Agroforestry Systems For Improved Productivity Through The Efficient Use Of Water

Report to the
WATER RESEARCH COMMISSION

by

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executive summary

1. INTRODUCTION

The relatively low rainfall and limited arable land in South Africa make it imperative to effectively and efficiently use its natural resources for food and fibre production. This is even more important for emerging and subsistence farmers whose practices often lack access to information and use of production technologies.

Agroforestry systems, (whereby there is a deliberate planting of trees in combination with food/forage crops for the benefit of people and the environment) have been reported to be potentially productive in degraded and marginal soils. However, in South Africa, the implementation of agroforestry systems has been relatively slow and may be attributed to lack of farmer knowledge on applicable crop and tree combinations. A major challenge is to build the capacity of small-scale farmers to implement agroforestry systems to increase production and food security. The aim of this project was to implement on-station agroforestry systems to determine their impact on water and plant production.

The objectives of the project were to:

- Synthesize knowledge available locally and internationally on agroforestry systems (combinations of trees and crops).
- Select two different bio-climatic zones for study areas (preference to areas with relative lack of research).
- Select one or more applicable agroforestry systems per bio-climatic zone based on consultation with a cross section of end-users to include local knowledge (in the relevant bio-climatic zone and stakeholder review/endorsement of selections).
- Select one or more tree and crop species combination per agroforestry system based on consultation with a cross section of end-users to include local knowledge (in the relevant bio-climatic zone).
- Design on-station trials with appropriate controls.
- Establish on-station trials with appropriate controls.
- Conduct appropriate water dynamics, soil fertility/health dynamics and plant productivity measurements on-station to understand the production processes with particular reference to efficient use of water.
- Use such understanding to develop or refine applicable computerized models to extrapolate results from on-station to on-farm.
- Undertake technology transfer in the form of information days and/or demonstrations to local communities/ NGOs/CBOs and extension services.
- Document impact of the selected agroforestry systems on efficient use of water, soil health dynamics and plant production.

2. AGROFORESTRY IN SOUTHERN AFRICA AND POLICY PERSPECTIVES

This review of the development of agroforestry and policy in South Africa concluded that in South Africa there was a lack of participation in agroforestry due to poor development of cross-sectoral policy at regional and national levels. In South Africa, the past focus has been on intensive production by individual directorates, agriculture on the one hand and forestry on the other. The incorporation of agriculture and forestry into the same department in 2009 should provide the consolidated support for the development of new agroforestry policy in the future.

3. AGROFORESTRY SYSTEMS: SITE AND SPECIES SELECTION

The major part of the study was conducted at the University of KwaZulu-Natal's Research Farm (Ukulinga) outside Pietermaritzburg (Coast Hinterland Thornveld bioclimatic zone). In addition, lessons learnt from an on-farm agroforestry project (funded by the WRC-K5/1351) in the Southern Tall Grassveld bioclimatic zone were used to address the problem of fodder shortage for small scale dairy farmers.

Choice of crops in agroforestry systems will depend on the farmers' specific objectives. The potential crops that included traditional crops as well as new crops that had shown potential elsewhere were: Pigeon pea (*Cajanus cajan*), maize (*Zea mays*), cowpea (*Vigna unguiculata*), pumpkin (*Cucurbita pepo*), Guinea grass (*Panicum maximum*), weeping lovegrass (*Eragrostis curvula*), kikuyu (*Pennisetum clandestinum*), and velvet bean (*Mucuna pruriens*).

Potential tree species were: Leucaena (*Leucaena leucocephala*), mulberry (*Morus alba*), sweet thorn (*Acacia karroo*), fever tree (*Acacia xanthophloea*), black wattle (*Acacia mearnsii*) and physic nut (*Jatropha curcas*).

The potential species were tested to give farmers various options for agroforestry systems (alley cropping, fodder banks and silvopastures) depending on their specific objectives.

4. PRODUCTION IN ALLEY CROPPING SYSTEMS

4.1. Effects of alley cropping *Cajanus cajan*, *Mucuna pruriens* and maize on production and soil fertility.

The experiment was a randomised block (three blocks) each with five treatments.
List of treatments:

1 Sole Maize (*Zea mays*) for control
2 Maize and chemical fertilizer (46% Urea)
3 Maize and Pigeon pea (*Cajanus cajan*) (also for control)
4 Maize, Pigeon pea and chemical fertilizer (46% Urea)
5 Maize, Pigeon pea and Velvet bean (*Mucuna pruriens*)

The results from this trial are not available as the MSc student (Inacio Nhancale) returned to Mozambique without completing his study after monkeys destroyed the crops.

4.2. The Production Potential of Alley Cropping of *Leucaena leucocephala, Morus alba*, and *Acacia karroo* intercropped with maize.

The trial was a randomised block design with four treatments (6.5x2.5 m in size) replicated six times. During the second season of planting (2003), *L. leucocephala* yielded a significantly higher fodder yield (1715 kg ha^{-1}; $p<0.001$) than *M. alba* (1101 kg ha^{-1}) and *A. karroo* (1140 kg ha^{-1}). Although *M. alba* produced higher fuel wood (728 kg ha^{-1}) in 2003, it is less suitable to address fodder deficits as it put most of its energy into wood growth and not fodder.

In the intercropped treatments the highest grain yield (1078 kg ha^{-1}) was recorded in the *A. karroo* plots, while *M. alba* had the least production (774 kg ha^{-1}). The maize stalk yield from *L. Leucocephala* (1989 kg ha^{-1}) and *A. karroo* (2349 kg ha^{-1}) plots had higher production than the control plots (1849 kg ha^{-1}) while that of *M. alba* was low (1608 kg ha^{-1}).

In this study, *L. leucocephala* proved to be a good potential tree species for use in alley cropping practices. Even during the dry periods that occurred in the second season of the trial *L. leucocephala* recovered well after harvesting and produced high fodder yield (1715 kg ha^{-1}) compared to other tree species (<1140 kg ha^{-1}).

4.3. Alley cropping wattle and *Acacia xanthophloea* with crops for food, and fuelwood.

Little or no research has been done on agroforestry technologies using black wattle (*Acacia mearnsii*) and the fever tree (*Acacia xanthoploea*), two nitrogen fixing trees common in South Africa. This trial evaluated the potential of these two tree species under alley cropping with maize and cowpeas as joint intercrops, under alley cropping with pumpkin.

In general the grain crop yields and biomass were significantly higher ($p<0.05$) under conventional practice (control = no trees) than they were under alley cropping for both seasons. The maize grain yields were 1.9 t ha^{-1} and 2.6 t ha^{-1} under alley cropping and 2.0 t ha^{-1} and 5.7 t ha^{-1} under conventional practice (control) in the first and second seasons. The grain yields of cowpeas were similar in both treatments in the first season (0.2 t ha^{-1}) but different in the second season when the yield increased to 0.3 t ha^{-1} under alley cropping and to 0.6 t ha^{-1} under conventional practice. The yield of pumpkin under alley cropping was 12.7 t ha^{-1} during the first season, decreasing to 8.5 t ha^{-1} in the second season. Under conventional practice, pumpkin fruit yield was about 18 t ha^{-1} in the first season and 11.5 t ha^{-1} in the second season. In this study the higher yield in the control plot has been reported to be a common finding at an early stage of alley cropping when the trees are still in the process of establishment. It is therefore recommended that agroforestry trials should be long term to show the benefits of species such as trees which take several years to establish.

5. PRODUCTION OF FODDER BANKS

The alley cropping trial was repeated with fodder grass species (*Panicum maximum* and *Eragrostis curvula*).

The results showed that tree growth and biomass production were higher in black wattle alley cropping than with the fever tree. The average diameter at breast height of black wattle after 12 months was 36 mm. Over the same period the total tree height was about 4060 mm. A tree pruning was done to one-year old black wattle in the whole trial and the prunings produced 2.68 t ha^{-1} in association with *E. curvula*. The fever tree did not grow significantly during the study period and was discarded from the study. Similarly, *P. maximum* had germinated very unevenly, and was excluded from the experimentation.

The fibre contents (neutral detergent fibre and acid detergent fibre) from this study were 41.9% and 39.9 for *E. curvula*. If black wattle is to be used as fodder, it must be mixed with highly digestible fodder such as *P. maximum* and legume plants, to increase animal intake and to avoid any risk of it becoming an animal hazard due to tannin effects.

6. PRODUCTION AND WATER USE OF A *JATROPHA* – *PENNISETUM* SILVOPASTORAL SYSTEM

In silvopastoral systems trees may be grown in single rows or in aggregate rows called sets with wide alleys for forage production between sets. In this trial we selected a design of single, double and triple sets with a tree planting density of 1111 *J. curcas* plants ha^{-1} and the alleys were planted with kikuyu. The trial was a randomised block design (3 blocks) with six treatments per block, i.e. 3 replicates per treatment.

The objective was to monitor the water balance and dynamics in the soil-plant-atmosphere system to understand the production processes with particular reference to the efficient use of water.

An automatic weather station was installed at the site for monitoring relative humidity, air temperature, wind speed, solar radiation, rainfall and vapour pressure deficit on an hourly and daily basis. Radiation Interception was measured with calibrated Delta-T tube solarimeters and pyranometers placed at uniform spacing across transects of tree rows. Water used by the trees (transpiration) was determined using the heat pulse velocity (HPV) method. The Eddy Covariance (EC) technique was used to measure evaporation rates. The Surface Renewal Method was used to estimate the sensible heat flux. A SLS40A surface layer scintillometer was used for measuring the surface energy balance in the silvopastoral trial. The software OEBRUN on the PC outputs the following components: Turbulent flux of sensible heat; Turbulent flux of latent heat (evaporation); Incoming solar radiation and net radiation and soil heat flux. In addition, a number of parameters were measured which were required for running and validating the Soil Water Balance model. Tree parameters included leaf area index, leaf area density, crown and tree dimensions and root density distribution. Crop parameters included grass biomass, height, lateral and vertical distribution of root density and leaf area index.

Tree Growth

The tree height data for the study period (February 2005-December 2008) showed that the plots with only *J. curcas* trees had the highest growth rates (maximum height 2.3 m) compared to the other planting layouts.

The tree growth parameters indicated that tree level and branch level allometric relationships of *J. curcas* using basal stem diameter and crown depth as predictor variables were very reliable. Stem diameter was easier to measure and had linear and direct proportionality with wood and foliage percentage. Neither below-ground interspecies competition nor tree spacing had any significant effects on allometry. Site-specific allometric equations are therefore valid for accurate, non-destructive and quick predictions of tree growth under various tree management conditions and are also valuable for comparative evaluation of suitability of sites for growing *J. curcas.* This is relevant because the species has attracted global attention for its potential as a source of biodiesel.

Seed production and harvesting

The highest seed yield was in 2009 (348.8 kg ha^{-1}) in the *J. curcas* only plots. The other treatments (where pasture competition was a limiting factor) ranged between 77.8 and 166 kg ha^{-1}. High oil yields are therefore unlikely due to the low seed production.

Tree water use

Measurements of daily total evaporation rates during December to February (summer) on clear hot days ranged between 3 to 4 mm day^{-1}. However, due to the deciduous nature of the species, water use was negligible (< 1 mm day^{-1}) during winter (May to August). The results have shown that two to four year-old *J. curcas* trees were conservative water users and therefore planting this species is not a stream flow reduction activity.

Soil water

In the *Jatropha*-only treatment soil water generally increased with depth as a result of the increase in clay content and decrease in roots and evaporation with depth. Distribution of profile water content across the tree row was not symmetrical. Soil water content on the south western side of the tree was significantly higher than the north eastern side, despite a symmetrical distribution of solar energy across the tree row. It was concluded that tree root growth was slightly skewed towards the north eastern side of the row. The lowest soil water content was observed under and between the tree-row pair.

Root distribution

The highest total root density in the standard spacing was underneath the tree (distance of 0 m). This was due to the presence of high woody roots and root hairs of the tree. The reason for the lowest root density at 0.75 m was the decrease in tree roots with distance (especially the woody roots) and that the contribution of the grass roots was also limited as grass cover was also low. Towards the middle of the alleys, root density increased. This increase was higher on the south western side, resulting in an asymmetrical root distribution.

Distribution of the total root density in the single-row was also asymmetrical. The highest total root density within the top 0.2 m depth increment was at 0 m distance (underneath the tree). Root length distribution across the tree row was very similar to that of the standard-spacing trial. Root density within 0.2-0.6 m was very low below the tree and higher on the north eastern side of the tree row than the south western side.

Competition Trial

The effect on the growth of 15-month old *J. curcas* trees by neighbouring forage species was addressed by removing planted pastures at 0, 60, 120 and 300 cm from the base of *J. curcas* individuals. Trees with the greatest pasture removal were able to grow on average 9.97% taller and produced main stems 11.7% thicker. Final height, basal diameter and percentage leaf abscission of trees with pasture removed up to 60 did not differ significantly from treatments with the greatest amount of competition. Therefore, removing up to 60 cm will allow for growth similar to that of trees with 300 cm of pastures removal while still providing sufficient pasture for grazing.

Preference trial

The palatability of *J. curcas* was determined through two two-choice cafeteria trials and a three choice trial. In the former, the goats only spent 0.19% and 3.77% of the time browsing *J. curcas* when either *A. karroo* or *A. nilotica* were available. In the three-choice trial (*J. curcas*, *A. karroo* and *Morus alba)* out of a total of 573 bites, the goats only took one bite of *J. curcas*. Since *J. curcas* is under no threat to herbivory, it is a suitable candidate for silvopastoral systems.

7. COMPUTERIZED MODEL TO SIMULATE THE PRODUCTION PROCESS AND EXTRAPOLATE FROM ON-STATION TO ON-FARM

Two-dimensional agroforestry systems, (hedgerow intercropping systems) involve a symmetrical geometry of planting trees and crops, which ensures homogeneity along the tree rows and within crop rows. The interactions across tree-crop interfaces result in characteristic crop growth profiles. The approaches of many of the radiation-driven models developed so far and applicable to hedgerow intercropping may be over-simplified or lack a full account of different solar positions; differentiation of radiation distribution with distance from trees and partitioning radiation transmitted through trees canopies to understorey crop absorption and transmission to soil surfaces. Although *J. curcas* and kikuyu were used in the model, it must be emphasized that the model applies to any potential agroforestry species.

The modelling approach used here was as follows:

- Radiation routine of the SWB-2D is used to simulate two-dimensional radiation distribution, including interception by trees and radiation reaching at various distances (from the hedgerow of trees) on the soil surface. The model uses 11 distances, which are also referred to as soil surface nodes.
- Water balance routine of the model is used to simulate two-dimensional soil water balance as well as transpiration by crops and trees;
- Radiation estimated at each surface node is used by the crop growth model as an input for crop growth and evaporation from soil at that distance;
- Every soil surface node except the one under the tree marks the mid-point in a crop row, which is grown as a single independent plant (‘crop column’).

Independent yield data collected from the trial were compared to model predictions to verify the model.

Kikuyu Growth and Productivity

The model predictions for kikuyu production at various distances from the tree rows were generally acceptable. Both measured and simulated were slightly less in the south-western side (SW) than the north-eastern (NE) side of the tree rows. Kikuyu growth was also less towards the tree row.

Tree water use

Validation results of tree water-use showed that simulated water-use were generally good and that the model has the potential to simulate tree water use in hedgerow intercropping systems.

Soil water and radiation distribution

The model underestimated profile water contents at the various distances, however considering the high spatial variability of soils, the results presented were considered acceptable.

Simulated solar radiation at various distances was different to the measured radiation. Radiation absorbed by crops at 2 m and at 1 m on SW and NE sides of the tree rows showed that the simulated radiation on the SW side was lower than the NE side. As expected radiation intercepted by the kikuyu rows close to the tree (at 1 m distance) was lower than further from the tree.

Model validation

Validation of the hedgerow intercropping model developed in this project has confirmed its potential for modelling agroforestry systems in South Africa. However, the model needs to be evaluated for more crop and tree species. The model could be improved by incorporating the mechanistic tree growth approach presented in this report.

8. CONCLUSIONS AND RECOMMENDATIONS

In spite of the benefits of agroforestry systems worldwide, the uptake of these technologies in South Africa has been slow. There is an urgent need to review South Africa's agroforestry policy and legislation to support agroforestry research and implementation. The aim of this project was to implement on-station agroforestry systems to determine their impact on water and plant production in order to facilitate the adoption of agroforestry locally. With the approval of the reference group the study focused on a single bioclimatic region, the Coast Hinterland Thornveld. The objectives of the project outlined in section 1.2 were all met.

Research on potential species in different bioclimatic areas needs to be long term since the results from the alley cropping trials in this study clearly demonstrate that benefits of agroforestry are generally not realized in the first two seasons after establishment. The long term nature of agroforestry systems necessitates the use of models to facilitate the planning and optimisation from the wide range of species and tree spacing options available for implementation. The agroforestry systems established in this study enabled the development of a hedgerow intercropping model. The model performed well in the determination of crop growth changes with distance from tree rows and estimation of tree water-use. For future applications the model could be improved by incorporating tree growth and productivity as a predictor. It also needs to be evaluated for various crop and tree types (field, cash, shade-loving crops; evergreen and deciduous trees). An economic return estimator that takes into account values of crop and tree outputs and estimates system return needs to be included in the current model. This makes the model not only a field-level management and planning tool but also a decision-making tool from an economic return point of view (by manipulating the row width and orientation; tree and crop selection).

On-farm trials of different species combinations selected by farmers need to be implemented and documented to promote the potential effectiveness of agroforestry practices. Realistic timeframes for potential benefits need to be given to rural farmers before they establish agroforestry systems. The failure of *A. xanthophloea* and *P. maximum* to establish in the on-station alley cropping trial highlights the importance of testing species before promoting them to rural farmers. The results from this study indicated that a good potential tree species for use in alley cropping practices is *L. leucocephala*. Even during the dry periods that occurred in the second season of the trial *L. leucocephala* recovered well after harvesting and produced high fodder yield (1715 kg ha-1) compared to *A. karroo* and *M. alba* (<1140 kg ha-1). Throughout the three agroforestry systems tested, one of the main lessons learnt for farmers is that good agronomic practices (e.g. weeding, irrigation) are critical for the success of crop and tree species.

