarcane has a theoretical conversion efficiency of 10 350 litres per hectare or 600 litres of anhydrous ethanol (EtOH) per ton of sugar. It would appear that the production of ethanol from sugarcane is almost double the productivity from sweet sorghum (about 5 746 litres per hectare). But more importantly is the fact that sugarcane takes 12 months to mature whereas sweet sorghum matures in about 120 days (Zimbabwe trials) depending on variety. That means theoretically it is possible and desirable to grow at least two sweet sorghum crops in one sugarcane season to ensure its competitiveness with sugarcane ethanol yields.

5.6.1 Potential Yield of *Jatropha*

The potential yield of *jatropha* used in this work is mostly from literature and some experiments that were done in Zimbabwe in the early nineties. In the literature quoted from the Ministry of Science and Technology (Cultivation and Management of *Jatropha Curcas*, August, 2005), it was estimated a potential productivity of about 5 000 kg of dry seed per hectare per annum could be obtained under optimal conditions. However, the productivity varies from the date of planting to the year of maturity as indicated by the summary table (Table 5.4):

Table 5.4 Potential seed productivity of *Jatropha curcas* according to maturity.

Source: Ministry of Science and Technology, 2005 (Zimbabwe).

PRODUCTIVITY (kg/ha/year)		
Year	Fruit	Seed
1	610.7	91.5
2	3 000	450.0
3	18 666.7	2 800.0
4	26 666.7	4 000.0
5	33 333.3	5 000.0

The productivity of the *jatropha* plant is dependent on management practices, for example at Art Farm, near Harare (Highveld) wider spacing gave higher yields (2tons/ha) than close spacing (0.5 ton/ha) in the same year. Unfortunately the spacing was not specified. Soil types; were also found to influence plant yield. In relatively poor soils the yields are about 1 kg of seed per tree. In lateritic soils the yields are 0.75 kg to 1.0 kg per tree. Under low input conditions (no fertilizer, minimal weeding and pest control), yields can range between 3 000 – 5 000 kg per hectare (Ministry of Science and Technology, 2005). Therefore while the *Jatropha curcas* plant is capable of surviving under marginal soil and climatic conditions, its yield is affected by them. In Zimbabwe, *jatropha* is mostly grown as a hedge in Mutoko and Mhondoro.

5.6.2 Conversion efficiency of the jatropha seed oil to biodiesel

In a case study by Jeremy Woods (Rosillo-Calle *et al.*, 2006), a simple feasibility assessment of producing bio-diesel from *Jatropha curcas* was done. The seeds are assumed to comprise 65 % of the total mass of the dry fruit and the seeds contain 19.0 % oil and 4.7 % polyphenol. Planting densities and yields as already mentioned are highly site-specific. Woods (2006) assumed 2500 plants per hectare can be planted and each plant can produce at least 1 kg of *Jatropha* fruit annually – then the total fruit mass obtained per hectare = 2500 kg. Therefore:

- ✓ Seed mass = 65 % of 2500 = 1625 kg
- ✓ Assuming a 60 % oil content of the seed (Zimbabwe trials assume 35% seed oil content), the total amount of oil that can be recovered from the *Jatropha* fruit will be 975 kg/ha = 36855 MJ/ha
- ✓ The extraction efficiency of oil expellers is approximately 60 % so the final recoverable oil yield is calculated as 22000 MJ/ha (585 kg oil/ha)

Given that the development status of *jatropha* as a commercial crop is currently at a very early stage, great care should be taken in evaluating potential yields that could be obtained. The results obtained by Woods would differ from samples from trials conducted in Zimbabwe through the production assumptions inherent in the calculations.

5.6.3 Comparison of conversion efficiencies of the different fuel crops

The potential energy conversion efficiencies of the three fuel crops are shown below (Table 5.5). The potential bio-fuel yield to be expected from the different fuel crops are useful as a decision making tool on what crop to invest in for a sustainable bio-fuel industry. However, these figures do not include the production costs and hence it is necessary to factor in the element of costs before establishment of a bio-fuel industry.

