Jatropha curcas in South Africa: An Assessment of its Water Use and Bio-Physical Potential

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Report to the Water Research Commission on the project "Investigation into the Impacts of Large-Scale Planting of *Jatropha curcas* on Water Resources, through Process-Based Research and Modelling"

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EXECUTIVE SUMMARY

This research project came about in response to the proposed introduction of various so-called "wonder-crops" into South Africa, amongst them *Jatropha curcas*. Interest centred on poverty alleviation, job creation and the provision of alternative energy sources; however, questions regarding the hydrological and ecological effects of large-scale cultivation of these crops were unable to be answered. Indeed, confident quantification of the impacts of these species on water resources was not possible, because of insufficient research worldwide.

International interest in *J. curcas* as a drought-tolerant, fast-growing, renewable bio-energy crop has grown significantly in recent years. The crop has a number of additional advantages and because of this, large-scale schemes for planting *J. curcas* have been proposed in South Africa. Despite this interest, to the authors' best knowledge, there has been no previous assessment of the water use of *J. curcas* anywhere in the world. The Department of Water Affairs and Forestry (DWAF) (Sub-directorate Stream Flow Reduction) consequently drafted a discussion paper proposing that, until further information became available, *J. curcas*, and other species proposed for large-scale cultivation, be declared Stream Flow Reduction Activities (SFRAs).

Aim and Objectives

The effective management of commercially planted species in terms of water resources requires accurate data on generalised water use and bio-physical patterns, relevant to areas having planting potential. This was the approach followed in this project, which strove to gain an understanding of the biophysical requirements and associated water-resource impacts of *J. curcas*. The aims and objectives of this project, as defined in the project proposal, were, therefore:

- To develop predictive capability with respect to the impacts of large-scale planting of *J. curcas* on water resources in South Africa, through a process-based research and modelling study;
- To provide information regarding the bio-physical requirements of *J. curcas* and produce maps through an ARC-View GIS-modelling framework;
- To gauge the perceptions and levels of understanding of *J. curcas* and of SFRA processes and licensing amongst potential *J. curcas* users and other interested parties through a qualitative research process;
- To contribute towards SFRA recommendations through the provision of *J. curcas* water-use data.

Specific data limitations were encountered during the course of this project including limited yield and related climate and other biophysical data for *J. curcas* (in South Africa and internationally) and the limited number of sites for monitoring *J. curcas* in South Africa.

Knowledge Review and Biophysical Assessment

An international knowledge review was first conducted to gather information on all aspects of the cultivation, hydrology and production of *J. curcas*. The knowledge review aimed to contribute to the overall investigation with regard to the feasibility, viability and advisability of the wide-scale introduction of *J. curcas* in South Africa. The knowledge review confirmed that although *J. curcas* has many potential uses, relatively little is known about the ecological and hydrological impacts of the crop.

The knowledge review also formed the basis of a more detailed biophysical assessment, which attempted to derive yield estimates for *J. curcas* in South Africa. Remarkably little information could be found anywhere in the world on the yield and physical growth requirements of *J. curcas.* Yield estimates, based on climate and other biophysical aspects, could not be obtained with the current status of yield information available. The crop-yield modelling, therefore, followed a three-phase approach where modelling complexity increased with each successive phase:

- First phase – cut-off limits were used to map areas where *J. curcas* will not grow under dry land conditions
- Second phase – a weighted modelling approach using climate and other data was applied. This information was indexed against known yield to produce yield estimates
- The third phase undertook a more formal equation-driven analysis to produce estimates of potential yield

The first phase of the yield-modelling procedure concentrated on eliminating all areas where *J. curcas* will not grow due to climate and physical constraints and showed that, contrary to popular perception, substantial areas in the centre of the country will not support *J. curcas* because of the low rainfall and the number of frost days. Areas on the eastern and southern areas of the country will allow for the growth of *J. curcas*.

The second phase of analysis produced weighted results by using an assessment of relative importance of each of the index values to the overall crop yield. This assessment showed very similar results to the third phase of analysis, which performed a yield estimate using actual crop-yield equations.

Unfortunately, the literature did not come up with any yield equations, and not enough information was available to perform a regression analysis. Crop-yield equations were, therefore, derived by manipulating equations for banana plantations, eucalyptus plantations and sunflower cropping. These were chosen as they encompass the oil-producing properties of *J. curcas* with its tree-like growth. The equations were combined and manipulated, taking into consideration *J. curcas*' own tolerance limits. Whilst the equations do not pretend to give precise estimates, they can be used as a good indication of expected yield for different areas.

The yields generated by the crop-yield equation (Refer to Figure 3.4, Section 3.4.1) showed that the highest potential yields in South Africa are likely to be obtained in the coastal areas of KwaZulu-Natal and the Eastern Cape, and inland on the eastern slopes of the escarpment (Drakensberg mountains) in

Mpumalanga, where yields of over 8 t of seed/ha may be achieved. Other areas may produce yields of over 3 t of seed/ha. Yield mapping also shows that low yields of less than 2 t of seed/ha can be expected in the northern parts of the country and along the south-eastern seaboard. The inland and central interior is not suitable for *J. curcas* due to low rainfall and frost.

Water-Use Assessment

This project was primarily concerned with conducting a hydrological (water-use) study of *J. curcas* through climate, transpiration, and soil-moisture measurements. To this end, two appropriate test sites, representing optimal growth conditions and where field measurements could be made, were selected:

1. 4-year-old trees at the Owen Sithole College of Agriculture (OSCA) near Empangeni on the KZN north coast. This was an agricultural research trial, planted in January 2002. The environment could be classified as sub-tropical.

2. 12-year-old trees along the fence-line of a rural homestead in the Makhathini flats, northern KZN. These represented mature trees in a more tropical environment.

Continuous hourly measurements of sap flow / transpiration, climatic variables and soil-water dynamics were carried out at the OSCA site over 17 months. Sap flow and selected climatic variables (temperature, relative humidity and solar radiation) were measured at the Makhathini site (no soil moisture) for a 16-month period.

An automatic weather station (AWS) at OSCA recorded rainfall, temperature, relative humidity, solar radiation, wind speed and wind direction. These variables were measured at 10-second intervals, and averaged or totalled at hourly intervals. The data was aggregated to daily, monthly and annual values. Hourly fluctuations in temperature, relative humidity and solar radiation were recorded at the Makhathini site and these data supplemented with additional daily data from the website of the South African Sugarcane Research Institute.

Transpiration of *J. curcas* was monitored using the Heat Pulse Velocity (HPV) technique through the measurement of sap flow. Transpiration rates were observed to be season-dependent due to the deciduous nature of *J. curcas*. Maximum transpiration rates in summer contrasted with a cessation of activity in the cooler and drier winter months; however, the Makhathini sap-flow data declined far more dramatically and significantly earlier in the winter season. Indications are that, apart from the obvious seasonal fluctuations in transpiration, *J. curcas* transpiration rates at the Makhathini site are highly rainfall dependent. This is likely to be as a result of the sandy soils associated with this area, which have rapid drainage and a low capacity to retain water in the root zone. The sap flow in the Makhathini trees is, therefore, strongly influenced by fluctuations in water availability, while the OSCA trees appear to be limited only by season (deciduous, drier and cooler winter conditions). For these reasons, and possibly tree-age differences as well, the OSCA trees have noticeably higher sap-flow rates. However, in terms of volumetric water use these are offset by the greater cross-sectional area of the older and larger Makhathini trees.

The resumption of transpiration after winter dormancy coincided closely with the first good rains, the development of new leaves and the onset of warmer / wetter conditions. Once the leaves had developed, sap-velocity responses were closely associated with ambient conditions. Hourly transpiration responses to changes in vapour-pressure deficit were detectable from the hourly data, and this translated into significant daily variation. Trends over the longer term appeared to be dictated principally by season, but it is interesting to note how daily transpiration rates fluctuated widely, possibly due to the timing and amount of individual rainfall events, and their replenishing effect on soil-moisture availability, as well as energy availability (solar radiation).

By scaling up the individual tree-transpiration measurements, the average total annual transpiration for the 4-year-old *J. curcas* plantation of 740 spha at Empangeni is estimated to approximate 144 mm. Scaling up from single trees at the Makhathini site gives stand transpiration values of 361.8 mm and 298.9 mm. These values are more than double those for the 4-year-old trees at Empangeni, and reflect the greater size (increased leaf area) of the Makhathini trees.

To test the hypothesis that *J. curcas* trees cause significant changes in soil-water dynamics, continuous measurements of matric potential and soil-water content were carried out at the OSCA site, both inside the Jatropha plot and in an adjacent grassland control site of mown Kikuyu (with the sensors at corresponding depths beneath the soil surface). These measurements confirm the veracity of the transpiration results.

Water-Use Modelling and Mapping

Three potential models suitable for the simulation of transpiration in plant species (FAO56, WAVES and SWB) were reviewed during the course of the project. The FAO56 model was considered to be the most appropriate and easily parameterised for the simulation of transpiration in *J. curcas*. The modelling exercise applied the FAO56 reference evapotranspiration and crop-factor approach, and utilised the observed transpiration results obtained in this project to back-calculate a unique set of monthly basal crop-coefficient values for 4- and 12-year-old *J. curcas* trees.

As an alternative to the FAO56 modelling exercise, Leaf Area Index (LAI) values were also used in approximating transpiration from stands of *J. curcas*. LAI measurements for both sites were regressed against the final transpiration totals, and a 3rd order polynomial curve that passed through the origin as well as a hypothetical maximum LAI value (3.2) was fitted to the data. Potential maximum annual-transpiration totals were calculated to be approximately 300 mm for the 4-year-old trees at OSCA and 500 mm for the 12-year old trees at Makhathini. These results were obtained under conditions of below-average rainfall, especially at OSCA where rainfall for the year was just 61% of the annual mean.

An extrapolation exercise was conducted to obtain water-use impacts on a national scale for *J. curcas*. The basal crop coefficients, estimated during the FAO56 modeling exercise described above, were multiplied in a GIS environment by spatially explicit monthly totals of Penman-Monteith equivalent reference evapotranspiration (ET_o) obtained from Schulze (1997). These transpiration estimates for *J. curcas* were then compared with estimates for Acocks Natural Veld types (using A-Pan evaporation and crop factors derived by Schulze, 1995) to determine whether *J. curcas* would transpire more or less water than indigenous vegetation types.

The difference between the *J. curcas* transpiration and the Acocks vegetation transpiration was calculated and expressed as a percentage relative to the original Acocks vegetation transpiration. The analysis shows (refer to Figure 5.1 and Figure 5.2, Section 5.3.1) that the water use by *J. curcas* is considerably lower than that of the original Acocks vegetation, with the exception of summer and autumn estimates for the Winter Rainfall Region. Extrapolations to the Winter Rainfall Region must, however, be treated with extreme caution as all water use is estimated using factors derived for the summer rainfall region.

The results showing that stands of *J. curcas* can be expected to use less water than the Acocks vegetation, which might otherwise be growing there, could be considered biased given that the experiment was carried out in a year where the rainfall was 61% of the mean. *J. curcas* has a tendency to drop its leaves and go into senescence during dry periods. The evapotranspiration could, thus, be understated. In order to get a better estimate of potential evapotranspiration under normal conditions, an LAI approximation relationship was developed and the values were used in the water-use mapping analysis. The evapotranspiration values from the LAI approach (Refer to Figure 5.4, Section 5.3.3) show that on average, the estimated evapotranspiration is 50% higher than when using the measured K_{cb} values. However, even when comparing the water use of *J. curcas* (using the Makhathini data) to the Acocks Veld types using the LAI approach, it was found that in the majority of the country *J. curcas* still uses less water than the Acocks Veld types.

It appears as though the planting of *J. curcas* would be unlikely to have a negative effect on annual streamflow in South Africa. This is because the crop uses, in most instances, less water at an annual scale than the original Acocks vegetation that it would replace. It can be concluded from these estimates that *J. curcas* should not be considered a SFRA.

Perceptions Study

The perceptions and levels of understanding of SFRA processes and licensing amongst *J. curcas* users and other interested parties were assessed through a qualitative research process that consisted of two independent surveys.

The first target group consisted of stakeholders responsible for monitoring and legislation and, therefore, comprised employees from Government departments (Department of Water Affairs and Forestry (DWAF), Department of Agriculture (DoA) and the National Energy Regulator). In-depth personal interviews were conducted with these participants in order to clarify their stance on *J. curcas* and the issues around it.

The key issues highlighted during the interviews were the potential invasivity of *J. curcas*, water-use potential of the plant, food-security issues and the economic viability of planting *J. curcas*, particularly with regard to the poor. DWAF is primarily concerned both with stream flow reduction and the wider issues of catchment degradation and management – particularly where plantings are unwisely effected. The DoA sees food security and possible invasivity as major issues, while the DME/ Energy Regulator, on the other hand, aims to maximise the production of biodiesel as a replacement fuel – creating a tension between these Departments.

In essence, the interviews with selected regulators and monitoring agents illustrated that there is a critical lack of knowledge when it comes to *J. curcas* and the implications of potential large-scale planting in South Africa. It is evident that the key government departments (particularly DEAT, DoA and DWAF) should adopt a consensus around *J. curcas* and communicate their position to other government departments and the general public.

The second target group consisted of potential producers and processors of *J. curcas*. A semi-structured questionnaire was used to guide telephonic interviews. From these interviews, it was evident that potential growers and processors were not well informed regarding establishment, survival and yield, areas which show growth potential, water-use implications, and government's position on *J. curcas* as a potential SFRA and alien invasive plant. It is difficult to believe that investments can be considered on the basis of the information these growers had to hand – and brings into question the motivation behind such project development - particularly where this involves rural communities.

The private-sector interest in *J. curcas* has largely been stimulated by the perceived potential to generate biofuel/diesel, although an economic analysis (Hallowes, 2005) illustrates that this is not a lucrative option. *Jatropha curcas* has been presented as a wonder-plant when, in reality, very little is known about it and actual large-scale success stories cannot be found. Due to the lack of knowledge about *J. curcas* amongst potential growers and processors, it is important for government to engage with these stakeholders and disseminate correct information so that educated decisions can be made.

Recommendations

1. *Jatropha curcas* can be most successfully grown in South Africa along the Eastern Escarpment and most areas along the coast. Places where highest yields would be obtained are in KwaZulu-Natal, the Eastern Cape and certain areas of Mpumalanga. Areas of low and variable rainfall, and areas susceptible to anything more than mild frost, should be avoided. Any investigation and investment should be focused on these areas, which also have very high poverty indices.
2. From the water-use measurements and modelled impacts on water resources, it would appear that *J. curcas* is unlikely to have a negative impact on stream flow; therefore, *Jatropha curcas* cannot be declared an SFRA on the basis of this research. Further research into the water-use characteristics of the species may still be undertaken, but planting cannot at this stage be restricted on the basis of water use.
3. *Jatropha curcas* has been presented as a wonder-plant when, in reality, very little is known about it and actual large-scale success stories cannot be found. Care should be taken in promoting the wide-scale propagation of *J. curcas.*
4. The outcomes of this research project should be widely disseminated - amongst both potential growers and the regulators. The project should be formally presented to the National Biofuels Task Team. Growers need to be informed of both the opportunities and constraints pertaining to *J. curcas*.

In addition to these recommendations, areas of further research, both related to water use and other aspects such as economics and invasivity have been proposed.

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ACRONYMS

ACRU	Agricultural Catchments Research Unit
AWS	Automatic Weather Station
BTP	Binga Trees Project
CARA	Conservation of Agricultural Resources Act
CSIR	Council for Scientific and Industrial Research
DAEA	Department of Agriculture and Environmental Affairs
DME	Department of Minerals and Energy
DOA	Department of Agriculture
DWAF	Department of Water Affairs and Forestry
ET	Evapotranspiration
GIS	Geographical Information Systems
GTZ	German Technical Assistance
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
ICRAF	International Centre for Research in Agroforestry
KSA	Key Strategic Area
KZN	KwaZulu-Natal
MAP	Mean Annual Precipitation
MAT	Mean Annual Temperature
MSSA	Marketing Surveys & Statistical Analysis
NEMA	National Environmental Management Act
OSCA	Owen Sithole College of Agriculture
PAW	Plant Available Water
RAW	Readily Available Water
RH	Relative Humidity
SAPIA	Southern African Plant Invaders Atlas
SASRI	South African Sugar Research Institute
SFRA	Stream Flow Reduction Activity
TBVC	Transkei, Bophuthatswana, Venda, and Ciskei
VPD	Vapour Pressure Deficit
WRC	Water Research Commission

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND & RATIONALE

When this project began, a number of business initiatives were proposing the introduction of a number of exotic so-called “wonder-crops” for large-scale planting in South Africa. Species such as *Jatropha curcas*, Bamboo and Industrial Hemp were identified. The motivations behind these initiatives were the laudable themes of poverty alleviation, job creation and business development. However, questions around the potential hydrological and ecological effects of the associated land use changes could not be answered due to a lack of information. Confident quantification of the impacts of these species on water resources was open to debate, because of insufficient field-based experimental or other direct research under South African, or indeed any, conditions.

Large-scale schemes for the planting of *J. curcas* were being proposed, and Government had no idea how it should respond to the development opportunity. Due to the significant areas proposed for planting these species, the Department of Water Affairs and Forestry (DWAF) (sub-directorate Stream Flow Reduction Allocations) drafted a discussion paper proposing that all such species be declared Stream Flow Reduction Activities (SFRAs).

This project specifically considered the prospective establishment and consequent hydrological impact of *J. curcas*, an oil-seed-bearing plant, which can be used, *inter alia*, as biofuel and in soap manufacture. International interest in *J. curcas* as a drought-tolerant, fast-growing, renewable bio-energy crop has grown significantly in recent years. India has apparently initiated large-scale plantings of this species in efforts towards the increased use of bio-diesel as an alternative to fossil fuel imports (Francis *et al.*, 2005), and there has been talk of extensive developments planned for various Southern African countries (Swaziland, Namibia, Mozambique, and Madagascar), although no experience on the progress or success of such projects has yet been published, nor could progress be established.

The prime ingredient in the manufacture of bio-diesel is the oil present in the seeds or kernels of certain plants. Research has indicated that *J. curcas*, whose seed oil is inedible (toxic) to humans and animals, has potential as a bio-diesel feedstock. Other advantages attributed to this plant are that it tolerates arid conditions and marginal soils, and is unpalatable to livestock, reputedly making it suitable for restoration of degraded land and use in other "waste" lands.

However, knowledge around the potential environmental impacts (e.g. invasiveness and water use) of this species is scant, which is of particular concern in South Africa, where the Government has received numerous requests for permission to plant this species. The growing interest in this species reached a stage where the relevant Government Departments (Water Affairs and Forestry, Agriculture, Environmental Affairs, Minerals and Energy, etc.) required the information necessary to make an informed decision on whether to actively promote, or to discourage, the propagation and commercialisation of *J. curcas*.

Until now these departments have postponed a decision on *J. curcas,* and at time of writing, there is still a moratorium on the planting of this species in South Africa. It is likely that this decision will only be made when these Departments are confident that they have enough information on the potential social, economic and environmental impacts of this species in South Africa.

In order to manage, it is necessary to measure. The effective management of commercially planted species in terms of water resources requires accurate data on generalised water use and bio-physical patterns, relevant to areas having planting potential. This was the approach followed in this project, which strove to gain an understanding of the water-resource impacts and bio-physical requirements of *J. curcas*.

1.2 AIMS AND OBJECTIVES

This project was funded through the Water Research Commission's Key Strategic Area (KSA) 1 (Water Resource Management), Thrust 2 (Integrated Water Resources Development). The four goals of the project were to:

- Develop predictive capability with respect to the impacts of large-scale planting of *J. curcas* on water resources in South Africa, through a process-based research and modelling study;
- Provide information regarding the bio-physical requirements of *J. curcas* and produce maps through an ARC-View GIS-modelling framework;
- Gauge the perceptions and levels of understanding of *J. curcas* and of SFRA processes and licensing amongst potential *J. curcas* users and other interested parties through a qualitative research process;
- Contribute towards SFRA recommendations through the provision of *J. curcas* water-use data.

1.3 METHODOLOGY

One of the aims of the project was to develop predictive capability with respect to the impacts of large-scale planting of *J. curcas* on water resources through hydrological process studies and modelling, using appropriate techniques (transpiration, soil moisture and climate measurements). This was completed by firstly conducting a comprehensive knowledge review on all aspects of *J. curcas* relevant to its potential wide-scale propagation in South Africa and then identifying appropriate test sites where field measurements could be made. Continual measurements of transpiration, soil moisture and climatic variables were carried out over an 18-month period so that the evapotranspiration trends of *J. curcas* could be simulated using appropriate models. Results were then verified against measured data and extrapolated to all areas where *J. curcas* was predicted to grow successfully.

Another aim of the project was to provide information regarding the bio-physical requirements of *J. curcas* and produce maps through an ARC-View GIS-modelling framework. The initial focus was on a knowledge search concentrating on both literature and expert opinion to identify aspects that would influence *J. curcas* yields. The investigation then shifted toward identifying methodologies that could be used to determine the crop yield relating to climate condition. The water-use characteristics associated with *J. curcas* were then analysed with experimental evidence used to assess water usage patterns of the plant. The results of the analysis are presented in ARC-View GIS and are discussed in this report.

The third aim of the project was to gauge the perceptions and levels of understanding of *J. curcas* and of SFRA processes and licensing amongst potential producers and processors of *J. curcas* and other key stakeholders, such as government departments and regulators. A questionnaire was developed to guide fieldworkers in gathering data and in-depth personal and telephonic qualitative interviews were undertaken. The data was analysed and a discussion around the issues identified is presented in this report.

The fourth aim of the project was to contribute towards a recommendation on the declaration of *J. curcas* through the provision of water use and other data gathered during the course of the project. This is one of the key outcomes of the project presented in this project report.

1.4 DATA LIMITATIONS

Specific data limitations were encountered during the course of the project, namely:

- There is a limited amount of information in terms of yield and related climate and other bio-physical information on *J. curcas* available.
- International experts consulted on *J. curcas* yield did not respond to information requests or were unable to provide information, which complicated the data-collection process.

- Although yields are supplied for other areas in the world, this information was not linked explicitly to climatic data.
- A crop-yield equation for *J. curcas* could not be established; therefore, other yield equations had to be adapted.
- There is almost no *J. curcas* planted in South Africa; therefore, it was a challenge to find two suitable sites for monitoring purposes.
- With respect to monitoring of the two sites, some data gaps did occur due to faulty equipment. The sites were closely monitored and any deficiencies were quickly corrected; where appropriate, data has been patched.
- A limited number of potential producers and processors were available to be interviewed, and only a few were willing to participate in the research.

1.5 STRUCTURE OF THE REPORT

This report consists of six further chapters in addition to the introduction and is structured as follows:

Chapter 2	Chapter 2 presents the findings of the knowledge review conducted at the beginning of the project and provides an overview of the characteristics of *J. curcas*, hydrology, agronomy, the distribution and extent of plantings in South Africa, the economics associated with growing and processing the plant, its uses, and discusses threats to and opportunities for expansion in South Africa.
Chapter 3	Chapter 3 investigates the bio-physical requirements that influence crop growth, survival and yield and determines the physical viability of planting *J. curcas* in South Africa. The chapter also briefly examines the areas in South Africa that would benefit most from planting *J. curcas,* based on a poverty analysis.

Chapter 4	Chapter 4 describes and illustrates the final analysis of the climate, transpiration and soil-moisture data collected from the two monitoring sites over a 17-month monitoring period. It also discusses a modelling exercise that was carried out to simulate the observed transpiration data.
Chapter 5	The focus of this chapter is on extrapolating water-use estimates of *J. curcas* on a national scale and comparing the estimated evapotranspirative demand for *J. curcas* against that of the Acocks Natural Veld types. The results of the analysis are presented as GIS maps.
Chapter 6	Chapter 6 presents the results of the qualitative interviews conducted with stakeholders responsible for monitoring and legislation related to *J. curcas* and with potential producers and processors of *J. curcas.* It relates the findings of the interviews back to the outcomes of the other research conducted where possible and concludes with some discussion on the implications of the findings.
Chapter 7	Chapter 7 briefly discusses the overall outcomes of the research and makes strategic recommendations related to the approach that should be taken towards *J. curcas* and other potential SFRAs. Areas of further research are also highlighted.

CHAPTER 2: KNOWLEDGE REVIEW[1]

2.1. INTRODUCTION

This chapter synthesises the information on the possible hydrological impacts of *Jatropha curcas* and its value and viability as an economic crop in South Africa. Chapter 3 examines the bio-physical requirements for the growth and production of *J. curcas* in more detail.

2.2. *JATROPHA CURCAS*

Jatropha curcas belongs to a very large family, *Euphorbiaceae*, which includes cassava and rubber. It has numerous common names depending on the country where it is found, but is most commonly referred to as physic nut, Barbados nut or purging nut. The Zulu common name is *Inhlakuva*. It is a multi-purpose tree of Mexican and Central American origin with a long history of cultivation in tropical America, Africa and Asia. Considerable amounts of physic-nut seed were produced on the islands of Cape Verde during the first half of the twentieth century, constituting an important contribution to the country's economy. Seeds were exported to Lisbon and Marseille for oil extraction and soap production (Becker and Makkar, 2000).

The seeds and leaves of the tree are poisonous, fast growing, multipurpose and drought resistant, and can be cultivated in areas of low rainfall. During dry seasons, it tends to shed its leaves. Where annual rainfall is high (>1000 mm), it does better in hot, rather than temperate, climates. It can grow in soils that are quite infertile, and is usually found at lower elevations (below 500 m.). Since it will survive with little or no fertilizer input, it is an attractive species for

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resource-poor farmers, although higher rainfall and fertilizer inputs can substantially increase its yields (Pratt *et al.*, 2002).

The form of *J. curcas* is a shrub or tree with smooth grey bark, spreading branches and stubby twigs, which exude a milky or yellowish sap (latex) when broken. Estimates of maximum height vary from 5 to 8 m, and probably depend on growing conditions. Its leaves are deciduous, 3- to 5-lobed in outline, 6 – 40 cm long and 6 – 35 cm broad (Figure 1). Its yellowish flowers are bell-shaped and the plant is monoecious, so flowers are unisexual, although occasionally, hermaphrodite flowers occur (Dehgan and Webster, 1979). Pollination is by insects, usually bees. Fruits are 2.5 – 4 cm long, finally drying and splitting into 3 valves, all or two of which commonly have an oblong black seed (Morton, 1977; Little et al., 1974).

Figure 2.1: Photo showing the leaves and fruit (with seed kernels exposed) of *J. curcas* (photo courtesy of Reinhard Henning).

2.2.1 Bio-Physical Requirements

Globally ranging from Tropical Very Dry to Moist through Subtropical Thorn to Wet Forest, *J. curcas* is well adapted to arid and semi-arid conditions. Worldwide, most *J. curcas* species occur in seasonally dry areas of grassland-savannah and thorn-forest scrub (ICRAF, 2003). In terms of radiation requirements, the species is reported to prefer full sunshine (PIER, 2004); however, there are references to better growth under partly shaded growing conditions, where the trees were planted amongst existing bushy vegetation (JANUS, 2004). Agricultural research stations in South Africa are currently evaluating the species to determine optimal growing conditions. The species is known to produce higher yields under sub-tropical conditions, which makes it suited for cultivation along the Kwa-Zulu Natal (KZN) coastal belt. Growth and yield are likely to be determined by rainfall and temperature fluctuations.

2.2.1.1 Rainfall

Jatropha curcas is drought resistant and cases are reported of it surviving for several years without rainfall in Cape Verde (PIER, 2004). Trees require a minimum Mean Annual Precipitation (MAP) of 250 mm (which may be supplemented by fog or mist, as is likely the case in Cape Verde). They grow well with 500 mm or more, but grow optimally with an annual precipitation of up to 1200 mm (Becker and Makkar, 2000; BUYSOMALI, 2003).

2.2.1.2 Temperature

The trees tolerate a mean annual temperature ranging from 11.0 to 28.5°C, but optimal is 20 to 28°C (BUYSOMALI, 2003). They are reported to be mildly frost tolerant (PIER, 2004).

2.2.1.3 Altitude

Provenances have been collected on the Pacific Islands from altitudes varying from 7 to 1600 m above sea level. Usually they are found from 0 to 500 m

(PIER, 2004). This is the recommended altitude range for propagation (ICRAF, 2003).

2.2.1.4 Soils

Jatropha curcas grows best on well-drained soils with good aeration, but adapts well to marginal soils with low nutrient content (PIER, 2004). The trees even grow on coarse, sandy and saline soils, and can survive on the poorest stony soil, even in the crevices of rocks. The leaves shed during the winter months, forming mulch around the base of the plant, and the organic matter from shed leaves enhances earth-worm activity in the soil around the root-zone of the plants, which improves the fertility of the soil (Lele, 2004). The trees prefer a slight to medium slope of ground as opposed to flat ground, but do not tolerate waterlogged soils (JANUS, 2004).

A summary of the bio-physical requirements of *J. curcas* is presented in Chapter 3, Table 3.1. The table incorporates information sourced from this particular literature review, as well as additional information from a more detailed assessment of bio-physical requirements of *J. curcas,* which allowed for an assessment of crop yield and mapping the areas of potential in South Africa.

2.2.2 Hydrology

Not surprisingly, there is currently very little information on the hydrological impacts of *J. curcas*, which is the motivation behind this project. Extensive searches for hydrologically pertinent information were made on the Internet, in journals and books, and through personal correspondence with Department of Agriculture and Environmental Affairs (DAEA) staff. Based on extremely limited relevant literature, indications are that the species is not likely to have a significant impact on water resources.

The trees are deciduous, losing their leaves in the winter months and during periods of drought (Lele, 2004), thereby reducing transpiration appreciably.

They have shallow root systems (Henning, 1996), precluding the use of deep underground stores of water and normally five roots, consisting of one central and four peripheral, are formed from seedlings. A tap root is not usually formed by vegetatively propagated plants (Heller, 1996). At this stage, there is nothing to indicate that this plant should use any more water than bushy hillside vegetation, and could potentially use significantly less than, for example, sugarcane or an area of bush encroachment. The process-based water-use measurements undertaken in this project indicate this to be the case and provide the best hydrological knowledge on this species currently available worldwide.

Refer particularly to Chapters 4 and 5 of this report for details on water-use measurements and for comparative estimates of water use by *J. curcas* on a spatial basis across South Africa.

2.2.3 Agronomy

There is wide-ranging, and often conflicting, evidence in the literature, which suggests that stakeholders and the scientific community do not have a good understanding of *J. curcas*. It is a relatively new crop and full commercialisation could take decades. Given the very limited knowledge on the cultivation of *J. curcas,* the following paragraphs have been included in this review for the sake of completeness and as of likely value to prospective growers.

Francis *et al.* (2005) report that despite numerous projects investigating the use of *J. curcas* plantations for various purposes in several countries, reliable scientific data on its agronomy is currently lacking. They believe that as *J. curcas* is still a wild plant, careful selection and improvement of suitable germplasm is necessary before mass-production can be realised. Agronomic conditions, such as optimum soil texture, amounts of water, spacing, pruning intensity and micro and macro nutrients required, need to be assessed in both pilot and large-scale plantations. The biological requirement of the closely related castor seeds could provide an estimate of the requirements for *J. curcas* seeds (Francis *et al.*, 2005).

2.2.3.1 Propagation

Jatropha curcas is easily propagated by direct seeding, pre-cultivated seedlings, transplanting of spontaneous wild plants and direct planting of cuttings. Although the seedlings grow very fast, it is recommended that they stay in the nursery for 3 months until they are 30 - 40 cm tall. By then, the plants have developed their repellent smell and will not be browsed by animals (Jøker and Jepsen, 2003). At this stage, they should be moved out of the nursery to allow them to acclimatise before planting (Figure 2.2).

Figure 2.2: 1-month old *J. curcas* seedlings placed outside a nursery to acclimatise.

The choice of propagation method depends on use. Plants propagated from seeds are generally preferred for the establishment of long-lived plantations for oil production. Direct sowing should only be used in areas with high rainfall and the seeds must be sown after the beginning of the rainy season. For quick establishment of hedges and plantations for erosion control, directly planted cuttings are best. Cuttings of 30 cm length have been found to have the highest survival rate (Jøker and Jepsen, 2003). ICRAF (2003) recommends planting widths of 2x2 m, 2.5x2.5 m and 3x3 m, which is equivalent to crop densities of 2,500, 1,600 and 1,111 plants/ha, respectively.

2.2.3.2 Site Preparation and Irrigation

Sites may initially be prepared by ploughing and disking. Individual planting pits may be prepared using hoes, and a hole that is just bigger than the plant bag is adequate. Once planted, the plots should be irrigated initially to ensure the survival of the newly planted seedlings, although the species is extremely drought tolerant. Nut yields are likely to be strongly influenced by available moisture, so supplementary irrigation in dry climates should improve productivity. It should be borne in mind that the trees are susceptible to water-logging, especially in poorly drained soils (JANUS, 2004), and caution should be taken not to over-irrigate. Once the trees are established, survival is usually excellent, with close to 100% survival under frost-free conditions (C. Everson, pers. comm., Jan 2006).

2.2.3.3 Weed Control and Mulching

Seedlings are susceptible to competition from weeds and grass during their early development, so weed control is important (C. Everson, pers. comm., Jan 2006). Weed infestations are best controlled by first mowing and then spraying with a broadleaf-weed herbicide. This strategy encourages the growth of grass between the trees, which could be useful in terms of erosion control and the provision of additional fodder for livestock. However, in cases where a complete absence of under-canopy vegetation is sought, a broad-spectrum herbicide (e.g. RoundUp) may be used to clear all the vegetation. Care should be taken to avoid drift of the herbicide onto the trees.

Mulches help keep the soil well aerated by reducing soil compaction that results when raindrops hit the soil. They help to maintain a more uniform soil temperature (warmer in the winter and cooler in the summer) and promote the growth of soil micro-organisms and earthworms. Mulches eliminate mowing around trees and provide a physical barrier that prevents damage from mowers. Following periods of mowing in order to control weeds, there is likely to be an abundance of mulch (grass and weed cuttings). These may be applied to the base of the trees to reduce weed re-growth, conserve moisture and reduce frost damage in winter. This is a necessary precaution in sites that may experience some frost.

2.2.3.4 Insect Control

No published records of insect infestations in South Africa were found during the literature review; however, anecdotal evidence of the potential seriousness of insect attacks suggests that this is a significant threat to *J. curcas*. A species of flea beetle, which is a member of the *Chrysomelidae, Alticinae* family, and has been identified as an *Aphtona* species, is known to vigorously attack *J. curcas* trees in South Africa (C. Everson, pers. comm., Jan 2006). These beetles are known to preferentially feed on *Euphorbiaceae*. Initial indications of insect problems were loss of condition in the trees through wilting, and defoliation. Specialist advice on controlling the insect was sought and the solution was found to be a combination of PREV-AM and CYPERFOS 500 EC insecticides. These contain Borax, Orange Oil, Chlorpyrifos and Cypermethrin, and are classified as insecticide groups 1B (Organophosphate) and 3A (Pyrethroid).