Another of the potential agroforestry systems implemented in this study was the silvopastoral agroforestry system. In this system *J. curcas* trees, which have potential to produce biodiesel, were planted in different alley rows with kikuyu, a valuable pasture fodder species. The low probability of herbivory makes *J. curcas* a suitable candidate for silvopastoral systems. However, the planted pastures needed to sustain livestock may impose a negative competitive effect on the growth and productivity of 15-month old *J. curcas* trees. It is recommended that a 60 cm radius around the base of individuals be kept clear of pasture species to enhance *J. curcas* growth. Therefore with some degree of plantation maintenance, *J. curcas* could be a promising component in silvopastoral systems. However, the highest seed yield, which was achieved in 2009 in the *J. curcas* only plots, was very low (348.8 kg ha^{-1}). In the other treatments (where pasture competition was a factor) seed yield was significantly lower, ranging between 77.8 and 166 kg ha^{-1}. High oil yields are therefore unlikely due to the low seed production. The potential of *J. curcas* as a suitable alternate source of energy in South Africa is therefore questionable. The results of this study support the stand taken by the government to ban the widespread planting of *J. curcas* until the potential impact of the species could be evaluated through a comprehensive research programme. While the results of this study provide valuable insight into the water-use, seed production, palatability and competitive effects of *J. curcas*, further research needs to be carried out (e.g. on alien invasiveness) before it can be used effectively for agroforestry purposes.

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acronyms

AF	Agroforestry
ANOVA	Analysis of Variance
CARA	Conservation of Agricultural Resources Act
CCN	Carbon Credit Notes
DOY	Day of Year
DWAF	Department of Water Affairs and Forestry
ET	Evapotranspiration
FAO	Food and Agricultural Organization
HPV	Heat pulse Velocity
ICRAF	International Center for Research in Agroforestry
NFAP	National Forestry Action Plan
ODA	Overseas Development Agency
RM ANOVA	Repeated Measures Analysis of Variance
SADC	Southern African Development Community
SR	Surface Renewal
SWB	Soil Water Balance
TC	Thermocouple
UKZN	University of KwaZulu-Natal
VPD	Vapour Pressure Deficit
WRC	Water Research Commission

1 INTRODUCTION

1.1 A GENERAL OVERVIEW OF AGROFORESTRY

In developing countries the low availability of input technologies and high costs of fertilizer too often result in poor crop yields and low productivity and therefore also food scarcity. Poor tillage methods and agricultural practices lower the productivity of land even more. This again results in lower yields and the cycle keeps repeating itself. Part of rural life is the constant search for fuel wood and as trees are continuously felled for this purpose, the natural ability of the land to prevent erosion is reduced. Wilson and Kang (1981) referred to predictions made by the Food and Agricultural Organization (FAO) in the seventies that by the year 2000, 60% more food will be required to meet the demands of the world population. That time has been passed, and the demand may even be greater than expected.

Marginal or degraded areas can be made more productive and self sufficient by integrating trees, crops and animals and combinations thereof in different components. The benefits of introducing or maintaining a tree component in land use systems are becoming more attractive for land rehabilitation and sustainable production purposes. Increasing evidence supports the view that multiple production systems involving trees have some beneficial economic and environmental consequences in many land use programs. Trees have deeper, better-developed root systems and, therefore, provide better access to sub-surface water and nutrients. They aid in withdrawing nutrients in large volumes from the soils and recycle it by means of leaf drop, which leads to a higher pH beneath trees (Gholz, 1987; Farrell, 1990; Bisschop, 1994). More scientists have focused on this principle, with the result that agroforestry as a science has grown in leaps and bounds.

Agroforestry may be the most important solution towards sustainable development in Africa, as it can be used to address three important problems associated with Third World development, *viz.* low production, soil erosion and sufficient quantities of fuel wood (Cameron, Gutteridge & Rance, 1991; Fenn, 1995). In arid and semi-arid areas, agroforestry could help provide insurance against climatic extremes. Shrubs and trees could provide food, fodder and fuel wood, windbreaks and live fences; and reduce surface runoff, evaporation and soil erosion (Swaminathan, 1987). In South Africa the implementation of agroforestry systems has had little support from the government. This is likely due to the fact that the components of agroforestry (agriculture and forestry) previously fell under two different departments. The recent amalgamation of these departments into the Department of Agriculture, Forestry and Fisheries should now facilitate the development of these systems in South Africa. The following overview reports on agroforestry within the South African context.

1.1.1 Definition

The International Center for Research in Agroforestry (ICRAF) defined agroforestry as "…a collective name for all land-use systems and practices in which woody perennials are deliberately grown on the same land management unit as crops and/or animals. This can be either in some form of spatial arrangement or in a time sequence…". To qualify as agroforestry, a given land-use system or practice must permit significant economic and ecological interactions between the woody and non-woody components. Another definition used by ICRAF reads, "…Land use that involves deliberate retention, introduction or mixture of trees or other woody perennials in crop/animal production fields to benefit from the resultant ecological and economic interaction…" (www.icraf.cgiar.org).

Agroforestry is credited with improving the utilization of space by improving recycling of nutrients and organic matter. This translates into improved soil chemical, physical and biological characteristics with a reduction in the use of chemical fertilizers and improved infiltration of rainfall. Higher aggregate biomass production is obtained from agroforestry mixtures than from monoculture. Microclimatic extremes are reduced, as is soil erosion. Limited resources can be used more efficiently in the following manner: sunlight by multi-storied levels, soil nutrients by deep roots, water by providing shelter and the retaining of moisture by mulch, land by sustaining soil fertility. Agroforestry thus provides a more favourable environment for sustained cropping, the creation of habitat diversity and provides a more continuous flow of more products over time (Cameron *et al.*, 1991; Anonymous, 1992).

The practice does, however, have disadvantages. Most important of these is the increased competition of trees with agricultural crops for water, nutrients and light. This competition could lead to reduced yields of both trees and associated crops. The useable crop area is reduced due to tree alleys/plots, which could also act as a habitat for pests. Allelopathic effects by trees could reduce crop yields. Importantly, agroforestry systems are usually labour intensive, which could be a deterrent to the adoption of the practice. There is also the fear that certain species may become invasive or provide favourable conditions for the habitation of pests.

It is, however, increasingly accepted that the advantages of agroforestry, particularly the environmental aspects, clearly outweigh the disadvantages, and that many of the disadvantages can be eliminated or minimized by manipulating management practices.

1.1.2 Classification and examples of agroforestry systems

Agroforestry is practised in several different formats, but can be classified in four main groups (Swaminathan, 1987):

Agrosilvopastoral	-	*combinations of crops/timber/livestock*
multi-level plantations/homegardens	-	*fruit/timber/crops*
silvopastoral or	-	*timber/livestock*
Agrisilvicultural	-	*crops/timber*

It can also be classified in terms of the time of production, *viz.*

simultaneous cropping	-	boundary/contour hedges, alley cropping, parklands, silvopastoral, windbreaks, etc.
Sequential cropping	-	shifting cultivation, relay intercropping, improved fallow, taunga, multistrata systems, etc. (www.icraf.cgiar.org).

Agroforestry principles can therefore be incorporated in the farming system or home garden in various ways. Borders around farmland form a significant niche in which trees may be planted. Traditionally this niche has been one of those most exploited for tree planting by small-scale farmers. As farm borders typically include unproductive land, tree planting in this niche can increase overall farm outputs. Living fence-post trees are typically planted further apart and managed less intensively than hedges. The tree is used together with other materials (barbed wire, wooden slats, etc.) to form a barrier. Hedges and living fences protect crops, define borders, provide privacy, and act as small windbreaks. By slowing wind speeds, windbreaks help conserve soil moisture and prevent wind erosion, and therefore increase crop yields. Crops immediately next to the windbreak may be adversely affected by competition. Windbreak trees do not necessarily require intensive management. Planted close together hedges require frequent trimming to encourage secondary branching and to create an impenetrable hedge. Yields include fuel wood, fodder production and green manure. Hedges can also be planted in rows with cash crops or pasture planted in the alleys between the rows (alley cropping).

ICRAF published a comprehensive account of agroforestry in dryland Africa, where trees are used as hedges, windbreaks, for soil/water conservation, improved fallow systems and in homegardens (Rochelau, Weber & Field-Juma, 1988). At least 755 species of shrubs and trees in Africa serve as browse plants and many of these fix nitrogen (Skerman, 1977). Research in Africa has concentrated mainly on *Leucaena leucocephala* and *Gliricidia sepium*.

1.2 RATIONALE AND OBJECTIVES

Less than 15% of land area in South Africa is arable. This implies that there is very limited scope for conventional food production, both on irrigated and dryland. In addition to limited arable land, South Africa is a water-scarce country. Its rainfall is below the world-average, and its distribution is somewhat unreliable. The relatively low rainfall and limited arable land in South Africa make it imperative to effectively and efficiently use its natural resources for food and fibre production. This is even more important for emerging and subsistence farmers whose practices often lack access to information and use of production technologies.

Small-holder agriculture, particularly in Africa, has been faced with land degradation. This is due to a number of factors, including poor management and limited production factors. Declining soil fertility is increasingly threatening the sustainability of small-scale farming systems, especially as few farmers have access to affordable external nutrient inputs. In addition, shortages of wood and high quality fodder for livestock are serious constraints to farm productivity. In order to improve the status of land resources and sustain their productivity, there is a need for a "shift" from the current production practices. Agroforestry systems, (whereby there is a deliberate planting of trees in combination with food/forage crops for the benefit of people and the environment) have been reported to be potentially productive in degraded and marginal soils. Agroforestry is also perceived to have potential for the rehabilitation of such degraded and/or marginal lands. However, in South Africa, the implementation of agroforestry systems has been relatively slow and may be attributed to lack of farmer knowledge on applicable crop and tree combinations that benefit the people and the environment. Negative perceptions of trees (e.g. bush encroachment and high water-users) may also contribute to the slow uptake of agroforestry. A major challenge is to build the capacity of small-scale farmers and poor communities to implement agroforestry systems that enable them to increase production while simultaneously rehabilitating and improving the land resource. An on-farm agroforestry project (funded by the WRC) was initiated in the Southern Tall Grassveld bioclimatic zone of the Upper Thukela to address the problem of fodder shortage for a small scale dairy farmer (K5/1351). The current project will build on the lessons learnt from this project to promote both sustainable production and food security – while improving the livelihoods of the poor.

This research project proposed to address the following objectives:

- Synthesize *knowledge available* locally and internationally on agroforestry systems (combinations of trees and crops).
- Select two different *bio-climatic zones* for study areas (preference to areas with relative lack of research).
- Select one or more *applicable agroforestry* systems per bio-climatic zone based on consultation with a cross section of end-users to include local knowledge (in the relevant bio-climatic zone and stakeholder review/endorsement of selections).
- Select one or more *tree and crop species combinations* per agroforestry system based on consultation with a cross section of end-users to include local knowledge (in the relevant bio-climatic zone).
- Design *on-station trials* with appropriate controls.
- Establish *on-station trials* with appropriate controls.
- Conduct appropriate water dynamics, soil fertility/health dynamics and plant productivity *measurements* on-station to understand the production processes with particular reference to efficient use of water.
- Use such understanding to develop or refine applicable computerized *models* to extrapolate results from on-station to on-farm.
- Undertake technology transfer in the form of information days and/or demonstrations to local communities/ NGOs/CBOs and extension services.
- Document *impact* of the selected agroforestry systems on efficient use of water, soil health dynamics and plant production.

1.3 OUTLINE OF REPORT

This introductory chapter outlines the classification and examples of agroforestry systems as well as the rationale and objectives of the study. This is followed by a synthesis of recent trends in agroforestry in southern Africa (Chapter 2) and agroforestry policy development in South Africa (Chapter 3). Chapter 4 describes the study area and the characteristics of potential agroforestry species for the trials. The next three chapters describe the aim, experimental design, implementation and results of specific agroforestry systems: alley cropping (Chapter 5); fodder banks (Chapter 6) and a silvopastoral system (Chapter 7). In Chapter 8 the research results on the development of allometric relationships for one of the trees used in the silvopastoral system, *J. curcas,* are presented. In Chapter 9 the research findings are used to develop, test and refine computerized models to simulate the production from these on-station agroforestry systems. In Chapter 10 the study is brought to a conclusion with a summary of research findings, recommendations for policy makers and implementers, and a reflection on the application of on-station trials for model testing and verification.

2 AGROFORESTRY IN SOUTHERN AFRICA

2.1 INTRODUCTION

The development of agroforestry in southern Africa commenced with the establishment of a collaborative programme between ICRAF and national agroforestry and forestry research institutions in Malawi, Zambia and Tanzania which were later extended to Zimbabwe and Mozambique (Kwesiga & Agumya, 2002). Research focused on problems such as declining soil fertility, shortage of fodder, fuel wood and poles, and environmental degradation. This was followed by the screening and performance studies of tree species relevant to the *Miombo* eco-region. Second-generation issues emerging after the establishment of agroforestry included pests and diseases, allelopathic effects, demands on water resources, increased demand for germplasm, problems related to markets, credit and subsidies and the need to integrate farmers' needs into research. In South Africa, Esterhuyse (1989) provided a first overview of the possibilities of agroforestry, using examples such as the fruit/nut farmer using wind breaks, the bushveld/lowveld farmer using fire breaks or thinned out savannah, or the forester intercropping maize or other crops with timber, and lastly fodder trees. This was followed by recommendations regarding alley cropping, management techniques, fertilizer, pruning, etc. (Anonymous, 1996a), as well as tree planting for fuel production purposes (Anonymous, 1996b).

This report presents an overview of agroforestry relative to the current project which examines the role of agroforestry for improved production through the efficient use of water. Fodder crops came to attention in a report drafted for the Water Research Commission on drought tolerant and water efficient fodder shrubs (Le Houérou, 1994). The author highlighted three species, *viz.* saltbush *(Atriplex nummularia)*, cactus (*Opuntia ficus-indica)* and Agave *(Agave americanum)*. Topics addressed included the use for fodder, economic value, water/soil conservation, fuel wood production, use for fencing and rehabilitation of degraded areas. Various research projects were identified, including the establishment of saltbush, optimal feed combination of drought tolerant fodder shrubs, alley farming, utilization of drainage and brackish water for the irrigation of saltbush, and the introduction of other drought resistant fodder crops.

Universities and other research institutions started to focus on agroforestry and addressed aspects such as the screening of adapted species, uses of different fodder shrubs, propagation of species, fruit production and the water-use efficiency of tree species. In this report water-use efficiency is defined as the biomass produced per unit of water transpired, termed productive green-water use. Many advances have been made throughout Southern Africa, although these remained largely inaccessible to the target community, as it was not disseminated from the various institutions. This in effect hampered the undertaking of an effective synthesis of available knowledge on agroforestry (Kwesiga & Agumya, 2002). According to Underwood (2002) the Philippines successfully integrated agroforestry technologies into their landcare programmes and similar attempts were also initiated in the South African Landcare program.

2.2 FIRST REGIONAL AGROFORESTRY CONFERENCE, WARMBATHS, 2002

The Regional Agroforestry Conference held in Warmbaths during 2002 was a first attempt to address the need to synthesize available knowledge generated in Southern Africa. The main findings at the conference were that:

- Short duration planted fallows using N2 fixation and fast-growing tree/shrubs could be used to overcome nutrient depletion.
- Alley cropping is not suitable for replenishing soil fertility in most parts of semi-arid southern Africa.
- Efforts should be made to increase fodder production, using tree fodders as protein supplements.
- Rotational woodlots should be developed to meet the fuel wood and timber demand, reducing pressure on natural woodlands.
- The potential of a number of indigenous fruits were high for supplementing the food needs and cash income of farm families, as well as increasing the nutritional status (Kwesiga, 2002).

Various new issues also emerged at the conference. Most important of these was that progress was hampered by the potential threat of pests and diseases, the impact of HIV/AIDS and sustainability of funding. As for the relevance of HIV/AIDS it was noted that research and support aimed at the smallholder-household, needed new relevance to account for the implications of the HIV reality, specifically with regard to labour inputs (Ajayi, Kuntashula, Phira, Kwesiga, Mafongoya, Masi, Franzel & Swallow, 2002; Chikandi, 2002).

In general, the following themes emerged:

- From the **USA**: innovative, multidisciplinary problem-orientated projects are needed, e.g. the development of computer-based decision support systems for tree selection; monitoring of environmental benefits; carbon sequestration and economic models (Nair, 2002).
- From the experience of other **SADC** countries – Agroforestry is a viable option, provided there is a coherent policy and investment strategy for improved soil fertility and rural household incomes, food security and sustainable resource management (Matakala, 2002).
- More attention should be given to **integrated farming systems** including use of fodder trees for livestock (Otsyina, Kusekwa, Hove, Maasdorp, Msangi & Shem, 2002).
- There is the potential for greater utilisation of **fruit**, including cultivation, propagation, improvement, management and processing (Akinnifesi, Kwesiga & Simons, 2002; Kift, Ropets & Matsha, 2002; Maliro & Kwapata, 2002; Mhango & Akinnifesi, 2002; Mhango, Mkonda & Akinnifesi, 2002;Mithöfer & Waibal, 2002; Mumba, Simon, Swai & Ramadhani, 2002; Mumba, Otsyina, Franzel & Chibwana, 2002; Shackleton, 2002).
- There is a need to **demonstrate the benefits** of agroforestry at different scales (Mtambanengwe, Mapfumo & Mutamba, 2002).
- **Soil water studies** indicate that trees do not necessarily compete with crops in good rainfall seasons (Everson & Everson, 2002), although they might compete for light.

- **Fodder and fuel wood** shortages are a major problem which received wide attention with 18 papers reporting on the use of *Leucaena*. These typically addressed the successful supplementation of poor quality roughage diets with fodder from browse plants. As pruning can be quite laborious, a pruning regime for fodder/kindling or poles, needs to be determined (Botha & Rethman, 2002).

As for the adoption of agroforestry technologies, constraints were reported from various countries:

Malawi -	labour constraints, no striking short-term impact, faulty technology (Carr, 2002).
Zambia -	non-involvement of local leaders (Kabwe, Grundy & Mafongya, 2002) and absence of appropriate policy and institutional framework (Ajayi, Kuntashula, Kwesiga, Franzel, Ayuk, Swallow & Mafongoya, 2002).
Zimbabwe -	a history of tree-removal for agriculture (Mapfumo, Mtambanengwe & Mutamba, 2002)
Uganda -	the need to establish a national network to address fragmented and uncoordinated efforts (Nkuuhe, Okorio & Esegu, 2002).
Tanzania -	the need to have a natural resource policy and collaborative network, addressing insecurity of tenure (Bakengesa, Otsyina, Ok'ting'ati & Mbwamo, 2002).

Possible negative aspects were highlighted by Zimmerman (2002):

Many agroforestry species could be classified as alien invaders, costing more in terms of environmental damage, habitat degradation and loss of water/biodiversity than the benefits derived from them. This would require careful screening, the development of mechanisms to prevent escapes/invasions and cost effective control measures to reverse unmanageable invasions back to the manageable.