Table 5.5 Potential conversion efficiencies of the different fuel crops

Feedstock	Theoretical yield	Source
Sweet sorghum (Keller cultivar)	5 746 litres per hectare	Woods (2000)
Sugarcane	10 350 litres per hectare	Woods (2000)
<i>Jatropha curcas</i> plant	585 kg oil per hectare	Rosillo-Calle <i>et al.</i> , (2006)

5.7 Economics of Bio-Fuel Production

5.7.1 Introduction

The discussion of bio-fuel production cannot be limited to the issues of production and processing alone but needs an overall evaluation of the economic viability of the whole production chain. Such factors like availability of land, input costs, labour costs, transport costs, processing infrastructure and marketing have to be considered in planning for the establishment of a bio-fuel industry. In practice, this entails a 'cost-benefit' analysis that systematically reviews the complete chain from crop production through harvesting and transport to processing of the bio-fuels until marketing.

The major activities that need to be considered when evaluating the economics of bio-fuels are:-

- Land Preparation
- Planting
- Crop growth and Management
- Harvesting
- Loading
- Transport
- Unloading
- Juice extraction
- Conversion

 Ethanol

Woods (2000) in his study on the integration of sweet sorghum-sugarcane mix for bio-energy and crystalline sugar production identified factors or methods of optimizing bio-energy production, for example:

- ✓ Year round agricultural production for efficient utilization of land, labour and equipment.
- ✓ Increasing the efficiency with which biomass is converted to bio-fuels.
- ✓ Minimizing potential problems, primarily logistical.
- ✓ Maximizing potential benefits (environmental, economic, social).

The overall aim is to enhance the economic viability of the bio-energy project. In the cultivation of sweet sorghum and sugar cane, the final outputs (bio-fuel) of the production chain are closely coupled to the agronomic productivity of biomass per unit area, with the post-harvest processing simply defining the efficiency with which the products are isolated from the 'residues'.

5.7.2 Land Availability

The viability of bio-fuel production systems to transport costs and therefore distances is very sensitive. Therefore a detailed evaluation of land availability is a necessary prerequisite for any future bio-fuel project. In Zimbabwe, the assumption is that land for bio fuel crop cultivation is readily available but there are no official figures available to verify this assertion. Studies will need to be carried out identify suitable areas with the most suitable climatic conditions. These studies should link availability of land and the proximity to processing plants in view of the transport costs that will be incurred.

5.7.3 Productivity of the fuel crops

As discussed earlier, while ‘potential’ yield was the main goal of this research, the ‘actual’ yield under existing climatic conditions need to be assessed for the different regions of Zimbabwe before final establishment of a bio-fuel industry. The requirements of the different fuel crops and their suitability in the various regions of the country are a necessary prerequisite in the planning process. For example the availability of water can be a limiting factor for cultivation of sugarcane in some parts of Zimbabwe, particularly in areas like Masvingo (Region IV) and Buffalo Range (Region V) where the highest yields are forecast by model simulation under non-limiting conditions. It has already been established through various trials worldwide that sweet sorghum production will require significantly less water per litre of ethanol production than sugarcane i.e. 1.4 and 2.7 m³l⁻¹ EtOH for sweet sorghum and sugarcane derived ethanol production respectively (Woods, 2000).

Representative (realistic) yields for both sweet sorghum and sugarcane with irrigation were given as, 60 t_{fab} ha⁻¹ (46 t_{stems}) yields for sweet sorghum over 4 months growth period, and 150 t_{fab} ha⁻¹ (115 t_{stems}) for sugarcane over a 12 months growth period.

5.7.4 Fibre Production

To improve the utility of sweet sorghum, fibre produced as residue (by product) from the crushing process during extraction of the fermentable sugars has a number of potential uses:

- Can be burnt to provide stem for electricity generation to run the mills for the sugar crystallization process. Can also be used in the fermentation and distillation for ethanol production.
- Leaves are also a source of energy – but it is important to note that the primary sink for nitrogen and other nutrients is the leaves and excessive removal (> 50% of total leaf biomass) may result in decreased soil fertility (Bransbeck and Cortez in press; Woods *et al.*, 1994)

5.7.5 Energy Balance

For a bio-fuel production system to be successful it must demonstrate strongly positive energy balance i.e. the energy content of the bio-fuels produced must be greater than the energy required to produce the bio- fuels (dominated by fossil fuel). In his trials Woods (2000) demonstrated a positive ration of 1.9 for the sugarcane-based production of ethanol, electricity, and crystalline sugar at Triangle Ltd. A predicted energy balance for ethanol and electricity only from both sugarcane and sweet sorghum of 3.3 and 4.7 was calculated.