A further symptom of the insect damage was blackened tips to the branches, appearing as if the trees had been scorched by fire. At this stage, the trees had suffered complete defoliation with not a single leaf evident. Even the emerging buds were eaten off by the insects before being able to emerge. However, after spraying with the above insecticides, there was a very rapid positive response. Within 48 hours of spraying, the insects had disappeared and the emergence of buds of new leaves was noted. Regular follow-up spraying is recommended until there is no sign of the insects.

2.2.3.5 Harvesting

Under good rainfall conditions, *J. curcas* starts producing seeds within 12-18 months but reaches its maximum productivity level after 4 to 5 years. For mature plants, 2- 3 tons of seeds/ha can be achieved in semi-arid areas, although yields of 5 tons/ha are routinely achievable under more favourable (wetter) conditions (Becker and Makkar, 2000). Oil may be extracted by means of hand-operated ram presses or expellers (Pratt *et al.*, 2002). With oil content of approximately 35% (Henning, 1996), this equates to an average yield of approximately 1.75 tons of oil per hectare.

Seed should be collected when the capsules split open. Collection is best done by picking fruits from the tree or hitting and shaking the branches till the fruits break off. Seeds collected from live fences can normally be reached by hand. For taller trees, it is possible to collect the fruits in a small bag that is attached to a stick. It has been reported that direct sunlight has a negative effect on the viability of collected seed, so seeds should be dried in the shade (Jøker and Jepsen, 2003).

The seeds are oily and do not remain viable for long (one year at most). Use of fresh seeds improves germination, which should take about 10 days with good moisture conditions. The International Centre for Research in Agroforestry (ICRAF) in Kenya is known to provide guidance on appropriate seed supply sources (ICRAF, 2003). In terms of harvesting, for medicinal purposes, the seeds are harvested as needed, but for energy purposes, seeds might be harvested all at once (Duke, 1983).

2.2.4 Distribution and Extent of Plantings

Though native to Central America, the species is almost pan-tropical now, and is widely planted as a medicinal plant that soon tends to establish itself (Duke, 1983). This immediately suggests that the plant has invasive propensities. *J. curcas* has attracted much interest around the world, and an Internet search produced references to trials and plantings in Belize, Burkina Faso, Cape

Verde, China, Comore Islands, Egypt, Ethiopia, Ghana, India, Indonesia, Madagascar, Malawi, Mali, Namibia, Nepal, Nicaragua, Papua New Guinea, Senegal, Somalia, South Africa, Sudan, Tanzania, Tunisia, Uganda, Zambia, and Zimbabwe. Significantly, the India Government announced a 'National Mission on Bio-diesel' in 2003, to be implemented on an area of 400,000 ha over five years (India, 2003). No literature following up on the success of this project has been discovered – but clearly there would be useful learning to be gleaned from this project, should it ever have been undertaken.

Within southern Africa, the plant is reported to have been distributed originally from Mozambique through to Zambia and also to the Mpumalanga and KwaZulu-Natal provinces in South Africa (Begg and Gaskin, 1994). The Southern African Plant Invaders Atlas (SAPIA), a mapping project that aims to collect information on the distribution, abundance and habitat types of alien invasive plants in southern Africa, has several records of a related species, *Jatropha gossypiifolia,* as being naturalised in South Africa but none for *J. curcas*. However, there is anecdotal evidence (Dave Hardy of the Botanical Research Institute), that it was naturalised in Venda where it has been planted as a hedge plant.

In South Africa, reliable information on the extent of existing plantings of *J. curcas* proved difficult to come by, and at the time of writing, no documented data was obtainable.

2.2.5 Uses of *Jatropha curcas*

Jatropha curcas is considered to be a multi-purpose tree. Studies and publications are available which have analysed potential products from, and uses of, the leaves, bark, seeds (oil) and roots. The majority of authors are of the opinion that the species has significant potential to increase rural farmers' incomes while providing employment for the poor (Henning, 1996; Becker and Makkar, 2000; BUYSOMALI, 2003; ICRAF, 2003; Biodiesel S.A., 2004; Lele, 2004). *Jatropha curcas* is deemed to be suitable for the production of biodiesel and related products due to a number of favourable factors, as noted by Lele (2004):

- Oil yield per hectare is among the highest of all tree-borne oil seeds.
- The species can be grown in areas of low rainfall (>250 mm per year) and in marginal soils.
- The trees are easy to establish, grow relatively quickly and are hardy to drought, although with limited frost resistance.
- *Jatropha curcas* thrives under plantation conditions but also produces adequate yields on low fertility, marginal, degraded, fallow, waste and otherwise unproductive lands, such as along canals, roads, railway tracks, field borders (as a live hedge), in arid/semi-arid areas and even on alkaline soils. As such, it can also be used to reclaim degraded lands.
- The plant is un-demanding in soil type and does not require tillage.
- Animals do not browse *J. curcas*.
- Being rich in nitrogen, the seed cake is an excellent source of plant nutrients and may be used as a fertiliser.
- The tree starts producing seed within two years of planting.
- Raising plants in nurseries, planting and maintaining them, as well as collection of seed, are labour-intensive activities. Except for the cost of fertiliser and transportation of the plants from the nursery, all the costs associated with propagation and planting of *J. curcas* are labour-based.
- *Jatropha curcas* can be established from seed, seedlings and cuttings.
- *Jatropha curcas* seeds are easy to collect, as the plants are not very tall.
- Various parts of the plant are of medicinal value. Its bark contains tannin, the flowers attract bees; thus, the plant has honey production potential.

The practical application of the above benefits was the aim of the so-called "*Jatropha* Project", which was initiated in Mali in 1993 by German Technical Assistance (GTZ) (Henning, 1996). The project worked to combine these and other factors into the so-called "*Jatropha* System" (see http://www.Jatropha.de). This system focuses not simply on the use of *J. curcas* oil as fuel, but rather on the use of this fuel as a crucial element to activate a circular system, combining ecological, economic, and incomegenerating effects. The "*Jatropha* System" promotes four main aspects of development, which combine to help assure a sustainable way of life for village farmers and the land that supports them, namely:

- Renewable energy.
- Erosion control and soil improvement.
- Promotion of women.
- Poverty reduction.

The spectrum of potential products and uses from the different parts of the *J. curcas* plant are represented in Figure 2.3.

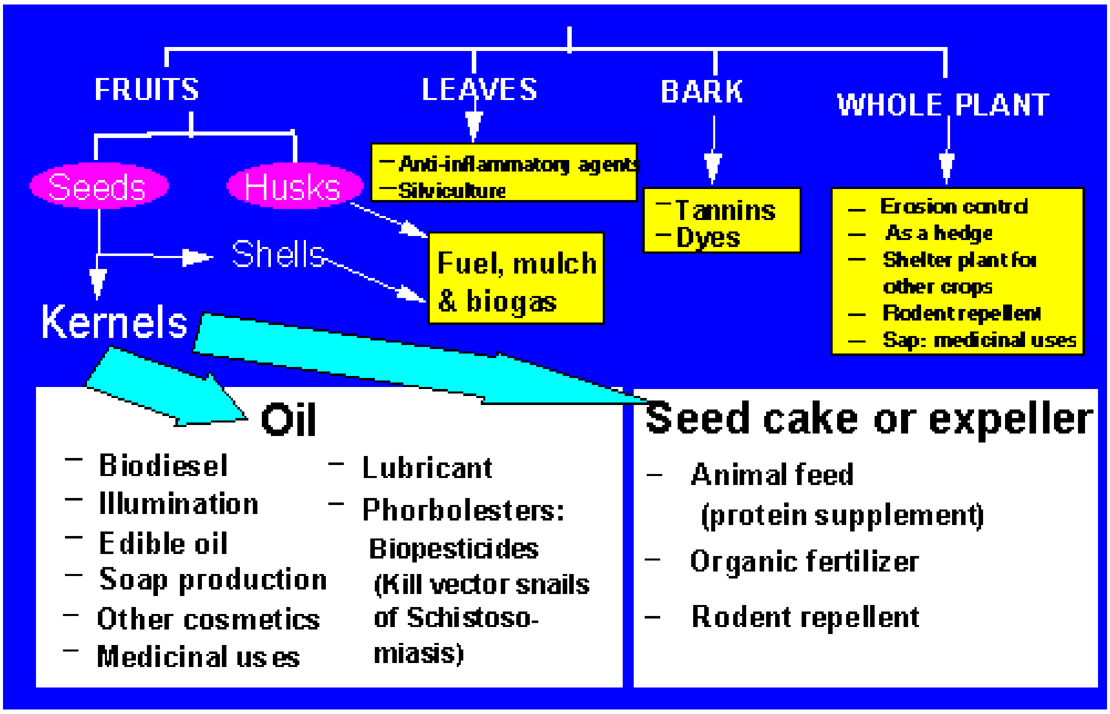

Figure 2.3: Parts of *J. curcas* and their possible uses (Becker and Makkar, 2000)

On the other hand, comprehensive scientific reviews by various authors have reached conclusions contrary to the poverty-alleviation arguments. For example, Openshaw (2000) argued that because *J. curcas* can be used in place of kerosene and diesel and as a substitute for fuel wood, it has been promoted to make rural areas self sufficient in fuels for cooking, lighting and motive power. This strategy was examined and found not viable. It was found that the oil has a much higher viscosity than kerosene or diesel, limiting its use in household lighting and engines.

Oil for soap making was the most profitable use. Openshaw (2000) concluded that some of the strategies used to promote the species were sub-optimal and could act as a deterrent instead of a stimulus in promoting rural development. Similarly, Pratt *et al.*, (2002) concluded that their expectations for *J. curcas* (inspired largely by the extensive literature available on this plant) were unfounded. In a Malawian study, they were not able to acquire technical and marketing know-how from established '*Jatropha* industries' within the country. Either way, there exists extensive literature on the potential benefits to mankind through the utilisation of this species, and these are further elaborated upon in the following sections.

2.2.5.1 Food and Nutrition

According to Ochse (1980), young *J. curcas* leaves may be safely eaten once steamed or stewed. They are favoured for cooking with goat meat and are said to counteract the smell of goat, which some people find too strong. The seeds are known to be poisonous (Duke, 1983; Begg and Gaskin, 1994); however, seed kernels from a *J. curcas* variety of Mexican provenance are reported to be edible (known as "Florida Pistachio" nuts), although no long-term experience of this has been gained in Central Africa (Makkar *et al.,* 2001). Watt and Breyer-Brandwijk (1962) report that though purgative, the nuts are sometimes roasted and dangerously eaten.

Following oil extraction, the respective presscake is said to be a non-toxic livestock-fodder supplement due to the absence of the phorbol esters (Makkar *et al*., 2001). However, ICRAF (2003) recommends that the press cake not be used as animal feed because it contains toxic properties. It does, however, recommend its use as organic manure due to a nitrogen content similar to that of seed cake from castor bean and chicken manure (3.2 to 3.8%).

2.2.5.2 *Cosmetic and Skincare Products*

A long history of use suggests that *J. curcas* oil is safe for soap making. In the early part of the twentieth century, Cape Verde exported large amounts of *J. curcas* seed to Europe for soap making. *J. curcas* oil appears to have several desirable properties. It is rich in palmitic acid, with high levels of hydrophobicity, and makes a soft, durable soap under even the simplest of manufacturing processes. It is also used in West Africa, Zambia, Tanzania and Zimbabwe as a soapstock, including the manufacture of soft laundry soap (Pratt *et al.*, 2002).

2.2.5.3 *Medicinal Applications*

There is an extraordinary list of medicinal applications from across the globe. Clearly the *J. curcas* plant has some 'special' properties. So, for example, *J. curcas* soap is perceived in Malawi as a 'medicated' soap. The soap from unrefined oil is considered, like neem-based soap, to be an effective, gentle anti-scabies wash. The seed oil can be applied to treat eczema and skin diseases and to soothe rheumatic pain (Heller, 1996). It is also reported to be a strong purgative. The leaves are mildly laxative. They also have uses in the treatment of swellings, psoriasis and syphilis, and leaf extracts have anti-inflammatory effects (Wegmershaus and Oliver, 1997).

The bark is used as a pain reliever for flatulence and as a wound coagulant (Wegmershaus and Oliver, 1997). The milky latex may be applied topically to relieve bee and wasp stings (Watt and Breyer-Brandwijk, 1962). Except for soap making in West Africa, none of these uses has been commercialized (Pratt *et al.*, 2002).

Globally, folk use of *J. curcas* is common. Mauritians massage ascitic limbs with the oil, and people in Cameroon were known to apply the leaf decoction in arthritis (Watt and Breyer-Brandwijk, 1962). Colombians drink the leaf decoction for venereal disease (Morton, 1981). Bahamans drink the decoction for heartburn. Costa Ricans poultice leaves onto erysipelas and splenosis.

Guatemalans place heated leaves on the breast as a lactagogue (breast milk stimulant). Cubans apply the latex to toothache. Colombians and Costa Ricans apply the latex to burns, haemorrhoids, ringworm, and ulcers. Barbadians use the leaf tea for marasmus, Panamanians for jaundice. Venezuelans take the root decoction for dysentery (Morton, 1981). The root is used in decoction form as a mouthwash for bleeding gums and toothache. Otherwise, the roots are used for eczema, ringworm, and scabies (Perry, 1980; Duke and Ayensu, 1984).

2.2.5.4 Fuel and Energy

Pratt *et al.* (2002) state that opinions regarding the suitability of *J. curcas* oil as a motor fuel are very mixed. The oil is widely reported to be an environmentally safe, cost-effective renewable source of non-conventional energy and a promising substitute for diesel, kerosene and other fuels (Heller, 1996; Henning, 1996; Biodiesel S.A., 2004; Lele, 2004). For example, BUYSOMALI, (2003) reports that it can be used as a fuel in pre-combustion chamber diesel engines and as a lubricant. The seeds yield up to 31-37% oil, which is obtained by simple hand presses or by engine-driven expellers. The oil burns without smoke and has apparently been employed in street lighting near Rio de Janeiro in Brazil. It is also widely used for healthy and safe lighting in the home.

Pratt *et al.* (2002) report that many researchers have described *J. curcas* as a potential domestic fuel for cooking and lighting, with properties similar to kerosene. They concluded that it was, in fact, a very poor kerosene substitute. High ignition temperatures and viscosity as compared to kerosene led them to conclude that *J. curcas* oil will not burn well, and would clog up the tubes and nozzles in a conventional kerosene stove or light. Approaches to circumventing these problems were tried, and a low-intensity lamp with a wick was developed. The oil lamp required a very short wick so that the flame was very close to the oil surface, ideally floating on the oil surface (Figure 2.4).

Figure 2.4: An example of a simple lamp fuelled by oil pressed from *J. curcas* seeds (BUYSOMALI, 2003).

Investigations by Pratt *et al.* (2002) considered *J. curcas* as a source of an eco-friendly, economic substitute fuel oil for engines, stoves and lamps. However, their review of literature revealed that there are far more efficient oil-yielding species, led by commercial hybrids of oil palm *(Elaeis guineensis).* Although *J. curcas* can yield up to 2,400 litres of oil/ha under plantation conditions *with efficient extraction* (Gaydou et al, 1982), the oil output/ha and energetic yield/ha were reported to be barely more than one half of that attainable with oil from commercial oil palm. What merits consideration, however, is that *J. curcas* will grow in much harsher environments than oil palm.

With certain modifications to conventional diesel engines, the GTZ project in Mali found *J. curcas* oil to be an economic substitute for diesel in remote locations (where diesel is expensive); to some extent *J. curcas* oil could be blended with diesel to avoid the need for engine modification (Henning, 1996). However, research in Zimbabwe concluded that *J. curcas* oil was flawed as a diesel substitute (Pratt *et al*., 2002). It was found to be inferior to diesel in its energy content, flash point, and solidifying point. Diesel, as a hydrocarbon, has 8-10 carbon molecules per mole; *J. curcas* oil, on the other hand, has 16-18 carbon molecules per mole; thus, it is more viscous and has a poorer ignition quality than diesel. Trans-esterification of the plant oil is then required to give the bio-diesel similar properties to mineral diesel, and this is a process that requires considerable investment. Under the world petroleum prices of the day, it was not considered economically viable as an alternative motor fuel, except possibly for certain types of engine. *J. curcas* oil apparently works well in a refined, but otherwise untreated, form in certain kinds of engines, such as the Lister engines commonly used to run small-scale flourmills or electric generators.

The extracted seed oil is thought to be a useful and biodegradable cutter bar lubricant for chain saws (Biodiesel S.A., 2004).

2.*2.5.5* ***Miscellaneous Applications***

Jatropha curcas is frequently planted around homesteads and bathrooms as a hedge/living screen in other parts of Africa and Asia. It is useful as a livestock fence since it cannot be grazed, being poisonous to ruminants (Begg and Gaskin, 1994). The hedges are also seen to be able to provide good protection for crops against livestock (Biodiesel S.A., 2004). The trees are also said to be effective as a hedgerow that prevents wind and water erosion (Henning, 1996). The drought tolerance of *J. curcas* makes it a suitable species for reclamation of eroded and degraded areas; therefore, it is also suitable for preventing soil erosion and shifting of sand dunes (Lele, 2004).

The Binga Trees Project (BTP) in Zimbabwe reported *J. curcas* oil use by tanneries where there was a demand of 600 litres (see http://www.*Jatropha*.de/zimbabwe/binga.htm). From the oil, it is reported by Pratt *et al.* (2002) that a number of individual fatty acids, or combinations of fatty acids, could be used as key intermediates in the manufacture of different products. These include:

- Fatty chlorides used in the making of detergents and soap.
- Fatty alkanolamides for laundry softeners.
- Fatty esters for cosmetics, pharmaceuticals and candles.
- Methyl stearates used for lubricating oils and greases.
- Fatty amines for metal working, paints and varnishes.

- Quaternary ammonium chlorides for plastics and printing inks.
- Methyl esters for specialty surfactants that are used in the formulation of detergents, cosmetics and lubricants.

The oil and aqueous extract from oil (active principle probably phorbol ester) has potential as an insecticide, for instance, in the control of four insect pests of cotton, including cotton bollworm, and on pests of pulses, potato and corn. Methanol extracts of *J. curcas* seed (which contains biodegradable toxins) have been tested in Germany for control of bilharzia-carrying water snails (Pratt *et al.*, 2002). In India, pounded leaves are applied near horses' eyes to repel flies (Watt and Breyer-Brandwijk, 1962).

The leaf juice stains red and marks linen an indelible black. The 37% tannin found in the bark is said to yield a dark-blue dye; latex also contains 10% tannin and can be used as marking ink (BUYSOMALI, 2003). The wood was used as fuel, though of poor quality, in Cape Verde (ICRAF, 2003).

2.2.6 The Economics of Growing *J. curcas* in South Africa

Hallowes (2005) has attempted a realistic look at ‘farm gate’ economics for the production of *J. curcas* under South African conditions. The particular focus of the research has been that of value to poor communities, and production aimed at the reduction of poverty. As already noted by Openshaw (2000) and Pratt *et al.* (2002), *J. curcas* abounds with listed ‘benefits’ but Hallowes *(loc cit)* provides the only broad analysis in the literature of the economics of crop production, and especially ‘profits’.

Hallowes (2005) puts a cash value to input costs, including labour, depreciation on establishment and maintenance, and transport. The analysis also looks at a range of production scenarios: the sale of raw seed; production and sale of hand-pressed oil for bio-diesel or soap; and the production and sale of soap as a finished product. Input costs are recognised as being variable and are grouped into high-, medium- and low-cost categories, with an overall low input cost considered unrealistic in most instances (for example, where a family uses its own labour to collect seed and does not consider this as a cost incurred). Crop sizes of 1-15 ha are factored for, as are different pricing structures. The key cost is labour, and a farm labour income of R650-R800 per month (approximately $100 p.m.) is considered the minimum. If it is not possible to recoup this amount, then the operation must be questioned. Using the production-level maps, also reproduced elsewhere in this report (Chapter 3), which are in accord with extraction rates in the order of 1.75 t/ha offered by Henning (1996), Hallowes draws the following conclusions:

- That the production of raw seed for sale to refineries cannot be profitable except under the unlikely lowest-cost scenario.
- That the production and further pressing of seed for oil is even less profitable.
- That the production and sale of *J. curcas* oil for soap can derive substantial profits except for the “high-cost, low-income” scenario, but that there remains the question of marketing, and the likely rapid saturation of the market. Soap could not provide the sole offset for oil production except at local scale.

Thus, fitting the farm-gate returns to estimated yield maps, Hallowes shows the that the “high-cost” scenario will result in severe economic losses to producers, with a possible break-even achieved for soap, although not providing for a minimum wage. As costs come down and putative incomes increase, the situation starts to turn around, with soap eventually proving a possible R5,000 – R10,000/ha in high yielding areas under the unlikely low-cost, high-income scenario.

Hallowes (2005) is clear that it is only economically viable for “the poor” to produce oil or sell seed in a low-cost scenario. And, although soap will produce a sustainable livelihood income under low- to medium-cost scenarios, it is more likely that a medium to high cost will pertain. The biggest cost lies in the time taken to harvest the crop, and, in order to turn the economics around, it would be necessary to implement an efficient harvesting and de-husking method. Mechanical harvesting is not well suited to communities living on the margins, and this seems to be an essential approach if there is to be larger-scale commercial production of the crop.

2.2.7 Industry Potential – Threats to Expansion

The seeds of the *J. curcas* tree are known to be toxic to humans and animals alike (Duke, 1983; Begg and Gaskin, 1994), causing acute abdominal pain and nausea about half an hour following ingestion. Diarrhoea and nausea continue, but are not usually serious. Depression and collapse may occur, especially in children. Two seeds are a strong purgative, and four to five seeds are said to have caused death, but the roasted seed is said to be nearly innocuous. Seeds contain the dangerous toxalbumin curcin, rendering them potentially fatally toxic (Duke, 1983).

As these plants are frequently grown as natural hedges, Begg and Gaskin (1994) caution that they will often be found in gardens and public areas and will, therefore, be easily accessible, especially to children. This could have potentially fatal consequences. Two publications document the poisoning of South African children by *J. curcas* (Joubert *et al*., 1984; Mampane *et al*., 1987). Animals do not usually eat this species of plant but in drought conditions, with an acute shortage of fodder, a situation could arise in which animals are forced to consume the plants and their constituents in varying amounts, in which case there would be potentially fatal poisoning (Begg and Gaskin, 1994). As a possible solution to this problem, trials with non-toxic varieties of *J. curcas* were carried out in Zimbabwe (Gubitz, 1997).

According to invasive plant experts, this species has a high potential for becoming an invasive alien plant in South Africa (Prof. Dave Richardson, Personal Communication). *Jatropha curcas* is a well-known invader in several countries and has been categorized as weed, quarantine weed, noxious weed, naturalized, environmental weed and cultivation escape in the sources summarized in Rod Randall's (2002) "A global compendium of weeds". According to Professor Richardson, the above findings, as well as the fact that at least 16 other species in this genus (and many other closely-related species in the family *Euphorbiaceae*) are also well know invaders in many parts of the world, suggest that *J. curcas* has a very high chance of becoming invasive in South Africa. As such, he suggests that the species be placed in the "very high risk" category, and does not recommend its cultivation in South Africa. As a result of reports such as these, the proposed plantings of this species in South Africa are understandably being considered with due caution.

Jatropha curcas is listed as a weed in Australia, Brazil, Fiji, Honduras, India, Jamaica, Panama, Puerto Rico, and Salvador (Holm et al., 1979). There have been reports of it naturalising itself along roadsides, on open slopes, and sometimes in forests in Fiji (Smith, 1981) and in Tonga (Meyer, 2000). Risk assessments for Australia and Hawaii classify this species as REJECT, SCORE 11 (PIER, 2004). This assessment was based on information on the biology of the species obtained from scientific literature and other documented sources, predicting the likely invasiveness of the species in Australia and in Hawaii and the high islands of the Pacific. The rating of "reject" indicates that the species poses a high risk of becoming a serious pest. The assessment emphasises that caution should be exercised in introducing species that naturalize or are known to be invasive elsewhere, and *J. curcas* clearly falls into this category (PIER, 2004).

In the Northern Territories of Australia *J. curcas* is considered under the National Weeds Strategy (http://www.weeds.org.au) to be a Class A (noxious weed, to be eradicated) and Class C (not to be introduced). However, Biodiesel S.A. (2004) argues that concerns about *J. curcas* escaping and posing danger as an invasive species have been assuaged by a long-abandoned experiment at the DAEA experimental farm on the Makhathini Flats in northern KwaZulu-Natal. They refer to a number of homesteads in the area that are surrounded by mature trees that were planted in the mid-1980s as living fences, all of which still bear seeds profusely. They suggest that there is no evidence to suggest that any seed has germinated elsewhere, almost 20 years after the first planting. *Jatropha curcas* is supposedly relatively common in Zimbabwe, with the seeds used by communities for soap and other local purposes, and this needs to be backed by the literature. It would be worth researching the situation in Zimbabwe in terms of both invasivity and perceived economic value.

The oil from *J. curcas* is an important product from the plant, but it is only one of a number of products. According to Openshaw (2000), too much emphasis seems to have been placed on the use of this oil for motive power. He cites Gubitz (1997), who reported problems with the use of the oil in diesel engines, and concluded that it is very doubtful if the plant oil can compete with diesel fuel at its current price, even if a "carbon tax" is imposed on fossil fuels. This is largely due to the high costs associated with the labour-intensive nature of seed collection. Thus, at present, there are technical constraints and economic factors against using *J. curcas* for motive power.

2.2.8 Industry Potential – Opportunities for Expansion

Possibilities exist for the crop to be planted on marginal or fallow land, and in rural areas as living fences or hedges, within the strictures of environmental guidelines. Its commercial and empowerment potential is thought to be promising; however, its popularity as a durable and sustainable cash crop has yet to be fully quantified.

According to Openshaw (2000), sooner or later, as (fossil fuel) oil reserves diminish and/or a substantial carbon tax is imposed worldwide on fossil fuels, carbon-based liquid fuels from biomass will become universally competitive. Meanwhile, countries have to gain experience in the growing and use of versatile plants such as *J. curcas* so that they will be in a position to capitalize on this knowledge once the oil becomes competitive with diesel. This may be achieved by looking at other uses for the plant and its products.

2.3. CONCLUSION

This review has sought to extract information about *J. curcas* related to hydrology, agronomy, the economics of growing and processing *J. curcas* and uses of the plant. This knowledge comes from practical experience gained through the implementation of an independent research project, as well as from a review of the literature. It attempts to consider the feasibility of establishment from a practical and agricultural perspective. It aims to contribute to the overall investigation around the feasibility, viability and advisability of the wide-scale introduction of *J. curcas* in South Africa.

There is currently a moratorium on the planting of this species outside of recognised research trials in South Africa. When a final decision on whether or not to support this crop is made by the relevant government authorities, the verdict will no doubt hinge on a number of factors. The decision is likely to weigh up the potential negatives, such as invasiveness, likely hydrological impacts, threats to food security, economic sustainability and the feasibility of using alternative non-toxic seed-oil producing species, compared to the potential benefits, such as the creation of business opportunities, use of degraded land, contribution towards a government bio-fuel quota and the quest for renewable energy supplies.

South Africa should review the situation in Zimbabwe (for community benefit and possible problems of invasivity) and should hold a watching brief on large-scale projects which have been initiated in India and in neighbouring southern African countries and Madagascar. Lessons should be learned from the projects before large-scale investments are made.

The following chapter examines the bio-physical requirements of *J. curcas* in more detail.

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CHAPTER 3: BIO-PHYSICAL ASSESSMENT[1]

3.1 INTRODUCTION

One of the goals of this project was to provide information regarding the bio-physical requirements of *Jatropha curcas* and produce maps through an ARC-View GIS-modelling framework. The purpose of this chapter is, therefore, to investigate the bio-physical requirements that influence crop growth, survival and yield and determine the viability of planting *J. curcas* in South Africa. It also briefly examines the areas in South Africa that would benefit most from planting *J. curcas,* based on a poverty analysis.

The economic and poverty-alleviation potentials of the crop are investigated in more detail another unpublished report (Hallowes, 2005). The high variability in economic aspects, such as changing fuel prices and labour, mean that economic aspects need to be constantly re-evaluated; thus, they have not been included in this report.

It is important to note that there is relatively little information available in local and international literature regarding the physical crop-growth requirements and yield of *J. curcas*. The research conducted was based on desktop Internet research and the knowledge review presented in Chapter 2. This data has been supplemented by climatic and water-use data gathered during the course of this project (refer to Chapter 4); however, accurate yield estimates based on climate and other bio-physical aspects cannot be obtained with the current status of yield information available. Yield estimates have been derived using explicit assumptions and generic equations to obtain initial values, which can be refined with further research. Initial results from the modelling exercises should be considered as mapping outcomes of expert opinion and should, thus, be seen as broad-scale yield estimates.

[1] When making reference to this section of the Report, please cite as follows: Hallowes, J. 2007. Bio-physical potential of *Jatropha curcas*. *In:* Holl, M., Gush, M.B., Hallowes J. and Versfeld, D.B. (Eds). 2007. **Jatropha curcas in South Africa: an assessment of its water use and bio-physical potential.** Water Research Commission, Pretoria, RSA, WRC Report 1497/1/07, Chapter 3.

3.2 RESEARCH SUMMARY

3.2.1 Bio-physical Aspects Limiting Crop Growth

The data compiled during the desktop research has revealed some constraints on the crop and although these do not translate directly into yield, they do assist in identifying areas where zones of high, medium and low yields can be expected. They provide a definitive description of areas where the crop cannot be successfully planted.

An initial review of literature for the knowledge review (See Chapter 2) provided some bio-physical data for *J. curcas,* which was supplemented by a more detailed review conducted to produce criteria to model areas suitable for the cultivation of *J. curcas*. Table 3.1 describes the cut-off limits used to describe the initial categories chosen for the weighted yield exercise. These criteria will be used in the initial assessments of the viability of growing *J. curcas* in South Africa.

Table 3.1: Criteria to be used for modelling areas suitable for the cultivation of *J. curcas*

Variables	Unit	Initial Review	Detailed Review	Criteria Used
Altitude	M	0 – 1600	0 – 1700	0 – 1700
Rainfall	Mm			
Unviable		<250	<600	< 300
Marginal		250 – 500		300 – 600
Adequate		500 – 900	300 – 1000	600 – 900
Optimal		900 – 1200		900 – 1200
Temperature	^{o}C			
Unviable			> 38	11 > X > 38
Marginal				11 – 15
Adequate		11 – 20		15 – 20 or 28 – 38
Optimal		20 – 28		20 – 28
Soils				
Unviable		Water logged		
Marginal		Soils prone to water logging		
Adequate		Low nutrient content		

Variables	Unit	Initial Review	Detailed Review	Criteria Used
Optimal		Well drained/good aeration		
Frost	Days frost			
Unviable			Heavy frost, long duration	>120 (> 60)
Unviable			Heavy frost, short duration	90 – 120 (30 – 60)
Marginal			Slight frost	0 – 90 (0 – 30)
Optimal			No frost	0 (0)
Slope	degrees			
Unviable				> 15
Adequate		Slight to medium 3 – 15		10 – 15
Optimal		3 – 10		3 – 10

The following points describe the rationale used in determining appropriate cut-off criteria:

- Altitude was excluded from the analysis as it presented problems in areas experiencing cooler climates than South Africa and is predominantly a temperature-driven phenomenon.
- In the Cape Verde islands, *J. curcas* can grow and produce a crop above the 250 mm of rainfall; however, this seems to be an exception as literature (Heller, 1996; Henning, 2000) cited the high levels of ocean mist could be supplementing the rainfall. In India, there were some conflicting messages with the crop being cited to produce yield with more than 300 mm, while in other areas it was stated that no viable crop was produced with less than 600mm of rainfall. The 300 mm value was finally chosen as the cut-off limit.
- Soils also play a role; however, no additional information was found when compared to the initial review.
- Frost appears to play a role and *J. curcas* has been cited in many references (Heller, 1996; Henning, 1996; Henning, 2004; *Jatropha* world, 2004; Stienswat et al., 1987; Zan, 1985) as only slightly frost tolerant, being able to withstand short duration light frost. The frost classes in the South African Atlas of Agrohydrology and Climatology were used as defined cut off limits for frost tolerance (Schulze et al., 2000).

- The slope classes from the initial review were used as limits for the growth of *J. curcas,* with only extremely steep slopes of more that 15 degrees being used as a cut-off limit.

Overall, a conservative approach was adopted to identify cut-off limits used to define areas that are suitable for growing *J. curcas*. It is important to note that certain of the choices made in this initial assessment are based on the literature review and on the best estimates that can be derived from this literature. The estimates are, thus, not concrete figures and should only be used as a guide as to where the crop may be grown in specific areas in South Africa. These estimates should be improved once more data becomes available on the crop in South Africa.

The parameters described in Table 3.1 can effectively be used to define areas where the planting of *J. curcas* is feasible and the results of this analysis are presented in Section 3.4, with a more comprehensive discussion of the methodology provided in Section 3.3.

3.2.2 Yield Information for *J. curcas*

As previously noted, at present, yield information for *J. curcas* in South Africa is unavailable. At this stage in South Africa, only limited hedgerows exist and there are no orchards or plantations at a stage where nut production is high enough to be commercially viable. Information from experimental plots is not available.

The yield values obtained from certain areas around the world, with associated references, are shown in Table 3.2.

Table 3.2: Seed yield of *J. curcas*: per shrub and hectare (Heller 1996)

Reference	Location	Age (years)	Yield (seed)	
			Shrub (g)	Hectare (kg)
Avila (1949) Cited Heller (1996)	Cape Verde		700-900	n.d.
Heller (1996)	India	3	n.d.	1733
Heller (1996)	Nicaragua		n.d.	5000
Heller (1996)	Mali	2	n.d.	2640
Ishii and Takeuchi (1987)	Thailand		n.d.	2146
Larochas (1948)	Mali		n.d.	8000
Martin and Mayeux (1984)	Madagascar		3000-3500	n.d.
Matsuno et al. (1985)	Paraguay	3	n.d.	100
Matsuno et al. (1985)	Paraguay	4	n.d.	700
Matsuno et al. (1985)	Paraguay	5	n.d.	1000
Matsuno et al. (1985)	Paraguay	6	n.d.	2000
Matsuno et al. (1985)	Paraguay	7	n.d.	3000
Matsuno et al. (1985)	Paraguay	8	n.d.	4000
Matsuno et al. (1985)	Paraguay	9	n.d.	4000
Naigeon (1987)	Cape Verde		n.d.	1750
Silveira (1934)	Cape Verde		n.d.	200-800
Stienswat et al. (1986)	Thailand	1	318	794
Sukarin et al. (1987)	Thailand	1	63.8	n.d.
Zan (1985)	Burkina Faso		955	n.d.
Henning	Mali		n.d.	8000
Behrens (1994)	Nicaragua		n.d.	5000
Jatropha world (website 2004)	India-Irrigated		n.d.	12000
Jatropha world (website 2004)	India		n.d.	3500
Henning	Tanzania		n.d.	5000
Henning	Zambia		n.d.	2000 – 5000
OSCA site measured (2006)	South Africa	3	1283	950

n.d. = not determined

The initial assessments of yield used this information, and various statistical properties, to produce a number of different categories associated with the standard deviation about a mean. These estimates are divided into categories, which were then associated with an index that was produced in the weighted modelling process, described in Section 3.3. The information provided by the weighted modelling process should be considered as a mapping outcome, based on expert opinion with various factors, such as rainfall and temperature, playing a role in estimated crop production.