2.3 OTHER TRENDS IN AGROFORESTRY

2.3.1 Carbon Credits

"Carbon credits" is one of the new buzzwords in agroforestry, referring to "carbon farming systems" where trees act as carbon "sinks" and remove excess carbon from the atmosphere. Following the Kyoto Protocol, carbon credit notes (CNN) can be traded on financial markets to deliver carbon credits to a purchaser at a future date. According to the Protocol, countries and companies would be rewarded for reduced carbon emissions and penalized for failing to reach agreed emission targets. Upon achieving a target, CNNs could be traded, or bought when failing to meet a target. In South Africa, CNNs will be aimed at large South African companies with international operations with carbon liabilities (Kupka, undated). The Baviaanskloof area of the Eastern Cape has been identified as having excellent carbon storing potential. In Venda, a project has been initiated to re-establish forest/vegetation next to the Kruger National Park. A development in the carbon credit field is to measure how much carbon is taken in by trees and transferred to the soil and what species of trees will be best (Terrell, 2002).

Additional benefits arising from carbon farming could also include reduced flooding, decreased erosion and the provision of raw materials for crafts, etc. One such (Mexican) project that commenced in 1997 with 40 farmers, now has 400 farmers collaborating, earning R700 000 per year selling carbon credit (Louw, 2003).

There are, however, warnings that carbon sinks might quickly become saturated and then return carbon to the atmosphere (Pearce, 1999). By photosynthesis, trees absorb CO_2, but also release it through respiration. Due to a time delay effect, there is a lag of ± 50 years during which higher temperatures will increase respiration. Predictions are made that by 2050 forests might have released much of the CO_2 absorbed. Claims of carbon credit are based on models of CO_2 accumulation that assume the current rates of CO_2 fertilisation will continue. These are not necessarily wrong, but might be an insecure way of doing it (Pearce, 1999).

2.3.2 Fodder shrubs

Carob

Carob is a well-known garden and street tree, also used to provide shade in parking areas and is increasingly being used for fodder (DWAF, 1992). Much research has been done with regards to its uses, growth requirements, seed production, cultivation and nutritional value of pods. It has a deep rooted system and grows on fairly poor soils. It is especially adapted to the Mediterranean conditions of the Western Cape. (McVeigh, 1996).

Elsenburg Agricultural College determined nutritional value of the fodder and included the tree in growth trials (Muller, 2003). After the first positive results from the nutritional and growth studies, a long-term project is now planned, including cultivar-evaluation, irrigation requirements, the production of individual trees and grafting (Muller, 2004).

Agave

Drought and frost resistant and adapted to a wide range of soil types, *Agave americana* is a good drought fodder and useful for bee-farming and was previously planted as hedges/fencing. It is now very successfully being used to produce an organic alcohol. Agave Distillers (Pty) Ltd near Graaff Reinet represent a group of seven farmers producing agave for distilling purposes. Their product is named "Agava" and not "tequila" due to international trade agreements. Although they produced only 400 l /day in 2003, the distillery has the capacity to produce up to 10 000 l/day (Ferreira, 2003; Moseley, 2003; Botha, 1999; Coetsee, 1996).

Mopane

Although commonly known as reaching invader status (bush encroachment), mopane can very successfully be used as feed supplement during times of drought (Gittens, 1996). Initiatives to turn the problem of bush encroachment into a supply for fuel and fodder need to be undertaken. Research conducted at the University of the North (UNIN) indicated that it is a valuable browse, but that livestock has to adapt to the odour. Mopane caterpillar, a delicacy in Limpopo and beyond, also feeds on the trees. UNIN is completing studies on the biology and ecology of mopane, especially regarding the stimulation of regrowth (Potgieter, Wessels & Nel, 1997).

Drought fodder shrubs

Rethman, Birnbaum, Degen & Van Niekerk (undated) identified various drought resistant fodder shrubs and completed studies on the propagation, establishment and characterisation thereof in order to develop production systems. These shrubs included *Atriplex, Cassia, Haloxylon, Boscia, Sutherlandia* and *Tripteris.* Various saltbush selections were tested to eliminate problems with palatability. Saltbush is widely used as a supplement in extensive grazing systems and for the rehabilitation of degraded rangeland (Genis, 2003).

2.3.3 Current Initiatives

Commercial Products from the Wild (CPW) (Van Wyk & Ham, 2004)

CPW is the result of a consortium between the Department of Forest Science of the University of Stellenbosch, the Institute of Natural Resources associated with the University of Natal and the Post-graduate School of Agriculture and Rural Development (University of Pretoria). Its main focus is the sustainable utilization, commercialisation and domestication of products from indigenous forest and woodland ecosystems (Van Wyk & Ham, 2004). The project was supported by a grant from the Innovation Fund and has successfully achieved all of its objectives, *viz.* the identification of high potential indigenous plant species for the development of commercialisation models; development of action plans for the sustainable utilization, commercialisation and domestication of indigenous products derived from woody ecosystems; identification of potential business partners who could be aligned with each of the products that will be identified for commercialisation and the development of business strategies and/or prototypes/products for commercialization.

Sub-projects included:

- Commercialization of medicinal bulb, root and herb products (KwaZulu-Natal, Durban area, with inputs from a community in Bushbuckridge).
- Bark for medicinal use (Umzimkulu Forests, Eastern Cape; Knysna Forests, Western Cape and Newlands Forests, Western Cape)
- Commercialisation of indigenous fibre products (Ilala – *Hyphaene coriacea* and iNcema – *Juncus kraussii)* (Maputaland, Zululand regions of KwaZulu-Natal)
- Commercialisation of indigenous fruit products (marula, wild medlar, Kei apple, large num-num) (Western Cape, Venda)
- Topgrafting of male marula trees (northern provinces).

Some of the main outputs of the project included the development of 26 new fibre products, 14 medicinal products and 6 fruit products, as well as the establishment of 2 fibre craft enterprises and 1 large fibre craft co-operative, 2 medicinal enterprises, a medicinal bark harvesters association with the legal rights to harvest bark from forests, and the empowerment of 8 small-scale farmers, trained in the cultivation of indigenous fruit trees and processing of indigenous fruit products.

Food and trees for Africa (FTA)

FTA is a national non-governmental nonprofit organisation established in 1990, addressing the need to urgently uplift the quality of life in township environments through greening of unhealthy, denuded and degraded landscapes. It invites high profile people to plant trees at projects, e.g. former President Dr Nelson Mandela, Baby Jake Matlala (former South African boxer and junior flyweight champion) and Archbishop Emeritus Desmond Tutu, etc. in order to draw attention to the projects. FTA founded a permaculture network in SA and was also appointed as sub-Saharan partners of Global ReLeaf – a network with greening organizations from Ukraine to Costa Rica, etc. FTA has distributed more that 2 million trees in the past 14 years (Naish, 2004).

FTA focuses on four main thrusts:

Permaculture

Permaculture is a phrase coined from the concept PERMAnent agriCULTURE, an approach developed in Australia by Bill Mollison. This approach to land use integrates human dwellings, microclimate, annual and perennial plants, animals, soils and water management into stable productive communities. Projects are established at schools, the Emthonjeni Correctional Services and various youth groups

Urban Greening

This programme focuses on the greening of urban areas as part of urban development. FTA facilitates the establishment of permaculture food gardens at schools, clinics and community centers. With the development of River Park in Alexandra, homeowners were supplied with 1 fruit tree and 1 shade tree each and community workshops were held to teach new homeowners to start a garden.

Eduplant

Eduplant focuses on poverty alleviation and community development at school level and is managed in collaboration with Woolworths, DWAF, MaAfrika Tikkun and LandCare South Africa. It is a leading schools food gardening and greening programme that aims to enhance food security, promote sustainable development, and build skills and capacity in school communities.

Trees for homes

This is a programme to ensure the planting of trees and increased environmental awareness that leads to cleaner and greener suburbs for low cost housing developments. It enhances the participation of low-income communities in local-level decision-making and helps to improve environmental management capacity among both local authority representatives and communities. More than 150 000 trees were distributed in new settlements in the TfH programme alone (Naish, 2004). Over 38 workshops were held, in addition to the training of more than 300 community-based educators (CBEs). Forty eight events were held to create awareness on the importance of caring for the environment and the role that trees play.

Cape Peninsula National Park – preservation of genetic material

Collectors from Imizama Yetho are being trained in permaculture, seed collection and propagation and then employed full time to gather seeds from forests, propagate it at nurseries in Newlands and replant the new material back in CPNP. The CNP project won the Natural Resources Conservation Award at Green Trust Awards.

Forestry in the Eastern and Northern Cape and Limpopo

Projects were developed to establish trees for fuel production in order to reduce stress on indigenous trees. In 1995, it was proposed to establish 3000 community forestry projects in the Northern Cape within 6 years, mainly with *Eucalyptys* species. The trees were to be harvested rotationally after 5/6 years (Coetsee, 1995). The establishment of treelots in the Northern Cape was enhanced with the appointment of a first forester in Upington in 1996. The main focus was the production of fuel wood and nurseries producing seedlings. After one year, 47 community forestry plots and 13 fuel wood plots had already been established (Anon, 1997.)

The Research Institute for Reclamation Ecology at the Potchefstroom University for CHE initiated a project aimed at the rehabilitation of asbestos mine dumps at Bewaarkloof near Polokwane (Anonymous, 1996a). Research focuses on the establishment of indigenous trees and shrubs (MPTs) for fuel and construction purposes. Innovative methods for establishment are investigated and 46 tree species have been established. The project is conducted within the framework of the Biomass Initiative (DME).

3 SOUTH AFRICAN POLICY PERSPECTIVE ON AGROFORESTRY

3.1 SADC DRAFT FORESTS PROTOCOL

The Southern African Development Community developed a Draft Forests Protocol (SADC, 2001) to be used as a framework for individual country's policies regarding forestry and related issues. Five articles are applicable to agroforestry:

Article 12 Community Based Forestry Management

State Parties shall

- adopt national policies and mechanisms to enable local communities to benefit collectively from the use of forest resources and to ensure their effective participation in forest management activities, including affirmative steps to seek and encourage such participation;
- develop regional guidelines and collaborate with the committee to share information and expertise related to community-based forest management, and;
- encourage local communities to grow and conserve trees and to participate in agroforestry initiatives.

Article 13 Women and Forests

State parties shall

- adopt national policies and mechanisms to enable effective participation of women in forest management activities, inducing affirmative steps to seek and encourage such participation
- develop regional guideline to share information and expertise related to the participation of women in forest management activities.

Article 16 Traditional Forest-related Knowledge

State parties shall

- recognise and protect the rights of local communities over their traditional forest-related knowledge and their right to benefit from the utilisation of this knowledge.
- in consultation with local communities, preserve and protect traditional forest-related knowledge, and provide for the equitable sharing of any benefits arising from the utilisation of this knowledge among those who hold it, and where appropriate develop standards, guidelines and other mechanisms in this regard.

Article 19 Capacity building

State parties shall

- actively promote education, training and capacity building in connection with forest-related activities to support the achievement of the objectives of this protocol
- actively involve existing and new facilities and institutions in the regions in education training and capacity building in connection with forest related activities

- Co-operate and collaborate with relevant international and other training and educational institutions and organisations concerned with forests, forestry or forest products, outside of the region
- Promote the strengthening and development, throughout the region, of centers of excellence in forest management, forest conservation and the production, utilisation and marketing of forest products
- Develop a regional programme for capacity-building in the forest sector, giving particular attention to the development of capacity at the rural or local level to participate in all aspects of forest management and marketing.

Article 20 Research and development

State parties shall

- actively promote research and development in connection with forest related activities to support the achievement of the objectives of this protocol
- Actively involve existing and new facilities and institution in the region on research and development in connection with forest-related activities, including the conservation of forests, sustainable forest management, and the production, utilisation and marketing of forest products.
- Co-operate and collaborate with relevant international and other research institutions and organisations concerned with forests, forestry or forest products, outside of the region.
- Promote the strengthening and development, throughout the region, of centers of excellence in research and development connected with forest-related activities
- Support the creation of regional, national and sub-national associations to study and make recommendations concerning the sustainable utilisation of forest and trade in forest resources and forest products, including research relating to:
  - The augmentation of benefits to economies in the region from the export of forest products
  - Voluntary certification of forest industries and forest products
  - Use of mechanisms providing for other international instruments for the benefit of the forest sector in the region
  - Development of innovation techniques and technologies that can be used in the region.

3.2 SOUTH AFRICAN WHITE PAPER ON FORESTRY

The Department of Water Affairs and Forestry developed a White Paper with the broad aim of welding together the three strains of indigenous forest management, commercial forestry and community forestry (DWAF, 1996). In South Africa, ± 40% of the population live in the countryside, rural towns and villages. These people are poor to very poor, the women between the ages of 16-65 outnumber men by 30-40%, men are usually absent and women take the position of heads of households. Unemployment can exceed 50%. Approximately 33% of households rely on wood for fuel and in some areas up to 80% of the population walk for 5 hr per week per household to fetch wood. Annually 9-11 million tons of wood are used, with 6.6 million of this being harvested from natural woodland. It equals the value of R1billion annually. In 20 years, 1.5 million households will still be without electricity. In the past, government focused on woodlots for fuel and construction. Farm windrows, shelterbelts and woodlots are now getting more attention and don’t need that much support.

A lack of adequate community forestry programmes resulted in shortfalls between fuel wood demand and fuel wood production, severe degradation of woodland and destruction of natural forest. Few communities will build tree growing into their local development initiatives.

International documents applicable to SA include:

- Forestry Principles – principles for a global consensus on the management, conservation and sustainable development of all types of forest
- Convention on Biological Diversity (signatory) – conservation of biological diversity and sustainable use of its components
- Agenda 21 – work plans for sustainable development
- Rio Declaration – broad principles to guide national conduct on environmental protection and development
- Framework Convention on Climate Change (Signatory)

The policy for community forestry contains two important elements, *viz.*

1. Government recognises that natural forests and woodlots play a vital role in the household economics of many disadvantaged communities. These should be sustainably managed and advantages should accrue to these local communities.
2. People should be encouraged to plant trees (indigenous) in gardens/fields/street/parks/plantations

Government's role will be to support communities and projects with relevant information and technology. Development should be stimulated, barriers identified and budget made available. Government will also support innovation with supportive research.

3.3 SOUTH AFRICAN NATIONAL FORESTRY ACTION PLAN (NFAP)

The NFAP was developed as a framework in which to implement the new Forest Policy. Funded by the British Overseas Development Administration (ODA). A planning task force focused on three areas, *viz.* community forestry, industrial forestry and natural forests and woodlands. Cross-cutting sectors affecting all three included research, technology and innovation; legislation; human resources development and labour and institutional development DWAF, 1997).

Working groups were set up to address each of these issues, resulting in the identification of the following key issues to be addressed in the NFAP:

- What can community forestry contribute to local en social economic and social development and to improving the quality of both urban and rural life?
- What institutional framework is required to enable community forestry to develop in rural and urban areas?
- What should be the role of local institutions in community forestry? How can these institutions be empowered to take a leading role?
- What should service providers provide to local communities to promote sustainable community forestry development? What information is needed and how should it be delivered?
- What conditions in terms of legislation, land tenure, finance and attitudes ("enabling conditions" are necessary to support self-sustaining community forestry? How can these best be into place?

Also questions to be answered included:

- How should research related to the forestry sector be organized and coordinated to effectively identify research requirements and to communicate information to users?
- How has research in the forestry sector been funded in the past and how should it be funded in the future?
- How can technology and information related to the forestry sector best be transferred to people at all levels of society that could benefit?

National Water Act (36 of 1998)

The gazetting of the National Water Act (36 of 1998) and the declaration of forestry as a Stream Flow Reduction Activity will influence the selection of species for agroforestry programmes. The planting of high value trees that use little water is an alternative land-use option for rural communities in search of income generation opportunities. As South Africa is a country with very limited water resources, research needs to focus on determining the water-use of species that have the potential to provide products to local markets. Agroforestry programmes can contribute to improving the environment, enriching the natural resources and creating income generating opportunities for previously disadvantaged communities while at the same time conserving water resources. However, the development of policy on agroforestry in South Africa has been neglected as the two departments involved in agroforestry (agriculture and forestry) were in separate directorates. Previously the directorate of forestry (including agroforestry) resided in the Department of Water Affairs and Forestry, while agriculture fell under the Department of Agriculture. In 2009 Forestry was incorporated into the Department of Agriculture and Fisheries. This incorporation of agriculture and forestry into the same department should provide the consolidated support for the development of new agroforestry policy.

Food security is part of the section 27 Constitutional rights in South Africa. The Constitution states that every citizen has the right to have access to sufficient food and water. The Department of Agriculture's Interim Position on Crop Production for Bio-diesel in South Africa adopts a "food first" policy regarding crops for biodiesel. This means that priority is to be "given to the production of food prior to fibre and other agricultural products". Alien species, such as *Jatropha curcas*, "must not be grown on agricultural land if the impact of the crop on the environment has not been established beyond doubt". The Conservation of Agricultural Resources Act (CARA) (Act No. 43 of 1983, amended 2001) makes provision for the control over the utilization of natural agricultural resources of South Africa in order to promote conservation of soil and water, vegetation and the combating of weeds and invader plants. CARA will therefore apply to the planting of bio-diesel crops on agricultural land. One of the consequences of CARA listed in schedule 3 of the National Environmental Management Act (NEMA) is that a full EIA is necessary for physical alteration of virgin soil to agriculture, or afforestation for the purposes of commercial tree, timber or wood production of 100 ha or more. In addition, an assessment for clearance of 1 ha or more of vegetation is needed where 75% or more of the vegetative cover constitutes indigenous vegetation or where this clearance takes place in critical biodiversity areas.

3.4 CONCLUSION

In South Africa there has been a lack of participation in agroforestry due to the past focus on intensive production of agriculture on the one hand, and forestry on the other hand. This is opposed to the USA where farmers are encouraged to use AF practices to improve farming systems, restore degraded environments and supplement incomes (Jacobson, 2004). Rethman (1999) was adamant that agroforestry principles can and should make a valuable contribution to animal, plant and forestry production systems in South Africa, as they incorporate an integrated and holistic approach to the development and management of adaptive land use systems, which recognize the importance of natural resources, human requirements and social considerations. In South Africa, there is a much greater scope for a critical analysis of the "natural" silvopastoral areas of the Karoo and Savanna areas, comprising ± 70% of the country, but also an urgent need to examine the reasons why newly developed agroforestry technologies are not being applied (Rethman, 1999).