In common with all biomass crops, both the energy balance and the economic viability of the system are very sensitive to the transport component. For example, for sweet sorghum with an average transport distance of 15 km (one way) about one third of the total energy required to produce and deliver the crop to the mill is consumed by haulage. The two largest energy consumers for both sweet sorghum and sugarcane are the fertilizers and transport inputs requiring approximately 70 % of the total inputs. Transport is the greatest single energy input (Figure 5.7).

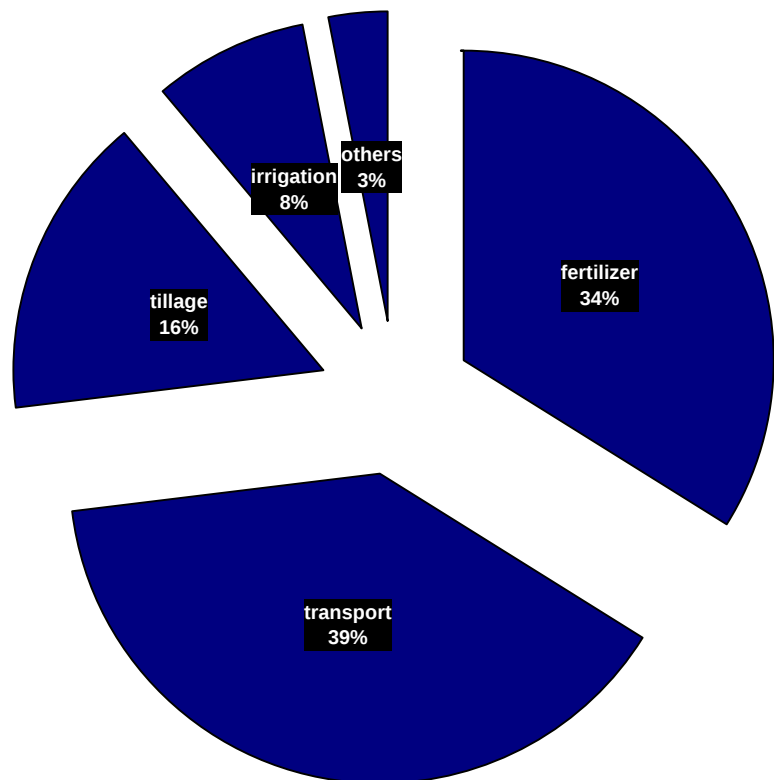


Figure 5.7 The various energy consumers in the production cycle of sweet sorghum from trials in the SE of Zimbabwe (adapted from Woods, 2000)

Evaluating the overall economics of bio-fuels production system at the micro-level is beyond the scope of this work.

5.8 A Market for Ethanol

The overriding assumption for the production of bio-fuel is that there will be a market for the commodity. The ethanol should be able to sell competitively against mineral fuel and this brings us to the assumed costs per unit volume that would make it cost effective. Sorghum-derived ethanol would be competitive with conventional gasoline if produced at a cost below US\$0.80 per litre at current (2007) prices. There are two possible markets for the bio-fuel produced, internal and external. In view of the national energy security concerns highlighted at the beginning, the domestic market should form the backbone of the overall ethanol market. The World Markets, while they hold the potential to earn the country foreign currency, could prove to be less organized and less certain given the novelty of trading in bio-energy (Rosillo-Calle *et al.*, 2006)

The increased demand for fuel ethanol has resulted almost entirely from the fuel alcohol programs of Brazil, USA and more recently France, who have adopted these programs in response to environmental and rural development pressures.