Added to this, an equation to estimate the likely yield from *J. curcas* was also generated based on other oil producing seed crops and climate information. No formal regression equation could be produced with the available data. There were no suitable physiologically-based plant- growth equations that could assist the process.

Tables 3.3 and 3.4 represent the statistical derivation of the yield associated with the above literature.

Table 3.3: Statistical derivation of yield

Range	**Mean**	**Median**	**Variance**	**Std dev 1**	**Std dev 2**
7300	3348	2820	4838469	2200	4399
Confidence Limits					
	50%	**70%**	**90%**	**95%**	**98%**
	411	632	1003	1196	1419
Upper bound	3759	3980	4351	4544	4767
Lower bound	2936	2716	2344	2152	1929

Table 3.4: Derived yield categories based on confidence limits

Yield definitions						
Yield Category	Excellent	Good	Average	Below average	Poor	Low
Limits	>4800	4800 – 3800	3800 – 2900	2900 – 2100	2100 – 1500	<1500

All values are in kg/ha of crop planted.

The various statistical properties have been used to derive the upper and lower limits of the yield categories. These yield categories were derived from the confidence limits presented in Tables 3.3 and 3.4.

This is assuming that the yield would follow a normal distribution curve. The data itself is skewed towards the lower-middle range yields, the median being less than the mean. This would suggest a slightly skewed distribution. It is assumed that this is due to the lack of data points resulting from a non-representative sample. It is likely that the yields results would follow a normal distribution if more data was available. Again, this analysis can be refined considerably once more information and data from actual trial plots becomes available. Five different categories have been produced from the results, ranging from excellent to very poor. These will be used as the assumed classification categories for the mapping analysis. The methodology is outlined in the following section.

An important aspect to remember, with respect to the data in Tables 3.3 and 3.4, that it is assumed that the crop has been planted for at least 3 years and thus, represents maturing to mature crops. The data are derived from Table 3.2 and will be used in the indexed modelling approach, where the anticipated yields are linked to a weighted index of climate suitability information. The areas with the highest suitability score are, thus, associated with the good/excellent category, while the areas with the lowest suitability score are associated with the low category. While this might not be scientifically ideal, it is expected that the results will be reasonable, as a conservative approach has been adopted.

In the tables, the statistical information derived from the international literature search has been used to derive categories of yield. Table 3.3 represents the ranked selection of yields obtained from literature and provides information on the statistical properties of the data, including the confidence limits. The confidence limits have been used to generate the categories for different yields, which are represented by Table 3.4.

3.3 METHODOLOGY

The crop-yield modelling follows a three-phase approach where modelling complexity increases with each successive phase:

- First step - **"unviable"** values or cut-off limits are used to produce areas where *J. curcas* will not grow under dry land conditions.
- Second step - applies a weighted modelling approach using climate and other data and indexes this information against known yield to produce yield estimates.
- The third step undertakes a more formal equation-driven analysis to produce estimates of potential yield.

The weighted-index approach and the yield-estimate approach are filtered using the **unviable** areas, or cut-off limits, as a mask to ensure that yield estimates are not produced in areas that will not support dry land *J. curcas* plantations.

The mapping section begins with a **viability** analysis, which produces results that can be used with high confidence as these areas represent areas where it is known that *J. curcas* will *not grow* due to temperature, rainfall or other constraints. It is the authors' recommendation that the **viability** analysis results can be used with confidence and that no attempt to plant *J. curcas* in the unviable areas should be entertained.

The second level of analysis also provides an indication of yield results in broad categories. The weighted results are produced by using an assessment of each of the index values' relative importance to the overall crop yield. These estimates and weightings are based on information produced from literature and the researchers' experience.

The main drivers in yield are considered to be rainfall and temperature, with other factors, such as soils, playing a less major role. These results provide the yields in specific categories and are likely to be on the conservative side, with yields in the broad-based category estimates that should be achievable. The results should be viewed with caution and used as broad-based estimates only. Choices about particular sites should be based on site-specific data and analysed thoroughly.

The final level of analysis was to perform a yield estimate using actual crop-yield equations. Unfortunately, the literature produced no existing equations and not enough information was available to perform a regression analysis. It was decided to produce crop-yield equations by manipulating equations already established for other plants in South Africa. These equations were manipulated taking into consideration *J. curcas*' own tolerance limits and comparing these with the other plants' characteristics.

The information produced is relatively precise; however, its accuracy may not be that high. These estimates should, thus, be considered as providing a general estimate of yield in a particular area and not an actual estimate. More site-specific information should be considered with more detailed analysis if *J. curcas* is being considered as a crop in an area. Caution should be exercised in using these estimates and it is recommended that the equations be revised when better information becomes available.

There is, however, a real and immediate requirement to provide some form of mapping to identify those areas where the production of *J. curcas* would be viable. Fortunately, some information can be gleaned from the literature indicating specific criteria for crop planting and providing broad yield estimates. Each phase is explained in detail in the descriptions in the sections 3.3.1 (cut-off limits and criteria), 3.3.2 (weighted-modelling approach) and 3.3.3 (formal crop-modelling equations).

3.3.1 Initial Feasibility 'Unviable' Limits

The first phase of the yield-modelling procedure concentrated on eliminating all areas where *J. curcas* will not grow due to climate and physical constraints. The following elements were chosen as the 'unviable' or cut-off limits:

Table 3.5: 'Unviable' or cut-off limits

Parameter	Criteria
Rainfall	< 300 mm (MAP)
Temperature	< 11°C (MAT) > 38°C (MAT)
Soils	Waterlogged
Frost	> 30 days heavy frost > 60 total frost period duration
Slope	> 30%

MAT (Mean Annual Temperature)

Altitude was presented as a criterion that can be considered when determining areas suitable to grow *J. curcas* (Refer to Table 3.1); however, altitude was not considered in this mapping exercise. This is because altitude is considered a substitute for temperature if temperature values are not available. Temperature values were available in this case and for that reason, temperature, rather than altitude, has been used as a criterion in the mapping exercise. A conservative approach was chosen in setting the cut-off limits as it was considered better not to plant crops in marginal areas.

The map produced in this exercise (Figure 3.2, section 3.4.1) shows those areas considered viable for the planting of *J. curcas*. This map is then used as a mask on the weighted averaging approach and the crop-yield equation estimates, so as to prevent people expecting yields in areas where the crop is most likely to fail.

3.3.2 Crop-Yield Estimates: Weighted Category Approach

The methodology followed to produce the weighted yield values was as follows:

- Information was sourced through a literature survey, Internet search and expert interviews to identify if any yield equations or other information, such as cut-off values, were available for *J. curcas.*
- Information was compiled into a usable format as described earlier in section 3.2.1 and summarised in Tables 3.2, 3.3 and 3.4.
- This analysis was performed in ArcView, using the spatial analysis and the model-builder extension (The model structure is shown in Figure 3.1), using the following steps:
    1. Obtain all the relevant bio-physical information to perform the analysis. The following information was obtained using the South African Atlas of Agrohydrology and Climatology (Schulze et al., 1997). Information used in this analysis was:
        - Rainfall (Mean annual mm)
        - Temperature (Mean annual mm)
        - Soil fertility (Index value ranked 1 – 6 from 84 soil zones)
        - Slope (angle °)
        - Frost duration (days)
        - Days with heavy frost (days)
        - Altitude (m).
    2. Reclassify all the information into specific index categories.
    3. Use the reclassified values to perform analysis with the following weightings provided to specific elements:
        - Rainfall considered the main driver (weighting 40%)
        - Temperature secondary driver (weighting 35%)
        - Soil fertility (slight impact weighting 10%)
        - Combined frost (weighting 5%)
        - Slope (weighting 5%)
        - Altitude (weighting 5%).

- **Note**: Weightings were derived from the literature review describing relative importance of each indicator as well as from discussions with various people as to the main drivers for crop growth.
- Slope in this assessment should, perhaps, be used as a cut-off limit where the maximum slope for cultivation allowed by the DOA should be used.
- Areas regarded as unviable are defined as restricted and weightings do not apply.
- These values were then grouped into 5 categories, which correspond to the information provided in Tables 3.3 and 3.4.

The results of the analysis are provided in Section 3.4. The results look intuitively correct and conservative values have used; however, these results should not be considered as absolute values as this will cause misinterpretations. They should rather be seen as indications of where *J. curcas* can be grown and a broad indication of the type of yield one may expect in a particular area.

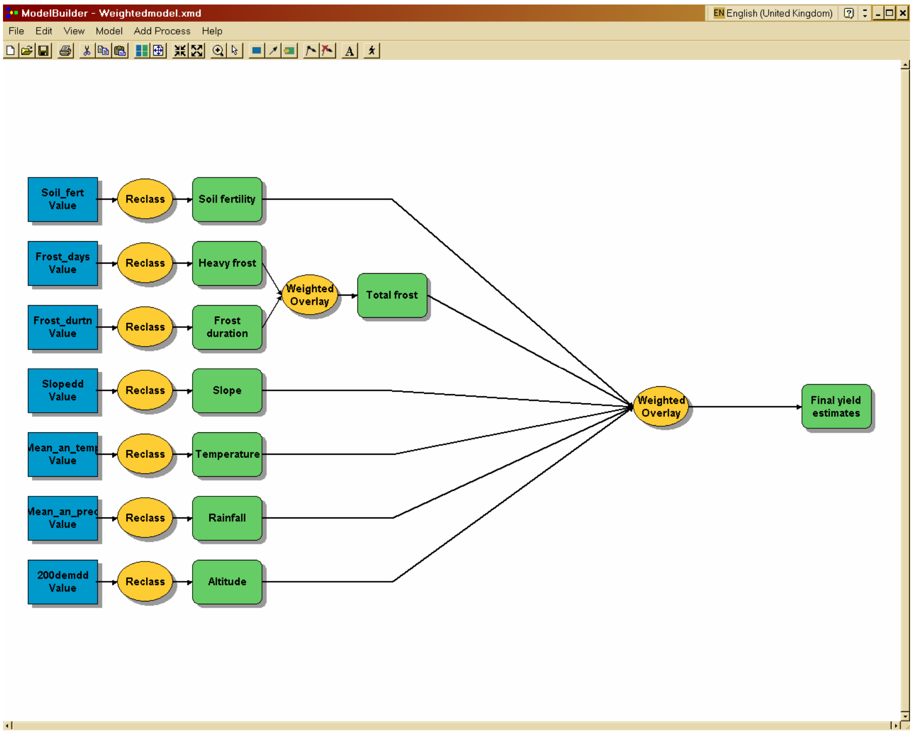

Figure 3.1: Model describing how the *J. curcas* initial yields were derived

3.3.3 Crop-Yield Estimate: Physical and Regression Approach

Better information that will enable researchers to produce estimates of yield either from a regression analysis or from a physical process-based modelling approach is constantly being sought. Until such information is obtained, it is not possible to perform this type of yield analysis. It was, therefore, decided to link *J. curcas* yields to other oil-producing plants and tree crops growing under South African conditions. Equations from banana plantations, eucalyptus plantations and sunflower cropping were combined to give yield equations. These crops where chosen as they encompass the oil-producing properties of *J. curcas* with its tree-like growth.

The equations derived are described as follows, but it is recommended that these be used only as broad-based indicators and not as reliable estimates of the yield of *J. curcas* in specific regions. The equations for these crops are derived from Smith (1996) and are generic equations used for crop yield in South Africa. The main drivers for these equations are temperature (heat units) and precipitation.

The equations were combined and manipulated according to the known sensitivities and tolerances of *J. curcas* from a temperature and rainfall perspective. The final maps of *J. curcas* distribution are intuitively correct and correspond well with the weighted index approach. Whilst the equations will not to give exact estimates in areas, they could be used as a good indication of the general trend in a particular area.

Equation 3.1: *Jatropha curcas*-yield equation produced by combining a Sunflower-yield equation with a tree-growth equation generated from the Smith Climatic Criteria (Smith, 1994) and the South African Atlas of Agrohydrology and Climatology (Schulze, 2000).

Y_{jat} = (P_{jat} * P_{jatu} * D_{jat} / 100)

Y_{jat} = *J. curcas* seed Yield (t / ha/ season)

P_{jat} = Effective rainfall fraction for Mean Annual Precipitation

$= 0.2 + 0.002\ (P_{jatu} – 300)$ for $300 =< P_{jatu} < 600$

$= 0.8 + 0.001\ (P_{jatu} – 600)$ for $600 =< P_{jatu} < 900$

$= 1.1 + 0.0012\ (P_{jatu} – 900)$ for $900 =< P_{jatu} < 1200$

$= 1.45 - 0.0012\ (P_{jatu} – 1200)$ for $1200 =< P_{jatu} < 2000$

$= 0.49 - 0.00025\ (P_{jatu} – 2000)$ for $2000 =< P_{jatu} < 3800$

P_{jatu} = Mean annual precipitation

D_{jat} = Dry matter index for *J. curcas*

$= 0.1 + 0.0003\ (H_{jat} – 1000)$ for $1000 =< H_{jat} < 1600$

$= 0.28 + 0.00013\ (H_{jat} – 1600)$ for $1600 =< H_{jat} < 2200$

$= 0.36 + 0.00009\ (H_{jat} – 2200)$ for $2200 =< H_{jat} < 2800$

$= 0.42 + 0.0001\ (H_{jat} – 2800)$ for $2800 =< H_{jat} < 4800$

H_{jat} = Accumulated heat units (Base 10 ^{o}c) in degree days for the entire year

Further to the above exercise, the research team has set up a generic modelling framework, which will enable the users to estimate the crop yield of *J. curcas* using a set of specific modelling parameters. The ArcView framework is flexible enough to encompass any outcomes produced by the further research.

The cut-off limits for *J. curcas* are used as the temperature drivers to limit the extent of the Equation 3.1 and the precipitation cut-off values were also used to refine the equation. It was also understood from the literature, that the plant undergoes stress above certain temperature and rainfall values and these were also included in the equation format.

The model developed has the ability to take several different equations; however, Equation 3.1 was selected because it provides the closest fit. The generic framework does make it possible to capture regression results and other multiple equation forms. All equations can be readily changed to better describe the yield obtained in specific areas once better yield information and results are obtained. The other equations, which have been created in the generic framework, take the following forms.

Equation 3.2: Multiple regression model framework using rainfall, temperature, heat units

Yjat = A (Pjat) + B (Tjat) + C (Ejat) + D (Hjat) + E

Yjat = *J. curcas* Yield
A,B,C,D,E = Equation constants associated with linear regression
Pjat = Precipitation index for *J. curcas* could be mean or other amount
Tjat = Temperature index for *J. curcas* could be mean or other amount
Ejat = Evaporation index for *J. curcas* could be mean or other amount
Hjat = Heat unit index for *J. curcas* could be mean or other amount

This equation will enable users to exclude specific variables, which have high correlations in the regression matrix, such as temperature and evaporation by simply including a 0 for those elements of the equation.

Equation 3.3: Multiple incremental equation using rainfall and temperature as predictive variables

Yjat = A(Pjat) * B(Xjat) / C
Yjat = *J. curcas* Yield
A,B,C = Equation constants
Pjat = Precipitation index for *J. curcas* could be mean or other amount
Xjat = Temperature, heat, evaporation or other index to be multiplied by rainfall to produce *J. curcas* yield estimates.

This equation can also be manipulated and the criteria changed more generically. An ArcView project has been created to produce these equations and can readily be manipulated to create desired equations when better information becomes available. This equation takes on a form similar to that described in Equation 3.1 but is the more generic variety.

The results of yield equation 3.1 are shown in Figure 3.4. The yields vary from 0 to as high as 9 tonnes in areas along the KwaZulu-Natal coast and areas on the eastern escarpment. The majority of the area, however, experiences yields in the region of 1 – 3 tonnes per hectare with high yields being the exception rather than the rule. The crop cannot be grown in many areas of the country due to temperature (frost) and rainfall cut-offs.

3.4 INITIAL RESULTS

This section of the report focuses on the results produced by the crop-yield analysis and discusses results produced by the poverty-mapping analysis.

3.4.1 The Crop-Yield Analysis Results

Figure 3.2 illustrates the outcome of the research conducted in the first phase, or the 'unviable' approach, described in Section 3.3.

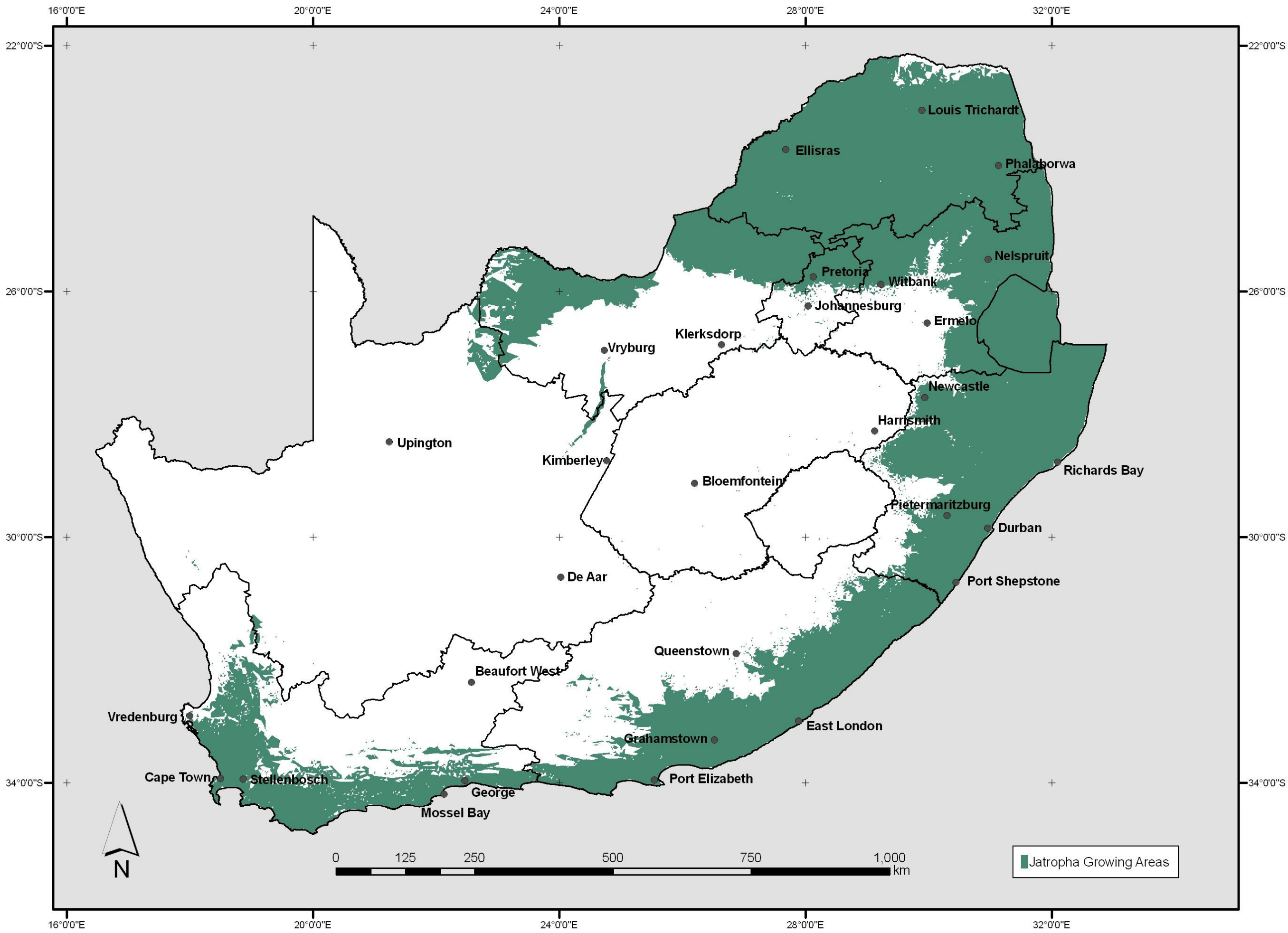

Figure 3.2: *Jatropha curcas*: areas where it can be successfully planted in South Africa

The cut-off values used to produce the areas where it is possible to grow *J. curcas* are provided in Table 3.5. It can be seen that substantial areas in the centre of the country will not support *J. curcas* because of the low rainfall and the number of frost days. Other areas on the eastern and southern areas of the country will allow for the growth of J. *curcas* based on the climatic criteria presented in Table 3.5.

Table 3.6: Comparison of initial yield categories mapped to those expected to be derived in practice.

Mapping category	Category described in Table 3.4	Corresponding yields
Excellent	Excellent	>4800
Good	Good	4800 - 3800
Average	Average	3800 - 2900
Below average	Below average	2900 - 2100
Low	Low	2100 - 1500
Marginal	Marginal	>1500

The results produced by the weighted analysis approach are shown in Figure 3.3, where the categories and associated yields are indexed.

It can be seen that yields are higher in the coastal areas where temperature and rainfall are higher, with areas along the eastern escarpment also having good yields. High yields for dry land *J. curcas* are possible in areas along the KwaZulu-Natal and Eastern Cape coasts, and the eastern parts of the Mpumalanga escarpment moving to the adjacent Lowveld areas. The vast majority of the country is **not** suitable for growing *J. curcas*. Low yields (1.5 – 2 tonnes per hectare) are also likely in many areas. Large parts of the North West Province are unsuitable for plant growth due to frost and very low yields are achieved in the dry interior, typical of much of Mpumalanga and Limpopo.

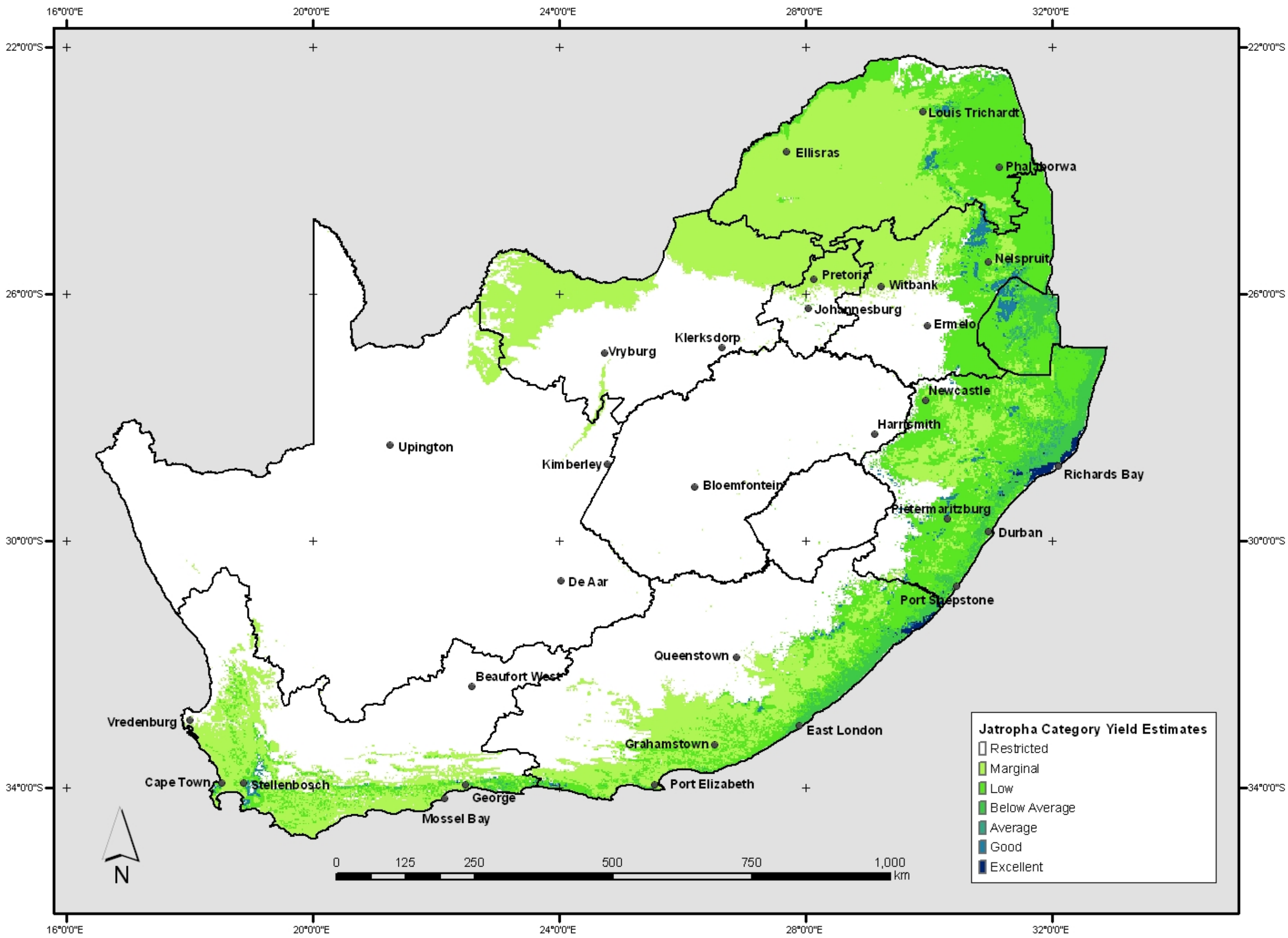

Figure 3.3: Anticipated yields produced using the weighted index approach

In Figure 3.4, the yield estimates are shown as produced by the yield equation, which has resulted from the amalgamation of two equations produced by Smith (1994) and Schulze (2000).

As one can see, the yields generated by the crop-yield equation are similar to those produced by the rough results in the weighted-yield analysis. The highest potential yields are again obtained along the coastal areas along the KwaZulu-Natal and Eastern Cape coast and inland on the eastern slopes of the escarpment (Drakensberg mountains) in Mpumalanga, where yields of over 8 t of seed/ha are possible in some areas. Many other areas may produce yields of over 3 t of seed/ha. The inland and central interior is not suitable due to low rainfall and frost. The map also shows that areas in the northern parts of the country and along the south-eastern seaboard probably will produce low yields of less than 2 t of seed/ha.

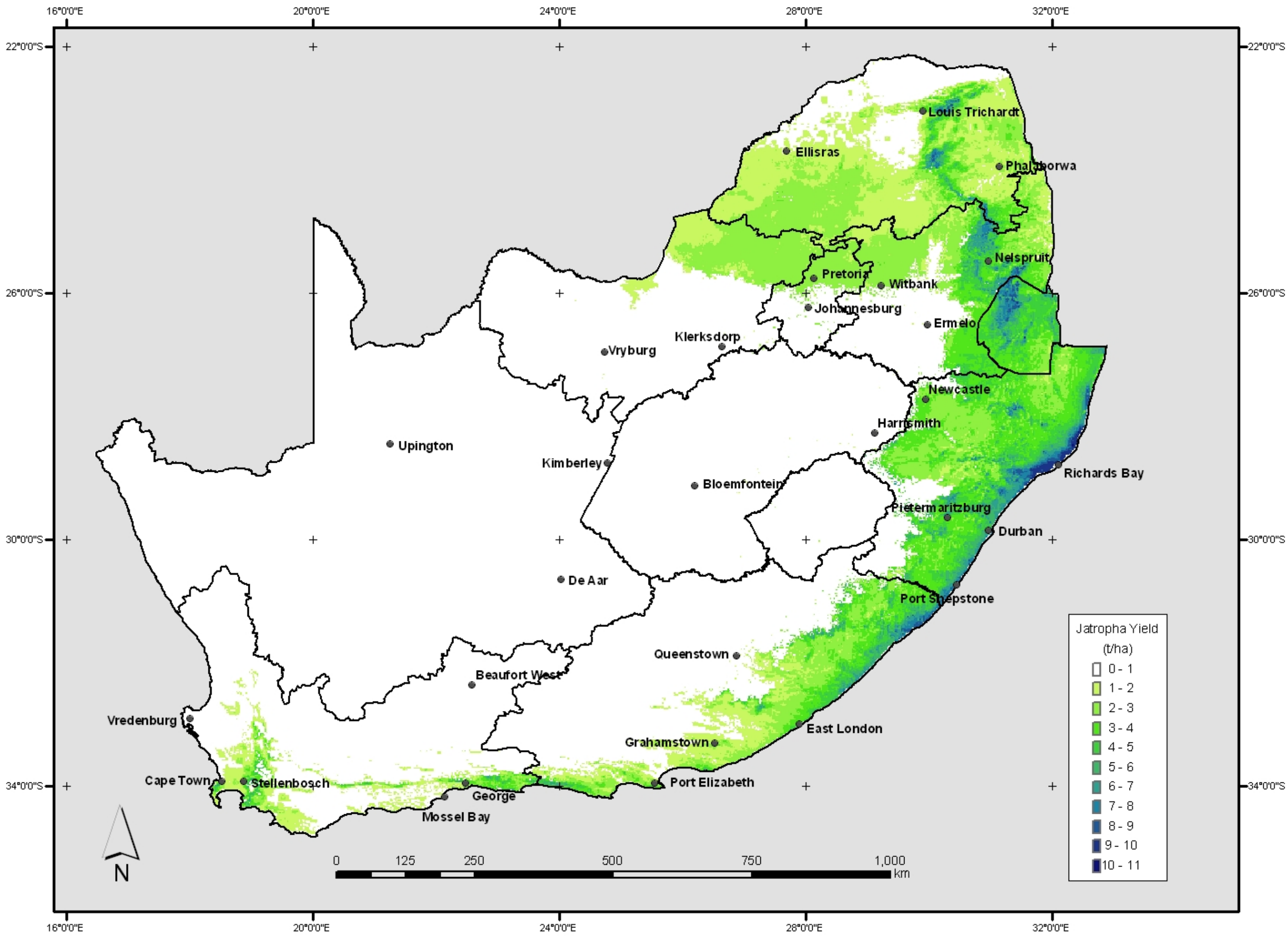

Figure 3.4: Final yield-analysis results using heat unit and rainfall-driven crop-yield equation

Figure 3.4 has slightly higher yields than predicted by the rough-weighted approach and is likely to give a better local estimate of yield because it shows more detail.

3.4.2 Results of Poverty Analysis

The results of the poverty analysis are presented in this section. Figure 3.5 is a result of a multi-criteria analysis using various indicator indices of poverty, hazard vulnerability and situational vulnerability. The poverty priority index presented in Figure 3.5 is a result of taking the weighted averaging approach, whereby each of the different indicator indices is given different weightings in a method known as Multi Criteria Decision Analysis (MCDA). This method allows for the comparison and scoring of both quantitative and qualitative values.

Figure 3.5 shows that the communities in the eastern areas of the country, particularly those areas corresponding to the old TBVC states, to have the highest poverty indices. These are the most critically in need of help. The majority of these areas also correspond to areas where there is a high potential to plant *J. curcas*; thus, the potential for *J. curcas* as a poverty-alleviation tool is highlighted.

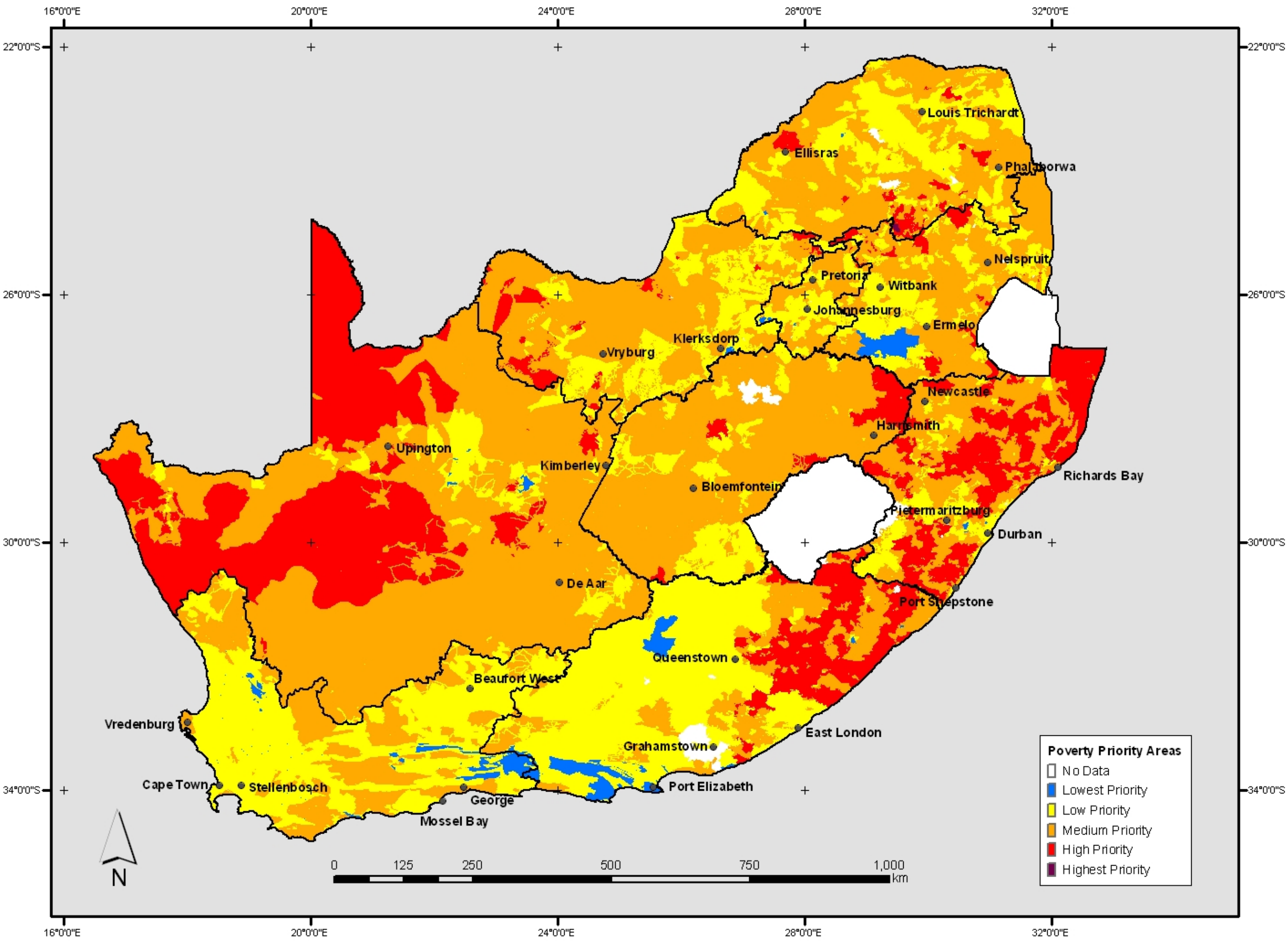

Figure 3.5: Poverty priority index

3.5 CONCLUSIONS

This chapter of the report has focussed on the potential of *J. curcas* to grow and produce meaningful yields and has briefly highlighted how areas of growth potential overlap with poverty-stricken areas in South Africa. There is evidently wide-ranging and often conflicting evidence in the literature, which suggests that currently there is not a good understanding of *J. curcas*. It is a relatively new crop and full commercialisation could take decades.