4 AGROFORESTRY SYSTEMS: SITE AND SPECIES SELECTION

An important criterion in the selection of the study sites was that they represent a moist and semi-arid region close to communal areas and researchers. This was considered important in the dissemination of information to rural farmers, in maintaining good data and in optimising human resource and travelling costs. The proposed sites for the on-station trials were therefore Ukulinga Research Farm (UKZN) and Hatfield Experimental Farm (UP).

4.1 MOTIVATION FOR STUDY SITES

One of the main objectives of this project was to design and establish appropriate on-station trials in order to test efficient agroforestry systems in terms of water use. The selection of sites was to a large extent based on the land and experimental facilities available to the project team. Both the Universities of KZN and Pretoria have experimental farms where a number of agroforestry related crops have been planted previously and a number of systems and methodologies are in place. Since agroforestry trials take a long time to establish, the existing trials provided a variety of systems that could demonstrate a number of options to potential communities. Both of the universities were well situated in relation to potential target communities.

It was decided to conduct the bulk of experimental work on Ukulinga farm, as the majority of project members were in the near vicinity, with some trials already established. Although smaller trials were also planned for Hatfield experimental farm, the retirement of both Dr. At Kruger (CSIR) and Prof. Norman Rethman (UP), and the emigration of the main PhD student, resulted in a loss of personnel to conduct the research. In addition, since the original proposal, Hatfield lost valuable land and agroforestry trials to the development of the Innovation Hub. A decision was therefore made by the reference group to carry out all the field work at the Ukulinga Research Farm. The university farm was also easily accessible for rural communities to visit the trials. Networking with other research programmes at the University enabled the project to facilitate cross visits and have input by a number of different communities in the same bioclimatic region.

4.2 UKULINGA RESEARCH FARM

4.2.1 Biophysical description

Ukulinga is the research and training farm of the University of KwaZulu-Natal in Pietermaritzburg. The farm falls in the humid zone (Figure 4.1.) and is classified as Bioresource Group 17- Coast Hinterland Thornveld (Camp, 1997). This vegetation type has been subject to severe degradation of its natural resources. Research carried out on the farm will therefore be particularly relevant to communities in this zone.

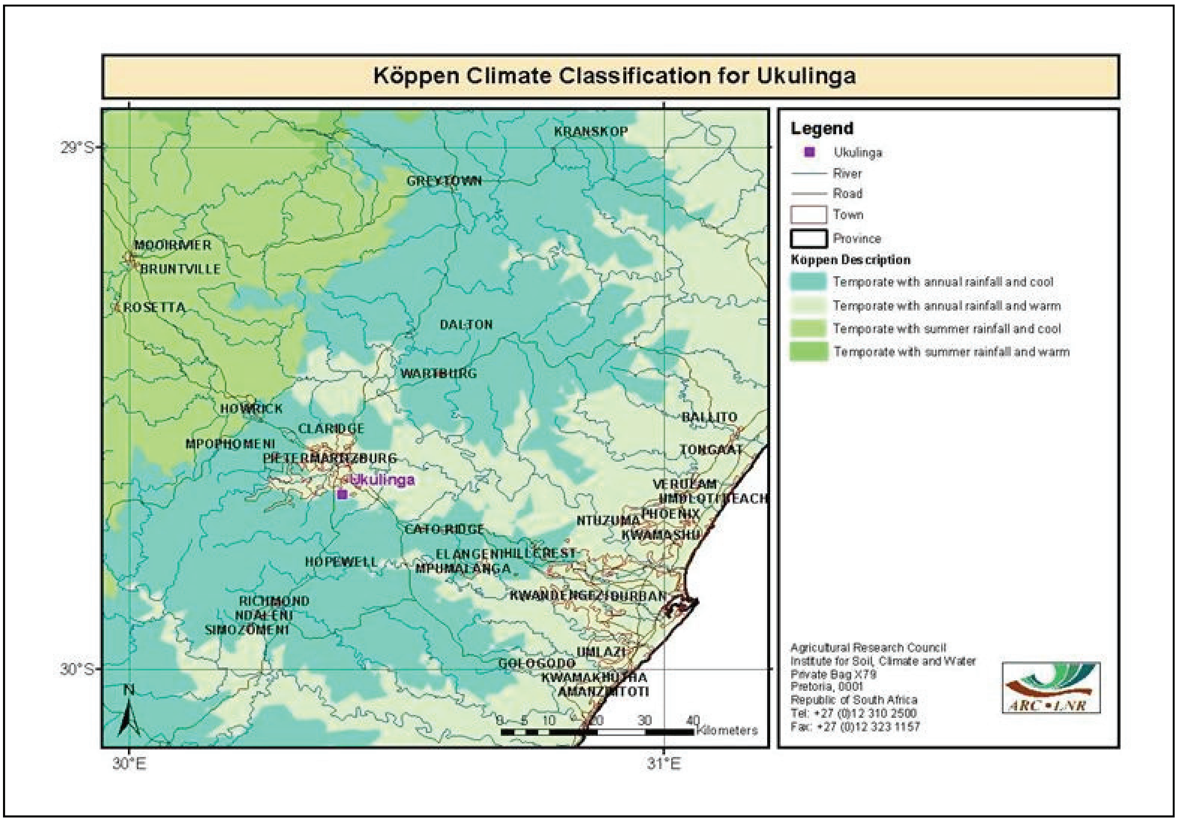

Figure 4.1 Köppen climate classification and location of the Ukulinga Experimental Farm

The Coast Hinterland Thornveld is found at the upper margins of river valleys and is a secondary veld, dominated by *Acacia* species, which have expanded from the valley vegetation into the grassland areas which are classified as Dry Ngongoni Veld. This vegetation zone generally occurs between 450 m and 900 m in the major river valleys between the Thukela River and the Mzimkhulu River. It is 113 367 ha in extent.

4.2.2 Climate

The mean annual rainfall range is from 644 mm to 825 mm. Ukulinga averages 680 mm from 106 rain days. Winter rainfall amounts to 23% of the total annual rainfall, with four rain days in June and July, the mid-winter months. The mean annual temperature for this bioresource group is 18.4°C, within a range of 17.2°C to 19.5°C. Summers are warm to hot (mean January maximum temperature is 26.9°C) and winters are mild (mean July minimum temperature range is 6.0-7.4°C). Moderate frosts are experienced occasionally. The range in the mean annual evaporation is from 1 625 mm to 1 763 mm. According to the Köppen classification the area is temperate with annual rainfall and warm (Figure 4.1).

4.2.3 Vegetation

The Coast Hinterland Thornveld is a secondary veld which, before major disturbance occurred, is likely to have been an *Acacia* wooded grassland and woodland. The dominant vegetation patterns now are wooded grassland, woodland, bushed grassland and bushland thicket. The original woodland was dominated by *Acacia sieberana*, but much of it has been encroached by species such as *Acacia karroo, A. nilotica, Ziziphus mucronata, Maytenus heterophylla, Brachylaena elliptica, Erythrina latissima, Cussonia spicata, Aloe candelabrum, Euphorbia ingens, Rhus pentheri, Grewia occidentalis* and *Ehretia rigida*.

Initially the grassland was dominated by *Themeda triandra*, but this species is now low in relative abundance and the dominant grass is the unpalatable *Aristida junciformis*. The drastic deterioration in the quality of the veld has resulted from the common practice of burning throughout the year to promote a flush of fresh growth, followed by selective overgrazing. The production of alternative fodder sources will reduce the grazing pressure on the natural grassland.

4.2.4 Water resources

This bioresource group has a poor supply of water. Some localised areas are situated close to streams or rivers, which supply adequate water for domestic use and livestock watering purposes. Since there is limited water available for irrigation for farming purposes, it is essential that selected agroforestry species are not excessive water users.

4.2.5 Land use and potential

The area represented by this bioresource group is generally of a rugged nature, with 33% of the total area arable. High potential soils make up 18% of the bioresource group. In the remaining area soils are weakly developed, usually shallow topsoils underlain by lithocutanic B-horizons. Where soil development has proceeded further, red or black clays may characterise the subsoil. Problem soils, a lack of water and the frequency of droughts make this area difficult to farm successfully. However, the potential exists for the production of *Jatropha* which can tolerate poor soils. Many areas are close to markets which raise the potential of this species for income generation.

4.3 SELECTION AND DESCRIPTION OF THE CROPS AND PASTURES FOR SUBSISTENCE FARMING AGROFORESTRY SYSTEMS

One of the critical factors in the success of agroforestry systems in meeting farmers' objectives of increased production is the integrated management of available water, soils, trees and crops. There are various strategies to achieve this including crop rotations and intercropping suitable crops between the trees (Altieri, 1999). Choice of crops in agroforestry systems will depend on the farmers' specific objectives. The following potential crops include crops that may be new to farmers that have shown considerable potential elsewhere, as well as traditional crops that are known by farmers.

4.3.1 Pigeon pea (*Cajanus cajan*)

Cajanus cajan (L.) Millsp., also known as pigeon pea, is a perennial woody leguminous shrub, mostly grown as an annual.

Value: Pigeon pea is commonly used as a grain cash crop, fodder, and green manure. These sweet tasting seeds are eaten both as fresh shell beans and as dry beans. The stalks can be used for fuel, thatch, and basketry. The plant is a vigorous, drought-tolerant legume which provides large pods that are easily harvested. Pigeon pea is a heavy bearer, producing yields of up to 11 t ha^{-1}. The nutritional value of pigeon pea varies depending on harvesting stage (green pods or mature seeds). It is known that pigeon pea is rich in protein (up to 28%) and is equally rich in other nutrients such as starch, soluble sugars, crude fibre, fat, and minerals and trace elements like calcium, magnesium, copper, iron and zinc (Mathews, 2003). It therefore has the potential to improve the food security of people in resource poor areas. Although pigeon pea is not grown commercially in South Africa, large quantities are imported annually to meet the ever-growing demand for its de-hulled, split seed (dhal) for human consumption. The green, immature seeds are a good substitute for garden peas and are more nutritious then the dry seeds.

It is a nutritious, high-protein pulse crop and the leaves can be used for animal feed. Being a fast-growing plant it also makes good shade for other vegetable crops. Other advantages include: i) Productive for up to 5 years (lives for 10-12); ii) Woody parts can be used for firewood (10-12 t ha^{-1} $annum^{-1}$); iii) Water and nutrients from deep in the soil can be absorbed by its deep taproot; and iv) Plants can be used along contour barriers for erosion control.

The main benefit of pigeon pea is its positive effect on soil fertility. Its root nodules enrich the soil by adding about 40 kg of nitrogen per hectare (Valenzuela and Smith, 2002). In some areas pigeon pea is capable of fixing 41 to 280 kg ha^{-1} of nitrogen (Stephens, 2003).

Pigeon pea has the ability to survive and give good economic returns in drought prone environments and low input farming systems. They would therefore be useful in many of the erratic rainfall areas of South Africa. The development of new pigeon pea varieties, especially a high yielding, relatively non-photosensitive, short-duration type has helped to extend this crop to non-traditional production areas.

Climatic and soil requirements: Pigeon pea is one of the major grain-legume crops of the tropics and sub-tropics and plays an important role in the cropping systems adopted by smallholder farmers in a large number of developing countries in the semi-arid regions. Pigeonpeas can be grown on a wide range from sandy soils to heavy clay soils, which are not deficient in lime (Mathews, 2003, Valenzuela and Smith, 2002). The optimum pH is between 5 and 7. The altitude varies from sea level to 3,000 m above the sea level. It requires an annual rainfall of 600 to 1000 mm.

Establishment: It is suited for early planting and will succeed under hot growing conditions. It can be established by direct sowing at 3 cm depth or by seedlings in hedgerows at 1 m spacing between plants and 2 m spacing between rows (International Research Institute). Pigeon pea is also known for its ability to access insoluble phosphates in soils low in phosphorous, increasing the availability of soluble phosphorous for crops grown in rotation with it. When used as green manure, pigeon pea should produce quick improvements in the topsoil. Its extensive root system makes soil more friable, improves its tilth, and facilitates water infiltration (Valenzuela and Smith, 2002).

4.3.2 Maize (*Zea mays*)

Value: Maize is the main staple food for many rural people in South Africa and is therefore an important crop in agroforestry systems. It is widely used as human food, feed grain and as a fodder crop. About 66% of the global maize harvest is fed to livestock, 20% is consumed directly by humans, 8% is used in industrially processed food and non-food products, and 6% is seed or wasted (Dowswell *et al.,* cited in Nhancale, 2000). The average yield of maize (*Zea mays L.*) in developed countries is 6.2 t ha^{-1} and 2.5 t ha^{-1} for developing countries (Dowswell *et al.*, 1996). However, FAO (1996) recorded much lower national average yields of maize in Mozambique: 0.56 t ha^{-1} in 1993/94-crop season; 0.68 t ha^{-1} in 1994/95 and 0.94 t ha^{-1} in 1995/96. The incorporation of maize and legumes in agroforestry systems has the potential to increase maize production without the cost of fertilizers.

Climatic and soil requirements: The main growing season under rainfed conditions is between October and March. Maize is very sensitive to drought and the optimal rainfall requirement is between 500 to 1000 mm. The main limitations to crop growth and reproduction in African soils are nitrogen and phosphorus which have to be supplied in large quantities.

Establishment: Typically, farmers grow maize during the rainy season and little is grown during the dry season. Maize responds strongly to nitrogen fertilizers, but most farmers have not been able to afford the recommended rates since the elimination of fertilizer subsidies. Maize can therefore benefit from nitrogen fixing tree species in agroforestry systems. Frequent drought periods during the rainy season or delays in the start of the rains often decimate crop yields (Sanchez, 1995). Mulch from tree species can retain moisture and increase crop yields. The growth of the maize plant from planting to harvesting comprises 120 to 250 days depending on variety of maize planted (Hanway, 1971; PANNAR, 2003). The different stages require special conditions and management (e.g. water, nutrients, weed control and other agronomic practices) if higher yields are to be obtained.

4.3.3 Cowpea (*Vigna unguiculata*)

Cowpea is a very versatile crop in that it can be used as a vegetable, dry seeds, hay, silage, cover crop or green manure.

Value: Cowpea is a creeper legume plant which fixes nitrogen in the soil and improves soil fertility. It also spreads and covers the soil, reducing soil erosion and weed emergence, and increases the soil moisture by reduction of water evaporation in the soil. The crude protein content of cowpea herbage is usually high, ranging from 16 to 25 %, and is often favourably compared with that of Lucerne. It has the potential to supplement the starchy-based diets in rural people particularly in Sub-Saharan Africa (Rij, 1997). It is therefore a good option in rural farming systems.

Climatic and soil requirements: Cowpea is most suitable for moderately humid areas of the tropics and subtropics although some varieties show considerable drought resistance. The plants cannot withstand frosts and excessive heat can also reduce their growth (Bogdan, 1977).

Establishment: Cowpea is established by seed and sowing rates for fodder production range from 25-35 kg ha^{-1} for wide-row cultivation to about 100 kg ha^{-1} when broadcast. Inoculation is important to increase herbage yields (Bogdan, 1977). Cowpea has been sown with maize, sorghum, *Euchlaena mexcana, Panicum antidotale* and *Paspalum dilatatum* with satisfactory results (Bogdan, 1977).

4.3.4 Pumpkin (*Cucurbita pepo*)

Pumpkins are a vegetable crop that can enhance the contribution of agroforestry systems to food security.

Value: Most pumpkins are a good source of vitamin A and their seeds are also highly nutritious.

Climatic and soil requirements: Pumpkins are a warm-season crop that are adapted to a wide variety of well-drained soils. Light-textured soils are preferred in colder areas because they warm up more quickly in the spring. Large amounts of soils organic matter and a soil pH of 6.5 to 7.5 favour maximum production.

Establishment: Pumpkins can be irrigated less often, because they have deeper root systems. They are therefore suitable for systems where water is limited.

4.3.5 Guinea grass (*Panicum maximum*)

Silvopastoral agroforestry systems integrate animals, trees and grazing crops to increase the carrying capacity of the land. By allowing livestock to graze understorey products there can be an increase in both animal and tree production. *Panicum maximum* is a shade tolerant species that is an ideal species for silvopastoral systems. As this species is indigenous to South Africa it is known by farmers and is a suitable species to plant.

Value: Panicum maximum produces good grazing, silage and hay. Rotational grazing in silvopastoral systems with 3 to 9 week intervals increases herbage and animal yields. Well fertilised and irrigated *P. maximum* can produce 40-50 t DM ha^{-1} while in India a yield of 226 t fresh herbage ha^{-1} year^{-1} in 12 cuts was recorded for the sewage-irrigated grass (Narayanan & Dabadghao, 1972). *Panicum maximum* is reputed to be very palatable to all kind of stock, at least at reasonable early stages of growth, a few weeks after the last cut or grazing. As a cultivated grass *P. maximum* is much valued for its high productivity, palatable herbage and good persistence. There is a tremendous variation of nutritive value of *P. maximum* herbage, which depends mainly on the stage of growth where the herbage was harvested (Bogdan, 1977). At the later stages of growth the leaves remain highly palatable, whereas the thick stems of robust varieties are left uneaten. Crude protein content ranges from 4 to 14%, but higher contents of CP have been recorded. Content of crude fibre ranges from 28 to 36 % and depends mainly on the frequency of cutting. Phosphorus content usually exceeds 0.15% and is normally adequate for cattle requirements.

Climatic and soil requirements: Panicum maximum usually responds well to fertilisers, especially nitrogen (Bogdan, 1977) and will therefore benefit from the nitrogen fixing properties of legume trees species.

Establishment: P. maximum can be established either by seed or vegetatively, by tuft splits. Mulching with straw which retains moisture near the ground surface can improve the establishment (Bogdan, 1977).

4.3.6 Weeping lovegrass (*Eragrostis curvula*)

Eragrostis curvula is also a potential grass species for silvopastoral systems. The main reason for this is that it is a drought-resistant plant which occurs naturally in South Africa.

Value: It is valued for ease of establishment, reasonable yields, and palatability. Its good growth in spring and autumn make it ideal for fodder and hay (Bogdan, 1977). It is recommended for leys with alfalfa in drier farming areas (Bodgan, 1977). It is considered excellent for protecting terraces and for grassing water channels, and is valuable for erosion control. The crop can provide summer or winter pasture which makes it ideal to address winter fodder shortages in rural areas. Annual productivity ranges from 1 to 10 t ha^{-1}. The digestible dry matter content is about 60%. The crude protein of *E. curvula* is approximately 12 % but can drop to 3.4% in uncut plots. It is therefore important to graze it regularly.