Given the recent concerns over climate change and the need to reduce green house gases (GHGs), where a good energy balance can be demonstrated in bio-ethanol production(>2), may increase demand significantly over the next decades.

5.9 Clean development mechanism (CDM) of the Kyoto Protocol 1997)

Lastly, in the assessment of the economic viability of the production of bio-ethanol or bio-diesel, it is important (especially for developing countries) to consider the impact of the “Clean Development Mechanism” (CDM) to the UNFCCC. This mechanism was crafted at the Kyoto Protocol (1997) as one of the ways in which developed countries who are Party to the Convention are obliged to cut greenhouse gas emissions by 5% for the period 2008 to 2012 of the 2000 emissions baseline can reduce their emissions. The developed countries are encouraged to engage developing countries (non Annex 1 Parties) who are not obliged to reduce greenhouse gas emissions through ‘clean’ technology transfer projects, whereby it will be proven that by adopting such measures, the host country’s assumed reduction in emissions (quantified in equivalent CO₂ emissions) will be credited to the donor country for qualification in their reduction targets. This facility if adopted by African countries (Zimbabwe included) could offset the production costs of bio-fuel production and make it a profitable investment. Rural communities would stand to gain from the cultivation of fuel crops as a cash crop if properly managed.

CHAPTER 6: CONCLUSION

6.1 Introduction

The main aim of this study was to assess the agro-climatic potential of fuel crops in Zimbabwe. This was done through simulation of the potential yield of sweet sorghum, using the DSSAT version 4.0 Crop Simulation Model under existing climatic conditions in Zimbabwe.. The potential yields for Sugarcane and Jatropha were obtained from literature sources.

The outcomes of the research effort were two fold; (1) revised surface solar radiation maps using satellite data and (2) simulation of potential yield of sweet sorghum variety Keller.

6.2 Revised radiation maps

The outcome of revised solar radiation maps was not successful due to the large differences (> 20 %) that were found between satellite surface solar radiation observations and ground based measurements. However, the potential of using satellite data for radiation measurements remains a feasible proposition and better option given the few ground observation network for radiation currently in Zimbabwe. Research work to validate the satellite data with ground based data is a necessary prerequisite before this source of data can be relied upon.

6.3 Simulated potential biomass production

The simulated potential biomass production for sweet sorghum (Keller) were found to be generally high for Karoi site (Natural Region IIa) and Masvingo (Natural Region IV). Although yields obtained over Buffalo Range were found to be relatively low, the productivity rate for the area was found to be quite high, more than over Karoi. High productivities for the sweet sorghum fuel crop were also linked to date of planting, with generally low yields for crops planted in winter. However, for the sugarcane and jatropha fuel crops, planting date is only critical for young plants susceptible to frost.

6.3.1 Sensitivity of sorghum yield to environmental changes.

Potential yields were found to decrease generally for the environmental changes simulated; (i) a maximum temperature rise of 2 °C and (ii) reduction in surface solar radiation of 5 MJ/m²/day. Potential yields also vary between varieties, but not significantly, as exemplified by the two sorghum varieties; Keller (sweet variety) and Pioneer 8333 (grain variety).

In conclusion, the results are not an end in themselves but a means to an end. The debate of bio-fuel production is quite involved linking diverse scientific disciplines; crop science, modeling,

GIS, agro-technology transfer, economics, Trade, Power generation, vehicle engine specification, climate change among others. Results of the study and other literature sources suggest that the climate of Zimbabwe is suited to the cultivation of fuel crops. Logistics of land availability, level of mechanization, infrastructure development and transportation have implications on the economic viability of bio-fuel and shall need to be considered in any future plans to invest in the production of bio-fuel for the transport sector. Furthermore, the by-products of the processing chain are an important factor in the economic equation of bio-fuel production. And so is the Market (internal and external) which will ultimately determine the viability of the bio-energy industry.

The Agro-technology Integrated Package (AIP) developed by Woods (2000) can factor in not only the crop modeling but the influence of introducing novel technology in the production system. Further development of the model could provide a useful tool in evaluating the economic viability of the bio-fuel production in Zimbabwe, particularly when using sweet sorghum or sugarcane as feedstock.