It was found that large parts of central South Africa are unsuitable for *J. curcas* due to temperature and rainfall constraints.

The highest potential yields were produced along the eastern escarpment and north-eastern coastal areas with yields reaching as high as 9 tonnes of seed per hectare. Other areas may produce lower potential yields with an average in the 2.9 to 3.8 tonne range.

Large parts of the suitable areas of the country can be expected to produce **less than 2.9 tonnes of seed per hectare**. While all efforts were made to make the maps as realistic as possible, they should be used with caution as they are based as much on expert opinion as on hard empirical evidence. The modelling framework has been structured in such a way that results can be recalculated as and when better data becomes available.

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CHAPTER 4: WATER-USE ASSESSMENT[1]

4.1 INTRODUCTION

A key goal of this project was to develop predictive capability with respect to the impacts of large-scale planting of *Jatropha curcas* on water resources in South Africa, through a process-based research and modelling study. To the authors' best knowledge, there has been no previous assessment of the water use of *J. curcas* anywhere in the world.

This chapter covers the methodology applied in determining water use in this component of the project, and presents the water-use data collected from the two monitoring sites over an 18-month monitoring period. Transpiration rates are estimated. The chapter also discusses the parameterisation and application of the FAO56 model to simulate the observed transpiration data, and concludes with the implications of these findings.

4.2 METHODOLOGY

The methodology for this component of the project revolved primarily around conducting hydrological (water-use) studies of *J. curcas* using appropriate techniques (transpiration, soil moisture and climate measurements). The individual components of this methodology were:

1. To conduct a comprehensive knowledge review on all aspects of *J. curcas* relevant to its potential wide-scale propagation in South Africa, with particular emphasis on hydrological aspects (see Chapter 2).

[1] When making reference to this section of the Report, please cite as follows: Gush, M.B. and Moodley, M. 2007. Water use assessment of *Jatropha curcas*. *In:* Holl, M., Gush, M.B., Hallowes, J. and Versfeld, D.B. (Eds). 2007. **Jatropha curcas in South Africa: an assessment of its water use and bio-physical potential.** Water Research Commission, Pretoria, RSA, WRC Report 1497/1/07, Chapter 4.

2. To identify appropriate test sites (flat, non-riparian, stone-free site with deep soils) representing optimal growth conditions for *J. curcas* where field measurements could be made.
3. To carry out continual measurements of *J. curcas* transpiration using appropriate equipment (Heat Pulse Velocity (HPV) technique) on selected trees, as well as the collection of additional physiological data required for final water-use calculations.
4. To conduct continuous measurements of soil moisture, using appropriate equipment (e.g. tensiometers for matric potential / CS616 probes for water content).
5. To collect soil samples and analyse them so that water-retention curves and saturated hydraulic-conductivity values for the site could be derived.
6. To continuously monitor all relevant climatic variables required for modelling, using an automatic weather station with cell-phone data transfer capability.
7. To simulate the evapotranspiration trends of *J. curcas* using appropriate models, and to verify results against measured data and potentially extrapolate these to a larger scale.

4.2.1 Site Selection

Jatropha curcas is known to produce higher yields under sub-tropical conditions, which makes it suitable for cultivation along the KwaZulu-Natal (KZN) coastal belt of South Africa. Consequently, monitoring sites were sought in the Zululand region of the KZN North Coast. The objective was to find suitable sites to conduct the proposed transpiration, soil moisture and climatic measurements. A number of potential sites were visited, but based on the selection criteria discussed below, the following two sites were selected:

1. 4-year-old trees at the Owen Sithole College of Agriculture near Empangeni.
2. 12-year-old trees at a homestead in the Makhathini flats, northern KZN.

4.2.1.1 Empangeni (OSCA) Site

The Owen Sithole College of Agriculture (OSCA) is located approximately 20 kms outside Empangeni, on the KZN north coast. The identified monitoring site (Grid reference S 28º 38' 36.7"; E 31º 55' 36" and Altitude 44.2 masl) consisted of a *J. curcas* trial at OSCA that had been planted in January 2002, using seed (of Zimbabwean origin) from the Makhathini Research Station. It is a valley-bottom site, close to a stream but non-riparian, being approximately 30 m from the stream channel. The site was maintained under controlled conditions (weed control, but no irrigation), and consisted of 24 *J. curcas* trees planted in two blocks of 6X2 trees. Spacing was 4.5 m (between rows) by 3.0 m (within rows). The trees were 2.5 m tall, had stem diameters of approximately 10 cm at a stem height of 15 cm, and a bark thickness of 7 mm when monitoring commenced on 27 January 2005.

The trees at this site were appropriate for HPV measurements as a number of the trees had suitable lengths of single stem, which is desirable for the HPV technique (Figure 3.1). A further incentive for using this site was the presence of sufficient open area alongside the *J. curcas* trees, where a control (grassland) site for soil moisture measurements could be established. The study could, therefore, assess the differences in water uptake / infiltration patterns between the different vegetation types.

Figure 4.1: 4-year-old *J. curcas* trees selected for monitoring at Owen Sithole College of Agriculture, Empangeni. Note the leafless state of the trees due to the season (winter). Date of photography: July 2004.

4.2.1.2 Makhathini Site

The second site selected for monitoring consisted of mature *J. curcas* trees situated along the fence-line of a rural homestead in the Makhathini flats region of Northern Zululand (Figure 4.2). The site (Grid reference S 27º 24' 06.9"; E 32º 11' 48.6" and Altitude 75.2 masl) was non-riparian and was situated approximately 20 kms east of Jozini, close to the Makhathini Research Station. Based on anecdotal evidence from local inhabitants, the trees were estimated to be approximately 12-years old (planted January 1994).

Figure 4.2: A fence-line of 12-year-old *J. curcas* trees at a homestead on the Makhathini flats near Jozini, northern KwaZulu-Natal. Date of photography was July 2004.

The trees were the largest yet seen, and some of them had an adequate length of single-stem to be suitable for HPV measurements. Other issues considered were the security of the site, co-operation of the landowner, and the possibility of conducting additional analyses of tree physical properties after monitoring. Regarding security, the advantage of the site was that the instrumentation could be installed within the confines of the homestead, close to the house. The standard precaution of enclosing the most valuable instrumentation (loggers and multiplexers) in a metal strong-box was employed.

This site presented an opportunity to obtain water-use measurements from trees that were significantly different to those at OSCA (Empangeni). They represented mature trees in a more tropical environment, as opposed to very young trees in a sub-tropical environment at OSCA, and consequently provided both a useful contrast and an additional set of information against which to compare the output of simulation models.

4.2.2 Heat Pulse Velocity (HPV) Theory

The HPV technique is an appropriate technique for the measurement of sap-flow/transpiration rates in trees, and consequently facilitates the quantification of water use in species to which it is applied. In single-species tree plantations, such measurements are relatively easily scaled up to provide an estimate of sap flow over a larger area (e.g. a plantation). The heat ratio method (HRM) of operation applied in the HPV technique allows the measurement of very slow sap-flow rates, which is beneficial in drier environments such as those generally experienced in South Africa. The Heat Ratio Method is fully described in Burgess *et al.*, 2001, and the description below is largely drawn from that reference.

The Heat Ratio Method measures the ratio of the increase in temperature, following the release of a pulse of heat, at points equidistant below and above a heater probe. In order to achieve this, three parallel holes are accurately drilled (with the help of a drill guide strapped to the tree) into the sapwood (xylem) portion of tree trunks. The upper and lower holes are both situated 5 mm from the central hole (above and below, respectively). Copper-constantan thermocouples (sap-flux sensors), wired to a multiplexer or logger, are inserted into the upper and lower holes to a specific depth below the cambium (below-bark insertion depth). A heater probe, wired to a relay control module, is inserted into the central hole. The sap-flux sensors are locally constructed from Type T Copper-Constantine thermocouples embedded in 2 mm outside-diameter PTFE tubing, while the 60 mm long line-heaters are made from 1.8 mm outside-diameter stainless steel tubing, with a constantan filament.

At a pre-determined time interval (usually hourly), the temperatures in the upper and lower thermocouples are measured and the ratio (upper over lower) is logged. Directly thereafter, the central (heater) probe releases a short (0.5 second) pulse of heat, which diffuses through the adjacent wood and is taken up by the sap moving upwards through the xylem of the tree. As the heat pulse is carried up the tree by the sap, the upper thermocouple begins to warm. Logging of the changing heat ratio commences 60 seconds after the initiation of the heat pulse and is measured continuously (approximately every second, depending on the processing speed of the logger) until 100 seconds after the heat pulse. The average of these ratios is calculated and utilised in subsequent formulae to derive the sap velocity. These formulae are described in Burgess *et al.*, 2001. Data loggers are programmed to initiate the heat pulses and record the heat-ratio changes in each of the thermocouple pairs. Further measurements of sapwood area, moisture content and density, as well as the width of wounded (non-functional) xylem around the thermocouples, are used to convert sap velocity to a total sap-flow rate for the entire sample tree. These measurements are usually taken at the termination of the experiment due to the destructive sampling required to obtain them.

The conversion of sap velocity to sap flow is readily derived as the product of sap velocity and cross-sectional area of conducting sapwood. The gross wood cross-sectional area is calculated from its under-bark radius. Heartwood is discounted by staining the sapwood or by observing the dark colour often associated with heartwood. Where sap velocity is estimated at several radial depths (probe insertion depths), the total sapwood area is divided into concentric annuli, delimited by midpoints between measurement depths. In this way, point estimates of sap velocity are weighted according to the amount of conducting sapwood in the annulus they sample. The number of probe sets (2 thermocouples and one heater) utilised per tree is dependent on the diameter of the tree, and ranges from 4 to 12. The thermocouples are typically inserted to four different depths, since flow rates differ relative to sapwood depth (Figure 4.3). Sap-flow rates are usually fastest in the younger xylem near the cambium and slower in the older, deeper xylem.

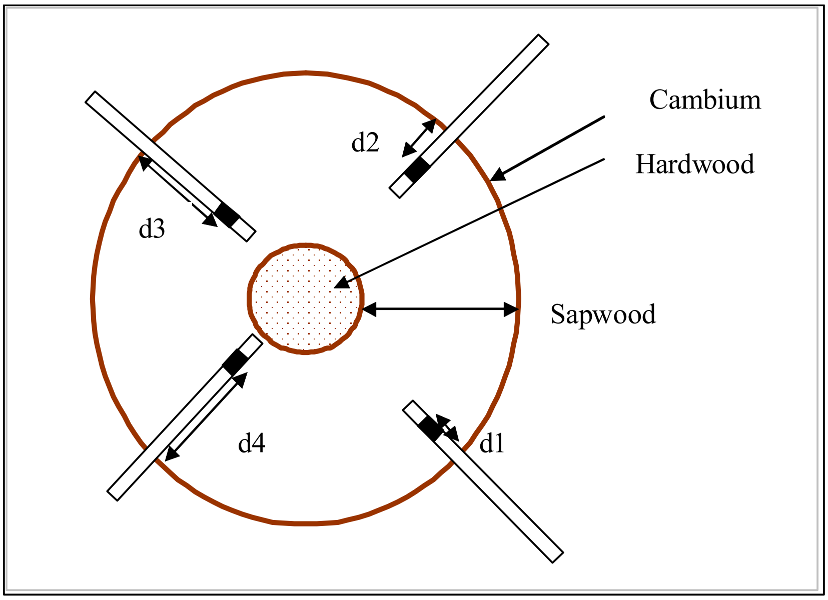


Figure 4.3: Illustration of different probe set insertion depths applied in the HPV technique (heat-ratio method).

Occasionally it is necessary to reposition sapflow-monitoring probes to compensate for increased diameter growth in the trees. This is necessary due to the fact that the insertion depth associated with a particular probe set significantly influences the final sap-flow calculations using this technique. These depths are measured extremely accurately at the time of installation; however while the sample tree stem diameter expands with growth, the probes tend to remain at their original position (relative to the centre of the stem), so the insertion depths gradually become deeper over time. It is, therefore, necessary to periodically remove, re-measure and re-insert the probes to the desired depths. This is especially important in a fast-growing species such as *J. curcas*.

As a result of occasional incidents of logger downtime, it is sometimes necessary to patch periods of missing data from time to time. The patching technique that was used in this particular study essentially consisted of simple linear-regression analysis, whereby simultaneous periods of good data were plotted against each other, regression equations representing their relationship were established and those equations were used to in-fill periods of missing data where necessary. Good relationships were found to exist between HPV data from different probe sets, and even from different sites

(OSCA and Makhathini). Tree size, mean daily vapour-pressure deficit (VPD), and the temporal and spatial patterns of soil-water deficits (rainfall-related) accounted for most of the variation in observed sap-flow rates.

4.2.3 Soil-moisture monitoring strategy

Soil-water retention is an important parameter that regulates the storage and movement of water within the soil and ultimately, plant growth. Whereas water content provides an indicator of the actual volume of water stored in the soil, water potential provides a measure of the tension or matric potential, which relates the pressure with which water is held in the soil against atmospheric pressure. To test the hypothesis that *J. curcas* trees cause significant changes in soil-water dynamics, continuous measurements of soil-water content were carried out at two locations at the OSCA site. These consisted of a tree site (with the sensors directly beneath the tree, in and below the root zone) and a grassland site (with the sensors at corresponding depths beneath the soil surface) as a control for comparative purposes. The grass site consisted of mown Kikuyu. Watermark sensors for matric potential and CS616 probes for water-content measurements, were utilised.

The CS616 system of measurement relies on the principle that the dielectric permittivity of the soil is sensitive to soil-water content. The CS616 probe itself has two parallel rods that are inserted into the soil at the appropriate depths and connected to a CR10X logger. An electromagnetic pulse is propagated along the probe rods at a velocity that is dependent on the dielectric permittivity of the soil. The signal travels the full length of the probe rods and is reflected from the rod ends travelling back to the probe head. The higher the water content, the slower the propagation velocity because of the additional time needed for polarisation of the water molecules. The travel time of the applied signal along twice the rod length is measured (frequency or period) and through a default calibration relationship related to water content. CS616 probe insertion depths were 15, 40 and 120 cm below soil surface.

The WaterMark sensors contain two concentric electrodes embedded in a reference matrix with a known pore-size distribution. These sensors measure the electrical resistance of the soil, which is dependent upon water content and temperature. The water potential is obtained through a calibration relationship supplied by the manufacturer. Since this relationship is temperature dependent, a measure of this parameter is also made through a thermocouple junction (copper constantan) and the output is used for correction of the water potential data. The advantage of this system is that once installed, it requires very little maintenance apart from regular checks of battery voltage. The WaterMark sensors were installed to depths of 15, 40, 80 and 120 cm below the soil surface, using slurries of mud to obtain a proper seal between the sensors and the soil.

Undisturbed soil cores, retained within a 50 mm X 75 mm stainless steel sleeve, were collected in triplicate from the OSCA site at soil depths of 0, 0.40 m and 1.0 m, and were used to measure water-retention properties. Each core was fully saturated and then transferred to a tension table where a step-wise decrease in matric potential was applied. The mass of the core was measured at each stage and from this information the mass water content corresponding to the matric potential was obtained. The bulk density (ρ_b) and the mass water content of the sample (θ_m) at each matric potential were used to calculate the volumetric water content (θ_v) using the relationship $\theta_v = \theta_m \times \rho_b/\rho_w$ (where ρ_w = density of water). The measurement of the wilting point, which corresponds to the water content of the soil at a matric potential of -1500 kPa, was undertaken on a subsample that was crushed to pass a 2 mm sieve.

Readily available water (RAW) and plant available water (PAW) were calculated as the amount of water retained between matric potentials of -10 and -100 kPa and -10 and -1500 kPa respectively (Smith *et al.,* 1995). The water-retention data was fitted by the van Genuchten (1980) (VG) model, $\theta = \theta_r + (\theta_s - \theta_r) [1 + (\alpha.h)^n]^{-m}$, where θ is the actual volumetric water content, θ_s is the saturated water content, θ_r is the residual water content usually taken as the water content at the wilting point (-1500 kPa), h is the water potential, α is a curve fitting parameter, the inverse of which relates to the air entry potential, and m and n are dimensionless parameters related to the pore size distribution (Van den Bergh *et al.,* 1997).

The extraction of soil cores and installation of soil-moisture monitoring instrumentation provided opportunity for observations on the root distribution of *J. curcas*. Lateral roots of varying sizes were observed in the soil profile down to a depth of approximately 50 cm. The literature suggests the presence of a strong tap-root but it was not possible to observe this on the basis of these few excavations.

4.2.4 Instrumentation

Continuous measurements of sap flow / transpiration, climatic variables and soil-water dynamics were carried out at the OSCA site. Measurements were taken on an hourly basis for a 17-month period from DOY 33 (2005) until DOY 178 (2006) using a CR10X logger and two AM16/32 multiplexers (Campbell Scientific, Logan, UT). Only sap flow and selected climatic variables (temperature, relative humidity and solar radiation) were measured at the Makhathini site (no soil-water measurements) for a 16-month period from DOY 64 (2005) until DOY 182 (2006).

The instrumentation was wired up to the loggers and mutiplexers prior to installation to test that everything was working, and to configure the programs required by the loggers to monitor the sensors and output the data. Additional instrumentation and software required for installing and operating the system (e.g. Campbell Scientific keypads, Loggernet software, tools etc.) were already in the possession of the CSIR. The instruments installed at the Owen Sithole College of Agriculture (OSCA) and Makhathini sites demonstrated good reliability and yielded data of a consistently high quality. Crucial to this reliability was the maintenance of consistent power to the systems through the batteries. Initially, a solar panel was used to charge the battery that powers the system; however, after the loss of the solar panel due to theft, the battery alone was utilised. It provided sufficient power to run the system continually for approximately three months, after which the battery was swapped out with a fully charged unit. Based on the trend of voltage decline observed in the data, it was possible to extrapolate and approximate when the battery strength was likely to reach critically low levels. Assistants at the sites, or CSIR technicians, could then be alerted in good time to ensure timeous battery replacement, which minimised power-related data loss.

4.3 RESULTS

4.3.1 Climate Data

4.3.1.1 Empangeni Site

The automatic weather station (AWS) at OSCA recorded rainfall, temperature, relative humidity, solar radiation, wind speed and wind direction. These variables were continuously measured at 10-second intervals, and averaged or totalled at hourly intervals. The data were aggregated to daily, monthly and annual values. Data from these sensors (for the entire monitoring period) is presented below. Daily fluctuations in maximum and minimum temperatures, with daily rainfall totals, are illustrated in Figure 4.4.

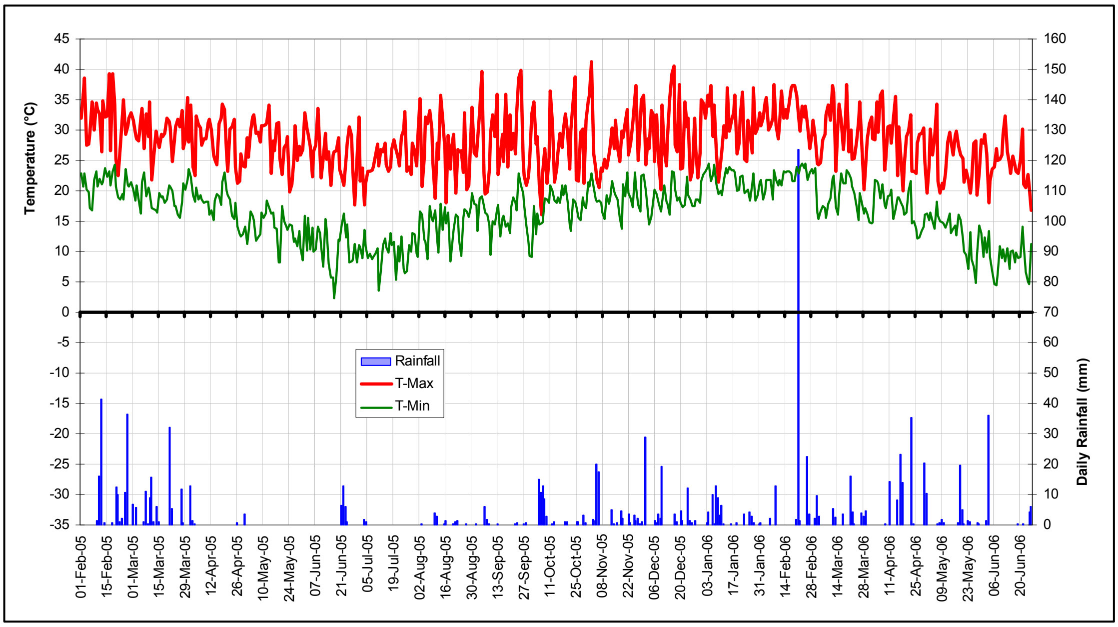


Figure 4.4: Daily Maximum and Minimum Temperatures (°C), together with daily rainfall totals (mm) from the site at OSCA, Empangeni.

Seasonal changes in temperature and rainfall are evident in Figure 4.4. Significant declines in temperature take place from April onwards, and a noticeable divergence between maximum and minimum temperatures occurs. The lowest recorded temperature for the entire monitoring period was 2.32°C on 17 June 2005, while the highest recorded temperature was 41.25°C on 2 November 2005. Mean annual temperature was 22.5°C, and average daily solar radiation was 15.16 $MJ.m^{-2}.day^{-1}$.

Wind speeds were low to average, with the daily average only exceeding 2 $m.s^{-1}$ in September and October. Rainfall for the entire 17-month monitoring period totalled 1016.8 mm, but for the same calendar year used to calculate transpiration totals (5 March 2005 to 4 March 2006), rainfall amounted to just 618 mm. This is significantly below the long-term mean of 1016 mm (Lynch and Schulze, 2006) and these dry conditions could be a significant consideration in the interpretation of the results of this study. Monthly values of all the climatic variables measured using the automatic weather station at OSCA are shown in Table 4.1 and Figure 4.5. Missing data was in-filled with daily data obtained from the website of the South African Sugarcane Research Institute (SASRI - “Empangeni” station).

Table 4.1: Monthly values of climatic variables recorded between February 2005 and June 2006 at OSCA, Empangeni.

Month	Total Rainfall (mm)	Ave. Max. Temp. (°C)	Ave. Min. Temp. (°C)	Ave. Max. RH (%)	Ave. Min. RH (%)	Ave. Wind. Speed ($m.s^{-1}$)	Ave. Wind. Direction	Ave. Solar Radiation ($MJ.m^{-2}.day^{-1}$)
Feb-05	133.8	31.7	21.1	93.6%	52.5%	1.48	163.1	20.72
Mar-05	108.4	29.7	19.1	97.7%	57.4%	1.16	106.2	17.32
Apr-05	19.1	28.0	17.7	96.5%	55.4%	1.15	178.4	13.78
May-05	0.1	28.0	13.7	97.6%	46.2%	1.11	163.5	12.41
Jun-05	26.0	26.4	10.8	97.4%	41.9%	1.10	162.6	11.18
Jul-05	3.0	25.2	9.8	97.9%	44.6%	1.16	170.6	12.03
Aug-05	11.9	27.1	14.3	93.4%	43.4%	1.98	166.8	12.21
Sep-05	11.4	28.1	16.0	92.4%	44.6%	2.08	185.5	14.51
Oct-05	60.1	27.9	17.3	93.5%	51.9%	2.11	177.2	15.89
Nov-05	65.5	28.9	19.2	92.2%	53.1%	1.84	183.1	18.68
Dec-05	82.8	29.0	18.7	93.2%	53.3%	1.57	203.2	19.35
Jan-06	59.6	30.7	21.7	94.4%	60.0%	1.12	155.8	15.96
Feb-06	168.1	32.7	22.3	93.9%	54.6%	1.23	157.6	18.75
Mar-06	58.8	29.4	18.9	95.3%	57.1%	1.11	179.2	15.85
Apr-06	116.4	28.5	17.3	95.3%	54.5%	0.93	165.7	11.89
May-06	43.3	25.2	13.1	96.2%	50.9%	0.88	187.1	8.83
Jun-06	48.5	24.4	8.9	97.6%	47.9%	0.85	176.6	8.47

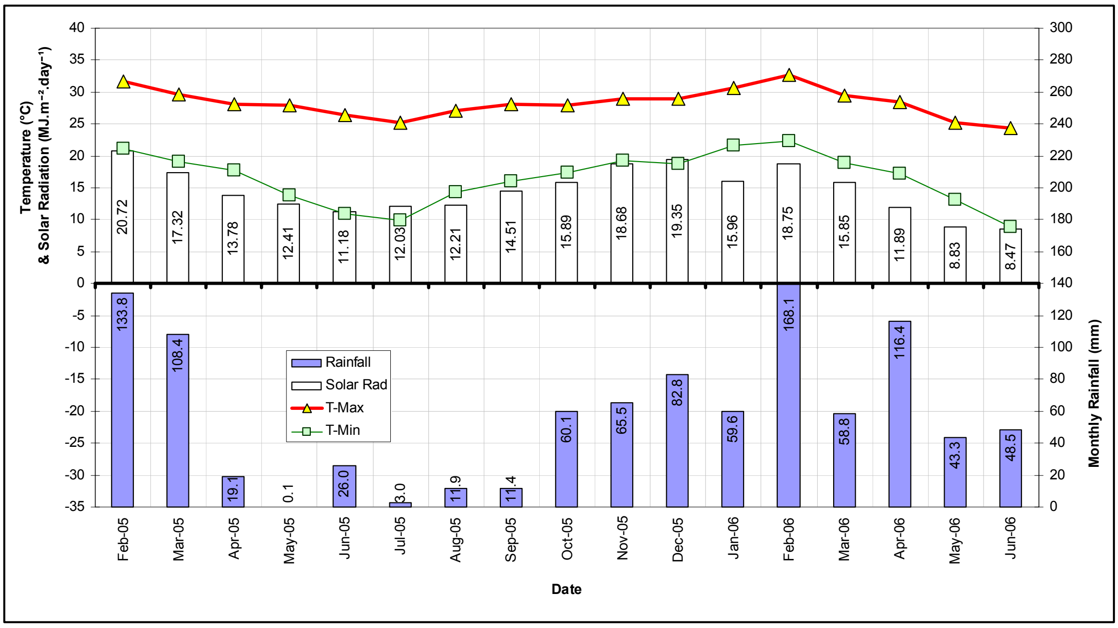


Figure 4.5: Monthly values of climatic variables recorded between February 2005 and June 2006 at OSCA, Empangeni.

4.3.1.2 Makhathini Site

Hourly fluctuations in temperature, relative humidity and solar radiation were recorded at the Makhathini site. These data were supplemented with additional daily data, obtained from the website of the South African Sugarcane Research Institute (SASRI - "Makhathini" station). Monthly values appear in Table 4.2 / Figure 4.6.

Table 4.2: Monthly values of climatic variables recorded between March 2005 and June 2006 on the Makhathini flats, near Jozini.

Month	Total Rainfall (mm)	Ave. Max. Temp. (°C)	Ave. Min. Temp. (°C)	Ave. Max. RH (%)	Ave. Min. RH (%)	Ave. Wind. Speed ($m.s^{-1}$)	Ave. Solar Radiation ($MJ.m^{-2}.day^{-1}$)
Mar-05	38.5	29.5	20.0	95.7%	54.2%	1.17	18.41
Apr-05	23.6	28.2	18.9	94.6%	52.6%	1.17	14.31
May-05	3.7	28.1	14.6	96.4%	42.9%	1.14	14.01
Jun-05	5.6	27.2	11.7	95.3%	38.1%	1.10	11.92
Jul-05	0.8	26.0	10.6	96.1%	39.6%	1.03	13.45
Aug-05	15.8	27.9	15.8	92.1%	40.5%	1.25	13.71
Sep-05	6.4	30.4	16.4	90.0%	35.8%	1.48	17.38
Oct-05	16.7	29.9	18.4	88.3%	42.7%	1.58	16.27
Nov-05	118.1	29.7	19.9	90.2%	49.0%	1.57	18.52
Dec-05	54.2	30.3	20.2	88.6%	46.1%	1.51	18.22
Jan-06	87.1	31.1	22.4	92.3%	56.2%	1.26	17.87
Feb-06	68.8	32.7	23.1	92.5%	49.5%	1.14	19.87
Mar-06	27.8	31.0	19.5	85.0%	46.0%	1.30	17.03
Apr-06	26.3	29.8	17.7	85.4%	45.4%	1.04	15.31
May-06	0.5	27.3	13.9	88.4%	35.6%	1.03	11.55
Jun-06	2.6	26.2	11.2	90.9%	37.8%	0.88	9.99

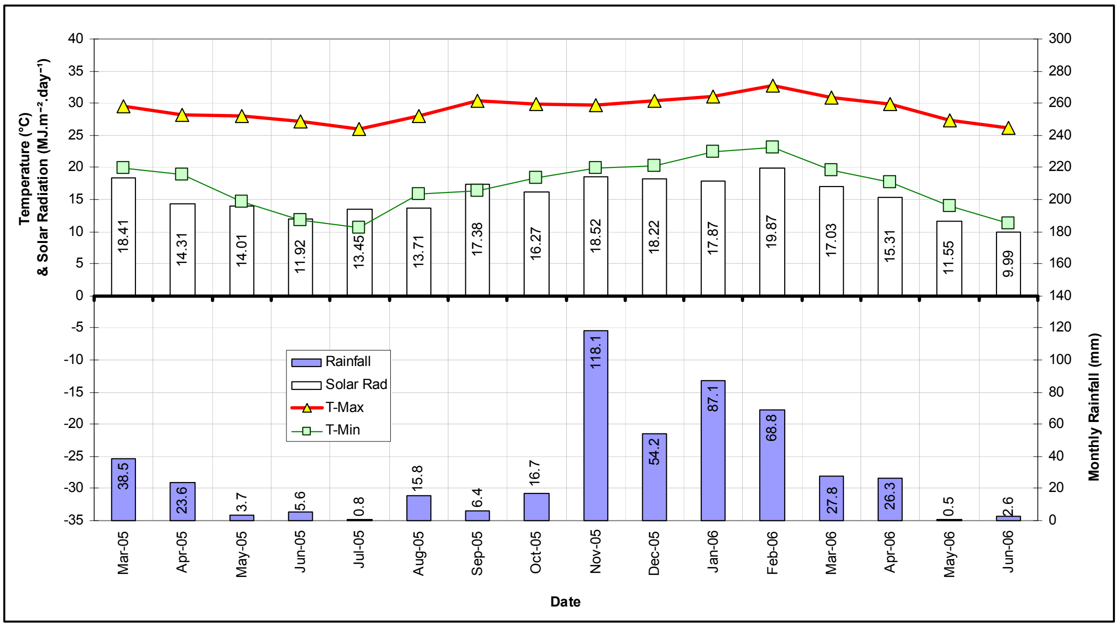


Figure 4.6: Monthly values of climatic variables recorded between March 2005 and June 2006 at the Makhathini site.

The lowest recorded temperature for the entire monitoring period at the Makhathini site was 5.3°C on 17 June 2005. Interestingly, the lowest recorded temperature at OSCA was recorded on the same day, at 2.3°C. The highest recorded temperature for Makhathini was 41.0°C on 2 October 2005. Mean annual temperature was 23.4°C, which was 0.9°C warmer than the OSCA site. Average daily solar radiation was 16.13 $MJ.m^{-2}.day^{-1}$ (1 $MJ.m^{-2}.day^{-1}$ higher than at the OSCA site).

Wind speeds were consistently low for this site, with the daily average only reaching a maximum of 1.58 $m.s^{-1}$ in October. Rainfall for the entire 16-month monitoring period totalled just 496.5 mm, while for the same calendar year used to calculate transpiration totals (5 March 2005 - 4 March 2006), rainfall amounted to 439.6 mm. This is below the long-term mean for the site of 582 mm (Lynch and Schulze, 2006) but the drought was not as severe as that experienced at the OSCA site.

4.3.2 Transpiration

4.3.2.1 Empangeni Site – 4-year-old J. curcas trees

Figure 4.7 illustrates uncorrected HPV data between February and June 2005, collected from a single probe set within a 4-year-old *J. curcas* tree at the OSCA site.

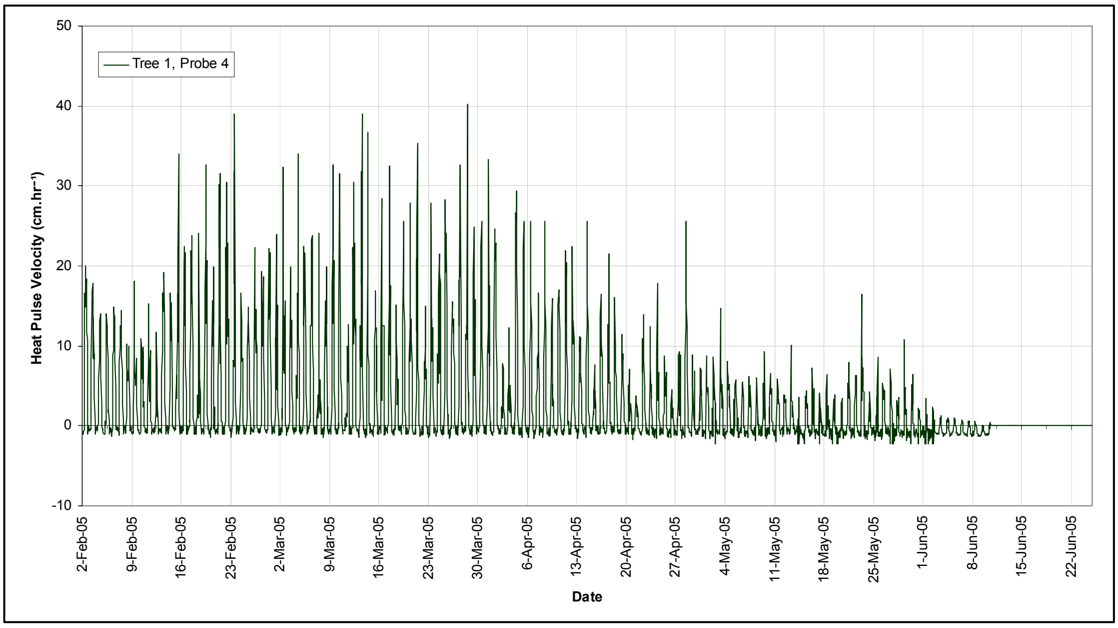


Figure 4.7: Hourly HPV data (cm/hr) collected from probe set 4 (tree 1, probe 4) at the OSCA site, near Empangeni.