Climatic and soil requirements: Eragrostis curvula is adapted to a wide range of climatic and edaphic conditions in South Africa, including low rainfall (525 mm), sandy and acidic soils (Donaldson, 2001).

Establishment: Eragrostis curvula does best if established in January-February at a seeding rate of 2.5-4.5 kg ha^{-1} for broadcast sowings or 1.5-2.5 kg ha^{-1} for row plantings (Donaldson, 2001).

4.3.7 Kikuyu (*Pennisetum clandestinum*)

Kikuyu is a robust, creeping summer perennial grass which develops thick, closely-noded runners both below the soil (rhizomes) and on the soil surface. The runners root at the nodes from which secondary branches develop.

Value: Since this grass was introduced into South Africa 80 years ago it has become an important pasture grass in the high rainfall areas and under irrigation. This crop is suitable exclusively for grazing and has little haymaking potential. Surplus summer production can, however, be conserved as foggage or silage, for use in autumn and winter. The carrying capacity of a kikuyu pasture can vary according to soil type, moisture supply, temperature and amount of nitrogen applied. One hectare of dryland kikuyu can provide roughage for 3 cows of 500 kg average mass each for 5 months. If there is irrigation and an adequate application of nitrogen, the carrying capacity increases to 6-7 cows for almost 7 months. Rotational grazing is helpful in the effective management of kikuyu. Four to six camps per herd are needed to provide for short grazing periods and the necessary rest periods.

The quality of kikuyu varies according to fertilizer applications, and change is also found during the growing season. In Table 4.1 the results of plant analysis of an irrigated pasture are shown. Nitrogen application was 400 kg N ha^{-1}.

Table 4.1 Kikuyu Analysis – Cullinan district (Williams, 1980)

Percentage (%)	Nov 1979	Dec 1979	Jan 1980	Feb 1980	Mar 1980	Apr 1980
Nitrogen	4,10	3,91	3,33	3,20	2,77	3,42
Crude Protein	25,63	24,44	20,81	20,00	17,31	21,75
Crude Fibre	25,16	25,76	29,34	27,68	26,59	24,58
Phosphorus	0,33	0,38	0,33	0,40	0,34	0,33
Calcium	0,37	0,39	0,25	0,33	0,26	0,30
Magnesium	0,33	0,36	0,26	0,29	0,25	0,33
Potassium	4,35	-	3,95	4,20	4,30	5,70

Well managed kikuyu should provide for a dairy cow producing 14-16 ℓ milk day^{-1} without the need for a concentrate feed (Donaldson, 2001).

Climatic and soil requirements: The successful cultivation of kikuyu corresponds with the amount of moisture, high soil fertility and adequate nitrogen fertilization. Under dryland conditions, an average annual rainfall of at least 700 mm is required for successful production. In areas with a slightly lower rainfall, kikuyu could possibly be successfully cultivated on soils with good moisture retention. Although kikuyu grows reasonably well on badly drained soils, it will not tolerate water logging (standing water) over a long period. Kikuyu can withstand mild frost. It begins to grow earlier in spring than most other subtropical grasses and continues to grow until late in autumn when the first frost occurs.

Establishment: Kikuyu can be established on soils that are high in humus but grows very slowly in old lands where there is little organic matter. It is, therefore, necessary to raise the fertility level of the soil by spreading a large quantity of kraal manure or by feeding animals on the land for 3-4 months. Although the organic matter content of the soil can be augmented later, it is preferable to do so before establishment.

4.3.8 Velvet bean (*Mucuna pruriens*)

Mucuna pruriens, also known as Velvet bean or simply mucuna is a vigorous annual climbing legume, originally came from southern China and eastern India, where it was at one time widely cultivated as a green vegetable crop (Wilmot-Dear's study as cited in CIMMYT, 1998). Mucuna belongs to the Fabaceace family, covers perhaps 100 species of annual and perennial legumes, including the annual velvet bean. Mucuna is self-pollinating; hence, natural out-crossing is rare.

Value: Seeds have a high nutritional value as they contain about 27% protein and are rich in minerals (especially K, Mg, Ca and Fe) (de la Vega *et al.*, and Olaboro's study as cited in CIMMYT, 1998). Like most other legumes, mucuna has the potential to fix atmospheric N through a symbiotic relationship with soil micro organisms (CIMMYT, 1998). The N is converted by the rhizobia on the roots of the plant to an available form that is stored in the leaves, vines, and seeds – making the plant an efficient source of N (CIMMYT, 1998). Mucuna is used as a green manure, cover crop that can help rebuild soils quickly. Within one year, a crop of mucuna beans is able to fix 150 kg of nitrogen per hectare. Crops such as maize, without root nodules, can then benefit as the fixed nitrogen fertilizer is released into the soil. In addition, mucuna also produces up to 35 tonnes of organic matter per hectare (Houngnandan *et al.*, 2000).

According to (Houngnandan *et al.*, 2000) in Brazil, yields of maize, soya, and wheat increased 47, 83 and 82% respectively since mucuna was introduced into the cropping system with a range of other soil conservation strategies.

Climatic and soil requirements: Most mucuna species exhibit reasonable tolerance to a number of abiotic stresses, including drought, low soil fertility, and high soil acidity, although they are sensitive to frost and grow poorly in cold and wet soils (Hairiah, 1992). Mucuna thrives best under warm, moisture conditions, below 1,500 m above sea level, and in areas with plentiful rainfall.

Establishment: Mucuna pruriens is the most widespread of the cultivated species and is usually established in a Mucuna-maize cropping system (CIMMYT, 1998). Mucuna is initially introduced between the rows of maize, where it continues to grow profusely after the maize harvest. Once it has matured (some 8 months later), the velvet bean crop is slashed, and maize is planted once again in the mat of decomposing leaves and vines. Velvet bean residues are not burned or incorporated into the soil but left as mulch on the soil surface. Seed from the velvet bean crop eventually germinates on its own in the maize field, and the cycle is repeated. This cropping practice reduces labour costs by controlling weeds and increases maize yields by supplying nutrients when they are most needed. Productivity gains are realized without a concurrent decline in the resource base (CIMMYT, 1998).

4.4 SELECTION OF POTENTIAL TREES FOR AGROFORESTRY SYSTEMS IN SUBSISTENCE FARMING

One of the key issues facing rural farmers is what tree species to plant? Depending on the objectives of farmers there is a wide range of tree species to choose from. Most species suitable for agroforestry systems are fast-growing exotic species that are not known to farmers. This report outlines potential tree species and describes their key features to enable farmers to make informed choices of trees to plant. However, it must be noted that some of the species are potential alien invasive plants and permission may be required for planting according to the Conservation of Agricultural Resources Act, 1983 (Act No 43 of 1983) (CARA). Regulations 15 and 16 under this Act, which concern problem plants, were amended during March 2001. Some of the potential agroforestry species are classified as plant invaders of Category 2. These are plants with the proven potential of becoming invasive, but which nevertheless have certain beneficial properties that warrant their continued presence in certain circumstances. CARA makes provision for Category 2 plants to be retained in special areas demarcated for that purpose.

4.4.1 Leucaena (*Leucaena leucocephala*)

Leucaena leucocephala ranges from shrubs (5 m high) to trees (20 m high). An average yield of forage production in the experimental trial at The University of KwaZulu-Natal was 2000 to 5000 kg ha^{-1} of edible dry matter. These fodder yields can therefore be used as winter supplementation to livestock when natural pastures provide low quality grazing.

Value: The leaves of *Leucaena leucocephala* are an outstanding fodder for animals (Esterhuyse, 1989). It is a popular choice by farmers because of the high protein content in its leaves. It has the ability to fix atmospheric nitrogen due to a symbiosis with rhizobium bacteria. Ruskin (cited by Kruger and Grossman, 1991) states that this symbiosis is exceptionally effective and rates of 500 kg N ha^{-1}year^{-1} have been reported. This is equivalent to 1 785 kg LAN (28% N) fertilizer and has the potential to save the farmer considerable costs in fertilizing. An altitude/temperature association is generally accepted as limiting the plants distribution to below 500 m.

The incorporation of *Leucaena* cultivation into subsistence farming systems would not only improve soil fertility but also alleviate nutritional constraints for ruminants. *Leucaena* pods and seeds had higher ($p<0.01$) crude protein (CP) contents than *Acacia* pods (Table 4.2). *Leucaena* leaves contain high crude protein, and are very palatable to ruminants.

Table 4.2 Chemical composition of the pods of *Leucaena leucocephalaa, Acacia karroo, Acacia sieberana,* Maize stover and veld hay (Ngwa *et al.*, 2000)

Species	Plant part	DM	Ash	OM	CP	NDF	ADF
L .leucocephala	Pod	943	47.4	952.6	246.9	408.9	284.7
A. karroo	Pod	935	63.7	936.3	193.2	459.7	384.2
A. sieberana	Pod	936.5	44.2	945.8	174.9	366.9	290.1
Maize stover	Straw	943	71.2	928.8	53.5	522.8	360.3
Veld hay	Hay	952	75.4	924.6	41.9	700.8	472.3

Although highly palatable, *Leucaena* contains an amino acid, mimosine, which can be poisonous if livestock are fed 100% on *Leucaena* forage (Morris, 2002). As a result, 100% diet of *Leucaena* can produce poor results, with animals either not gaining weight, usually accompanied by an enlarged thyroid gland, reduction in fertility, loss of hair and even abortion. However, Akingbade, Nsahlai, Morris & Bonsi (2000) reported that planned diet of *Leucaena* to ruminants had significant positive effects. For example, the average daily gains of pregnant goats grazing *Leucaena*-grass pasture were significantly ($p<0.05$) higher than their counterparts grazing veld. Kids from mothers grazing Leucaena-grass tended to be heavier ($p<0.05$) at birth than their counterparts of veld grazing. The significantly ($p<0.05$) higher average daily gains of pregnant goats on leucaena-grass pasture showed that the pasture was nutritionally superior to natural veld. Milk production increased with litter size and dam weight at kidding. These results indicate *L. leucocephala*'s potential for food security in rural areas.

The Agricultural Research Council and the University of KwaZulu-Natal has run trials outside Pietermaritzburg in KwaZulu-Natal to see how well goats perform on *Leucaena* (Morris, 2002). Boer goats did very well on *Leucaena*; even at high stocking rate (20 goats/ha). Each goat gained about 600g of live mass per week during the summer growing season. At times they put as much as 1.5 kg per week. *Leucaena* reduced the time between pregnancies and increased overall kidding rate (<130%), boosted male fertility.

Zacharias, Clayton & Tainton (1991) compared the performance of grazing beef steers grazing foggaged dry land kikuyu pastures and given limited access (3h d^{-1}) to *Leucaena* to that of steers grazing kikuyu only. Over the three years of the trial, animals grazing *Leucaena* performed better ($p<0.05$) and gained 24.8 ± 3.01 kg per animal more than those on kikuyu alone. On the basis of this three year trial the authors recommend that *Leucaena* should be considered as a supplement to veld in South Africa.

Leucaena leucocephala produces very good firewood of medium density, burns well with little smoke and leaves little ash (Pound and Martinez, cited by Loxton and Associates, 1990). Trials at Eshowe, KwaZulu-Natal have produced 11t ha^{-1} 6 mths^{-1} in agroforestry systems with maize (Loxton Venn and Associates, 1990). The wood harvested had an average diameter of 3.95 cm at 30 cm cutting height and an average length of 3.1 m. Stem dry matter (DM) yields of agroforestry planted at 2 m spacing of *Leucaena* varied between 1000 kg ha^{-1} and 4 600 kg ha^{-1}. With over 12 million people in South Africa using fuel wood as a major source of energy these woody productions from *Leucaena* make this species a widely recommended source of energy for rural people (Stratten, 1990).

Climatic and soil requirements: Leucaena leucocephala is not tolerant to very low temperatures. Ideally soils should be neutral or alkaline with ph 6.0-7.7. Below ph 5.5 roots are stunted and growth is slow (Maclaurin, 1982).

Establishment: This tree is a Category 2 species which has invasive properties under certain climatic conditions, but also has high potential for fodder and fuel wood. It is an ideal species for establishment in alley cropping systems, where trees are planted one metre apart in rows 5 m apart, and agricultural crops are planted between the rows (Esterhuyse, 1989).

4.4.2 Mulberry (*Morus alba*)

Mulberry foliage is characterised by high nutrient digestibility and an excellent level of protein, which makes it comparable to commercial concentrates for dairy cows. The tree produces fodder, shade, fruits and fuel wood. The productivity and quality of mulberry makes it suitable for incorporation into agroforestry systems (Singh and Makkar, 2000; Shayo, 1997).

Value: In general, wood for fuel is not good quality. Wood production of mulberry is affected by factors such as soil, and climatic conditions, mode of propagation and harvesting techniques. If the objective of a farmer is to yield more wood production, long intervals between harvesting is recommended (Shayo, 1997).

Fodder production in tropical regions is 10 to 30 t ha^{-1} yr^{-1}, while in temperate regions it is 25 to 30 t ha^{-1} yr^{-1} (Singh and Makkar, 2000). Shayo (1997) stated although yield per season increased with harvesting interval, the amounts and nutritive value of edible components decreased considerably due to senescence and drop of leaves. This would be a disadvantage if fodder is required during the winter period.

Tikader *et al.* (cited by Shayo, 1997) found that maximum mulberry yield could be obtained by harvesting 3 times per year. Shayo (1997) showed that mulberry harvested twice at the end of rainy season, and in mid dry season, gave considerably high amounts of fodder. This would be beneficial to livestock owners in rural areas whose animals face fodder shortages.

The leaf fodder of mulberry is reported to be of good quality and can be utilised profitably as a supplement to poor quality roughages (Table 4.3). Variations in fertility are due to age, fertility of the soil, and leaf position within the branch.

Table 4.3 Nutritional information of Mulberry leaves

Composition % of DM	Singh and Makkar (2000)	Shayo (1997)	Omar *et al.* (cited by Shayo, 1997)
Crude protein	15.0-27.6	18.6	14
Crude fibre	9.1-15.3		
Ash	63.3	14.3	13.3
Lignin	11	8.1	
ADF	28-35	20.8	38.3
NDF	33-46	24.6	44.5

Ruminants fed low quality forages require supplementation with the critically deficient nutrient to optimise productivity. Mulberry leaves are rich in nitrogen, sulphur and minerals and their supplementation could increase the efficiency of microbial protein synthesis in the rumen leading to higher microbial protein supply to intestines. The use of high protein mulberry tree fodder should therefore be encouraged to provide supplementation under different feeding situations (Shayo, 1997).

Climatic and soil requirements: Mulberry is a forage tree perfectly adapted to tropical conditions, which has shown numerous possibilities of use in ruminant diets. In Africa, it has been reported to occur in the humid, sub humid and semi-arid areas at an altitude up to more than 1000 m above sea level. The plant is frost-hardy but liable to wind-damage.

Establishment: This tree is a Category 2 species which has invasive properties under certain climatic conditions, but also has high potential for fodder. It grows rapidly in the early stages and reaches maturity at an early age; the growth rate falls off rapidly after approximately 10 years. It is tap rooted with minimum superficial roots, has good coppicing power and is tolerant to lopping and pruning. Pruning enhances the size and quality of leaves.

4.4.3 Sweet thorn (*Acacia karroo*)

Value: Bembridge and Tainton (cited by Barnes *et al.,* 1996) indicated that *Acacia karroo* is a preferred fuel wood almost everywhere it occurs. Bembridge (1990) found that in rural Ciskei, *Acacia* ranked the cheapest, preferred form of energy by a staggering 73% of the population as compared to 16% preferring dung. It burns brightly and evenly with little smoke and no odour. It produces good coals and little ash. It splits easily and, once dried, it does not easily absorb moisture again if left out in the rain.

The foliage and green pods of *Acacia karroo* are important sources of browse for livestock. When consumption of *Acacia karroo* browse and grass by goats was measured in woodland in the Eastern Cape Province of South Africa, *Acacia karroo* was preferred to grass and selected almost exclusively when available at high leaf densities (Teague, 1989). Cattle also browse *A. karroo*, particularly when it is the only green forage in the woodland at the end of the dry season, but they do not browse it preferentially as do goats (Barnes *et al.,* 1996).

The nutrient and mineral content of *A. karroo* browse varies with the population, individual tree, soil, climate, season, age and browsing pressure. The proximate nutritional and mineral analyses of *A. karroo* foliage and pods from the Cape Province in South Africa are shown in Table 4.4.

Table 4.4 Proximate nutritional and mineral analyses of *Acacia karroo* foliage and pods from the Cape Province in South Africa

1 = dry (winter); 2 = wet (summer); CP = crude protein; EE = ether extract including resins and lipids; NFE = ash and N-free extract including carbohydrates; and Na, K, Ca, P, Mg; all given as % dry mass. Fe, Cu, Mo, Mn and Co are given parts per million. Adapted from Steenkamp and Hayward (Barnes *et al.*, 1996).

Plant part	CP	CF	EE	ASH	NFE
1Foliage	13.7	13.0	3.6	10.6	59.2
2Foliage	14.7	14.0	4.6	9.8	56.9
	NA	**K**	**Ca**	**P**	**Mg**
1Foliage	0.12	0.87	2.90	0.11	0.49
2Foliage	0.10	0.81	2.58	0.14	0.48
	Fe	**Cu**	**Mo**	**Mn**	**Co**
1Foliage	517	3.4	1.39	34	0.14
2Foliage	334	3.8	0.99	31	0.13

Steenkamp and Hayward (cited By Barnes *et al.,* 1996) indicated the green foliage and pods of *A. karroo* are protein-rich (14-15% dry weight) and well supplied with phosphorus (0.11-0.20% dry weight). Dean *et al.* (cited by Barnes *et al.,* 1996) found that nitrogen levels in *A. karroo* foliage are high (23.8 mg g^{-1} dry matter).

Climatic and soil requirements: Acacia karroo occurs naturally in South Africa over a wide range of climate and rainfall distributions. In each of these zones, mean annual rainfall can vary from 200 to over 1500 mm. Mean annual temperatures are also variable with a high of 24°C to a low of 12°C in the Karoo. On the Zululand coast the maximum daily temperature may rise to 40°C with *Acacia karroo* thriving. It is also tolerant to frost (Barnes, Filer & Milton, 1996; Teague, 1989).

Establishment: This species can be established through suckers or seed. It is an aggressive colonizer that can take over grasslands.

4.4.4 Fever Tree (*Acacia xanthophloea*)

Acacia xanthophloea is a semi-deciduous to deciduous large tree reaching approximately 15 to 25 m tall and has an open, rounded to spreading or flattish crown which is sparsely foliated.