6.4 Recommendations

The establishment of a bio-fuel industry is imperative for the sustainability of our national development goals as well as our energy security concerns. National policy on bio-fuels and their sustainable development is needed to provide a legal instrument for investment.

The establishment of a national Bio-fuel R & D unit involving stakeholders to spearhead the development of a Bio-energy Industry in Zimbabwe would be ideal. Among its mandate, the task force could look at among other things;

- Suitable crops
- Suitable land
- Agricultural system identification
- Vehicles use of ethanol blend
- Complete agro-climatic mapping for fuel crops
- Climate Change and CDM and
- Satellite based radiation data

6.5 Future Issues

The application of crop simulation models has become more acceptable in the agricultural community during the last few years. For any application of a crop model, weather data is one of the key inputs. Hence the need for continuous weather data collection for all regions, a denser weather observation network with more frequently observed parameters. Automatic weather stations require that standards are developed for weather station equipment and sensors, installation and maintenance. There is also need for a uniform file format for storage and distribution of data.

More importantly, there still seems a large gap between the products generated by crop simulation models and decision support systems, and the application of these products by the potential user, be they farmers, consultants, extension workers, to local or regional or national policy and decision makers.

REFERENCES

- Albert, B. and Graves, A., 1988. [en.wikipedia.org/wiki/Sugar_cane] World Sugar Economy in War.
- Agdhasi F. 2004. Multiresolution Processing of Cloud Images, (*unpublished*). Department of Electrical Engineering, UZ, Zimbabwe.
- Bain J., 2006; Maize fuels clean; *South African Sunday Times*, May 21, 2006
- Barnes A.C., 1973; The Sugar Cane[en.wikipedia.org/wiki/Sugar_cane].
- Beinroth F.H., Jones, J.W., Knapp E.B., Papajorgji P., 1998; Evaluation of land resources using crop models and a GIS. *Understanding Options for Agricultural Production. Edited by Tsuji, et al., 1998.*
- Beyer H.G., Hammer, A., Heinnemann D., 1995; Satellite derived irradiance Statistics for Africa. Department of Physics – *Renewable Energy Group, Carl von Ossietzky Universitat, Germany.*
- Blassnegger, J., 2003. Biodiesel as Automotive Fuel-Bench tests. *Presentation of the BIOSTAB Project Results. Published by BLT, Rottenhauser Strasse 1, AT-3250, Austria.*
- Bogaert P., Mahau, P. and Beckers B., 1995: The Spatial Interpolation of Agroclimatic Data. *Agrometeorology Series Working Paper, Number 12, FAO, ROME, Italy – Environmental Information Management Services*
- Bonomo F. and Brignoli V. 1994; Correlation Between Cloud Frequency Esteemed From Meteosat Images and Direct Solar radiation at Ground Level.
- Boote, K.J. and Hunt, L.A., 1998. Data for Model operation, calibration and validation. *Understanding Options for Agricultural Production. Edited by Tsuji, et al., 1998.*
- Bradley, D., 2006. President , Climate Change Solutions, National Team Leader, Bioenergy Task 40: *Canada Biomass – Bioenergy Report. www.climatechangesolutions.com.*
- Brehmer, T. H., 2003. Utilization of biodiesel as a fuel for heating – Bench tests. *Presentation of the BIOSTAB Project Results. Published by BLT, Rottenhauser Strasse 1, AT-3250, Austria.*
- Climate Handbook of Zimbabwe (1980). *Published by the Department of Meteorological Services in Harare, April 1981.*
- Dajue, L., Editor, 1997; Abstracts of sweet sorghum. *Institute of Botany Chinese Academy of Sciences*
- Dajue, L., Editor, 1997; Proceedings: First International Sweet Sorghum Conference. *Institute of Botany Chinese Academy of Sciences*
- Dallianis D.C. 1997; Productivity, Sugar Yields, Ethanol Potential and Bottlenecks of Sweet Sorghum in the European Union. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L., 1997.*
- FAO.commodity (2005). (www.fao.int) Economics and Social Department (Statistics Division)