It is evident in Figure 4.7 that there is a clear diurnal trend to the data. This is consistent between all the probe sets. The peak transpiration rates vary but the gradual reduction in transpiration across all probes (as winter is approached) is noticeable. This diurnal trend is illustrated more clearly in Figure 4.8, which shows a typical daily trend of HPV (sap flow / water use), temperature and relative humidity (RH), measured on 22nd March 2005 at the OSCA site.

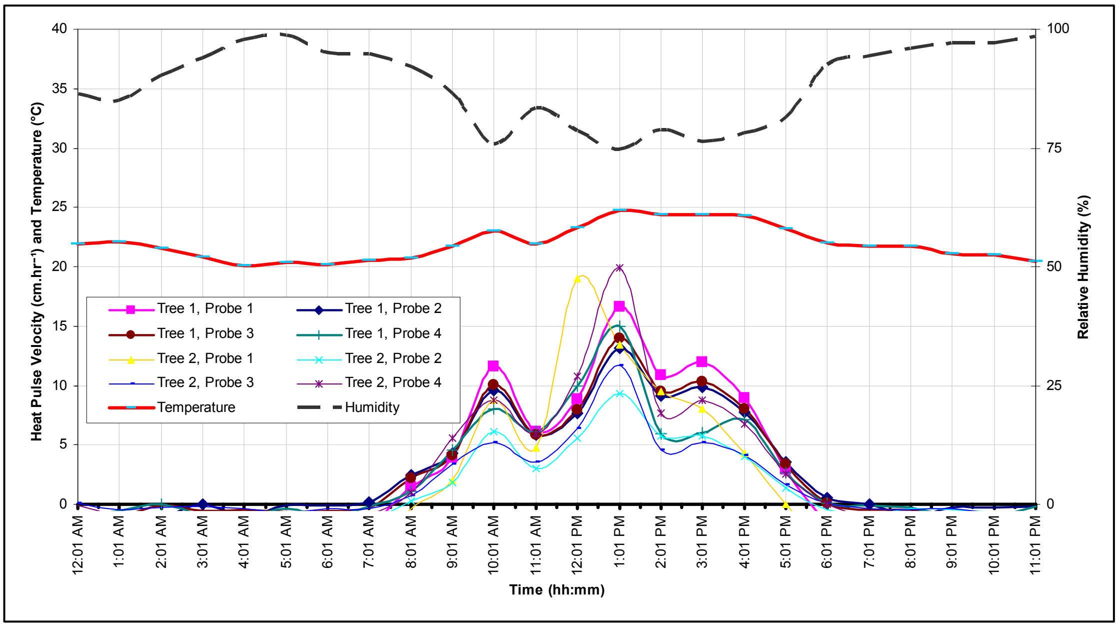


Figure 4.8: Hourly HPV (cm/hr), temperature (°C) and relative humidity (%) data from the 22nd March 2005 at OSCA.

In Figure 4.8, the increase in HPVs associated with the onset of daytime transpiration (linked to increasing temperatures and solar radiation and decreasing relative humidity) is evident in all the probe sets from approximately 07h00 onwards. Thereafter, the individual probe sets show good correlations between sap flow and vapour-pressure deficit (i.e. a combination of temperature and humidity). For example, when there are brief drops in temperature (and increases in humidity) at 11h00 and 14h00 respectively, there are corresponding reductions in sap flow. There are also excellent correlations between sap flow and solar radiation (Figures 4.8 and 4.9).

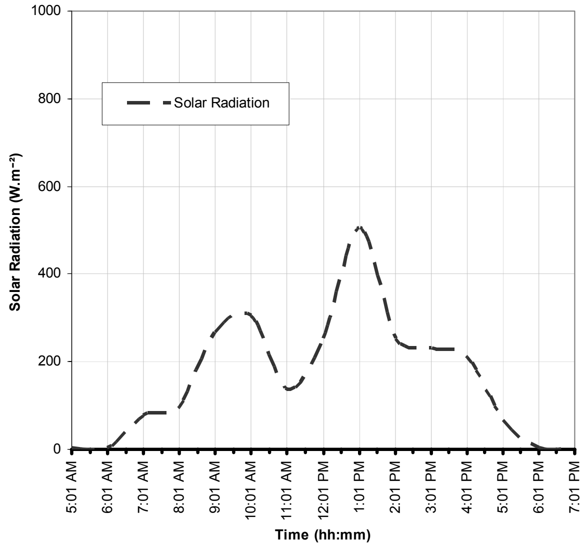


Figure 4.9: Hourly solar-radiation data (W/m²) from the 22nd March 2005 at OSCA.

In Figure 4.8, the HPVs decline noticeably after 15h00 until transpiration ceases at night (18h00). In later months (May / June) sap flow begins later and ends earlier (08h00 to 17h00) compared to the summer period illustrated here. Smaller sap-flow peaks were observed closer to the winter months, obviously being associated with reduced daylight length, changing tree physiological conditions and increasing water stress. Sap flow (transpiration) occurred in the trees until approximately 15 June, after which there was no recorded activity in the trees. This trend was consistent across all the probe sets.

The resumption of sap flow after winter dormancy coincided closely with the first rains and the resumption of warmer / wetter conditions in mid- to late October. The first flush of new leaves also occurred soon after the onset of warmer, wetter conditions early in October. There was a very uniform response from all the probe sets to these physiological and climatic drivers and the first definitive sap-flow movement was detected from 18 October onwards. Thereafter, it was possible to note a clear sap-flow response to available moisture. Three rainfall events of significant influence were those of the 5/6 November 2005 (37.4 mm), 1 December 2005 (29.1 mm) and 10

December 2005 (19.3 mm). Sap flow on those days was low (due to energy constraints resulting from reduced solar radiation because of clouds), but within a day or two thereafter, responses to the additional soil water provided by these events were manifested through increased sap-flow rates. However, what is interesting to note is that these increased sap-flow rates were not sustained consistently, and started to decline until the next rainfall event replenished the water available to the trees. These trends are illustrated in Figure 4.10.

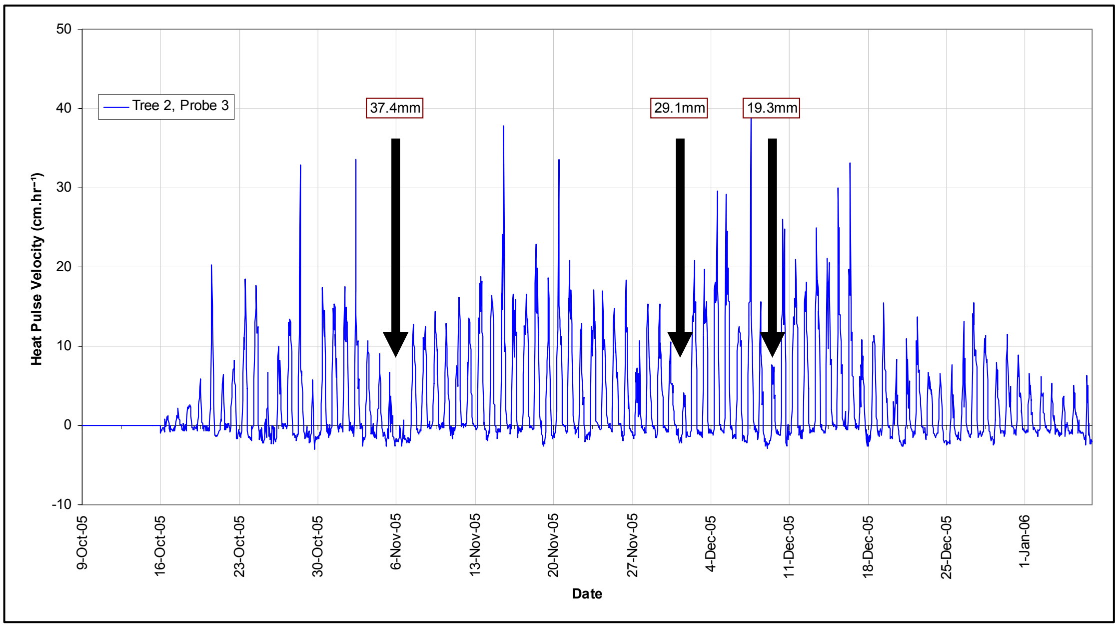


Figure 4.10: Hourly HPV data (cm/hr) collected from probe set 7 (tree 2, probe 3) at the OSCA site, near Empangeni. Note the influence of significant rainfall events.

Once HPV monitoring had been completed and all instrumentation had been removed from the Owen Sithole College of Agriculture (OSCA) site, it was possible to collect the additional supplementary information necessary to complete the HPV data analysis. The trees at the site could not be destructively sampled as they constituted an independent agricultural trial in their own right, so small wood samples were taken to determine the necessary additional data. A petrol-driven tree corer was used to extract 1 cm diameter cores from the tree stems, and these were scrutinised to determine sapwood depth. Traditionally, the heartwood / sapwood interface can be identified by observing the dark colour often associated with heartwood, or by staining the wood sample. The extracted *J. curcas* cores were consequently stained using Methyl Orange; however, no distinction between the sapwood and heartwood could be observed. It was concluded that the entire core consisted of sapwood and that the area of heartwood in this particular species was small. This was confirmed by cutting off a large branch close to the stem, whereby it was possible to determine that the heartwood radius was only approximately 10% of the sapwood radius (Figure 4.11). This relationship was used to determine sapwood depth in the main stem. Additional blocks of wood incorporating the thermocouple and heater probe insertion holes were chiselled out of the tree to determine the width of wounded (non-functional) xylem around the thermocouples (Figure 4.11). These wood samples were also used to determine sapwood moisture content and wood density.

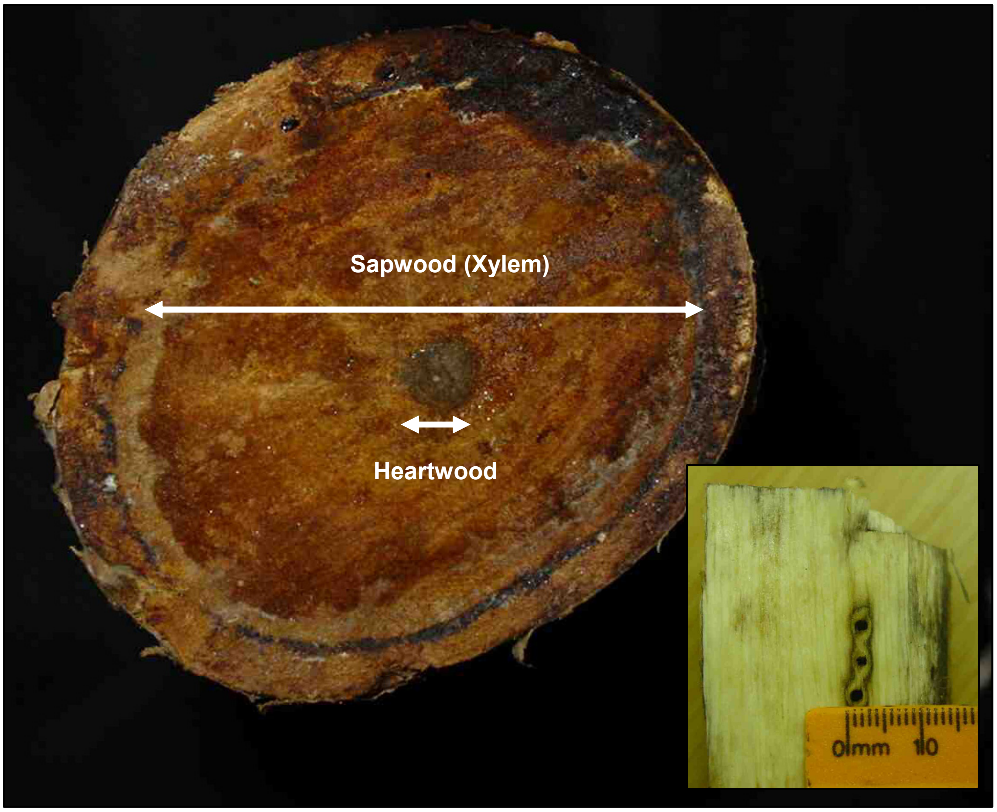


Figure 4.11: Cross-section of a *J. curcas* branch (70 mm diameter), used to determine the sapwood/heartwood ratio, and an example of a wound-width measurement (inset).

Table 4.3 shows the additional information gathered from the 4-year-old *J. curcas* trees (planted January 2002).

Table 4.3: Additional information gathered from 4-year-old *J. curcas* trees used to complete the HPV data analysis.

Tree No.	Stem diameter at probes	Bark width	Sapwood depth	Ave. wound width	Wood density ($g.cm^{-3}$)	Sapwood moisture content	No. of Probes
Tree 1	13.05 cm	7 mm	5.17 cm	4.5 mm	0.253	73.95%	4
Tree 2	14.64 cm	7 mm	5.89 cm	4.0 mm	0.253	72.80%	4

Using the techniques, formulae and additional information described in the HPV methodology section, uncorrected HPV data collected from the *J. curcas* trees at OSCA were patched and then converted to hourly sap flows. These hourly data were aggregated to daily, monthly and annual totals for both trees. Daily fluctuations in sap flow / transpiration ($litres.day^{-1}$) are shown in Figure 4.12.

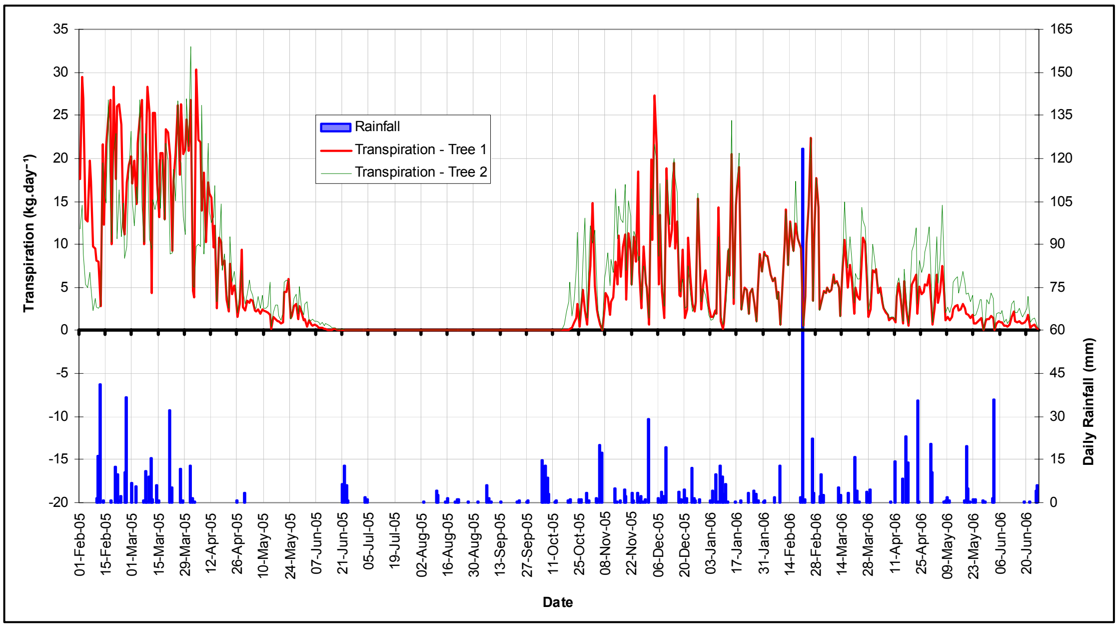


Figure 4.12: Daily transpiration values (litres) for two 4-year-old *J. curcas* trees, as well as rainfall at the OSCA site, between February 2005 and June 2006.

It is obvious from Figure 4.12 that transpiration rates are season-dependent due to the deciduous nature of *J. curcas*. Maximum transpiration rates in summer contrasted with a cessation of activity in the cooler and drier winter months. The resumption of transpiration after winter dormancy coincided closely with the first good rains, the development of new leaves and the onset of warmer / wetter conditions in mid- to late October. There was a very uniform response from both trees to these climatic drivers. Once the leaves had developed, sap velocity responses were closely associated with ambient conditions. Hourly transpiration responses to changes in vapour-pressure deficit (dryness of the air) were detectable from the hourly data, and this translated into significant daily variation. Trends over the longer term appeared to be dictated principally by season, but it is interesting to note how daily transpiration rates fluctuated widely, possibly due to the timing and amount of individual rainfall events, and their replenishing effect on soil-moisture availability, as well as energy availability (solar radiation). The highest water-use values recorded were daily transpiration totals of 30.3 litres (tree 1) and 32.9 litres (tree 2), while daily averages over a year (5 March 2005 - 4 March 2006) were 5.2 litres and 5.4 litres respectively.

Once the individual tree water-use values had been established, these were scaled up to represent a larger area (i.e. a *J. curcas* plantation). This was done by measuring the planting density of the sample trees. Tree spacing at the OSCA study site was found to be 3 m within the row and 4.5 m between rows. This translated into a planting density of approximately 740 trees.ha^{-1}. Over a calendar year (5 March 2005 to 4 March 2006), the transpiration totals for the sample trees were 1899 litres and 1983 litres for trees 1 and 2. By scaling the individual tree-transpiration measurements up to a hectare, and converting to mm-equivalent, the transpiration totals were calculated to be 140.6 mm and 146.9 mm for trees 1 and 2. Consequently, the average annual transpiration total for a 4-year-old *J. curcas* plantation (of 740 spha) could be taken to be in the region of 144 mm. The aggregated monthly transpiration totals (mm) are illustrated in Figure 4.13.

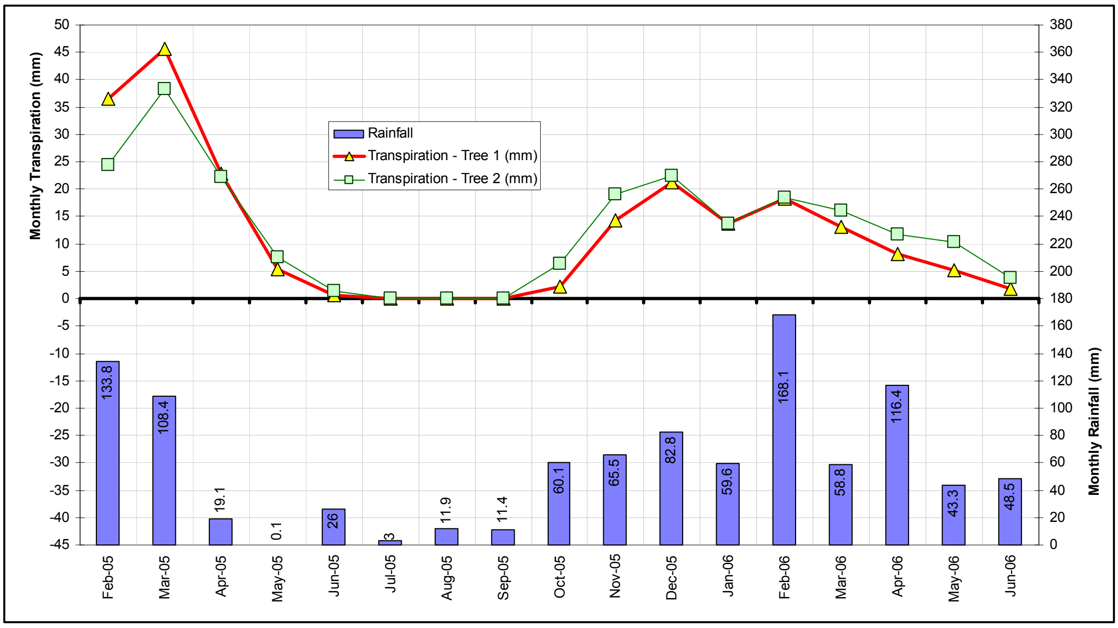


Figure 4.13: Monthly transpiration totals (mm) for two *J. curcas* trees at the OSCA site, (February 2005 to June 2006).

4.3.2.2 *Makhathini Site – 12-year-old J. curcas trees*

Figure 4.14 illustrates uncorrected HPV data collected from a single probe set within a 12-year-old *J. curcas* tree at the Makhathini site.

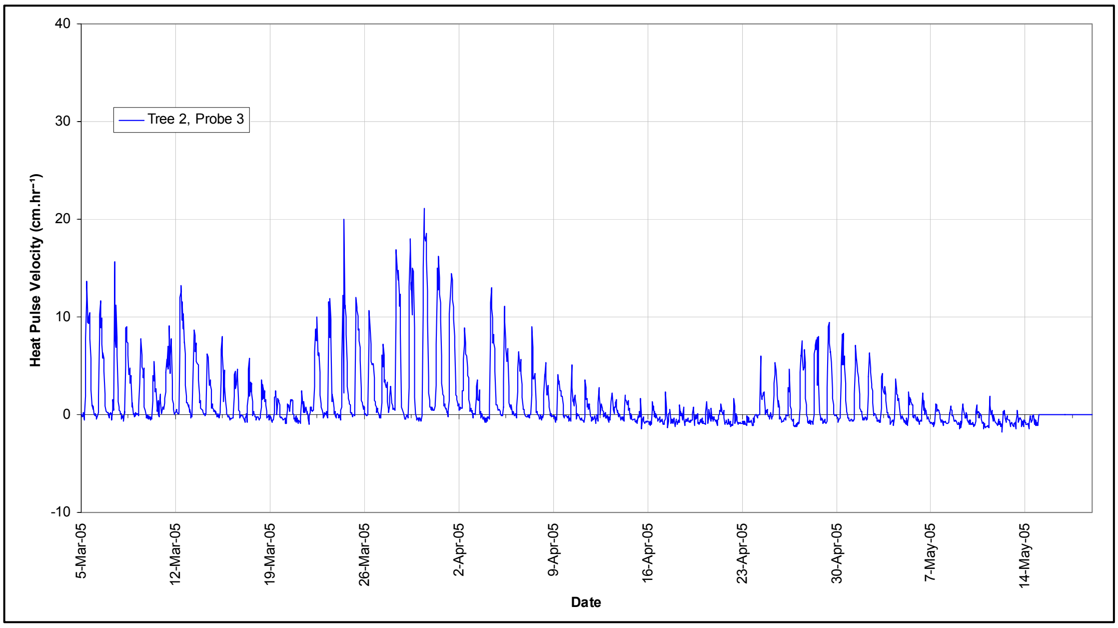


Figure 4.14: Hourly HPV data (cm/hr) collected from probe set 7 (tree 2, probe 3) at the Makhathini site.

The HPV data for the Makhathini site (Figure 4.14) shows a similar diurnal pattern to that of the OSCA site. The termination of sap flow at the approach of the dry winter months is also clear. However, there are some noticeable differences between the OSCA and Makhathini data. Firstly, the Makhathini sap-flow data declines far more dramatically and significantly earlier in the winter season. While the 4-year-old trees at OSCA continue transpiring until the end of May, the older Makhathini trees show no signs of sap flow after 10 May 2006.

In fact, the data in Figure 4.14 already indicates periods of water stress in mid-March and during the second half of April (decreasing sap flow). These were alleviated by individual rainfall events, which resulted in increased water availability. It would appear therefore, that sap flow in the Makhathini trees is strongly influenced by fluctuations in water availability, while the OSCA trees appear to be limited only by season (deciduous, drier and cooler winter conditions). For these reasons, and possibly tree-age differences as well, the OSCA trees have noticeably higher sap-flow rates. However, in terms of volumetric water use these are off-set by the greater cross-sectional area of the older and larger Makhathini trees.

Figure 4.15 shows varying daily trends of HPVs, and their relationship to temperature and relative humidity (RH) fluctuations, measured between the 1st and 4th April 2005 at the Makhathini site. Again, the influence of cooler, more humid conditions in suppressing sap flow is evident.

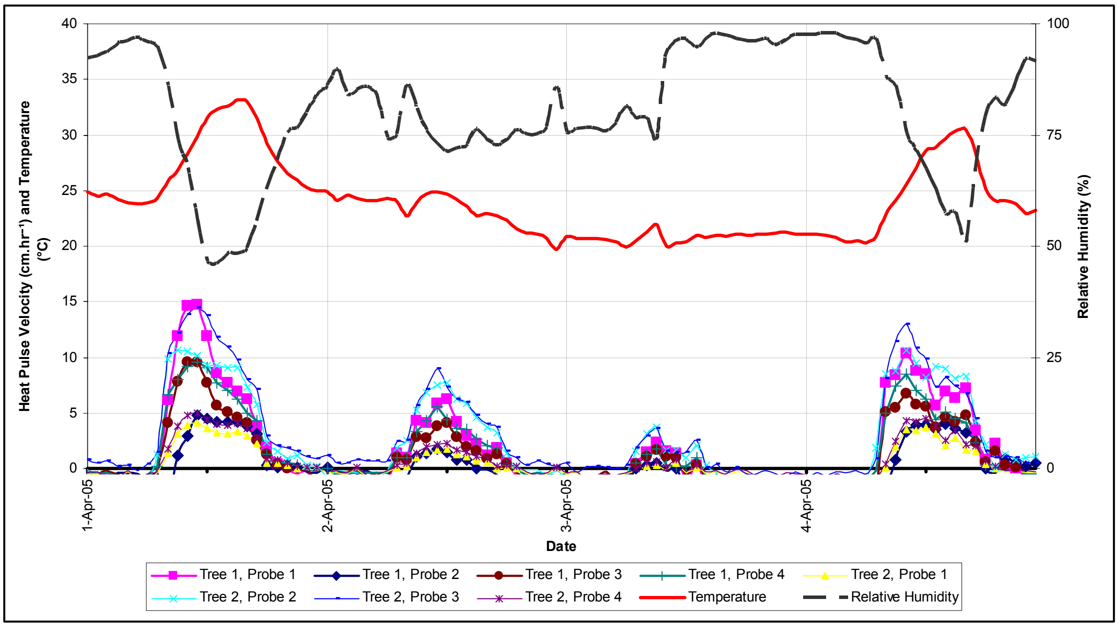


Figure 4.15: Hourly HPV (cm/hr), temperature (°C) and relative humidity (%) data between the 1st and 4th April 2005 at Makhathini.

A similar procedure to that described for the OSCA trees was followed in order to finalise the transpiration totals for the two sample trees at the Makhathini site. Table 4.4 shows the additional information gathered from the 12-year-old *J. curcas* trees.

Table 4.4: Additional information gathered from 12-year-old *J. curcas* trees used to complete the HPV data analysis.

Tree No.	Stem diameter at probes	Bark width	Sapwood depth	Ave. wound width	Wood density ($g.cm^{-3}$)	Sapwood moisture content	No. of Probes
Tree 1	38.13 cm	13 mm	15.86 cm	3.5 mm	0.253	67.1%	4
Tree 2	38.20 cm	13 mm	15.88 cm	3.5 mm	0.253	67.1%	4

Daily fluctuations in sap flow / transpiration ($litres.day^{-1}$) for the older trees at Makhathini are shown in Figure 4.16.

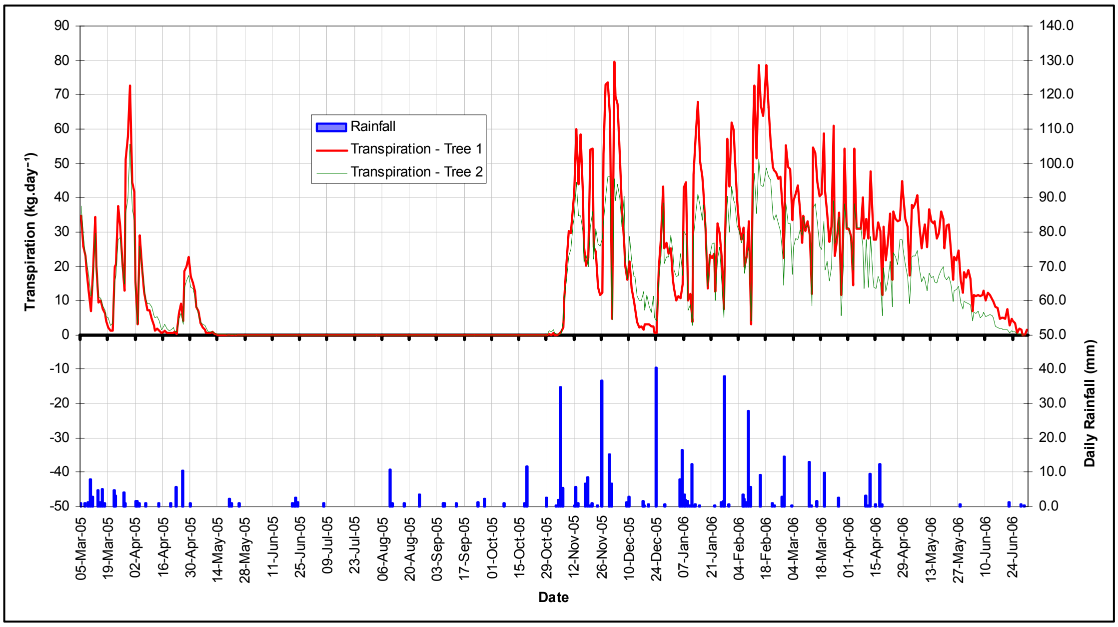


Figure 4.16: Daily transpiration values (litres) for two 12-year-old *J. curcas* trees on the Makhathini flats, between March 2005 and June 2006.

Apart from the obvious seasonal fluctuations in transpiration, it is evident from Figure 4.16 that *J. curcas* transpiration rates at the Makhathini site are highly rainfall dependent. This is likely to be as a result of the sandy soils associated with this area, which have rapid drainage and a low capacity to retain water near the surface where the bulk of the tree roots are.

Consequently, individual rainfall events initiate rapid responses in transpiration as the trees make use of the readily available soil moisture. However, as the water drains from the sandy soils, so the transpiration rates decline markedly, until the next rainfall event. This trend is most dramatic at the start of the hydrological year (October – January), but becomes less so towards the end (February – July), possibly because by that stage ground-water levels have risen, and also because transpiration rates have decreased.

The highest water-use values recorded were daily transpiration totals of 79.6 litres (tree 1) and 54.5 litres (tree 2), while daily averages over a calendar year (5 March 2005 to 4 March 2006) were 13.4 litres (tree 1) and 11.1 litres (tree 2). Tree 1 at Makhathini was observed to be using more water than Tree 2. There does not appear to be any obvious reasons for this, as both trees were similar in height, stem diameter and canopy leaf area. However, when the probes were removed from the trees at the end of the monitoring period, it was noticed that Tree 2 had an area of dead wood in one part of the stem, and it is possible that this had an impact on the overall water use of that tree.

A scaling-up exercise was also applied to the trees at Makhathini. Some assumptions were required because the sample trees consisted of just a single row of 10 trees along the homestead fence. These trees were spaced approximately 3 m from each other (as at OSCA), and so a similar planting density to the OSCA site was assumed (740 trees.ha^{-1}) despite the absence of additional rows of trees. Due to the absence of additional rows of trees (i.e. reduced competition for water, nutrients and light), it is likely that the scaled-up transpiration rates calculated here are slightly higher than would be experienced in a plantation environment.

Over a calendar year (5 March 2005 to 4 March 2006), the transpiration totals for the sample trees were 4884 litres and 4036 litres for trees 1 and 2. By scaling the individual tree transpiration measurements up to a hectare, and converting to mm-equivalent, the transpiration totals were calculated to be 361.8 mm and 298.9 mm for trees 1 and 2. These values are slightly more than double those for the 4-year-old trees at OSCA, and reflect the greater size (increased leaf area) of the Makhathini trees. Figure 4.17 illustrates the aggregated monthly transpiration totals (mm) for the Makhathini trees.

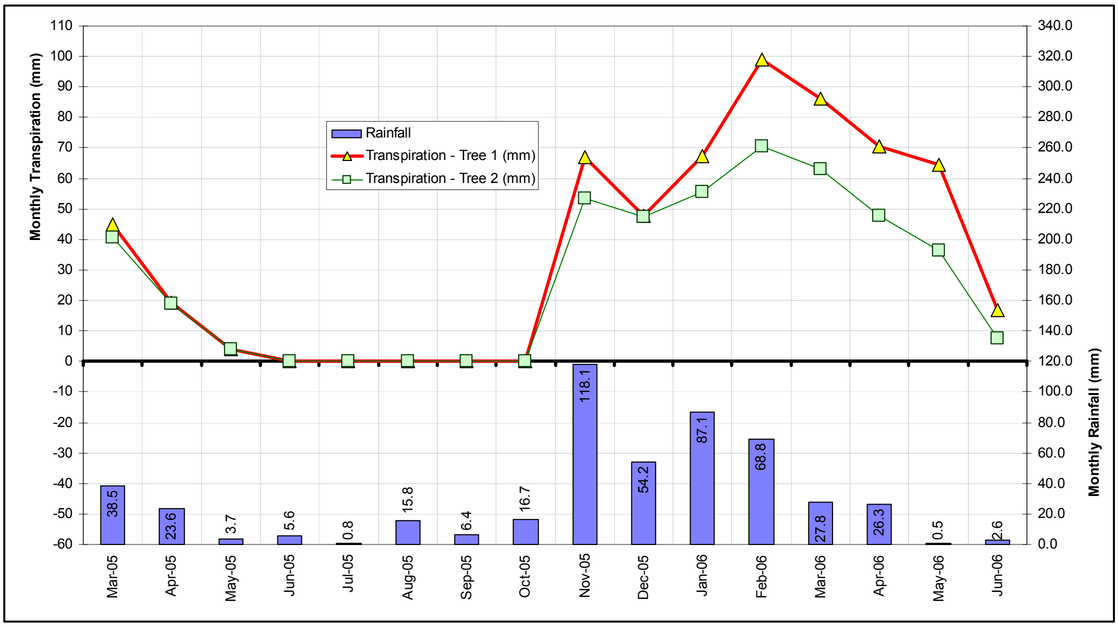


Figure 4.17: Monthly transpiration totals (mm) for two 12-year-old *J. curcas* trees on the Makhathini flats, between March 2005 and June 2006.

Compared to the monthly transpiration totals (mm) calculated for the OSCA trees (Figure 4.13), the trend observed in the trees at Makhathini (Figure 4.17) is somewhat different. Transpiration rates at the start of the monitoring period (March – May 2005) are lower at Makhathini than for the corresponding period the following year (March – May 2006). However, the opposite is true of the trees at OSCA. It is surmised that this has to do with the timing and extent of rainfall events. The monthly rainfall totals for the two sites appear to bear this out, and while OSCA had a relatively wet season in the first months of 2005, Makhathini was significantly drier. However, from the start of the next growing season (November 2005), rainfall at Makhathini was consistently good, while monthly rainfall totals at OSCA were more variable and generally lower. The large total for February 2006 at OSCA (168.1 mm) was made up primarily of a single storm event of 123.4 mm, which occurred on 21 February 2006. Due to the intense nature of this event it is likely that a significant proportion of the rainfall would have run off, without causing significant soil-moisture recharge.