Value: Acacia xanthophloea is the one of the fastest-growing thorn-tree species in southern Africa, with a growth rate of 1-1.5 m $year^{-1}$ (ICRAF, 1992). The wood is hard, heavy and a suitable general purpose timber but it should be seasoned before use otherwise it is likely to crack (ICRAF, 1992). Fever trees are planted as a source of firewood, although they produce a gum that leaves a thick, black, tarlike deposit when burnt.

Foliage and pods provide food for livestock (ICRAF, 1992). This plant has root nodules containing nitrogen fixing bacteria which play an important role in the nitrogen enrichment of soils which then has a positive impact on the growth of plants around the fever tree.

Climatic and soil requirements: Fever trees can be found in small groups around wet areas and along rivers especially in the Sand Forest of the coast (Grant & Thomas (1998).

Establishment: *Acacia xanthophloea* is easily grown from seed.

4.4.5 *Acacia mearnsii* (*Black wattle*)

This multipurpose tree is well known in Australia, South Africa, East Africa and South America (Duke, 1983). The common name of this tree is Black Wattle. It is a fast growing tree which flowers in its second year. It grows from 6 to 20 m tall, and 10.0 to 60.0 cm in diameter.

Value: The wood of debarked trees is dried and used for mine timbers, pulpwood, building material and fuel (Duke, 1983). According to National Academy of Science (NAS, 1980) the wood is dense (specific gravity between 0.7-0.85 g cm^{-3}) and has a calorific value of 3,500-4,000 kcal kg^{-1} and ash content of about 1.5%. It therefore makes excellent firewood. It also yields quality charcoal (specific gravity of 0.3-0.5 g cm^{-3}) with 6,600 kcal kg^{-1} of calorific value and 0.4% of ash. Trees provide bark 5-10 years after seeding (average 7) (Duke, 1983) and both bark and timber after 8-9 year rotation in high potential areas, increasing to 11 years in less productive areas (Schulze, 1997).

The foliage of *A. mearnsii* is not suitable for fodder. However, the bark is highly sought after in the tanning industry and has high potential for income generation. The tannin is used to produce leather. It is also used for wood adhesives and flotation agents (Duke, 1983). The pulp is suitable for wrapping paper and hardboard.

According to Duke (1983) black wattle in pure stands produces more tannin per hectare than most tanniniferous plants. Short rotations of 7-10 years or less are the most economical for plantation growth. This provides an annual thick wood production ranging from 10 to 25 m^3 per ha and yielding an average bark production of 800 to 4,000 kg ha^{-1}, depending on the site (NAS, 1980).

Wattle is an efficient N-fixer tree and is reported to annually yield 21-28 t ha^{-1} wet leaves containing 245-285 kg N (NAS, 1980). Some farmers claim that tobacco and vegetable yields are doubled in rotating with the black wattle in agroforestry systems because of the green manure that trees provide (NAS, 1980; Duke, 1983).

Climatic and soil requirements: It thrives on poor and dry soils but favours deeper, moister, more fertile soils. For an *Acacia*, it is relatively tolerant to frost, and its growth is slowed by high temperatures.

Establishment: It spreads naturally from seed, forming dense jungles (Esterhuyse, 1999). In South Africa it was declared an invader (NDA, 1999).

4.4.6 Physic nut (*Jatropha curcas*)

The tree is poisonous, fast growing, multipurpose and drought resistant.

Value: Growth and yield are likely to be determined by rainfall and temperature fluctuations. 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, there have been claims by Becker and Makkar (2000) of 2-3 tons of seeds ha^{-1} in semi-arid areas, and yields of 5 tons ha^{-1} under more favourable (wetter) conditions. Oil may be extracted by means of hand operated ram presses or expellers (Pratt *et al.*, 2002). With an oil content of approximately 35% (Henning, 1996), this equates to an average yield of approximately 1.75 tons of oil per hectare. Biodieselafrica (2004) calculated that a 20 ha *Jatropha curcas* farm could provide an annual income for a farming family of R60 000 in the 3rd to 4th year. They estimated that yields should increase in the following way:

1 Year 250 kg/ha seed = 120 kg oil
2 Year 1000 kg/ha seed = 480 kg oil
4 Year 5000 kg/ha seed = 2400 kg oil
6 Year 12000 kg/ha seed = 5760 kg oil.

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), so 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).

Climatic and soil requirements: The species is known to produce higher yields under sub-tropical conditions, which makes it suited for cultivation along the KZN coastal belt. Agricultural research stations in South Africa are currently evaluating the species to determine optimal growing conditions. It can grow in soils that are quite infertile, and is usually found at lower elevations (below 500 m). It can be cultivated in areas of low rainfall. In dry seasons it tends to shed its leaves. Where annual rainfall is high (>1000 mm), it does better in hot rather than temperate climates.

Establishment: Since it will survive with little or no fertilizer input, it is an attractive species for resource-poor farmers, although higher rainfall and fertilizer inputs can substantially increase its yields (Pratt *et al.*, 2002). *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). The choice of propagation method depends on use. Plants propagated by 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). Seedlings are susceptible to competition from weeds during their early development, so weed control is important. Satisfactory planting widths are 2x2 m, 2.5x2.5 m and 3x3 m, which are equivalent to crop densities of 2500, 1600 and 1111 plants ha^{-1}, respectively (ICRAF, 2003).

4.5 SOURCE OF PLANT MATERIAL IN THIS STUDY

A summary of the potential agroforestry plants that were tested in this trial and their sources are presented in Table 4.5**.**

Table 4.5 Summary of potential species for agroforestry systems and source of planting material

Plant name	Scientific name	Source of planting material
Pigeon pea	*Cajanus cajan*	Agricol Capstone Seeds Advanced Seed Co.
Maize	*Zea mays*	Afgri Farm City, Bethel Capstone Seeds Advanced Seed Co.
Cowpea	*Vigna unguiculata*	MacDonalds Garden Shop Agricol Capstone Seeds Advanced Seed Co.
Pumpkin	*Cucurbita pepo*	MacDonalds Garden Shop
Guinea grass	*Panicum maximum*	MacDonalds Garden Shop Agricol Capstone Seeds Advanced Seed Co.
Weeping lovegrass	*Eragrostis curvula*	Afgri Farm City, Bethel Agricol Capstone Seeds Advanced Seed Co.
Kikuyu	*Pennisetum clandestinum*	Whittet is the only cultivar for which seed is commercially available in the R.S.A. Agricol Capstone Seeds Advanced Seed Co.
Giant wattle	*Leucaena leucocephala*	University of KwaZulu-Natal
Mulberry	*Morus alba*	MacDonalds Garden Shop
Sweet Thorn	*Acacia karroo*	Silver Hill Seeds Dendroco
Fever Tree	*Acacia xanthophloea*	MacDonalds Garden Shop
Black wattle	*Acacia mearnsii*	MacDonalds Garden Shop
Physic nut	*Jatropha curcas*	MacDonalds Garden Shop Department of Agriculture, Makhathini Research Station

4.6 CONCLUSION

The potential species examined in this study will enable farmers to diversify their operations to improve overall production while conserving water and soil resources. The range of species that were tested in this trial together with the source of planting material will give farmers a number of options for agroforestry systems depending on their specific objectives. The species selected can provide a variety of services such as water and soil conservation, fertilization, fodder and food production, as well as products for additional income such as firewood, oil, fence posts and bark. On-farm trials of different species combinations selected by farmers need to be implemented and documented to promote the potential effectiveness of agroforestry practices.

5 PRODUCTION IN ALLEY CROPPING SYSTEMS

When designing and implementing on-station trials, it is important to consider the compatibility of the species with the site, the compatibility between species, the farm equipment available and the potential markets. This chapter describes the experimental design and implementation of three agroforestry systems (alley cropping, fodder banks and a silvopastoral system) for implementation in rural communities in KwaZulu-Natal. A variety of experimental designs were selected to optimize the number of choices available to farmers. Farmer evaluation workshops were held throughout the study so that feedback from farmers can be used for future recommendations and design of appropriate agroforestry for subsistence farmers.

5.1 EFFECTS OF ALLEY CROPPING *CAJANUS CAJAN, MUCUNA PRURIENS* AND MAIZE

5.1.1 Aim

The aim of this study was to determine the effect of alley cropping agroforestry systems on increasing maize production and soil fertility for application to smallholder farming systems.

5.1.2 Experimental design

The experiment was a randomised block (three blocks) design each with five treatments (Figure 5.1).

List of treatments:

1 Sole Maize (*Zea mays*) for control
2 Maize and chemical fertilizer (46% Urea)
3 Maize and Pigeon pea (*Cajanus cajan*) (also for control)
4 Maize, Pigeon pea and chemical fertilizer (46% Urea)
5 Maize, Pigeon pea and Velvet bean (*Mucuna pruriens*)

5.1.3 Implementation

The scheduled treatments that were implemented are presented in Table 5.1 and the main variables measured are listed in Table 5.2.

Total area: 80 x 35 = 2,800 m^2

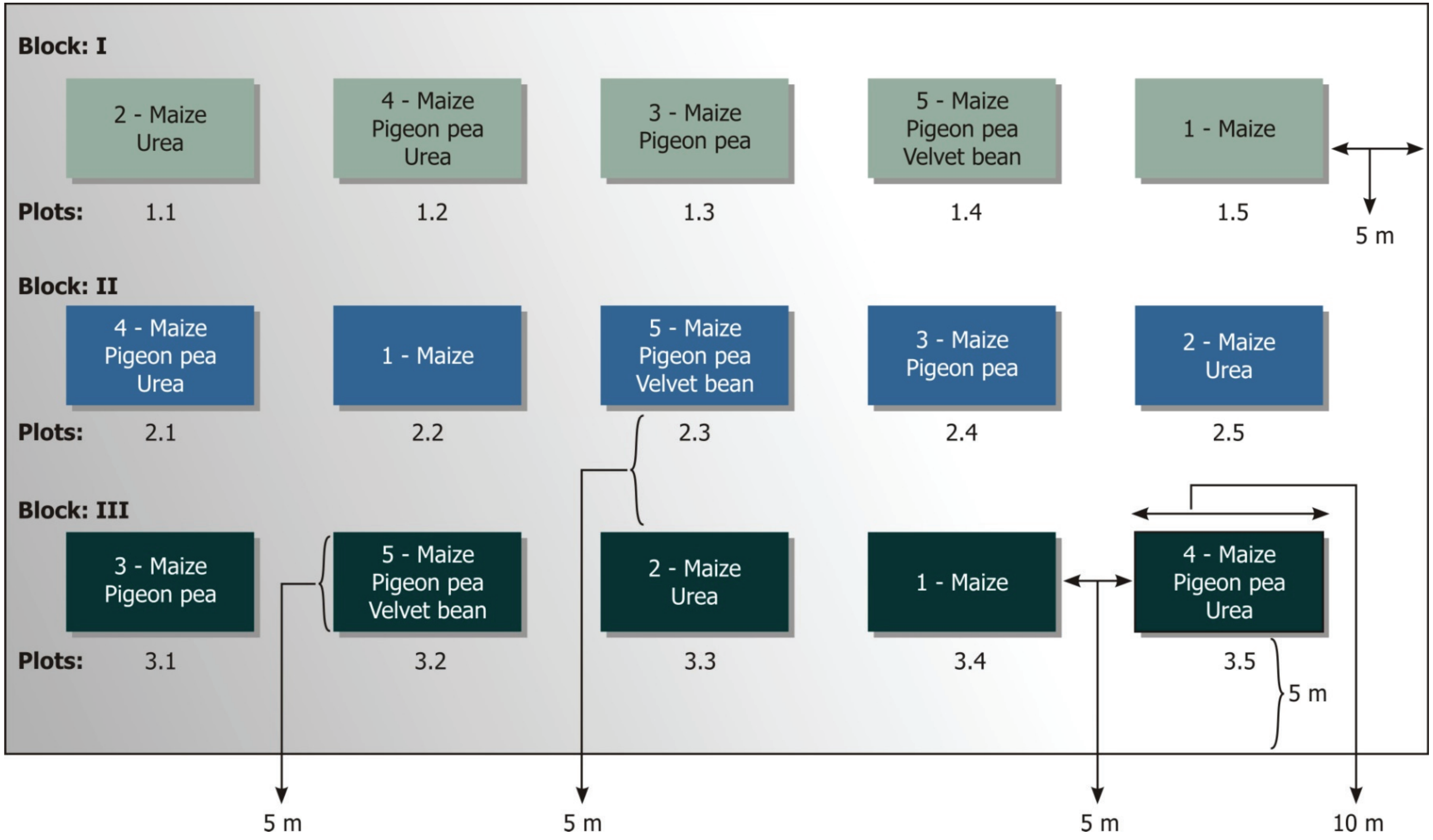

Figure 5.1 Experiment layout

Table 5.1 **Main field activities**

Activities	Sept-Dec 2003				January - December 2004												January - May 2005				
	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
PIGEON PEA CROP																					
Land preparation	X																				
Pigeon pea Planting		X					X														
Harvesting									X												
Ratooning/ Coppicing									X					X							
MAIZE CROP																					
Land preparation	X																				
Maize planting			X											X							
Urea appl.				X											X						
Agronomic Operations			X	X	X	X	X							X	X	X	X	X			
Harvesting							X											X			
VELVET BEAN																					
Land preparation	X																				
Velvetbean Planting				X											X						
Agronomic Operations				X	X	X	X	X							X	X	X	X	X		
Harvesting													X								

Agronomic operations included: irrigation, soil fertility, weed, pest and disease control.

Table 5.2 Main variables measured

Treat Nº	VARIABLES				
	Dependent			Independent	
	Crop yield		Biomass Production	Soil	
	Maize	Pigeon pea	Maize, pigeon pea and velvet bean	Fertility	Moisture
1	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓
3	✓	✓	✓	✓	✓
4	✓	✓	✓	✓	✓
5	-	✓	✓	✓	✓
6	✓	-	✓	✓	✓

5.1.4 Results and Discussion

The results from this trial are not available as the MSc student (Ignacio Nhancale) returned to Mozambique without completing his study after monkeys destroyed the crops.

5.2 THE PRODUCTION POTENTIAL OF ALLEY CROPPING OF *LEUCAENA LEUCOCEPHALA, MORUS ALBA*, AND *ACACIA KARROO* INTERCROPPED WITH MAIZE.

5.2.1 Aim

The aim of the trial was to investigate the interactions between different fodder tree species and maize in terms of production.

5.2.2 Experimental Design

The trial was a randomised block design with four treatments (6.5x2.5 m in size) replicated six times (Figure 5.2).

5.2.3 Implementation

The trial was established in August 2001 at the University Research Farm (Ukulinga farm). The site was prepared by heavy discing followed by rotovating to attain fine soil suitable for planting maize.

Trees were planted at a spacing interval of 0.5 m (12 trees per plot) and tree rows were 2.26 m apart. In the alleys were six maize rows. The six maize only plots were used as controls. Trees planted were exotic nitrogen fixing tree (*Leucaena leucocephala)*, an indigenous nitrogen fixing tree (*Acacia karroo*) and a fruit tree (*Morus alba*). Trees were initially irrigated once a week, for three consecutive weeks to allow an even sprout rate.

There were 18 rows of maize planted at a spacing interval of 30 cm within individual seeds and 75 cm apart between rows. Maize was planted during the beginning of summer rainfall (November 2001) after two months of tree establishment. An approximate amount of 250 kg/ha of fertilizer 2:3:2 + 5% zinc was applied when planting maize. Weeding was done through hand hoeing three months after planting.

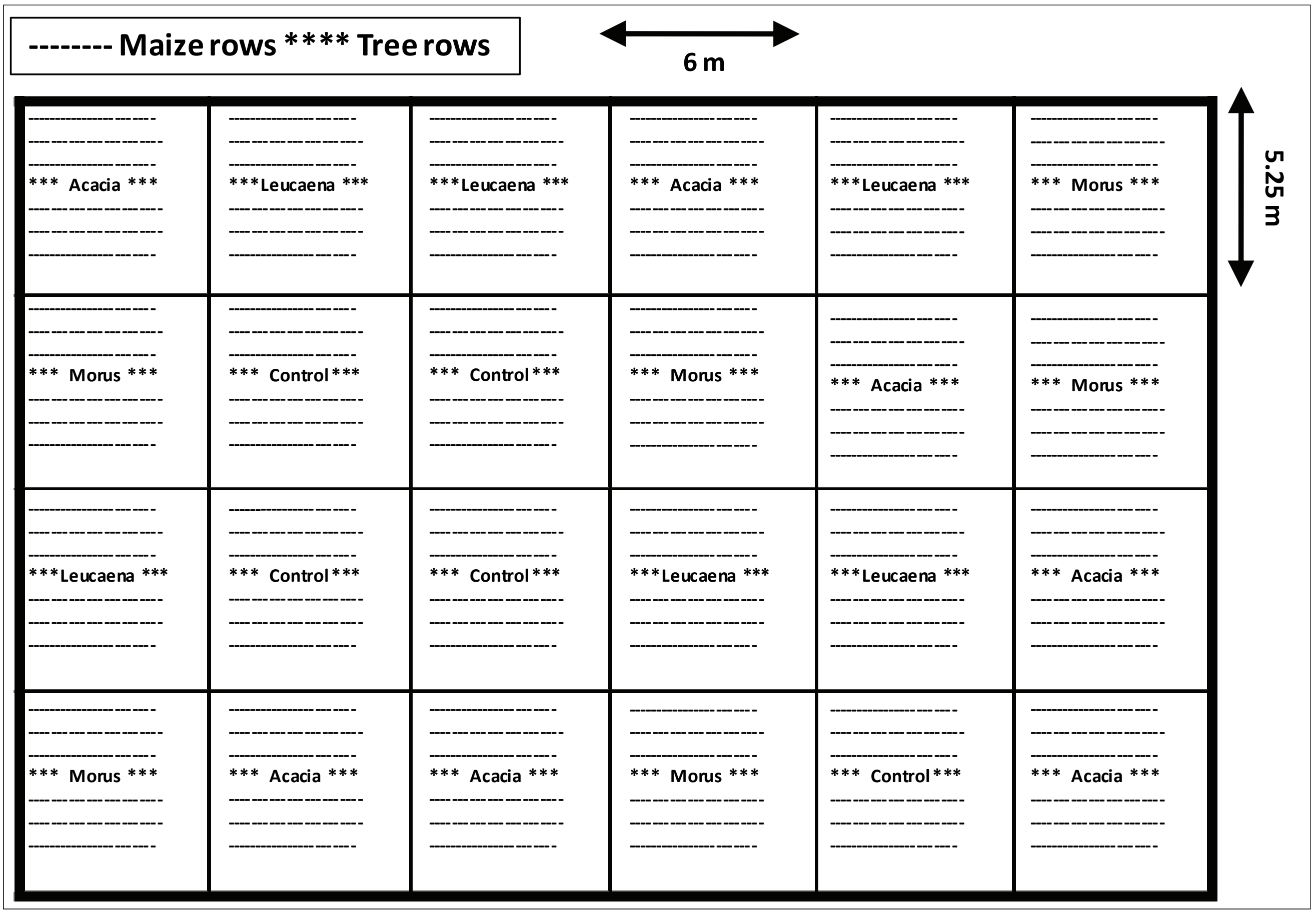

Figure 5.2 **Experimental design of an alley cropping system of *Leucaena leucocephala*, *Morus alba* and *Acacia karroo* intercropped with maize**

Variables measured

- ***Stem diameter and tree height:***

Stem diameter and tree height were measured in all the treatments to evaluate growth of tree species. The measurements were taken in January when trees where entering their fifth month after being planted and again when entering their eighth month prior to biomass harvesting. A consistent height of 10 cm from the base was used for measuring stem diameter. These measurements were repeated again in September, five months after pruning to evaluate recovery after harvest.