- Finealt Engineering; Biodiesel ‘ Jatropha Production and Management Pamphlet, August 2006 version.’ *Ministry of Science and Technology Development, Zimbabwe, 2006.*
- Gaoyun S., Yimin, S., Wei, L., 1997; The exploitation and utilization of sweet sorghum. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L., 1997.*
- Gautier, C., 1980. A simple physical model to estimate incident solar radiation at the surface from GOES satellite data. *Journal of Applied meteorology, volume 19, Issue 8 (August 1980; page 1005 - 1012)*
- Glen C. R., Cundiff, J.S., and Welbaum, G.E., 1991. Sweet Sorghum for a Piedmont Ethanol Industry. *Trans. Amer. Soc. Agr. Eng. 34(2):539-547.*
- Grassi, G., 1997. (European Biomass Industry Association, Brussels, Belgium); Sweet sorghum promising industrial energy crop: a global view. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L.*
- Hay R.K and Walker A. J., 1989; Introduction to the Physiological Processes Determining Crop Yield.
- Hinrichs R. A. and Kleinbach M (2006); ENERGY: Its Use and the Environment. 4th edition. Published by Thomson Brooks/Cole (www.brookscole.com).
- Hoogenboom, G., Jones., J.W., Porter, C.H., Wilkens, P.W., Boote, K.J., Batchelor, W.D., Hunt, L.A. and Tsuji, G.Y., 2004. Decision Support Systems for Agrotechnology Transfer (DSSAT) version 4.0.
- Hoogenboom, G., 2000; Contribution of agrometeorology to the simulation of crop production and its applications; *Agricultural and Forest Meteorology 103, pages 137-157.*
- Hunkar, M., 1998; Potential production of sweet sorghum in Hungary. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L.*
- Jakob, K. and El Bassam, N., 1997. Sweet sorghum, a sustainable for energy production in Europe – Results of 10 years of experiments (1985-95). *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L..*
- Jean-Marc G., Raquet, G., Girard M.C. 1996. A sorghum crop simulation model in France to establish potential sorghum growing area maps, using GIS. *First European Seminar on Sorghum for Energy and Industry. April 1-3, 1996: P68 [En] INRA 78850 Thiverval-Grignon-France.*
- Jones H.G., 1992. Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology. 2nd edition; Cambridge University Press.
- Junfeng, C., 1997. A study on the effects of climate on sweet sorghum productivity. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L.*
- Kibahozi, O., 2005. Mitigation options – use of Biodiesel; (*IMPACT-Magazine, February; Nairobi, Kenya*)
- Kulkarni D. N. et al., (1997); Sweet sorghum: Research and Prospects: Potential uses for energy production. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L., 1997.*