4.3.3 Soil Moisture and Soil Matric Potential

Some basic soil properties of the OSCA site are provided in Table 4.5. The water-retention function for the soils at OSCA is illustrated in Figure 4.18.

Table 4.5: Basic properties of the soil at the OSCA site.

Sample	Clay	Silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Hydraulic Conductivity $mm.hr^{-1}$	Bulk Density $g.cm^{-3}$
OSCA - Surface	12.49	18.21	16.55	33.30	15.75	3.70	23.27	1.59
OSCA - 0.40 m	18.78	17.77	16.55	30.15	13.00	3.75	9.07	1.67
OSCA - 1.00 m	22.21	15.59	14.50	25.30	16.20	6.20	14.50	1.47

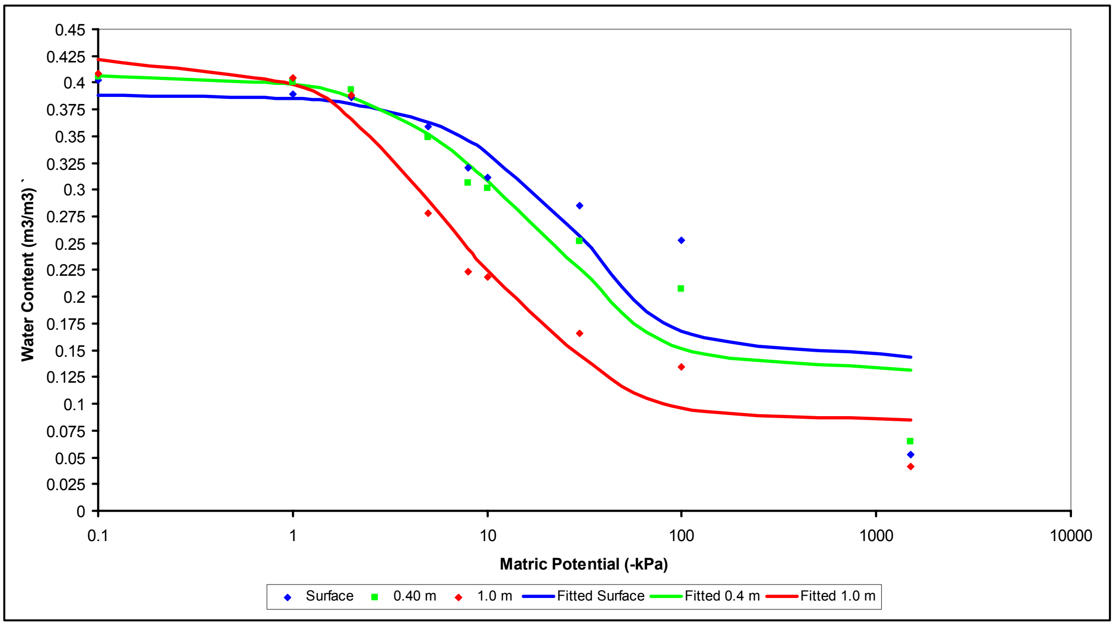


Figure 4.18: Water-retention curve for the soils at the OSCA site

The topsoil at the site is sandy loam in texture with a bulk density that is typical of this type of material. Clay contents increase with increasing soil depth, which is consistent with the process of clay illuviation, i.e. an enrichment of clay down the soil profile. The saturated soil-water content is also closely related to the total porosity, which in turn is uniquely related to the bulk density. There is an increase in total porosity with depth due mainly to the higher clay contents. It is interesting, however, that at a depth of 0.40m, despite the similar particle-size distribution and notwithstanding a marginally higher bulk density, the hydraulic conductivity is much slower compared with the near surface and deeper parts of the soil. The reason for this reduced hydraulic conductivity is not immediately apparent when comparing purely the physical characteristics of the soil but could be related to an accumulation of organic acids or other similar compounds at this soil depth.

The quarter April to June 2006 experienced above average rainfall at OSCA, which fell consistently across all three months. This had the effect of maintaining consistently high soil-water contents at the site. Figures 4.19 and 4.20 illustrate, respectively, soil-water-content fluctuations for the final quarter and for the entire monitoring period at OSCA. In Figure 4.19, clear responses in volumetric soil-moisture levels to individual rainfall events are evident. Responses appear through-out the soil profile at both the tree and grass sites, with the deep sensor (1.2 m) at the grass site being the only exception. In Figure 4.20, broad seasonal fluctuations in soil moisture are illustrated. What is noticeable is the difference in soil-moisture levels during the April to June quarter for the 2005 and 2006 years respectively. The effect of late season rainfall in 2006 on maintaining high soil moisture levels is evident. Levels in June 2006 are similar or higher to those experienced in the middle of the wet season (January 2006).

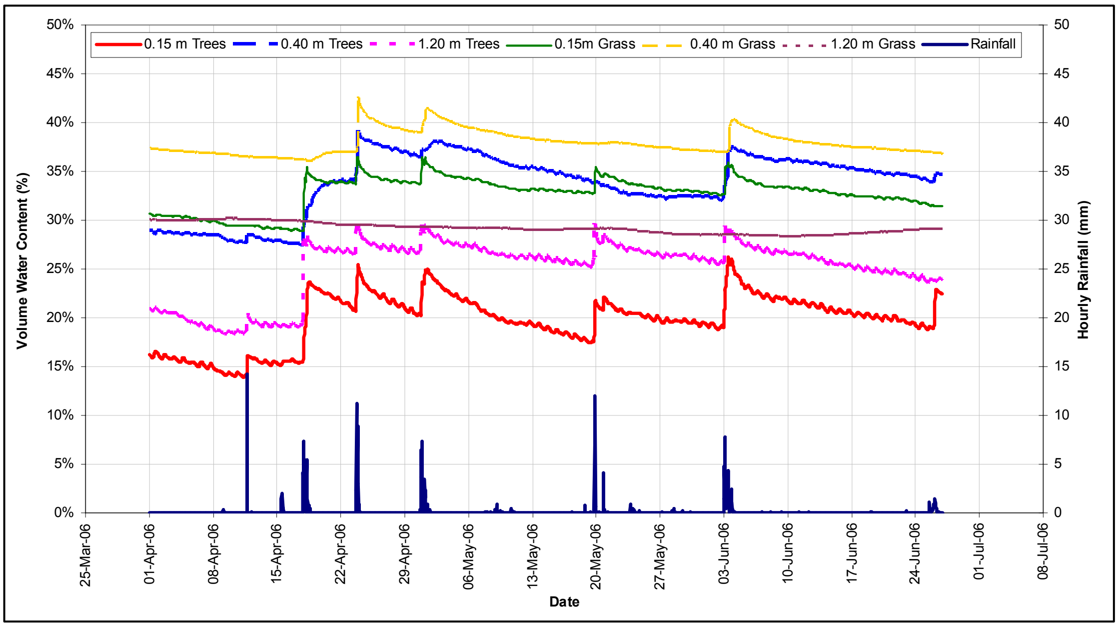


Figure 4.19: Hourly volumetric water content (%) fluctuations, with rainfall, at selected soil depths beneath grass and *J. curcas* trees at the OSCA site between April and June 2006.

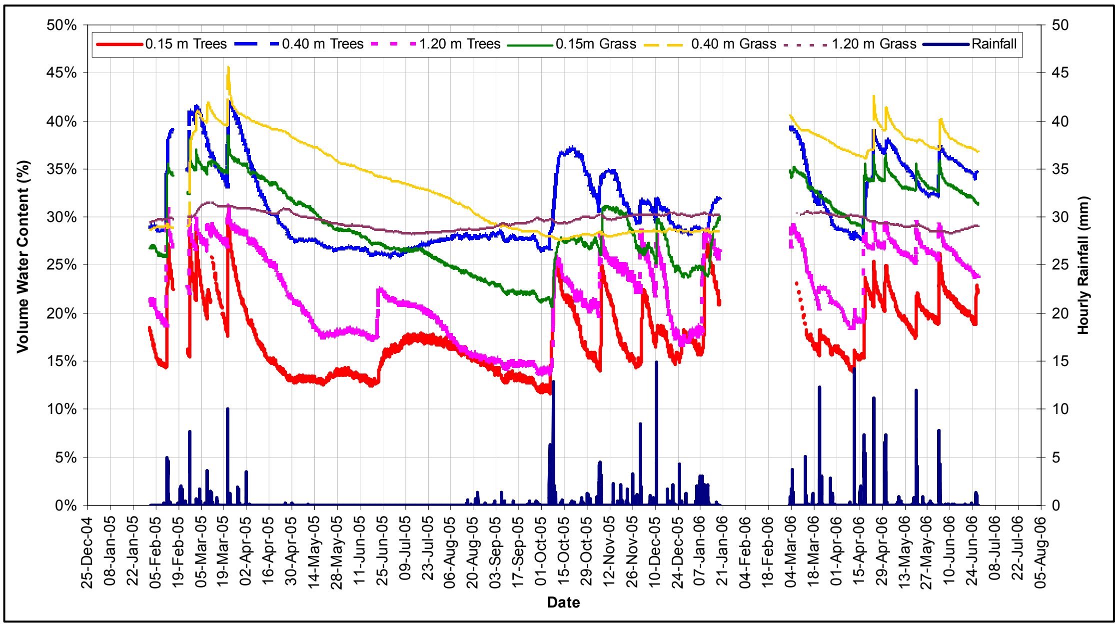


Figure 4.20: Hourly volumetric water content (%) fluctuations, with rainfall, at OSCA, for the entire monitoring period (March 05 to June 06).

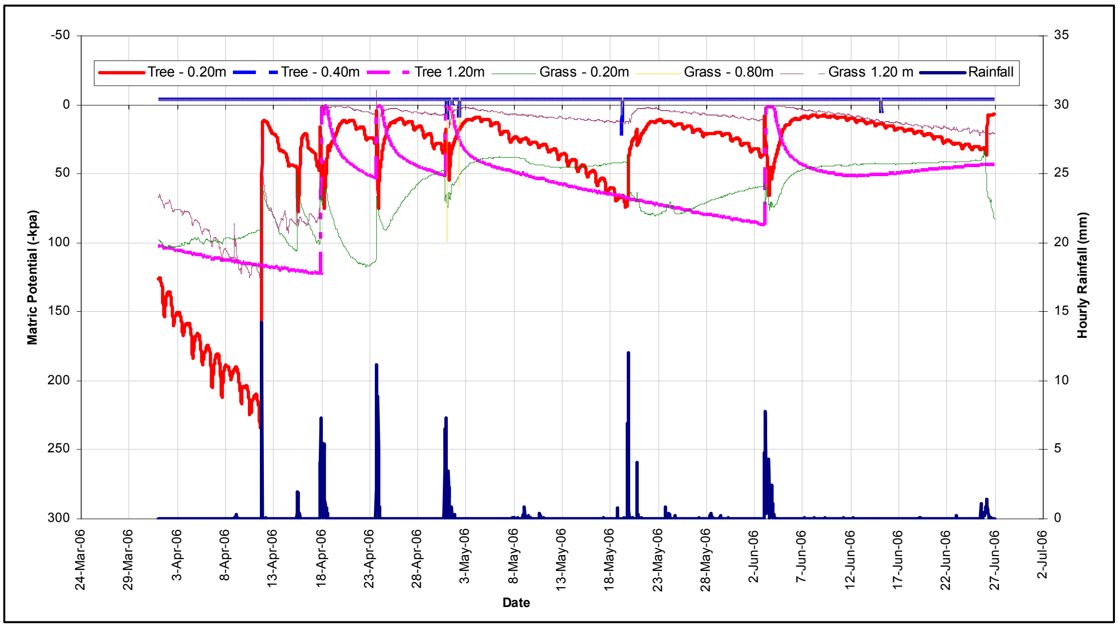


Figure 4.21: Hourly soil-matric potential (-kPa) fluctuations, with rainfall, at OSCA, for April to June 2006.

The response of the soil to the several rainfall episodes that took place from the latter half of April onwards is evident in the record of soil-matric potential (Figure 4.21). In general, matric potential increased as the water content increased, and declined thereafter as water either evaporated or drained to deeper parts of the soil. The comparatively higher hydraulic conductivity of the topsoil relative to the other parts of the soil would also account for the much more rapid changes in matric potential. What is also interesting from Figures 4.19 and 4.21 is that for both the grassed and tree sites the 0.40 m-deep soil layer appears to be consistently the wettest relative to the other depths. The much higher hydraulic conductivity of the topsoil compared to the subsoil means that water would tend to infiltrate fairly rapidly through the topsoil and then slow down as the wetting front advanced into the subsoil. Although not strictly a perched water table, this would then cause the topsoil-subsoil interface to remain fairly wet even in the absence of any further rain.

It is further interesting that when one compares the measured water contents across the grassed and tree sites, the latter appears to be consistently drier (Figure 4.20), in some cases by as much as 15%. Notwithstanding the uncertainties related to the atypical rainfall received at site, potential reasons to account for this is that interception of rainfall by the leaves of the *J. curcas* tree may be a significant factor or that much of the water that does infiltrate the soil is taken up directly by the tree roots. An additional reason to account for the trends observed, which could be a localised site characteristic, is that the soil beneath the trees was maintained fallow. This could have favoured an increase in surface runoff from the tree site compared with the grassed site with its higher soil-surface-detention storage.

4.3.4 Modelling

Three potential models suitable for the simulation of transpiration in plant species (FAO56, WAVES and SWB) were briefly reviewed during the course of the project. Of those, the FAO56 and SWB models were considered to be the most appropriate and easily parameterised for the simulation of transpiration in *J. curcas*. The following is a description of a modelling exercise performed using the FAO56 model.

4.3.4.1 FAO56 Model Description

The FAO56 model (Allen *et al.*, 2004) provides a means of calculating reference and crop evapotranspiration from meteorological data and crop coefficients. The effect of climate on crop water requirements is given by the reference evapotranspiration (ET_o), and the effect of the crop by the crop coefficient K_c. Actual crop evapotranspiration (ET_c) is calculated by multiplying ET_o by K_c:

$$ET_c = K_c * ET_o$$

The calculation of ET_o is based on the Penman-Monteith combination method, and represents the evapotranspiration of a hypothetical reference crop (short grass). The technique uses standard climatic data that can be easily measured or derived from commonly collected weather-station data. Differences in the canopy and aerodynamic resistances of the crop being simulated, relative to the reference crop, are accounted for within the crop coefficient (K_c). K_c serves as an aggregation of the physical and physiological differences between crops.

Two calculation methods to derive crop evapotranspiration (ET_c) from ET_o are possible. The first approach integrates the relationships between evapotranspiration of the crop and the reference surface into a single coefficient (K_c). The second approach splits K_c into two factors that separately describe the evaporation (K_e) and transpiration (K_{cb}) components (Allen *et al.*, 2004). The second approach was adopted in this particular study because the field data that had already been collected for *J. curcas* were measurements of transpiration (excluding soil evaporation), and were consequently directly comparable to the simulated values of K_{cb}.

4.3.4.2 FAO56 Input Data

Both the OSCA and Makhathini sites were used for separate *J. curcas* transpiration simulations. The necessary meteorological data required as input into the FAO56 model were available, either from the automatic weather stations deployed at the two field sites, or from climate stations managed by the South African Sugarcane Research Institute (SASRI). These data have been illustrated and discussed above. Where available, hourly data was aggregated into daily values, but occasional periods of missing data were patched using the daily SASRI data. All data was entered into a spreadsheet, and the necessary variables required by the final FAO Penman-Monteith equation were calculated on a daily time step. These variables were utilised in the final FAO Penman-Monteith equation (Allen *et al*., 2004), for the calculation of daily reference evapotranspiration (ET_o).

4.3.4.3 FAO56 Results – Reference Evapotranspiration

Information regarding the daily reference evapotranspiration (ET_o) values for the two sites is summarised in Table 4.6.

Table 4.6: A comparison of daily FAO56 reference crop evapotranspiration (ET_o) values for the OSCA and Makhathini sites (5 March 2005 – 4 March 2006).

	Max ET_o (mm)	**Min ET_o (mm)**	**Ave ET_o (mm)**	**Total ET_o (mm)**
OSCA	8.01	0.80	3.43	1251.7
Makhathini	8.53	0.96	3.64	1328.4

Plots of daily reference evapotranspiration values for the OSCA and Makhathini sites, for the entire monitoring period are illustrated in Figures 4.22 and 4.23.

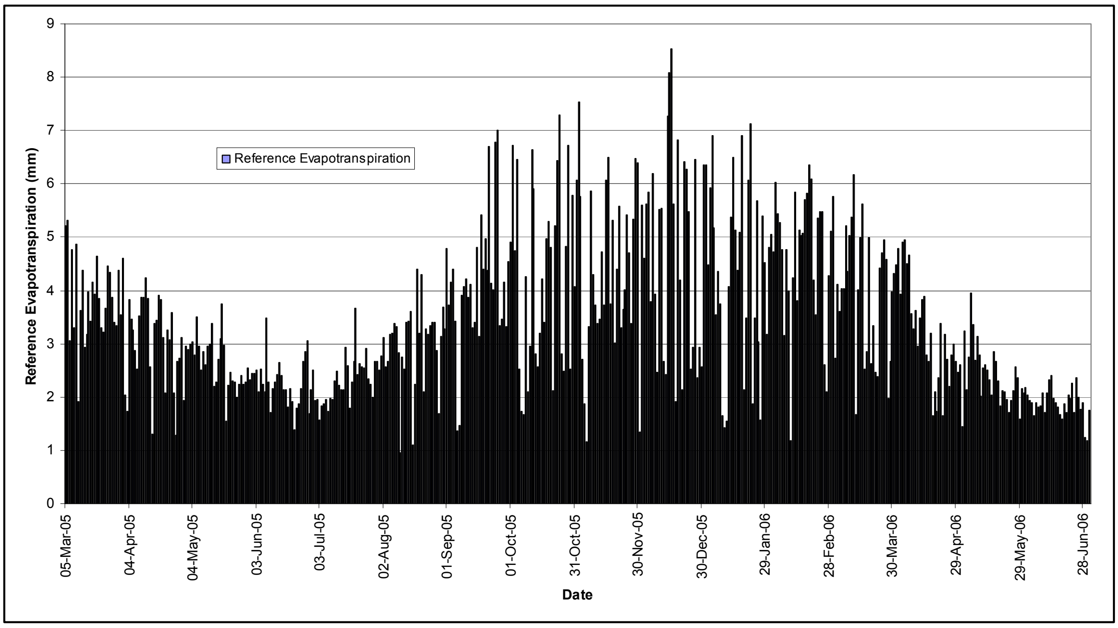


Figure 4.22: Daily FAO reference evapotranspiration (Allen, et al., 2004) for the OSCA site, between 2 February 2005 and 26 June 2006.

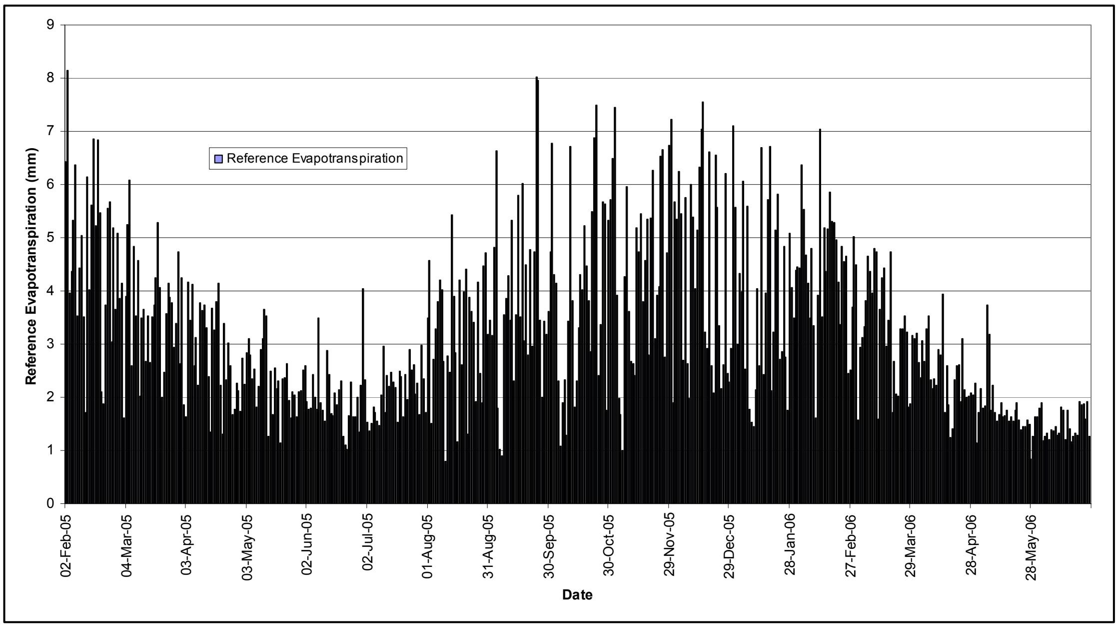


Figure 4.23: Daily FAO reference evapotranspiration (Allen, et al., 2004) for the Makhathini site, between 5 March 2005 and 1 July 2006.

From Figures 4.22 and 4.23, it is possible to discern the seasonal fluctuations in reference evapotranspiration (ET_o), as well as the significant variation in daily ET_o. Total annual ET_o (5 March 2005 to 4 March 2006) was 1251.7 mm for the OSCA site and 1328.4 mm for the Makhathini site. Monthly totals of ET_o for the two sites are compared in Table 4.7 and illustrated in Figure 4.24.

ET_o for the Makhathini site is generally higher than for the OSCA site, with March and August being the only two exceptions.

Table 4.7: A comparison of the monthly FAO56 reference crop evapotranspiration totals at the OSCA and Makhathini sites.

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Total
OSCA	112.8	84.9	72.8	60.3	65.0	99.8	117.9	124.7	133.3	137.8	118.4	123.6	1251.7
Makh.	104.1	91.0	82.3	68.0	71.5	92.3	124.8	132.1	134.9	144.4	134.9	130.4	1328.4

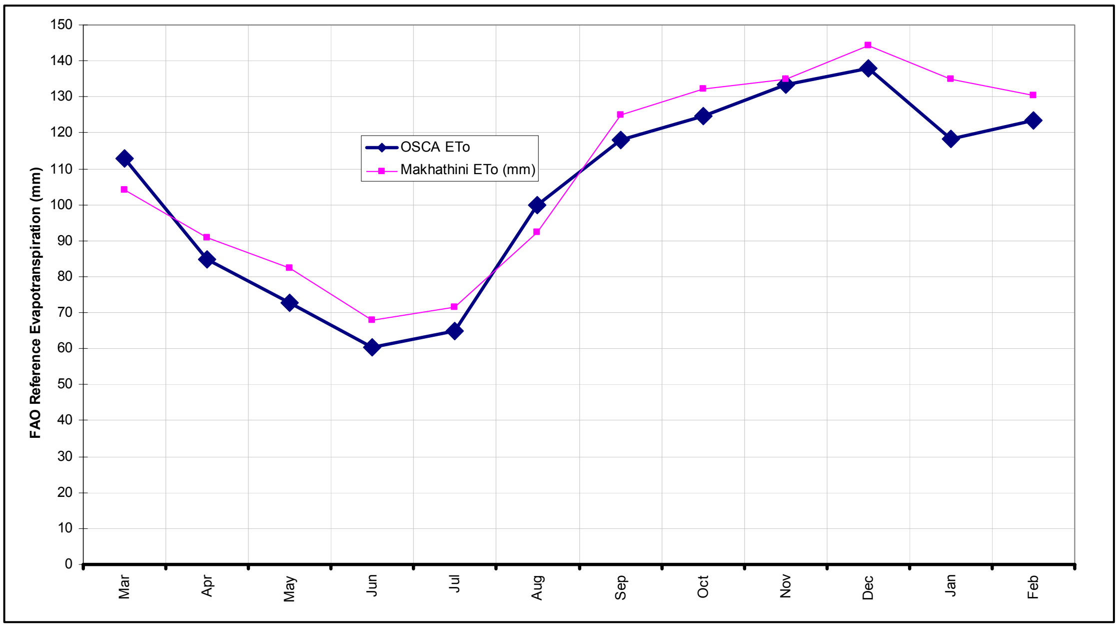


Figure 4.24: Monthly totals of daily FAO reference evapotranspiration (Allen et al., 2004) for the sites at OSCA and Makhathini.

4.3.4.4 FAO56 Results – Crop Evapotranspiration

The actual evapotranspiration of a specific crop (ET_c) may be simulated by multiplying the reference evapotranspiration (ET_o) by the crop coefficient (K_c). ET_c differs distinctly from ET_o as the ground cover, canopy properties and aerodynamic resistance of the crop are different from grass. The effects of characteristics that distinguish field crops from grass are integrated into the crop coefficient. Differences in evaporation and transpiration between field crops and the reference grass surface can be integrated into a single crop coefficient (K_c) or separated into two coefficients: a basal crop (K_{cb}) and a soil-evaporation coefficient (K_e), i.e. $K_c = K_{cb} + K_e$ (Allen et al., 2004). The approach followed for this particular modelling exercise was to calculate K_{cb} because sap-velocity observations (as recorded during this project) are used in the calculation of transpiration only (i.e. they exclude soil evaporation). This facilitated a direct comparison between simulated and observed values.

Traditionally, the first requirement in terms of the calculation of K_{cb} is the selection of an appropriate set of crop-development stages and crop coefficients for the crop being simulated. Thereafter, it is possible to construct the associated basal crop-coefficient curve. Once the daily crop-coefficient curve has been constructed, the calculation of actual crop transpiration is a simple matter of multiplying the reference evapotranspiration (ET_o) by the basal crop coefficient (K_{cb}) on a daily basis.

Tables in Allen et al., (2004) list crop-development stages and time-averaged crop coefficients for a number of crops growing in sub-humid climates, however, *J. curcas* is not included on that list. What were available were the observed transpiration rates for *J. curcas* trees at the two monitoring sites. Consequently, the methodology used to calculate K_{cb} was to divide the daily observed transpiration values by the calculated reference evapotranspiration (ET_o) values, to back-calculate K_{cb}. Using this approach, daily K_{cb} values were calculated for the entire monitoring period at both sites. Daily values were averaged for each month of the year, and where a particular month occurred twice (due to the monitoring period being greater than a year), those values were averaged. The following set of crop coefficients (K_{cb}) were generated using this technique (Table 4.8.)

Table 4.8: Monthly basal crop-coefficient (K_{cb}) values for 4-year-old (OSCA) and 12-year-old (Makhathini) *J. curcas* trees.

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

The trends in monthly basal crop-coefficient (K_{cb}) values for the OSCA and Makhathini sites listed in Table 4.8 are indicative of a seasonally dormant deciduous species. However, two months show apparent divergence from what would be expected in a smoothed form of these trends. January at the OSCA site, and December and January at the Makhathini site, have K_{cb} values that are lower than expected and appear to be anomalous. As these K_{cb} values were calculated using observed transpiration totals, this may be explained by the climatic conditions experienced during these two particular months at the respective sites (see Figures 4.5 and 4.6).

At the OSCA site, January was particularly dry (59.6 mm), well below the long-term mean for January of 131 mm (Lynch and Schulze, 2006). The solar-radiation total for January at OSCA was also significantly lower than normally expected for that month. This suggests that there were more overcast but dry days than normal. The net result of the corresponding reduction in vapour-pressure deficit and moisture availability would be reduced transpiration rates.

Similarly, at the Makhathini site in December the observed rainfall total of 54.2 mm was well below the long-term mean of 85 mm (Lynch and Schulze, 2006). If the observed transpiration totals for these two anomalous months are replaced with values complying with the expected trend, the following set of "smoothed" K_{cb} values could be expected (Table 4.9).

Table 4.9: "Smoothed" monthly basal crop-coefficient (K_{cb}) values for 4-year-old (OSCA) and 12-year-old (Makhathini) *J. curcas* trees.

K_{cb}	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
OSCA	0.18	0.18	0.26	0.21	0.14	0.06	0.00	0.00	0.00	0.04	0.14	0.15
Makh.	0.55	0.76	0.56	0.47	0.46	0.15	0.00	0.00	0.00	0.00	0.50	0.50

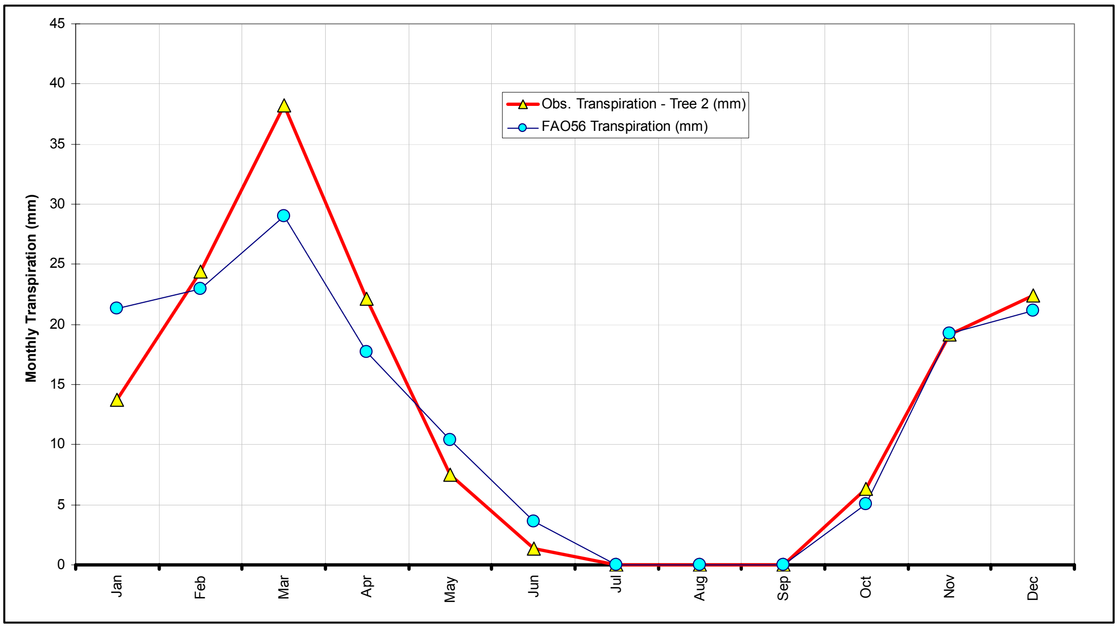
Based on this modelling exercise, monthly values and calculation procedures for reference evapotranspiration (ET_o), basal crop coefficient (K_{cb}) and crop transpiration (ET_c) are summed up in Table 4.10.

Table 4.10: Simulated monthly reference evapotranspiration (ET_o), basal crop-coefficient (K_{cb}) and crop-transpiration (ET_c) values for 4-year-old (OSCA) and 12-year-old (Makhathini) *J. curcas* trees.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot
ETo OSCA	118.4	128.9	112.8	84.9	72.8	60.3	65.0	99.8	117.9	124.7	133.3	137.8	1256.5
ETo Makh.	134.9	130.4	104.1	91.0	82.3	68.0	71.5	92.3	124.8	132.1	134.9	144.4	1310.7
	X	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	
Kcb OSCA	0.18	0.18	0.26	0.21	0.14	0.06	0.00	0.00	0.00	0.04	0.14	0.15	
Kcb Makh.	0.55	0.76	0.56	0.47	0.46	0.15	0.00	0.00	0.00	0.00	0.50	0.50	
	=	**=**	**=**	**=**	**=**	**=**	**=**	**=**	**=**	**=**	**=**	**=**	
ETc OSCA	21.3	23.0	29.0	17.7	10.4	3.6	0.0	0.0	0.0	5.0	19.2	21.1	150.4
ETc Makh.	74.2	98.9	58.4	42.6	37.6	10.1	0.0	0.0	0.0	0.0	67.0	72.2	461.1

Comparisons of observed monthly transpiration totals against those calculated using the modelling approach described above, are represented in Figures 4.25 and 4.26.

Figure 4.25: Observed and modelled (FAO56) monthly transpiration



totals (mm) for a 4-year old *J. curcas* tree at the OSCA site.

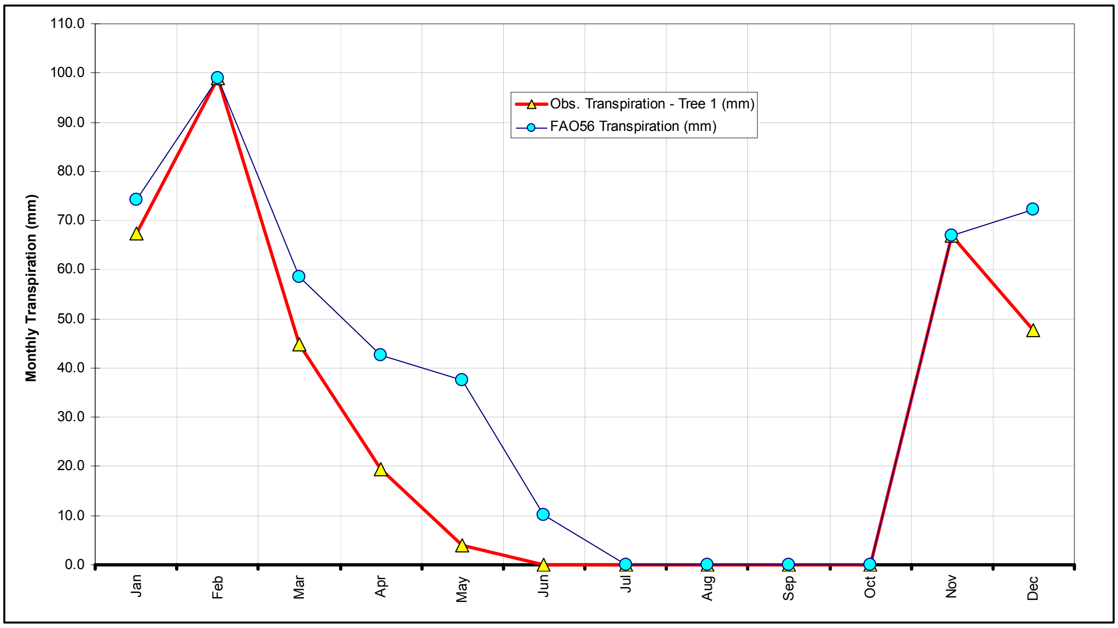


Figure 4.26: Observed and modelled (FAO56) monthly transpiration totals (mm) for a 12-year-old *J. curcas* tree at the Makhathini site.