- ***Tree pruning, maize grain and stalk harvest:***

The time of harvesting was subjectively determined by means of visual observation, primarily when competition for light occurred between trees and maize crops, and also when trees started dropping leaves.

Eighteen plots were harvested in April 2002 after seven months of establishment to determine the browsable material and the amount of fuel wood produced. This was obtained by pruning the trees to a consistent height of 1 m.

5.2.4 Results and discussion

During the second season of planting (2003), there was no significant difference in forage yield between *M. alba* (1101 kg ha^{-1}) and *A. karroo* (1140 kg ha^{-1}) (Figure 5.3). Although slow in establishing, *L. leucocephala* yielded a highly significant ($P < 0.001$) fodder production (1715 kg ha^{-1}) in comparison to *M. alba* and *A. karroo* (Figure 5.3).

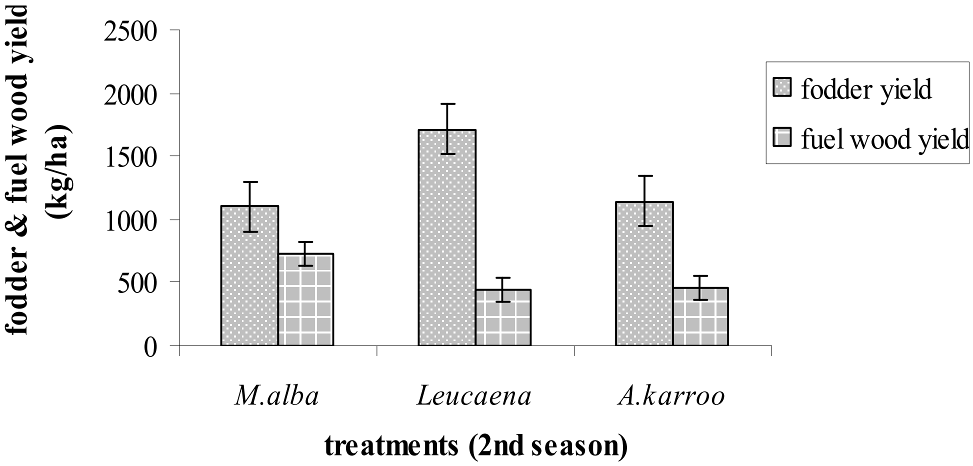

Figure 5.3 Average fodder and fuel wood yield in April 2003
Error bars indicate standard errors of differences of mean

In the second season of the trial, *M. alba* proved productive in meeting the needs of rural poor by producing higher fuel wood than other species. The yield increased from 444 kg ha^{-1} in 2002 to 728 kg ha^{-1} in 2003. Although a high yield was recorded, statistical tests revealed the difference in yield from three species was not significant ($P < 0.383$). *Leucaena leucocephala* and *A. karroo* produced 456 kg ha^{-1} and 439 kg ha^{-1} respectively. For *A. karroo*, this was a significant increase in fuel wood yield in comparison to 63 kg ha^{-1} during the first season. The greater fuel wood yield of *M. alba* when compared to *L. leucocephala* and *A. karroo* make this species more suitable for fuel wood production.

- ***Maize rows at 75 cm distance from the tree lines (2002)***

Different tree species had no significant effects on the average grain yield and stalk yield of the first maize rows (75 cm away from the tree lines) when compared to the control with no trees (Figure 5.4). From the partially intercropped treatments, *A. karroo* had the highest grain yield (898 kg ha^{-1}) and the *M. alba* plots (579 kg ha^{-1}) yielded the least production (Figure 5.4).

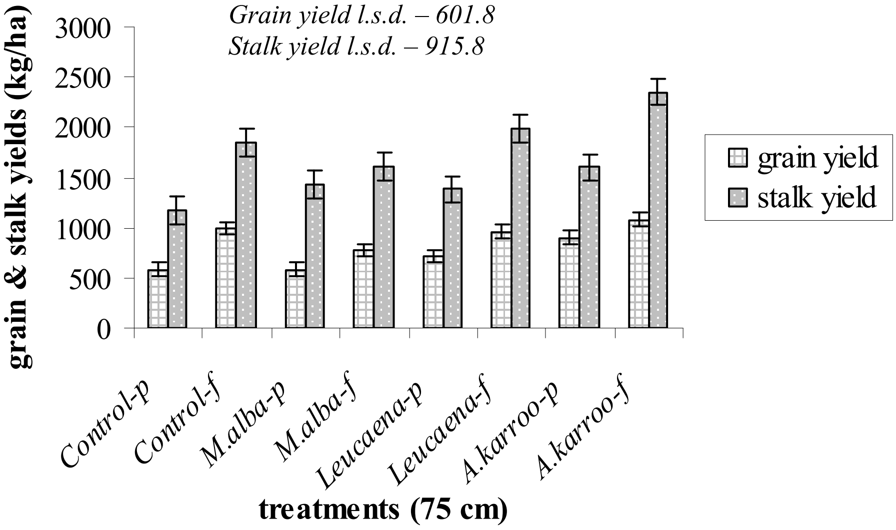

Figure 5.4 Mean maize grains and stalk production (kg ha^{-1}) in April 2002 (f=fully intercropped; p=partially intercropped). Error bars indicate standard errors of differences of mean

l.s.d. > Least significance difference

The same results were recorded from the fully intercropped treatments whereby the grain yield was highest in the *A. karroo* treatment (1078 kg ha^{-1}) and *M. alba* had the least production (774 kg ha^{-1}). The results from the fully intercropped plots indicated the treatments yielded no significant difference (P > 0.05) in stalk yield from the first row (75 cm) adjacent to the tree lines. The maize stalk yield from *L. leucocephala*-f (1989 kg ha^{-1}) and *A. karroo*-f (2349 kg ha^{-1}) plots had higher production than the control plots (1849 kg ha^{-1}) while that of *M. alba* was low (1608 kg ha^{-1}). The highest stalk yields from the partially intercropped plots were recorded in the *A. karroo* plots. Although there was no significant difference (P > 0.05) in stalk yield, the *A. karroo* plots had the greater production (1603 kg ha^{-1}) of mass per hectare compared to yield average of 1175 kg ha^{-1} from control plots (Figure 5.4).

- ***Maize rows at 150 cm distance from the tree lines (2002)***

The second maize rows which were 150 cm away from the tree lines had similar results with tree species having no significant effect (P > 0.05) on crop yield (Figure 5.5). The control plots yielded no significant difference in yield when compared to treatment plots. The control plots had greater yield in grain outputs when compared to both partial and fully intercropped treatments, though the difference in yield was tested not significant.

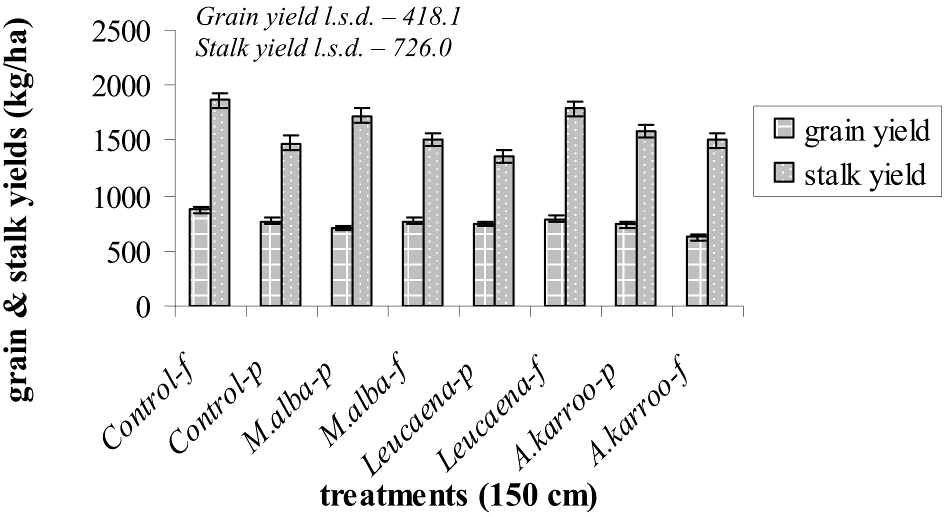

Figure 5.5 **Mean maize grains and stalk productions (kg ha^{-1}) in April 2002**

l.s.d. > Least significance difference
Error bars indicate standard errors of differences of mean

M. alba-p recorded a high stalk yield of 1725 kg ha^{-1} and *L. leucocephala* plots produced lower yield of 1354 kg ha^{-1} (Figure 5.5). In the fully intercropped plots, control plots had the highest yield (1861 kg ha^{-1}) compared to 1500 kg ha^{-1} and 1503 kg ha^{-1} from *A. karroo* and *L. leucocephala* respectively. Statistical test results showed both the planting arrangements had no significant effects (P > 0.05) on stalk yield.

- ***Maize rows at 225 cm distance from the tree lines (2002)***

The crop yield at 225 cm away from the tree lines was not significantly different (P < 0.05) from the control plots, implying that at this distance trees do not have a negative effect on grain and stalk yields. For instance, *L. leucocephala* plots recorded the highest grain output (701 kg ha^{-1}) in comparison to other treatments, though the difference was not significant (Figure 5.6).

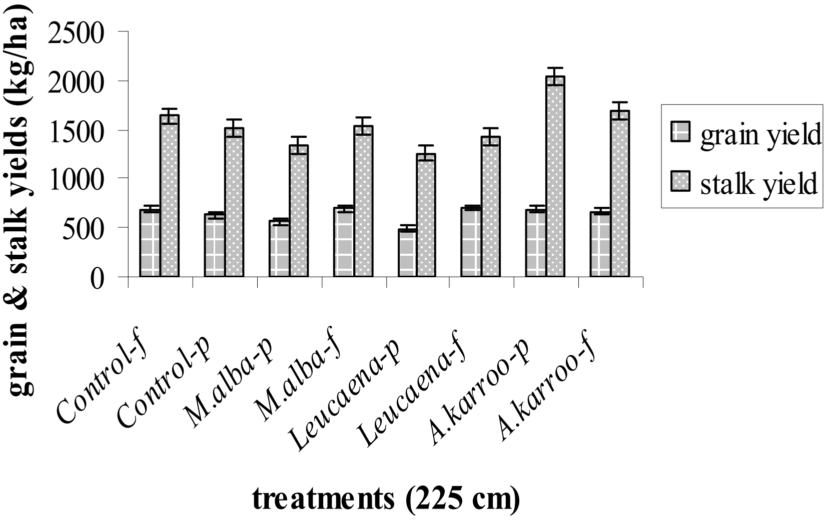

Figure 5.6 **Mean maize grains and stalk productions (kg ha^{-1}) in April 2002**

l.s.d. > Least significance difference
Error bars indicate standard errors of differences of mean

In 2003 the Pietermaritzburg region experienced a seasonal drought that resulted in low soil moisture content and high temperatures. These conditions had a negative effect on the crop yield in the trial. The maize stalks dried out and the growth form stunted before reaching the tusseling stage. As the maize stalks did not produce maize cobs only the stalk yield data are available.

The stalk yield from all treatment plots decreased in the second season when compared to the first season as a result of the drought. For example, the average stalk yield from all the adjacent rows to the trees (75 cm) decreased from 1671 kg ha^{-1} in the first season (Figure 5.4) to 1078 kg ha^{-1} in the second season (Figure 5.7) of the trial. The *A. karroo* treatment had the highest stalk yield of 1238 kg ha^{-1} which had decreased from 1976 kg ha^{-1} in the first season.

The results from second season revealed there was no significant difference ($P < 0.05$) between treatments and when compared to the control (Figure 5.7). In general the stalk outputs were less variable between treatments, when compared to the 2002 results.

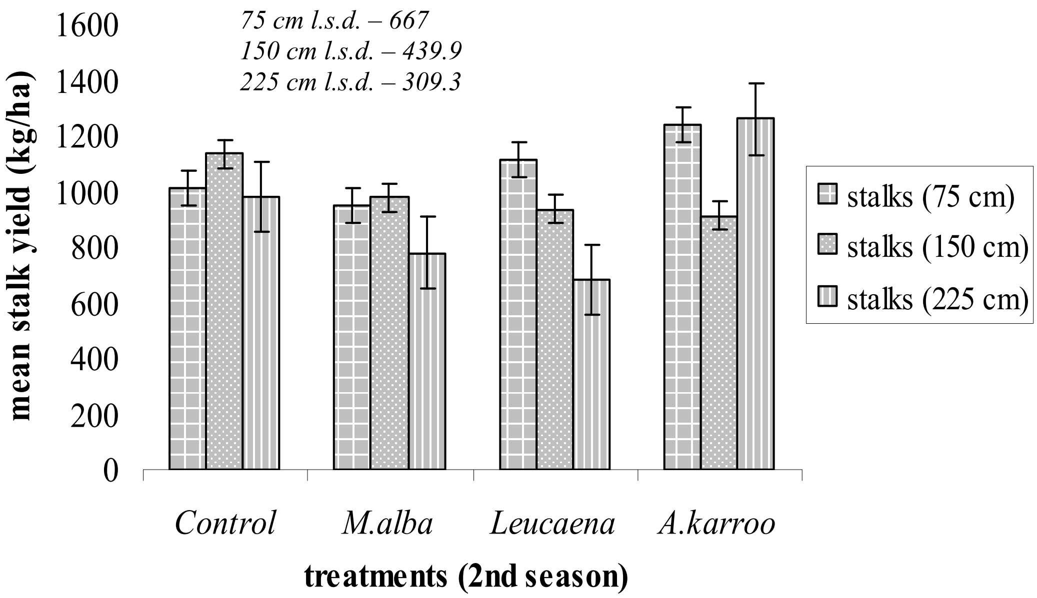

Figure 5.7 Mean maize stalk production (kg ha^{-1}) in April 2003

l.s.d. > Least significance difference
Error bars indicate standard errors of differences of mean

The 2002 October data revealed that *A. karroo* did not have a strong coppicing power. This is in contrast to *L. leucocephala* and *M. alba* which readily recovered from pruning by producing new green coppice shoots during winter. *Leucaena leucocephala* had a very slow establishment phase but once established it was a fast growing species that thrived under repeated cutting and coppiced readily.

High production is an advantage when addressing fodder deficits in rural areas. Although *M. alba* produced higher fuel wood yield, its fast growth rate makes it less suitable to address fodder deficits in rural areas. Since it reached maturity at a maximum height within a short period of time, its growth nature resulted in less fodder as it put most of its energy into wood growth. The highly branched trees are not suitable for alley cropping in agroforestry due to the shading effect. This suggests a strategy that for fodder yield purposes, *M. alba* should be regularly pruned to avoid the development of woody materials. Stewart and Salazar (1992) pointed out that aggressive branch expansion may inhibit the growth of other intercropped plants. Nevertheless, for fuel wood purposes, *M. alba* is the preferred species over the other tree species.

Acacia karroo was a slow growing indigenous tree species that was not as productive as *L. leucocephala*. There was no significant different in forage yield between *M. alba* (1101 kg ha^{-1}) and *A. karroo* (1140 kg ha^{-1}). However, *Acacia karroo* produced less woody material and more edible material which is more useful biomass for fodder purposes, especially to small stock.

In the second season of the study, *L. leucocephala* proved to be a good potential tree species for use in alley cropping practices. Even during the dry periods that occurred in the second season of the trial *L. leucocephala* recovered well after harvesting and produced high fodder yield (1715 kg ha^{-1}) compared to other tree species (<1140 kg ha^{-1}).

5.3 ALLEY CROPPING WATTLE AND *ACACIA XANTHOPHLOEA* WITH CROPS FOR FOOD AND FUELWOOD

Much research has been done on agroforestry technologies, using a variety of trees and shrubs. However, little or nothing has been reported about this technology using black wattle (*Acacia mearnsii*) and the fever tree (*Acacia xanthoploea*). These two nitrogen-fixing trees are common in South Africa and are fast-growing species which produce a considerable amount of biomass within a short period of time.

5.3.1 Aim

The aim of the study was to evaluate the potential of alley cropping two tree species, *Acacia mearnsii* (Black wattle) and *Acacia xanthophloea* (Fever tree), on the yields of maize, cowpea and pumpkin.

5.3.2 Experimental design

The trial comprised four treatments of alley cropping and two controls with three replications in a randomised complete block (RCB) design (Table 5.3). The alley cropping plot size was 10x10 m and the control plots 5x10 m (no trees).

Table 5.3 Alley cropping treatments

Control	**A$_1$** - Intercropping Maize and cowpea	**A$_2$** - sole pumpkin
Alley cropping	**A$_3$** - tree1 x maize x cowpea	**A$_4$** - Tree1 x pumpkin
	A$_5$ - tree2 x maize x cowpea	**A$_6$** - tree2 x pumpkin

- ***Spacing and number of plants***

Inter row spacing between trees was 4.0 m and inter tree spacing was 2.5 m. Maize spacing was 0.75 x 0.25 m and cowpeas were planted in the middle of maize rows 0.50 m apart. In the pumpkin plots the spacing was 1.50 x 0.5 m. This spacing was the same in alley cropping and control plots.

The trial consisted of 12 alley cropping plots where each plot had 3 tree rows and 5 trees per row (180 trees in total).

- ***Data collection***

Before sowing, soil samples were collected at 15 and 25 cm depths and analyzed for nitrogen to determine the effect of the nitrogen fixing trees. At the end of the crop season, the crop yield in terms of grain or fruit in the case of pumpkin and crop biomass was recorded.