- Mahove C. and Kwanayi M.W., 2002. Sugarcane Production Guidelines. *Agritex Advisory Notes (Ministry of Agriculture, Zimbabwe)*
- Mastorilli, M., Katerji, N., Rana, G., 1997. Productivity of sweet sorghum under Mediterranean climate. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L., 1997.*
- Monteith, J.L., Unsworth, M.H., 1990. Principles of Environmental Physics. 2nd Edition. *Published by Edward Arnold, New York.*
- Muropa A. and Shoko R., 2002. Investment Potential in Bio-Fuels Production and Processing in Zimbabwe. Industrial Development Corporation of Zimbabwe Limited. No. 20 in the IDCZ business development series.
- Nallathambi G., 1998. Studies on character association for alcohol yield in sweet sorghum (*Sorghum bicolor* L. Moench). *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L.*
- New M., Hewitson B., Stephenson D.B., Tsiga A., Kruger A., Manhique A., Gomez B., Coelho C.A.S., Masisi D. N., Kululanga E., Mbambalala E., Adesina F., Saleh H., Kanyanga J., Adosi J., Bulane L., Fortunata L., Mdoka M.L. and Lajoie R., 2006. Evidence of trends in daily climate extremes over southern and west Africa. *Journal of Geophysical Research, volume 111, D144102, doi:10. 1029/2005JD006289.*
- Nimbkar N. and Rajivanshi A.K., 1997; Sweet Sorghum R & D at the Nimbkar Agricultural Research Institute (NARI). *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L.*
- Ortiz R. A. (1998); Crop simulation models as an educational tool. *Understanding Options for Agricultural Production. Edited by Tsuji, et al.*
- Pinker R. T. and Laszlo I., 1992. Modeling surface solar irradiance for satellite applications on a global scale. *Journal of Applied Meteorology, volume 13, Issue 2 (Feb., 1992).*
- Ponomarev L.I., 1988. The Quantum Dice. *Mir Publishers Moscow.*
- Raes, D., Steduto, P., Fereres, E. Hsiao, T.C., 2006. The FAO revision framework and the Crop-Water Productivity Model: AquaCrop Yield Response to Water (*personal communication*)
- Prince G., 2006 (Communications Director, D1 Oils Plc;www.D1); First Jatropha Biodiesel Plant. *Brunswick Group, RNS number 1236A.*
- Ravi S.B. and Ratnavathi C.V. (1998); Pattern of dry-matter accumulation and partition between panicle and stalk in grain and sweet sorghum. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L.*
- REW (Renewable Energy World, 2006).
- Ritchie J.T., Singh, U., Godwin, D.C., and Boven, W.T., 1978; Cereal growth, development and yield. *Understanding Options for Agricultural Production. Edited by Tsuji, et al.*
- Rozenzweig C. and Iglesias A., 1994. The use of crop models for international climate change impact assessment. . *Understanding Options for Agricultural Production. Edited by Tsuji, et al.*
- Rosillo-Calle, F., deGroot, P., Hemstock, L. and Woods, J., 2006. The Biomass Assessment Handbook. Bioenergy for a Sustainable Environment. *Published by EARTHSCAN (www.earthscan.co.uk)*

- Shoko, K., 1999. The Agroclimatic Atlas of Zimbabwe (MSc. Thesis). *University of Zimbabwe*
- Stricevic, R., Vasic, G., and Petkovic, 1997. The state of production and growth possibilities of sweet sorghum in F.R. Yugoslavia. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L.*
- Tsuchibahashi N., (1997); Feasibility for cultivation of sweet sorghum (*Sorghum bicolor* (L) Moench) in Indonesian dry land. Growth and yields in dry season in comparison with rainy season. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L.*
- Tsuji, G., Hoogenboom, G. and Thornton, P.K., 1998. Understanding Options for Agricultural Production. Systems approach for sustainable development. *Published by Kluwer Academic Publishers.*
- United Nations Climate Change Secretariat, November 2005. Kyoto Protocol to the United Nations Framework Convention on Climate Change. secretariat@unfccc.int
- Walter, A., Dolzan P., and Piacente E. 2006. Biomass Energy and Bio-energy Trade: Historic Developments in Brazil and Current Opportunities. *State University of Campinas-Unicamp, DE/FEM/Unicamp, Campinas – Brazil.*
- Wolfgang Z. 2003. Vehicle test with diesel fuel/ FAME Blend. *Presentation of the BIOS TAB Project Results. Published by BLT, Rottenhauser Strasse 1, AT-3250, Austria.*
- Wolfgang Z. (2003): Stability of bio-diesel used as a fuel for diesel engines and heating systems. Presentation of the BIOS TAB Project Results.
- Woods, J., Hall, D.O., Vincent, A. and Muzondo, M., 1997. A computer-based model for the integration of sweet sorghum with sugarcane for the production of sugar, electricity and ethanol. *Proceedings: First International Sweet Sorghum Conference. Edited by Dajue, L.*
- Woods J., 2000. Integrating sweet sorghum and sugarcane for bio-energy; Modelling the potential for electricity and ethanol production in SE Zimbabwe. (PHD Thesis), *Kings College London, Division of Life Sciences, London, United Kingdom.*
- Woods, J., 2004. Demonstrating increased resource use efficiency in sugar industry of southern Africa through environmentally sustainable energy production. (jeremy.woods@imperial.ac.uk)
- www.fao.int
- www.jatropha-world.com
- www.newscientist (23 September, 2006)
- www.jatropha-curcas.org
- www.jatropha-biodiesel.org
- www.wmo.int