4.3.4.5 Use of Leaf Area Index for Transpiration Estimates

As an alternative to the above modelling exercise, Leaf Area Index (LAI) values could be used to approximate *J. curcas* transpiration. LAI measurements were taken on 22/23 December 2005 at both sites. A LAI of 1.28 was measured at OSCA, while an LAI of 2.26 was measured at Makhathini. These LAI values were regressed against the final transpiration totals, and a 3rd order polynomial curve that passed through the origin as well as a hypothetical maximum LAI value (3.2) was fitted to the data (Figure 4.27). The resulting model ($y = -26.554x^3 + 141.75x^2 - 25.431x$) provides a rough approximation of *J. curcas* transpiration (mm) relative to LAI.

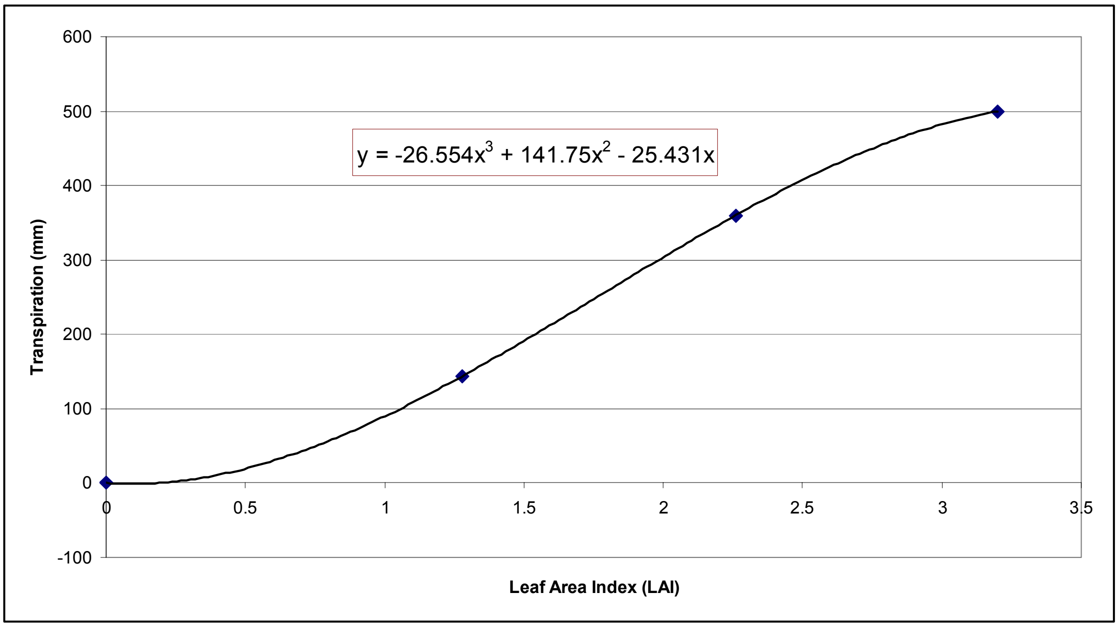


Figure 4.27: Relationship between Leaf Area Index and transpiration for different ages of *J. curcas* trees.

Using this model, it is anticipated that maximum transpiration rates for this species should not exceed approximately 500 mm. Considering the ideal tropical conditions under which the monitored trees were growing, whilst also remembering that rainfall for the monitoring period was below average, it is believed that this is a plausible assumption. As *J. curcas* is a deciduous species, it should be remembered that this model would only be applicable for LAI values recorded during mid-summer when leaf area is at a maximum.

4.4. CONCLUSION

An appraisal of the HPV data recorded over the entire monitoring period reveals a number of aspects. Firstly, HPVs, and hence sap flows / transpiration rates, were clearly seasonal due to the deciduous nature of *J. curcas*. Maximum sap velocities in summer contrasted with a cessation of activity in the cooler and drier winter months. The resumption of sap flow after winter dormancy coincided closely with the first rains and the onset of warmer / wetter conditions in mid- to late October.

There was a very uniform response from all the probe sets to these climatic drivers and the first definitive sap-flow movements in the respective probe sets occurred within a few days of each other. This was the case, not only within a single tree, but also between different trees. Once the leaves had developed, sap-velocity responses were closely associated with ambient conditions. Responses to changes in vapour-pressure deficit (dryness of the air) were detectable from the hourly sap-velocity data.

Trends over the longer term appeared to be dictated principally by season, with the cessation of sap flow in the 2005 and 2006 years respectively, occurring within a week of each other. This was despite significantly different rainfall patterns between the years. However, the magnitude of sap velocities appeared to be influenced by moisture availability through the timing and extent of specific rainfall events. This was particularly noticeable in the magnitude of sap velocities towards the approach of winter. For example, in June 2005 sap velocities above 5 cm/hr occurred very infrequently in the trees at OSCA, while in June 2006, velocities regularly exceeded that rate.

Although transpiration trends over a year were observed to be predominantly seasonal (due to the deciduous nature of the species), the tree does appear to respond noticeably to individual rainfall events. This behaviour is driven by the amount of soil water available to the trees at any particular time, and was especially evident at the sandy Makhathini site. Good correlations between solar radiation and sap flow were also observed (the link between available energy and transpiration). This was particularly evident at an hourly scale, where fluctuations in sap flow mimicked similar hourly fluctuations in solar radiation. Obviously in deciduous trees, this relationship only holds during the growing season when there are leaves on the trees (i.e. transpiration ceases during the winter even though solar radiation and VPD may still be high). The termination of transpiration in the trees during their leafless period (dry winter months) was confirmed by the sap-flow data. The overall effect of this dormancy is that there is significantly less total annual water use due to the planting of *J. curcas* than would be the case for vegetation that is capable of transpiring year-round.

In order to investigate likely maximum transpiration rates under ideal conditions, the month during which the highest transpiration values were recorded was selected for the OSCA and Makhathini sites respectively. March 2005 was selected for the OSCA site and February 2006 was selected for the Makhathini site. The average daily transpiration totals observed at the two sites during these months were extrapolated to the rest of the summer period, and summed for a full year. At the OSCA site, allowance was also made for some winter transpiration, given the possibility that the trees might retain a portion of their leaves during an exceptionally wet and mild winter. However, this was considered to be unlikely to occur at Makhathini, given the significantly drier environment (MAP of 582 mm compared to 1016 mm at OSCA). Based on this methodology, potential maximum annual transpiration totals were calculated to be approximately 300 mm for 4-year-old trees at OSCA and 500 mm for 12-year-old trees at Makhathini in an ideal year.

A modelling exercise using the FAO56 reference evapotranspiration and crop-factor approach, used the observed transpiration results obtained in this project to back-calculate a unique set of monthly basal crop-coefficient values (K_{cb} i.e. transpiration only) for 4- and 12-year-old *J. curcas* trees. This allows for the simulation of water-resource impacts of *J. curcas* over a wider scale, and is the focus of the following chapter in this report (Chapter 5) where water-use estimates are mapped for the different climatic zones across South Africa in which *J. curcas* might be planted.

From the results described in this chapter, it may be concluded that the water use of *J. curcas* trees is generally low. The major distinction in transpiration totals between the two sites was the result of tree-size (age) differences. Scaled-up sap-flow measurements resulted in estimates of total annual transpiration to be approximately 144 mm for a 4-year-old *J. curcas* tree, and approximately 360 mm for a 12-year-old *J. curcas* tree, both being grown at a planting density of around 740 spha. These results were obtained under conditions of below-average rainfall, especially at OSCA where rainfall for the year was just 61% of the annual mean.

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CHAPTER 5: WATER-USE MAPPING[1]

5.1 INTRODUCTION

The focus of this chapter is extrapolating water-use estimates of *Jatropha curcas* (based on the findings of Chapter 4) on a national scale and comparing the estimated evapotranspirative demand for *J. curcas* against that of the Acocks Natural Veld types. The analysis is presented in ArcView maps.

5.2 METHODOLOGY

The objective of the crop water-use modelling is to compare the water use of *J. curcas* to the water use of naturally occurring Acocks vegetation types in South Africa. This section describes the methodology used to achieve this objective.

5.2.1 Determining Spatially Distributed *J. curcas* Transpiration

The method used to estimate *J. curcas* transpiration was based on the FAO 56 methodology described by Allen et al. (2004). The FAO 56 methodology calculates crop evapotranspiration by computing a reference evapotranspiration and multiplying it by an associated crop factor. There are two approaches in the FAO 56 methodology: the first calculates the crop evapotranspiration as a single entity, and the second method separates crop transpiration and soil-water evaporation as two separate entities when determining total crop evapotranspiration. Equations 5.1 and 5.2 describe these two different methods respectively.

$$ET_c = ET_o \cdot K_c \quad (5.1)$$

[1] When making reference to this section of the Report, please cite as follows: Hallowes, J. 2007. Water use mapping of *Jatropha curcas*. *In:* Holl, M., Gush, M.B., Hallowes, J. and Versfeld, D.B. (Eds). 2007. **Jatropha curcas in South Africa: an assessment of its water use and bio-physical potential.** Water Research Commission, Pretoria, RSA, WRC Report 1497/1/07, Chapter 5.

$ET_c = ET_o \cdot K_{cb} \cdot K_e$ (5.2)

Where ETc = Crop evapotranspiration,
ETo = Penman-Monteith equivalent reference evapotranspiration,
Kc = Crop coefficient,
Kcb = Basal crop coefficient, and
Ke = Soil evaporation coefficient.

The value of K_c and K_{cb} change as a crop enters different stages in the growth cycle. The value of K_e also changes on a daily basis and is dependant on soil texture, climatic conditions, the canopy cover of the crop and the soil-water content in the top 10 - 15 centimeters of the soil. If K_c or K_{cb} data for *J. curcas* were available from Allen et al. (2004), it would have been a simple process to calculate its associated water use. However, such data was not available and had to be determined through experimental measurements, which were conducted over a 17-month period during this project. The "unsmoothed" K_{cb} values determined for the two different sites are presented in Table 5.1 (Refer to Chapter 4, Table 4.8).[2]

Table 5.1: Monthly basal crop coefficient (K_{cb}) values for 4-year-old (OSCA) and 12-year-old (Makhathini) *J. curcas* trees.

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

All of these values for K_{cb} were then multiplied by monthly totals of ET_o obtained from Schulze (1997) in a GIS environment. This resulted in spatially distributed estimates of *J. curcas* transpiration in the areas of South Africa where it was possible for the crop to grow. It was possible to determine the total annual water use by adding the monthly totals. Table 5.1 illustrates that the K_{cb} values for the two different-aged trees were substantially different. The

[2] Mapping was conducted using the "unsmoothed" K_{cb} values, i.e. the values that were calculated using observed transpiration totals at the two sites.

older trees transpired substantially more than the younger trees. It should also be noted that in the younger trees, there was no transpiration from July to September, and in the older trees, there was no transpiration from July to October.

5.2.2 Determining Spatially Distributed Acocks Vegetation Evapotranspiration and Transpiration

The water use from the naturally occurring Acocks vegetation types needed to be determined for comparison purposes. The method used to achieve this was similar to that used to calculate *J. curcas* transpiration. However, because K_{cb} or K_c values for the Acocks vegetation types were not available, it was not possible to use the FAO 56 Penman Monteith reference evapotranspiration to determine Acocks vegetation evapotranspiration and transpiration. Schulze (1995) calculates the water use by plants in a similar manner to Allen et al. (2004). However, instead of using the Penman-Monteith reference evapotranspiration, Schulze (1995) utilized A-Pan equivalent evaporation, and used a crop factor, *viz* CAY, instead of K_c. It should be noted that evapotranspiration has not been measured for all Acocks veld types and many of these are expert estimates of water use. Acocks vegetation evapotranspiration could thus be obtained by using Equation 5.3.

$$ET_c = E_o \cdot CAY \qquad (5.3)$$

Where ET_c = Crop evapotranspiration,

E_o = A-Pan Evaporation,

CAY = Crop coefficient,

Values for CAY were then multiplied by monthly totals of E_o obtained from Schulze (1997) in a GIS environment to get a spatially distributed water use (evapotranspiration) from Acocks vegetation in South Africa. In order to calculate the Acocks transpiration, for comparison to the J. *curcas* results, the Acocks evapotranspiration then needed to be reduced by a suitable amount that represented the soil-water evaporation component in the evapotranspiration total. As previously mentioned, the amount of soil water evaporation is variable and dependant on a number of factors. However, it was decided, after comparing K_c and K_{cb} values, for a variety of crops in the middle and end stages of the growth cycle from Allen et al. (2004), to reduce the evapotranspiration by 10% to reflect an approximate transpiration value for the Acocks vegetation types. The monthly transpiration data sets were then added together to obtain annual values of Acocks vegetation transpiration.

5.2.3 Determining the Difference between *J. curcas* and Acocks Vegetation Transpiration

The difference between the J. *curcas* transpiration and the Acocks vegetation transpiration was calculated and expressed as a percentage relative to the original Acocks vegetation transpiration. Therefore, in some areas, the water use per month of *J. curcas* could be higher than that of the original Acocks vegetation, and in some instances, it could be lower. In the case of a higher water use by *J. curcas*, the difference was expressed as a negative percentage. In areas with a lower water use by *J. curcas*, the difference was expressed as a positive percentage. This attempted to show that in areas where water use by *J. curcas* was higher than the Acocks vegetation, a possible reduction in water availability (streamflow) may occur. The opposite was represented by a lower *J. curcas* water use, *viz* a possible increase in water availability.

5.3 INITIAL RESULTS

This section presents the water-use results based on the analysis conducted using the above methodology. This section discusses J. *curcas* transpiration, Acocks vegetation evapotranspiration and transpiration, and the annual and monthly changes in transpiration that would occur if Acocks vegetation were replaced with J. *curcas*.

5.3.1 *Jatropha curcas* Transpiration

The annual transpiration results for *J. curcas* are presented in Figure 5.1 on the following page. The results for both sets of K_{cb} values are presented. There was a large difference between the two different sets of results for the two experimental sites. These can be largely attributed to the different tree ages (refer to Chapter 4).

The transpiration by J. *curcas* based on the OSCA K_{cb} values and the Penman-Monteith Reference evapotranspiration ranged from a low of 45 mm per year to a high of 258 mm per year. These values were lower compared to the results obtained with the Makhathini K_{cb} values, which were from 140 - 789 mm per year.

It must be noted that the experimental results presented in Chapter 4 were obtained in a relatively dry year. At the OSCA site, the precipitation received during the data-recoding phase was only 61% of the mean. Therefore, the trees may have been under stress and would have had a correspondingly lower water use. Therefore, whilst it appears that the transpiration from *J. curcas* appears to be low, further monitoring under a more diverse range of climatic conditions are recommended to assess is water use in the longer term.

Note should be taken that this analysis pertains to all areas where *J. curcas* can be grown, i.e. those areas where it is too dry or have heavy frost are excluded. Cognisance also needs to be taken of the location in which the experiments were performed. Both the OSCA and the Makhathini sites are situated in Northern KZN. The results from these two sites were assumed to represent the water-use pattern across South Africa as a whole. This assumption is unlikely to hold in reality given the different seasonal rainfall patterns and wide range of climatic conditions that occur in South Africa. This further emphasizes the need for more experiments and monitoring in other regions of South Africa.

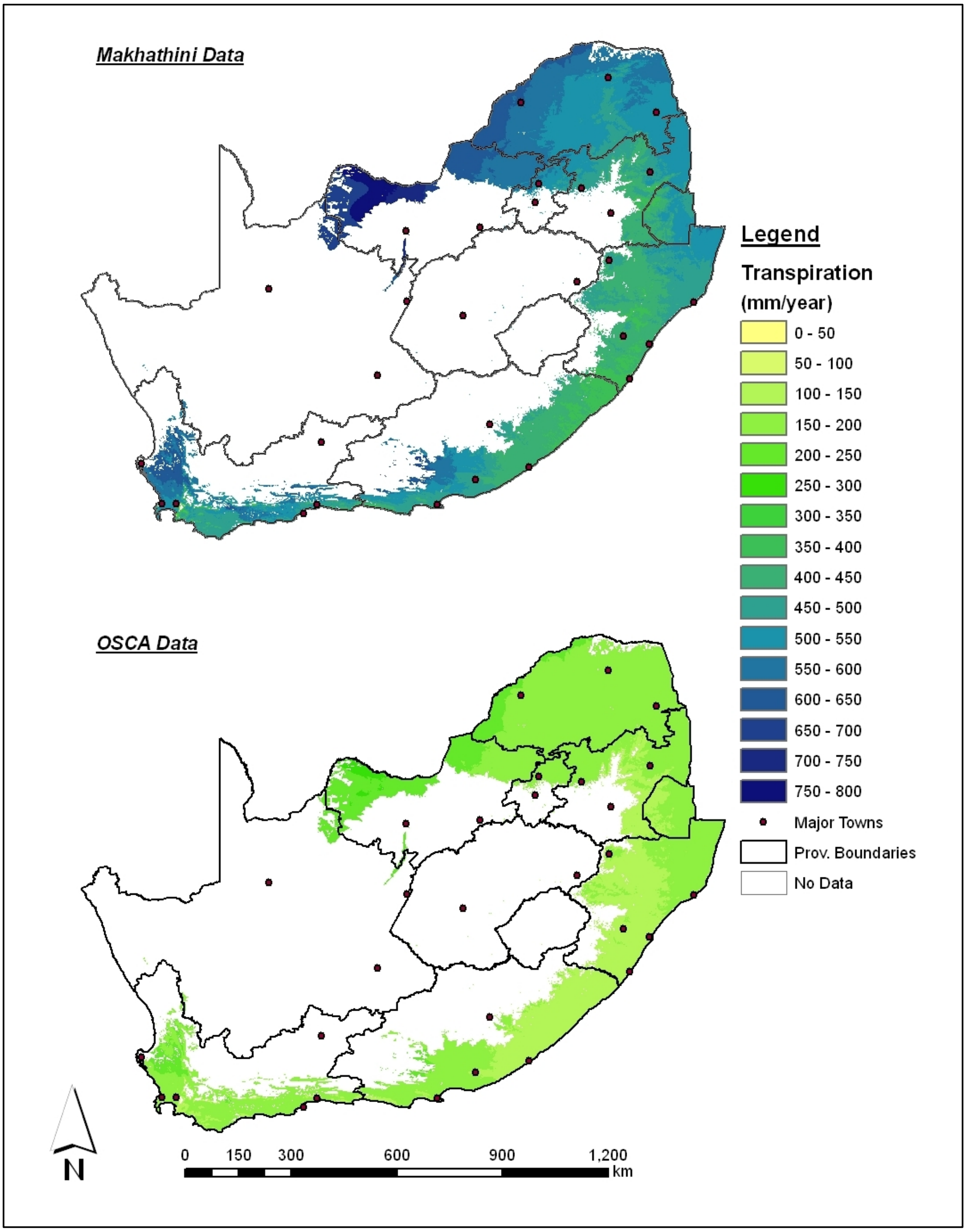

Figure 5.1: Annual *J. curcas* transpiration in South Africa based on OSCA and Makhathini K_{cb} values

5.3.2 Acocks Vegetation Evapotranspiration and Transpiration

The annual Acocks vegetation evapotranspiration and transpiration results are presented in Figure 5.2.

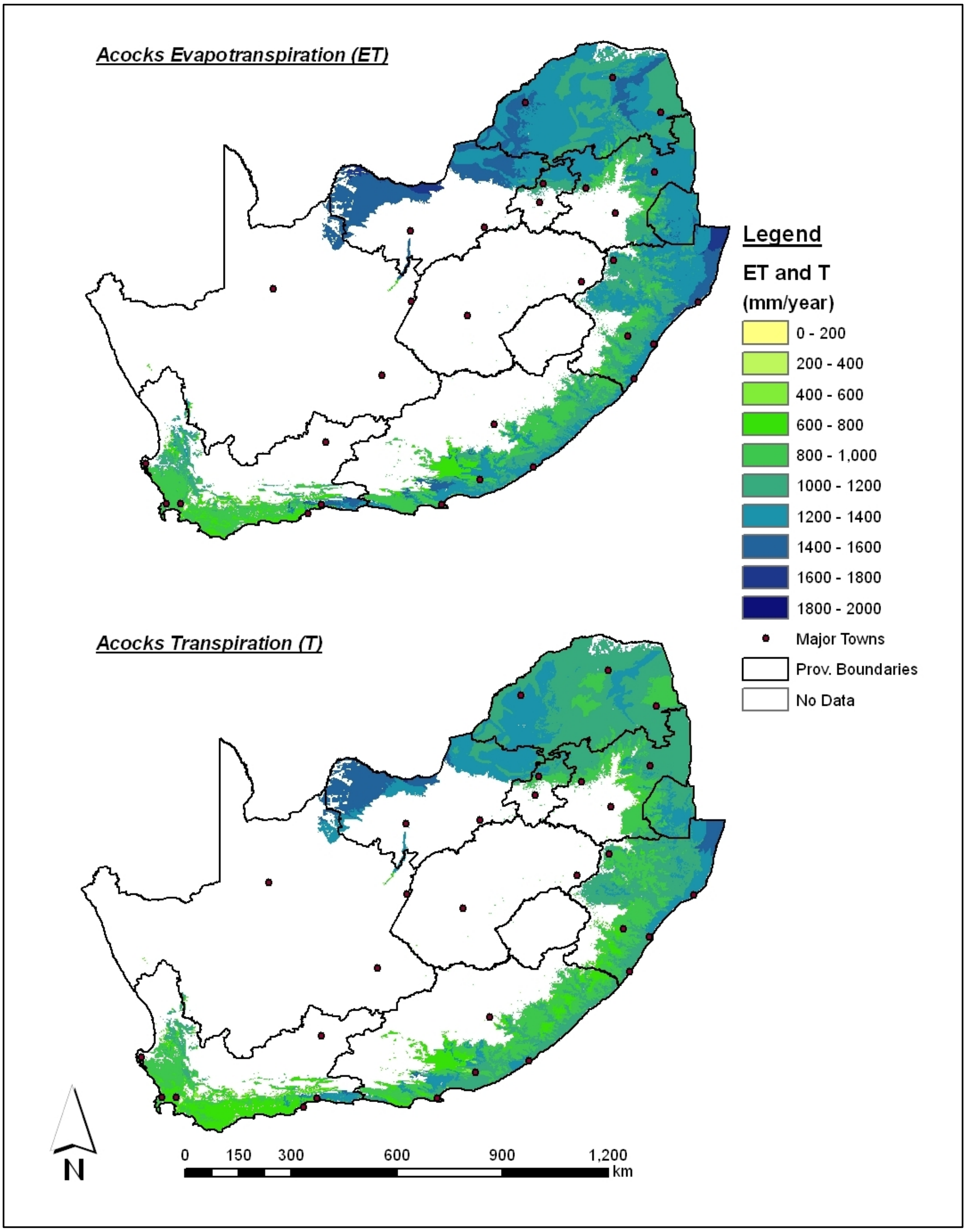

Figure 5.2: Annual Acocks vegetation evapotranspiration and transpiration in South Africa

In the areas of South Africa that *J. curcas* can be planted, the corresponding Acocks transpiration ranged from 298 - 1621 mm per year. These values were calculated by reducing the evapotranspiration by the aforementioned 10%. This was considered acceptable given the scale at which this analysis was undertaken. At a smaller scale, it is recommended that a daily modelling exercise be completed with the climate data obtained through the project and calculate the daily soil-water evaporation using procedures described by Allen et al (2004). The corresponding Acocks vegetation water can also be simulated using the ACRU model with the CAY factors that were used, but utilising a soil-water evaporation reduction that is dependant on prevailing conditions and not just a flat reduction. The actual Acocks evapotranspiration results ranged from 330 - 1800 mm per year.

From Figure 5.1 and Figure 5.2, it can be seen that the water use by J. *curcas* is considerably lower than that of the original Acocks vegetation. This was investigated in more detail at both an annual and seasonal scale and the results of this analysis are presented in the next sections.

5.3.3 Annual Changes in Vegetation Transpiration from Planting *J. curcas*

The annual changes in transpiration for *J. curcas* are presented in Figure 5.3. The impacts were determined for both the OSCA and Makhathini data sets. The equation (5.4) to determine the change in water use is defined as:

$$P_{change} = \left(\frac{WU_{Acocks} - WU_{Jatropha}}{WU_{Acocks}} \right) \times 100$$

(Equation 5.4)

P_{change}	=	Percentage change in water use
WU_{Acocks}	=	Evapotranspiration estimate for Acocks land use
$WU_{Jatropha}$	=	Evapotranspiration estimate for *J. curcas*

In terms of this equation, a positive value means that the Acocks water use (evapotranspiration) is higher than the *J. curcas* water use (evapotranspiration). In other words, planting *J. curcas* may potentially increase runoff and thus, water availability. Figure 5.3 illustrates a situation of "water availability" (represented by the yellow green and blue shades), which occurs because the transpiration of *J. curcas* is lower than the Acocks vegetation. This is largely due to the zero K_{cb} values during the months from July to September (OSCA data) and from July to October (Makhathini data).

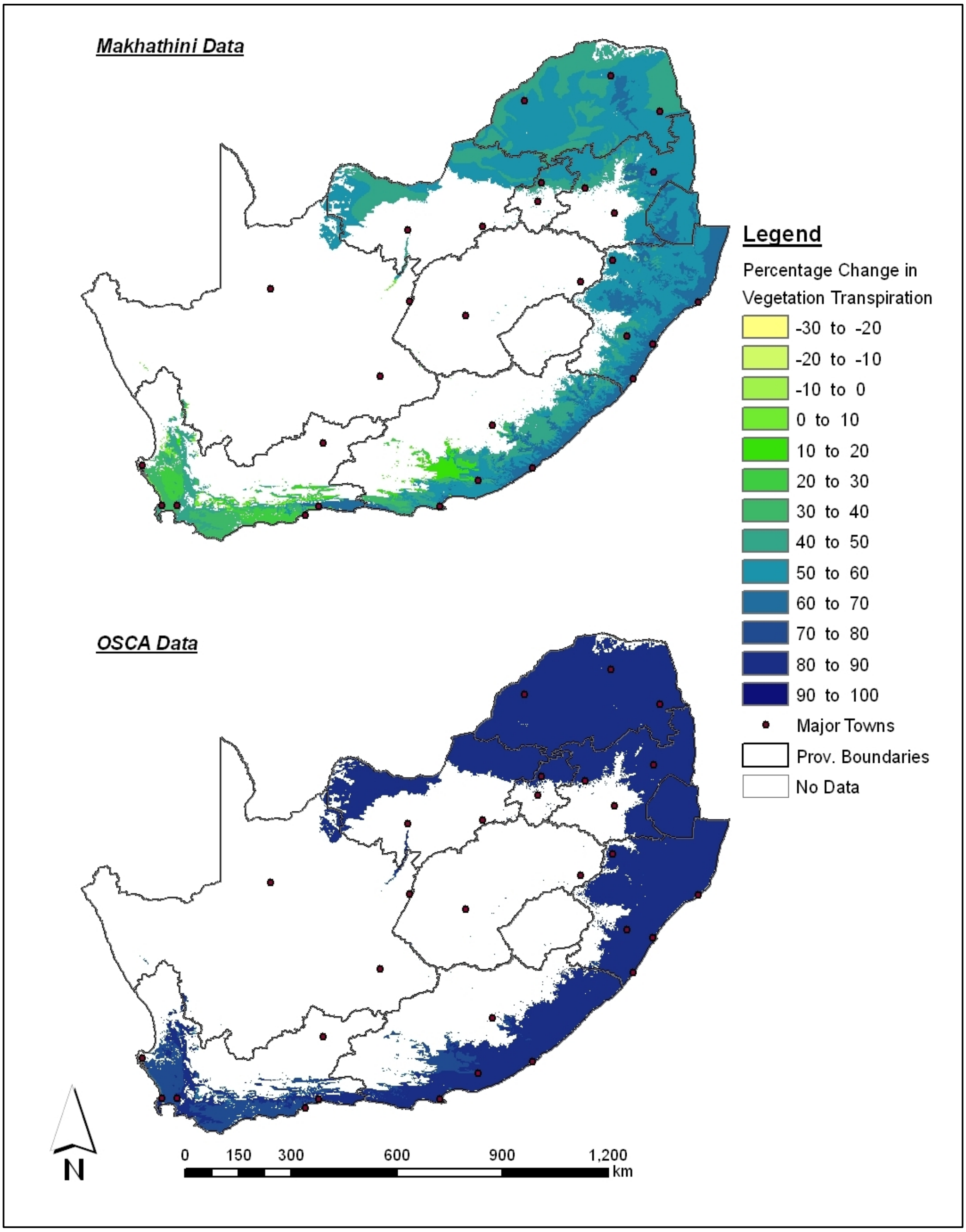

Figure 5.3: Annual percentage change in vegetation transpiration from replacing Acocks vegetation with *J. curcas* in South Africa

The experimental evidence shows that the evapotranspiration from *J. curcas* is much lower than for Acocks vegetation types throughout South Africa. This evidence could, however, be considered biased given that the experiment was carried out in a year where the rainfall was 61% of the mean. *J. curcas* has a tendency to drop its leaves and go into senescence during dry periods; thus, the evapotranspiration could be understated. In order to get a better estimate of potential evapotranspiration under normal conditions the LAI approximation relationship was developed in Figure 4.27, Section 4.3.4.5. These values were used in the water-use mapping analysis.

The evapotranspiration values from the LAI approach are shown in Figure 5.4. It can be seen that on average the estimated evapotranspiration using this approach is some 50% higher than when using the measured K_{cb} values. In Figure 5.5, the comparative water use of *J. curcas* using the LAI approach is used compared to the Acocks Veld types. It can be seen that in the majority of the country, when using the Makhathini data, there is still less impact (positive value) and potentially increased runoff if planting *J. curcas*. The picture is, however, not as pronounced as that given by the original measured estimates. One, however, must be cautious in extrapolating the results to the winter rainfall region as no experiments where performed there and the factors influencing plant growth and evapotranspiration may be very different.

It can be concluded from these estimates that *J. curcas* should still not be considered a SFRA as it produces an improvement in runoff quantity for the most of the area investigated. Given these results, a further analysis was performed using only the Makhathini information on a seasonal basis (Section 5.3.4). The Makhathini data is considered more representative as the trees are more mature, being more likely to represent values of maximum potential evapotranspiration.

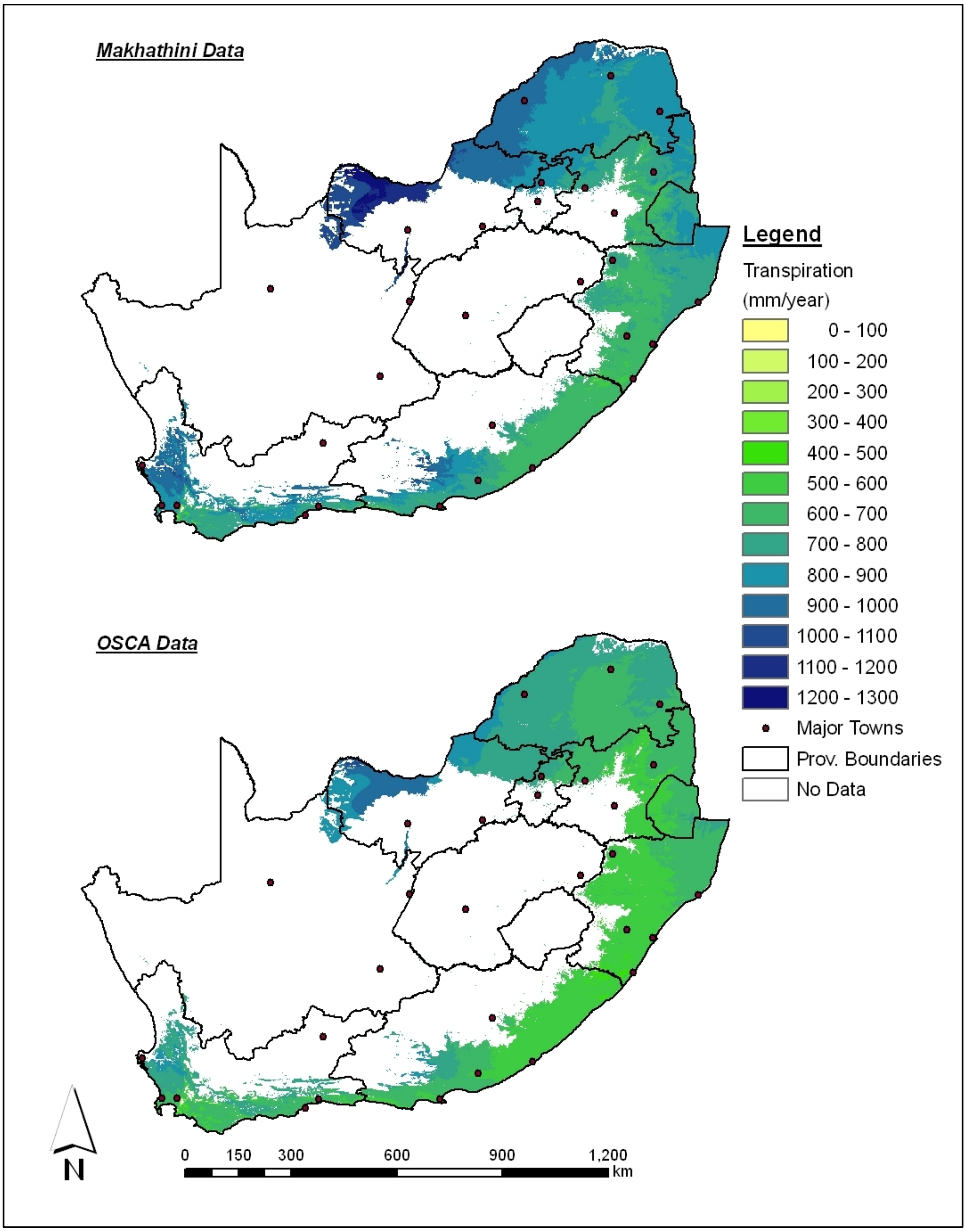

Figure 5.4: Annual *J. curcas* transpiration in South Africa based on modified OSCA and Makhathini K_{cb} values. Data was modified using a LAI relationship described in Chapter 4.

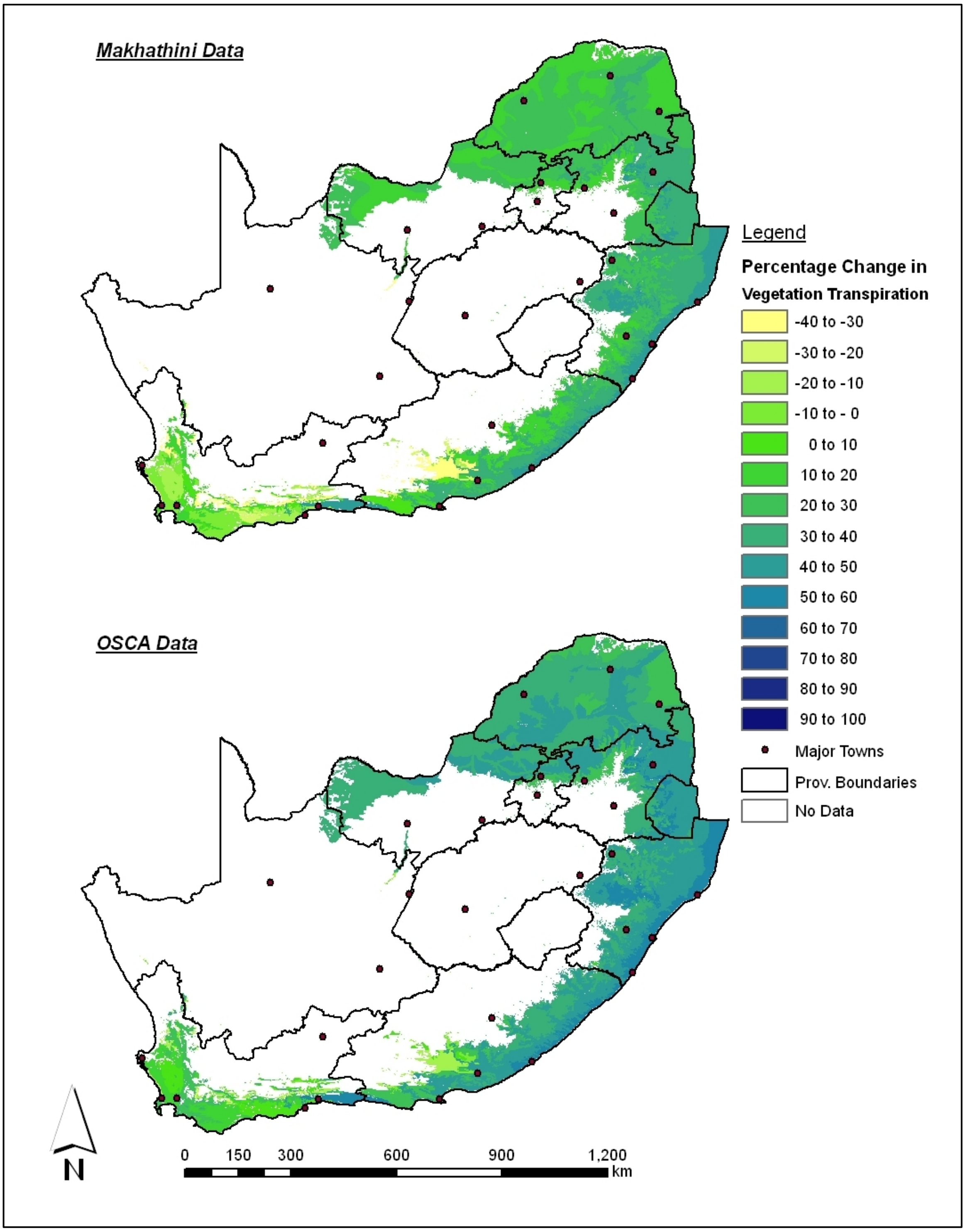

Figure 5.5: Annual percentage change in vegetation transpiration from replacing Acocks vegetation with *J. curcas* in South Africa. Data was modified using a LAI relationship described in Chapter 4.

5.3.4 Seasonal Changes in Vegetation Transpiration from Planting *J. curcas*

Jatropha curcas loses its leaves in periods of water and cold-temperature stress. Any impact on water resources is, therefore, highly seasonal. In order to establish whether the planting of *J. curcas* may bring about a temporal pattern of water stress (deficit), it is necessary to reduce the time scale and analyse seasonal results. Seasonal water use at Makhathini is presented using both the measured values and the enhanced LAI evapotranspiration estimates. For this analysis, spring includes the months September to November, summer the months December to February, autumn from March to May, and winter from June to August. The results obtained from the measured values are shown in Figure 5.6 and using the LAI relationship in Figure 5.7.

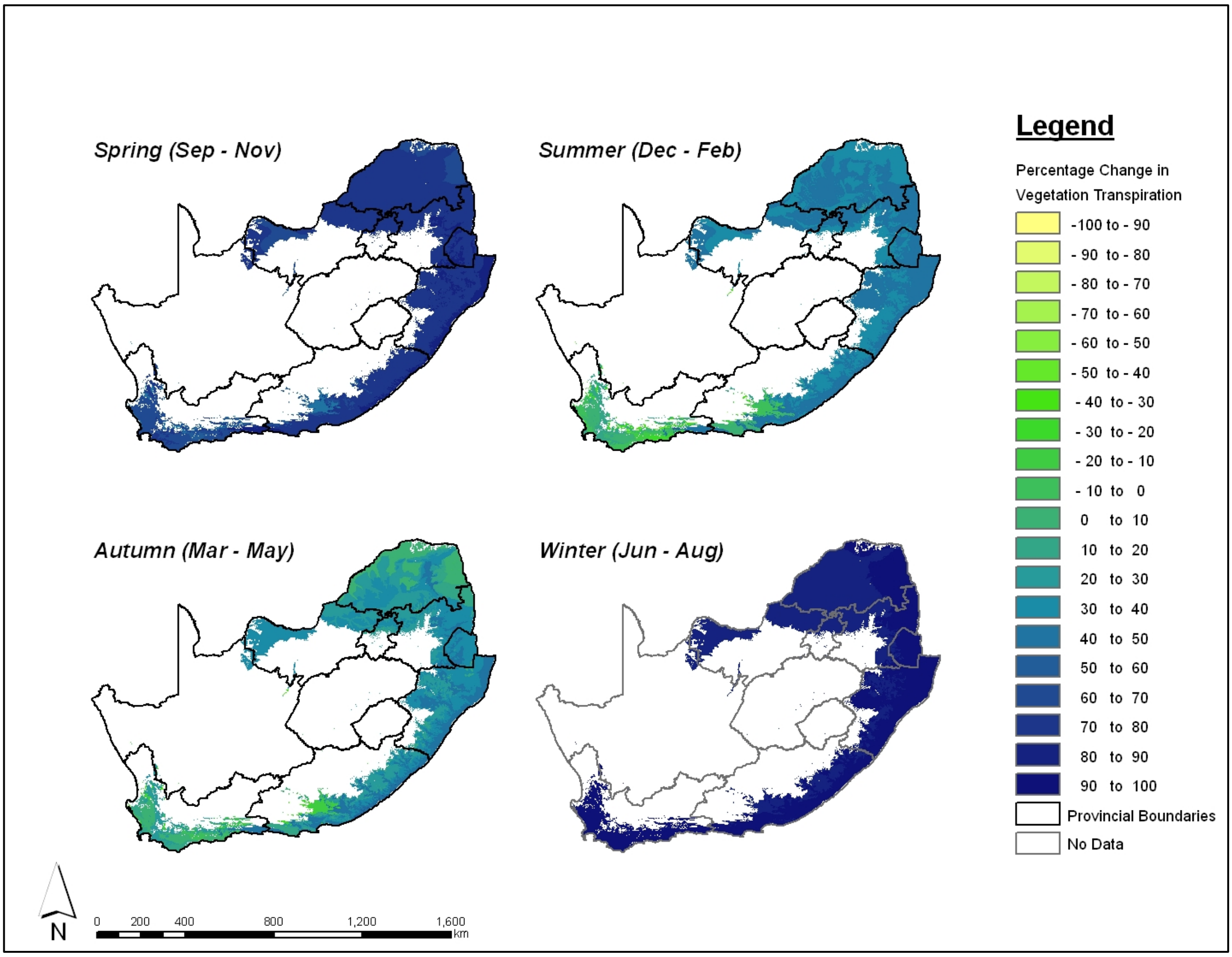

Figure 5.6: Seasonal changes in vegetation transpiration from replacing Acocks vegetation with *J. curcas* in South Africa, data displayed was derived from K_{cb} values determined at the Makhathini site.

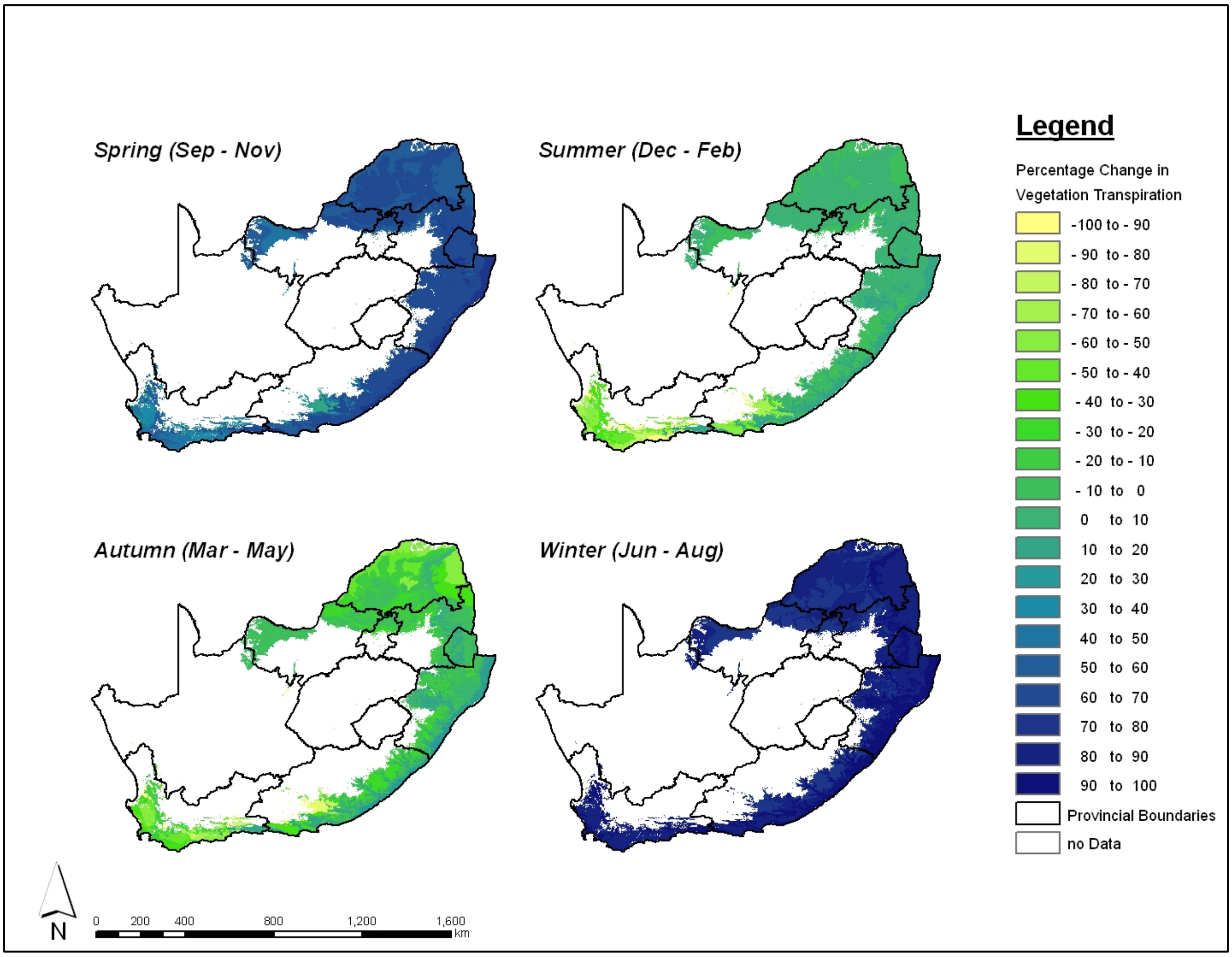

Figure 5.7: Seasonal changes in vegetation transpiration from replacing Acocks vegetation with *J. curcas* in South Africa, data displayed was derived from modifying K_{cb} values determined at the Makhathini measuring site with a LAI relationship derived by this project.

The seasonal impacts show that in the some winter rainfall areas, *J. curcas* transpires more than the existing Acocks vegetation during the summer and autumn months. This is logical, given that the natural vegetation in these areas is likely to be in a dormant phase due to the dry soil conditions resulting from low summer rainfall. However, this could be misleading and the results should be interpreted with caution. The K_{cb} data sets that were used in this analysis were derived from experiments in KZN, which is a summer-rainfall area. This highlights the need for more experiments into *J. curcas* transpiration in areas with different seasonal rainfall patterns and differing climatic conditions.

Using the LAI relationship with the enhanced evapotranspiration estimates, it can be seen that *J. curcas* has the highest water use during summer and autumn when compared to Acocks. It appears that *J. curcas* uses more water than the Acocks vegetation during autumn, reducing runoff in the north-eastern and south-western areas of the country. It should be noted that neither experimental site was in the above areas and extrapolating this information to such areas will not provide reliable results. Summer also shows similar patterns, however, for the majority of the area, no impact or minimal impact occurs. In all cases, with both experimental and LAI relationship estimates, it appears that *J. curcas* uses less water than Acocks vegetation in the winter and spring months. These estimates may, however, be low as *J. curcas* is dormant during the winter months, losing its leaves. Leaf loss does not occur consistently and depends on the both water availability and temperature factors.

Indications at present suggest that *J. curcas* is unlikely to use more water than natural vegetation in many areas. These results should however, be viewed with caution as they are based on paucity of experimental information.

5.4 CONCLUSION

From the results that were obtained from the GIS analysis, it appears as though *J. curcas* is unlikely to have a negative effect on annual streamflow in South Africa. This is because it uses less water at an annual scale than the original Acocks vegetation that it would replace. However, on a seasonal scale, the analysis reveals that *J. curcas* may use more water than the original vegetation in some areas at certain periods of the year. This is particularly evident from modelling for the winter rainfall areas of the Western, Eastern Cape and Limpopo provinces. This occurrence could be caused by the crop factors for *J. curcas* being based on measurements recorded in KZN, which receives summer rainfall. Therefore, the results from the maps are more pertinent for summer rainfall areas than winter rainfall areas. This needs to be kept in mind when identifying possible regions for planting *J. curcas* in South Africa.

It should be remembered that these conclusions have been based on a 17-month experiment at two sites in a climatically similar area. The results may, thus, not transfer well in terms of spatial and temporal extrapolation; thus, it is pertinent to bear in mind the following aspects associated with this analysis:

- The assessment is based on a 17-month experiment at two sites in KZN. Both sites experienced lower than normal rainfall. *Jatropha curcas* generally loses its leaves and senesces during dry periods. The evapotranspiration could be higher than recorded in this experiment on a larger scale.
- The experiment was performed in a summer-rainfall region and the crop-water use/ transpiration patterns could significantly change in areas of winter rainfall.
- *Jatropha curcas* tree does not always lose its leaves during winter; thus, evapotranspiration could be higher in warmer, wetter areas.
- The tree age has a clear impact on the transpiration rate; thus, the older-tree estimate should be taken as the more likely scenario of water use/ transpiration
- The estimate of soil evaporation was not taken into account and a rather crude assessment of the likely level of contribution was used. This may need to be revised with better estimates at a later date.

From the results obtained in this analysis, it appears that if *J. curcas* were to be planted, an increase, as opposed to a reduction, in observed streamflow might well be evident. However, this is largely dependant on the assumption of soil-water-evaporation levels constituting 10% of total evapotranspiration.

It also needs to be emphasised that there are other extremely important aspects, beyond the scope of this study, which should be carefully considered before the species is promoted for wide-scale poverty alleviation / bio-diesel production. These include its potential invasiveness / threat to biodiversity, economic returns given the costs of harvesting seeds, the toxicity of the plant to humans and animals, and the ease with which established plantations may be removed and converted to alternative land uses.

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CHAPTER 6: PERCEPTION ANALYSIS[1]

6.1 INTRODUCTION

One of the goals of this project was to gauge the perceptions and levels of understanding of SFRA processes and licensing amongst *Jatropha curcas* users and other interested parties through a qualitative research process. This chapter responds to this goal and describes the methodology applied and the analysis of the data collected during the survey process. The chapter concludes with some discussion on the implications of these findings.

6.2 METHODOLOGY

The perception assessment followed a qualitative approach and consisted of two independent surveys.

The first target group consisted of stakeholders responsible for monitoring and legislation and therefore comprised of employees from Government departments (Department of Water Affairs and Forestry (DWAF), Department of Agriculture (DoA) and the National Energy Regulator). In-depth personal interviews were conducted with these participants in order to clarify their stance on *J. curcas* and the issues around it.

The second target group consisted of potential producers and processors of *J. curcas*. Noting the interested parties that contacted the project team for information about *J. curcas* and the research being conducted, throughout the course of this project, generated a list of potential survey participants. Telephonic in-depth interviews were conducted with respondents and a semi-structured questionnaire used as data gathering instrument

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[1] When making reference to this Section of the Report, please cite as follows: van Vuuren, S. and Holl, M.A. 2007. Perceptions related to *Jatropha curcas*. *In:* Holl, M., Gush, M.B., Hallowes, J. and Versfeld, D.B. (Eds). 2007. **Jatropha curcas in South Africa: an assessment if its water use and bio-physical potential.** Water Research Commission, Pretoria, RSA, WRC Report 1497/1/07, Chapter 6.

6.3 RESULTS OF INTERVIEWS WITH SELECTED DEPARTMENTS

The key issues highlighted during the interviews were the potential invasivity of *J. curcas*, water use potential of the plant, food security issues and the economic viability of planting *J. curcas*, particularly with regard to the poor. In essence, the interviews with selected regulators and monitoring agents illustrated that there is a critical lack of knowledge when it comes to *J. curcas* and the implications of potential large scale planting in South Africa. The country has no experience of the crop whatsoever.

Government is certainly aware of the potential invasivity of *J. curcas* (it has been classified as a weed in Australia because of the supposed high risk of invasions) and this is a concern raised by the departments interviewed. The Department of Agriculture views *J. curcas* is a potential invasive and it has therefore been listed as a restricted plant according to the Conservation of Agricultural Resources Act (CARA). DWAF has suggested that a levy be imposed on all new plantations where there is any doubt as to the invasivity of crops so that funds are available to deal with the possible invasive plant problems at a later stage (DWAF Position Paper, 2004). The Working for Water Programme has been raising the issue of the potential invasivity of *J. curcas* since the beginning of this research project and deems it a key factor for consideration. There is no experience of actual invasivity within the country, perhaps not surprising given its extremely limited distribution, and experience has to be drawn from elsewhere. It is not clear who is taking responsibility for determining the invasive nature of *J. curcas* in the South African context.

Some individuals outside of DWAF and the Department of Agriculture perceive potential invasivity as less of a problem because government has allowed the planting of other invasive species, such as black wattle, in the past. Clearly, however, there is awareness around the seriousness of invasivity amongst most stakeholders, and government’s stance is understood.

DWAF confirmed that if *J. curcas* is found to use large amounts of water, then the Department will consider declaring it an SFRA and regulating the growing of the crop. Prior to this research project *J. curcas* could not be considered to be an SFRA because virtually nothing was known about its water use. Although preliminary results already available to Government, through this project's research, show that *J. curcas* does not seem to be a major water user and is therefore unlikely to qualify as an SFRA, DWAF remains concerned that large scale planting could have a significant impact on the stability of catchments and, as such, the crop is of both hydrological and environmental concern (DWAF Position Paper, 2005).

Both DWAF and DoA indicated that a further area of research, particularly considering the interest generated around *J. curcas* as a biofuel crop, should be to assess the water use of *J. curcas* versus other potential biofuels crops such as maize and sugar cane. The current research project may be sufficient to allay this although there does need to be expansion across climatic zones, and no attention has yet been given to irrigation.

Poverty alleviation was mentioned as a key consideration by all three government departments, who indicated that it is important to regulate potential land misuse and the exploitation of rural people by individuals looking to make a profit. Investors are potentially looking for huge tracts of land on which to grow biofuel crops (of which *J. curcas* could be one) and this land will likely be in the hands of poor, rural communities throughout the country. Linked to the issue of poverty alleviation is that of food security. The Department of Agriculture specifically mentioned that an assessment would have to be determined as to whether a (poisonous) non-food crop should be planted in areas where food crops could also be planted. In this regard, the Department of Agriculture has released its own position statement on biofuel crops and the potential threat to food security.

DWAF highlighted the fact that *J. curcas* appears to grow well in areas suitable for forestry and that the crop will have to show higher returns than forestry if it is to generate an interest amongst potential investors. Whether or not this is the case must still be determined although, based on economic analysis conducted to date (Hallowes, 2005) it appears as if *J. curcas* is unlikely to generate economic yields competitive with forestry.

Currently the Department of Minerals and Energy (DME) is responsible for the regulation of biofuel plants whereas the Energy Regulator acts as an advisor to the DME. The Department of Minerals and Energy is actively promoting the planting of crops for the purpose of producing biofuels (National Biofuels Strategy, 2006), aimed at meeting the target of 5% of total national energy fuel needs, and *J. curcas* is one of the crops being considered by investors.

The Energy Regulator perceives both DWAF and DoA to be opposed to *J. curcas* due to issues such as invasiveness, water use, economic viability and benefit to land owners. However, the interviewee claims this is a contradiction because other invasives have been allowed, animals naturally avoid toxic food materials, *J. curcas* has the potential to contribute towards poverty alleviation and it is not clear how much water *J. curcas* requires. The perception of the Energy Regulator is that *J. curcas* can be planted on marginal and degraded land and will therefore not interfere with food related crops. The Energy Regulator, being target-driven and perhaps not adequately aware of the legislation and policy guiding the regulation of crops in South Africa, focused more on the potential benefits of growing *J. curcas* as a biofuel crop than on the concerns raised by DWAF and DoA.

The Department of Agriculture noted that only a small part of South Africa might be suitable for growing *J. curcas*. (The research findings in Chapters 3 and 5 illustrate that this is in fact the case.) The Department reflected on a case in the North West Province where millions of Rands were apparently spent on growing *J. curcas*, discovering too late its sensitivity to frost, and losing the investment. DWAF visited another potential *J. curcas* site in Limpopo province in 2005 where investors were considering planting 15,000 hectares, only to find that the area would not be suitable for the crop at all. These two cases illustrate the critical lack of correct information available on *J. curcas*. The interviewee with the Energy Regulator also claimed that

J. curcas is a common sight in KwaZulu-Natal, a clear misperception as this project struggled to find any material on which to conduct water use research (see Chapter 4 on site selection).

DWAF is responsible for implementing and regulating the National Water Act (Act 36 of 1998), and for determining policy and legislation related to water use potential of crops. If *J. curcas* were declared an SFRA then DWAF would become responsible for regulating the crop. However, until such time that *J. curcas* is declared a SFRA (and from this report that seems most unlikely), DWAF will rely on decisions made both by the Department of Environmental Affairs and Tourism (DEAT) and the DoA in terms of NEMA and CARA offering sufficient protection to water resources and catchments (DWAF Position Paper, 2004). The DoA has taken a very strong line on the wide-scale planting of *J. curcas* for bio-diesel production due to the concerns discussed above and declared a moratorium on all further planting of the species for the next three years in July 2005, until such time as growth, water use, productivity and invasiveness have been adequately researched (DWAF Position Paper, 2005).

It is evident that the key government departments (particularly DEAT, DoA and DWAF) should adopt a consensus around *J. curcas* and communicate their position to other government departments and the general public.

6.4 RESULTS OF INTERVIEWS WITH POTENTIAL PRODUCERS

There were five respondents to this component of the project, which does not allow for a quantified approach to data analysis, rather the general trends and perceptions identified are discussed with a view to inform the discussion around *J. curcas*.

Most of the respondents are considering growing and processing *J. curcas* in South Africa. The respondents have been primarily dependent on the Internet in conducting research on *J. curcas.* As has been determined during the course of this study the Internet offers very little information on the bio-physical requirements, water use and potential yield of J. *curcas*. It is therefore unlikely that potential growers have all of the information necessary to make an informed decision about planting *J. curcas*. Even this study, which is definitive in its gathering of knowledge, points to huge gaps and uncertainties both nationally and internationally. None of the respondents had contacted any government department in South Africa about *J. curcas*.

When asked in which areas the respondents were considering planting *J. curcas* they mentioned the North West Province, KwaZulu-Natal, Limpopo Province and Namibia. As indicated by the analysis in Chapter 3, KwaZulu-Natal and Limpopo province are areas that can potentially sustain *J. curcas*, while only small areas of the North West Province are considered suitable due to the occurrence of frost.

Respondents are considering planting areas of *J. curcas* from as small as 3 hectares up to 130,000 hectares. The respondents expected to harvest for the first time between 1.5 years to 2 years after planting. From the literature review (Chapter 2) in this report it is known that under good rainfall conditions, *J. curcas* starts producing seeds within 12-18 months but reaches its maximum productivity level after 4 to 5 years. From this perspective, respondents have a general idea as to the length of time required to harvest.

When respondents were asked about harvest output, responses varied between 7 tons/ha to 18 – 20 tons/ha and up to 80 tons/ha. Based on the literature review (Chapter 2) 2-3 tons of seeds/ha can be achieved in semi-arid areas for mature trees, although yields of 5 tons/ha are routinely achievable under more favourable (wetter) conditions (Becker and Makkar, 2000). The analysis conducted in Chapter 3 illustrates that the highest yields can be obtained along the coastal areas along the KZN and Eastern Cape coast and inland on the eastern slopes of the escarpment (Drakensberg Mountains) in Mpumalanga where potential yields of over 8 tons/ha may be produced in some areas. Many other areas could produce yields of over 3 tons of seed per ha. The analysis also shows that areas in the northern parts of the country and along the southeastern seaboard will produce low yields in the order of a less than 2 tons/ha. It must be remembered that seed yields about 35% oil, a yield of 3 t of seed therefore supplying about 1 t of oil.

It is evident that respondents are ill-informed about the potential yields that can be achieved by planting *J. curcas* in South Africa. Unrealistic yield expectations were witnessed amongst stakeholders and interested parties throughout the project and the survey results confirm this.

Respondents indicated that the main motivation for planting *J. curcas* was for the purpose of producing Biofuel/diesel.

Respondents were generally uncertain about the amount of water *J. curcas* requires to grow. The perception of one respondent was that it requires “very little” water to grow while another believes it requires “quite some” water to grow. This uncertainty is not surprising considering that information of this kind has been unavailable in local and international literature. This project is the first to produce water use estimates for *J. curcas*. *Jatropha curcas* is viewed exclusively as a dryland crop, although the literature review (Chapter 2) refers to the benefits of irrigation, particularly on establishment. The irrigation of *J. curcas*, and this applies to most biofuel crops, is not part of the South African mindset at the moment – although this situation may well change.

Most respondents were aware that *J. curcas* is a potentially invasive species and is potentially toxic to humans if eaten. This is not surprising considering that this type of information is readily available on the Internet and through local and national literature.

Only two of the respondents indicated that they are aware of DoA’s moratorium on the planting of *J. curcas* and only one indicated that he was aware that *J. curcas* was being considered as a potential SFRA. Respondents are generally not aware of the implications of such declaration, although most respondents did seem to understand the meaning of Stream Flow Reduction Activity.

6.5 CONCLUSION

Key government departments have a number of concerns about planting *J. curcas* in South Africa. The propagation of *J. curcas* has been pushed to the forefront due to the recent renewed interest in its potential as a biofuel crop. It is important to assess the *implications of widespread planting*, not only from a water use perspective, but also in terms of its potential environmental, social, economic and ecological impacts, before government makes unwise decisions on either promoting or unduly regulating the crop.

From the interviews with potential growers and processors of *J. curcas* it is evident that they are not well informed regarding establishment, survival and yield, areas which show growth potential, water use implications, and government's position on *J. curcas* as a potential SFRA and alien invasive. The private sector interest in *J. curcas* has largely been stimulated by the perceived potential to generate biofuel/diesel, although economic analysis (Hallowes, 2005) illustrates that this is not a lucrative option. *Jatropha. curcas* has been presented as a wonder-plant when, in reality, very little is known about it and actual large-scale success stories cannot be found. Due to the lack of knowledge about *J. curcas* amongst potential growers and processors it is important for government to engage with these stakeholders and disseminate correct information so that educated decisions can be made.

6.6 REFERENCES

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CHAPTER 7: CONCLUSION

7.1 SYNTHESIS OF RESEARCH FINDINGS

Jatropha curcas has been heralded as a crop with major rural-development potential – primarily for the production of biodiesel through its oil-bearing seeds, although there are other potential uses – notably soap making, and medicinal. Neither the plant itself, nor its seeds, are edible. Very large projects are proposed for plantations of *J. curcas* - in India, Madagascar, Mozambique and also South Africa, driven by commercial interests. A worldwide literature review, conducted as part of this study, uncovered considerable enthusiasm but very little hard fact, and very little evidence of successful commercialisation. There is no evidence of any work related to water-use or impact on water resources.

Perceptions in South Africa amongst potential developers (growers) have been driven by the above enthusiasm, but may be misguided due to the lack of knowledge – and plans for extensive planting have not been based on experience of biophysical capability, nor with any understanding of potential impact. The national Departments of Agriculture, Environment Affairs and Water Affairs and Forestry have expressed concerns with regard to food-security and water-resource impacts, invasivity and biodiversity. This resulted in the Department of Agriculture placing a three-year moratorium on the planting of *J. curcas* (2004-2007) and the Department of Water Affairs and Forestry requesting that the Water Research Commission support research on water-use aspects, and whether *J. curcas* should be declared a Stream Flow Reduction Activity.

The results of this study are simple and startling. In the first instance, *J. curcas* may be drought-resistant but will not be economically productive outside of areas of relatively high rainfall (typically >800 mm). The coastal and high rainfall belts of the Eastern Cape, KZN and Mpumalanga can be expected to produce viable crops (3-8 tonnes of seed per hectare) but not the arid interior. *J. curcas* is also sensitive to frost, ruling it out for much of the country. Growers must take note of these results. A study into the economics of the crop has also shown that harvesting is very labour-intensive, often negating any chance of profitable cultivation.

Very few extant sites where *J. curcas* is being grown could be located within the country – and water-use research measurements were limited to trees planted in a kraal fence-line in Makhathini (northern KZN) and a small agricultural research plot close to Empangeni - tropical to sub-tropical locations. Water-use research showed a strongly seasonal response, with dormancy being largely rainfall related, the low-rainfall season also coinciding with cooler winters. Although rainfall over the trial period of 17 months was lower than normal, and results must be treated with some caution, *J. curcas* appears to be a relatively conservative water user. Extrapolation of results using climate modelling and mapping across the country, shows that *J. curcas* cannot reasonably be considered a Stream Flow Reduction Activity. On the contrary, it is often modelled to use less water that the natural vegetation it might replace – primarily a consequence of strong drought-induced dormancy. There are particular dangers, however, in extrapolating results from the summer-rainfall region to the winter-rainfall Western Cape.

This chapter makes recommendations with regards to potential growth areas, yield and the water use of *J. curca*s in addition to giving strategic recommendations about the future propagation of *J. curcas* in South Africa. Areas for further research are also provided in an attempt to point out information gaps.

7.2 RECOMMENDATIONS

- *Jatropha curcas* can be most successfully grown in South Africa along the Eastern Escarpment and most areas along the coast. Rainfall is a strong determinant of both survival and productivity (yield) despite the plant's reputation for drought resistance. The species has very limited resistance to frost. Places where highest yields would be obtained are in KwaZulu-

Natal, the Eastern Cape and certain areas of Mpumalanga. Any investigation and investment should be focused on these areas, which also coincide with areas showing the highest poverty indices.

- *Jatropha curcas* may survive but will not provide economic yields in the arid interior. Areas of low and variable rainfall, and areas susceptible to anything more than mild frost, should be avoided.
- The water-use results of *J. curcas* presented in this report can only be reliably applied to the summer-rainfall areas. The lack of water-use measurements in the winter-rainfall region means that extrapolations to the Western Cape, although attempted here, need to be treated with caution, particularly as the climatic impact on dormancy is not known.
- From the water-use measurements and modelled impacts on water resources, it would appear that *J. curcas* is unlikely to have a negative impact on stream flow. Water use does not seem to exceed that of the natural vegetation, which it might replace. **From this evidence, *J. curcas* would not be eligible for declaration as a Stream Flow Reduction Activity**. Reasons for this are the apparently conservative water use by the plant, and the strong seasonality (dormancy) exhibited on the measured sites.
- The impact of planting *J. curcas* on water resources can be spatially extrapolated by incorporating evapotranspiration estimates into a physically based hydrological model. Impacts can be considered for specific sites – within the limitations of the model and recognising that there is still very little actual measured data.
- *Jatropha curcas* has been presented as a wonder-plant when, in reality, very little is known about it and actual large-scale success stories cannot be found. Care should be taken in promoting the wide-scale propagation of *J. curcas.*
- Due to the lack of information and knowledge about *J. curcas* amongst stakeholders, it is important for government to engage with these stakeholders and disseminate correct information so that educated decisions can be made.

7.3 AREAS FOR FURTHER RESEARCH AND DEVELOPMENT

7.3.1 Water Related

- These are the first and the only known measurements of water use by *J. curcas* anywhere in the world. The assessment was for only two sites (two trees per site) and was based on a 17-month period when rainfall was lower than normal. More measurements are needed. The evapotranspiration estimates should be revisited for more sites, with a wider range of climate and age-class variation, and for a longer time frame than initially provided in this analysis.
- If there is any likelihood of *J. curcas* being gown commercially in the Western Cape, then water-use measurements should also be conducted in the winter-rainfall area.
- To maximize the benefits of already available information, the climatic data obtained should be combined with soil and canopy-cover information at the two study sites, so as to calculate the soil-water-evaporation component of total evapotranspiration. This should be completed in accordance with guidelines established by the Food and Agricultural Organisation (FAO56). Once total *J. curcas* evapotranspiration has been obtained for the two study sites, knowledge of the relationship between K_e and K_{cb} for the trees in different stages of its growth cycle and time of year could be used. This will assist in future comparisons with other field crops and vegetation types
- The water-use efficiency associated with economic returns should be investigated in more detail

7.3.2 Other

- Trial plots using plants of different provenances should be established in different parts of the country. These should be designed to meet research needs with regards to water use, dormancy, growth and productivity, and economic value
- The yield equations and mapping should be revisited in more detail when more information becomes available

- A more complete economic analysis should be performed as better costing and other information becomes available
- A market analysis should be performed for the production of soap using oil pressed from *J. curcas* seeds
- An economic analysis of the other products is required, especially those for medicinal purposes
- A task team should be established to assess planting projects and the production of *J. curcas* elsewhere in the world in order to evaluate successes and failures. This would probably necessitate a tour of these sites, as little practical information is available from the literature. It is imperative that a critical evaluation of this nature be undertaken before further investments are made, and particularly before large areas of land are devoted to the planting of *J. curcas*
- The invasivity of *J. curcas* in South Africa should be made the subject of a specific research project, including an investigation of existing sites in both South and southern Africa.