5.3.3 Results and discussion

In general the crop yields and biomass were significantly higher under conventional practice (control) than they were under alley cropping ($P<0.05$) for both seasons. The maize grain yields were 1.9 t ha^{-1} and 2.6 t ha^{-1} under alley cropping and 2.0 t ha^{-1} and 5.7 t ha^{-1} under conventional practice (control = no trees) in the first and second seasons respectively (Figure 5.8). The grain yields of cowpeas were similar in both treatments in the first season (0.2 t ha^{-1}) but different in the second season when the yield increased to 0.3 t ha^{-1} under alley cropping and to 0.6 t ha^{-1} under conventional practice. The yield of pumpkin under alley cropping was 12.7 t ha^{-1} during the first season, decreasing to 8.5 t ha^{-1} in the second season. Under conventional practice, pumpkin fruit yield was about 18 t ha^{-1} in the first season and 11.5 t ha^{-1} in the second season (Figure 5.8). In this study the higher yield in the control plot has been reported to be a common finding at an early stage of alley cropping when the trees are still in the process of establishment (Nair, 1993). It is therefore recommended that agroforestry trials should be long term to show the benefits of species such as trees which take several years to establish.

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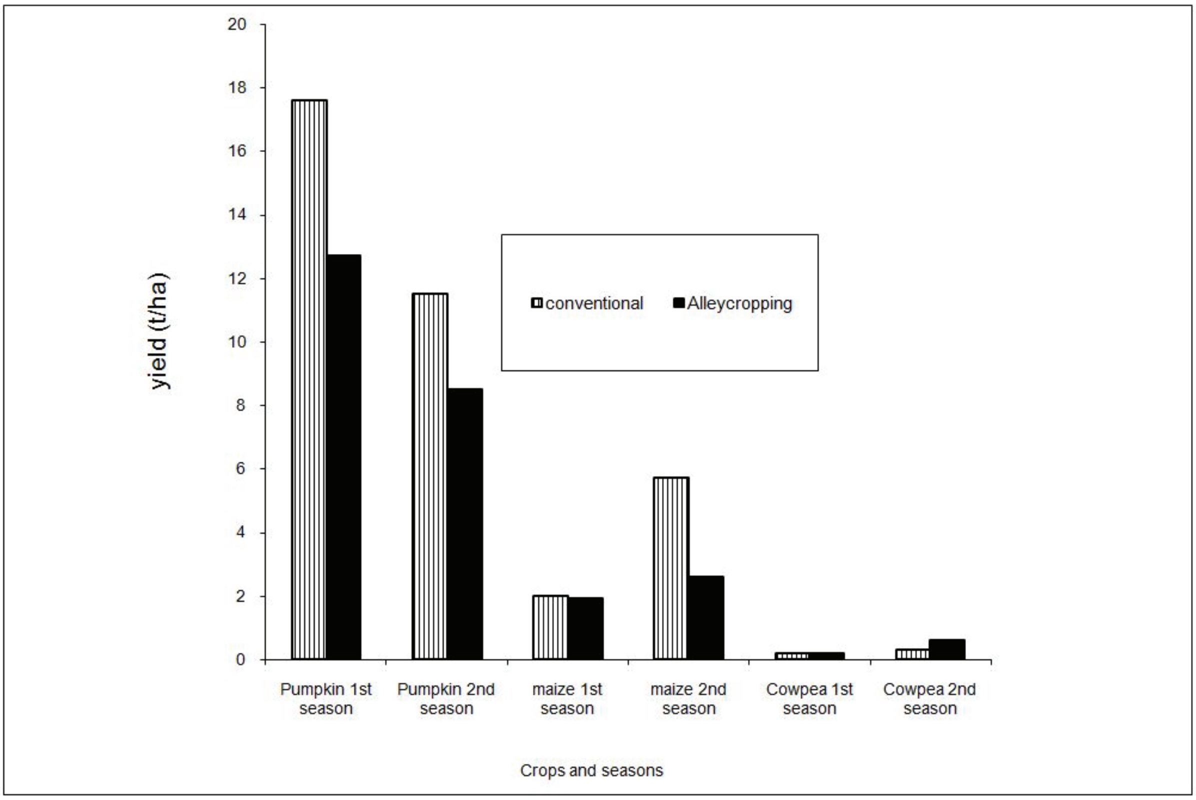


Figure 5.8 Crop yields in the 2003/2004/2005 cropping seasons under alley cropping and under the conventional system

No fertiliser was applied in this study because many farmers in rural areas do not use chemical fertilisers in their cropping systems. One of the main tenets of agroforestry is that leguminous trees maintain soil fertility (Palm, 1995) especially in relation to nitrogen deficiency. The yields in this study were similar to those reported earlier by Sanchez (1995) and Palm (1995). This seems to indicate that the soil at Ukulinga is not deficient in nutrients and hence the effect of alley cropping is unlikely to be appreciable at this stage. However with continuous nutrient mining due to cropping, the soil fertility will gradually decrease and alley cropping will gradually replace the soil nutrients making its effect notable. Williams (1928) cited by Sherry (1971) has shown that black wattle stands contain lime, potash and phosphoric oxides that can be released into the soil to provide phosphorus and potassium and lime, three substances which are essential for plant nutrition and soil pH balance. The afore-going shows that black wattle can be an important agroforestry tree species in nutrient-depleted soils.

6 PRODUCTION OF FODDER BANKS

6.1 AIM

The aim of the study was to determine the effect of alley cropping *Acacia mearnsii* (Black wattle) and *Acacia xanthophloea* (Fever tree) on the yields of two fodder species, *Panicum maximum* and *Eragrostis curvula.* These species can reduce soil degradation and supply fodder banks for livestock (particularly during the dry season) in rural areas.

6.2 EXPERIMENTAL DESIGN

The alley cropping trial was repeated with fodder grass species (*Panicum maximum and Eragrostis curvula)* replacing maize, pumpkin and cowpea (Table 6.1). Grass biomass was recorded in addition to tree biomass. The plot dimensions and treatment arrangements are illustrated below (Figure 6.1 a-c).

Table 6.1 Treatments in the fodder banks

Control	**B$_1$** - Panicum maximum	**B$_2$** - Eragrostis curvula
Fodder Bank	**B$_3$** - tree1 x *P. maximum*	**B$_4$** - tree1 x *E. curvula*
	B$_5$ - tree2 x *P. maximum*	**B$_6$** - tree2 x *E. curvula*

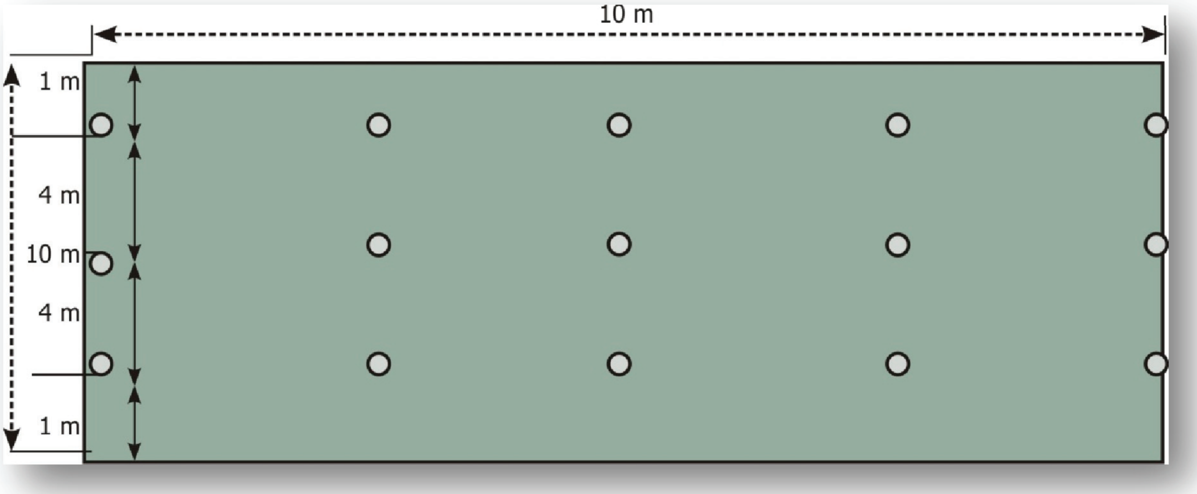
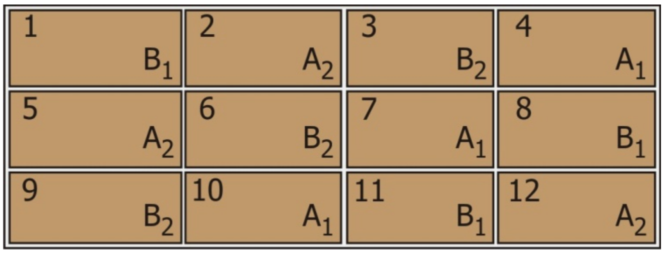


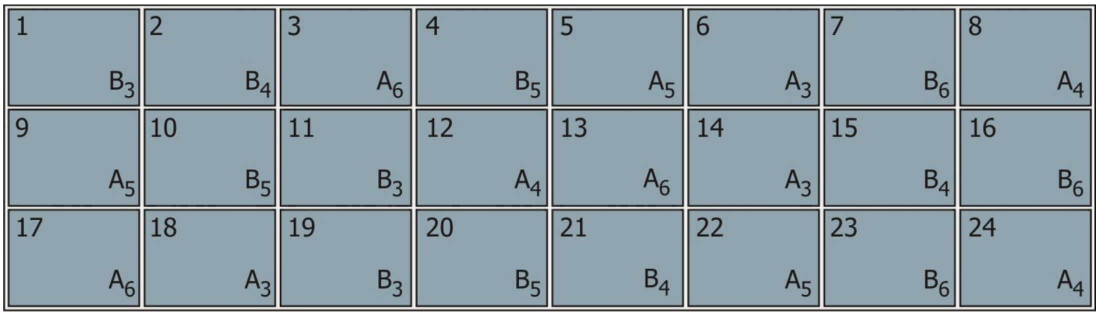
Figure 6.1(a) Alley cropping plot layout
(○ = trees)



1 B_1	2 A_2	3 B_2	4 A_1
5 A_2	6 B_2	7 A_1	8 B_1
9 B_2	10 A_1	11 B_1	12 A_2

Control:
A_1- Intercropping maize and cowpea, A_2- sole pumpkin, B_1- *P. maximum*, B_2- *E curvula*

Figure 6.1(b) Randomised complete block design of fodder bank trial – control plots



1 B_3	2 B_4	3 A_6	4 B_5	5 A_5	6 A_3	7 B_6	8 A_4
9 A_5	10 B_5	11 B_3	12 A_4	13 A_6	14 A_3	15 B_4	16 B_6
17 A_6	18 A_3	19 B_3	20 B_5	21 B_4	22 A_5	23 B_6	24 A_4

Treatments:
A_3- Black wattle x maize x cowpea, A_4- Black wattle x pumpkin,
B_3-Black wattle x *P. maximum*, B_4-Black wattle x *E. curvula*,
A_5-Fever tree x maize x cowpea, A_6- Fever tree x pumpkin,
B_5-Fever tree x *P. maximum*, B_6-Fever tree x *E. curvula*

Figure 6.1(c) Randomised complete block design of fodder bank trial

6.3 IMPLEMENTATION

The experiment was set up in rainfed and non-fertilisation bases to simulate rural farming conditions. The trees were planted first to avoid competition with the grasses. The seedlings were planted in rows with a spacing of 4 x 2.5 m. Each plot had 3 rows of 5 seedlings. The grasses were sown from seed drilled between the rows of trees in lines spaced 0.75 m apart. The first harvest of grasses was done in March 2004 and the second in March 2005. The grasses were cut to 5 cm using a motorised bush-cutter and weighed using a digital scale for fresh biomass determination. At the same time some samples of fresh grass were taken and dried in the oven at the temperature of 65°C for dry matter determination. In October 2004, a year after tree planting, all the trees were pruned and topped to a height of 1.5 m using pruning shears. The prunings were divided into two categories: the foliage and fine twigs (with middle diameter less than 1 cm) and the woody material including the remaining twigs and branches. Fodder was analyzed for Acid Detergent Fibre (ADF) and Neutral Detergent Fibre (NDF).

6.4 RESULTS AND DISCUSSION

During the study the germination of *P. maximum* was very poor. After several attempts with different lots of seed, the germination did not improve and it was decided to discard the species from the study. Therefore, this chapter will only present the results those that were attained with the black wattle and *E. curvula* experimental trial.

The biomass of the foliage and fine twigs of black wattle was 2.68 t ha^{-1} whereas the woody biomass was 0.99 t ha^{-1} (Table 6.2). The dry matter of *E. curvula* in the first season was 1.4 t ha^{-1} when grown with wattle and 1.14 t ha^{-1} in the control. In the second season (2004/2005) biomass was higher in the control 9.24 t ha^{-1} than in the wattle treatment (8.11 t ha^{-1}).

Table 6.2 Biomass of fodder banks

Species	Category	t ha^{-1}
Black wattle	Woody	0.99
	Foliage and Fine twigs	2.68
E. curvula Season 1	Foliage	1.14 (control) 1.40 (with wattle)
E. curvula Season 2	Foliage	9.24 (control) 8.11 (with wattle)

The values of neutral detergent fibre (NDF) and acid detergent fibre (ADF) for black wattle and *E. curvula* are shown in Table 6.3. For black wattle the NDF was 76.58% and the ADF was 68.1%. For *E. curvula* the NDF was 41.9% and the ADF was 39.9%. The values of NDF represent the percentage of non-digestible material in neutral detergent and it is used to estimate the percentage of fodder digestibility. The fodder digestibility is calculated using the formula (100 – NDF). In this case the digestibility of black wattle was 23.42% and for *E. curvula* it was 58.1%. The ADF is used to estimate the potential digestibility of NDF or the total forage digestibility. The total fodder digestibility is calculated by the formula (100 – ADF). The total digestibility for black wattle was only 31.9% while for *E. curvula* it was 60.1%. Comparing the digestibility of both species it is clear that *E. curvula* had a higher percentage of fodder digestibility and total fodder digestibility than black wattle, at the time when the samples were taken and analysed (end of wet season). Values of neutral detergent fibre (NDF) and acid detergent fibre (ADF) less than 35% are considered good, between 35% and 50% fair and poor if greater than 50%. Using this classification the NDF and ADF values from this study were fair in *E. curvula* (41.9% and 39.9%). If black wattle is to be used as fodder, it must be mixed with highly digestible fodder such as *P. maximum* and *Digitaria* sp., and other legume plants, to increase animal intake and to avoid any risk of it becoming an animal hazard due to tannin effects.

Table 6.3 NDF and ADF of black wattle and *E. curvula*

Species	NDF (%)	ADF (%)
Black wattle	76.58	68.1
E. curvula	41.9	39.9

The results showed that tree growth and tree biomass production were higher in black wattle alley cropping than with the fever tree alley cropping. The average diameter at breast height of black wattle after 12 months was 36 mm. Over the same period the total tree height was 4060 mm. A tree pruning was done to one-year old black wattle in the whole trial and the prunings produced 2.68 t ha^{-1} in association with *E. curvula*. The fever tree did not grow significantly during the study period and due to that fact, the species was discarded from the study.

In general the crop yields and biomass were greater under conventional practice (control) than they were under alleycropping, and the difference was statistically significant ($P<0.05$) for both seasons (Table 6.4). The maize grain yields were 1.9 t ha^{-1} and 2.6 t ha^{-1} under alleycropping and 2.0 t ha^{-1} and 5.7 t ha^{-1} under conventional practice (control) in the first and second seasons respectively. The grain yields of cowpeas were similar in both treatments in the first season (0.2 t ha^{-1}) but different in the second season when the yield increased to 0.3 t ha^{-1}under alleycropping and to 0.6 t ha^{-1} under conventional practice. The differences in yield between the two seasons may be attributed to the impact of weeds. In the first season weeds were difficult to control because the site had been fallow for years and the soil was still rich in weed seeds. Weed and shading control were more efficient in the second cropping season and the result was the increase in crop yield and biomass of the maize and cowpeas.

Table 6.4 The yield (t ha^{-1} ± standard deviation) of grain maize, cowpeas and pumpkin fruits in the 2004/2005 cropping seasons under alleycropping and conventional practice

Crops	Maize (t ha^{-1})		Cowpea (t ha^{-1})		Pumpkin (t ha^{-1})	
Season	Alleycropping	Control	Alleycropping	Control	Alleycropping	Control
First	1.9±0.59	2.0±0.99	0.2±0.09	0.2±0.03	12.7±5.32	17.6±7.45
Second	2.6±0.72	5.7±0.47	0.3±0.12	0.6±0.15	8.5±4.04	11.5±1.25

The yield of pumpkin under alleycropping was 12.7 during the first season, decreasing to 8.5 in the second season. Under conventional practice, pumpkin fruit yield was 17.6 t ha^{-1} in the first season and 11.5 t ha^{-1} in the second season. Under alleycropping of black wattle and pumpkin, competition was not a problem in the first cropping season because the pumpkin grew very fast suppressing the weeds while tolerating the shading from the trees. On the contrary, in the second cropping season, competition for water between the trees and crop was very critical and the result was the decrease in the yield and biomass of pumpkin in this season compared to the first cropping season. Water was the main constraint to the pumpkin yield and biomass because there was a shortage of rainfall in that season, particularly at flowering.

In conclusion, black wattle intercropped with maize, cowpeas and pumpkin, can be a useful alternative production system in places where black wattle grows well. The system needs to be well managed, however, in order to avoid competition between the trees and crops. Pruning can be useful to control competition between the tree and crop components. The amount of biomass produced from the system can maintain maize grain yields at 2 t ha^{-1} in poor soil. Intensive management (e.g. weed control will be necessary for targets of higher yields. The digestibility of black wattle was low. It can be improved, however, by mixing it with high-quality fodder, although the correct proportion in the mixture needs to be investigated.

7 PRODUCTION AND WATER USE OF A *JATROPHA-PENNISETUM* SILVOPASTORAL SYSTEM

7.1 AIM

To investigate tree-grass interactions (water dynamics, soil fertility/health dynamics and plant productivity) in a *Jatropha curcas/Pennisetum clandestinum* silvopastoral experiment to understand the production processes with particular reference to the efficient use of water.

7.2 EXPERIMENTAL DESIGN

In silvopastoral systems trees may be grown in single rows or in aggregate rows called sets with wide alleys for forage production between sets (Figure 7.1.) Recommended planting widths are 2x2 m, 2.5x2.5 m and 3x3 m, which are equivalent to crop densities of 2500, 1600 and 1111 plants ha^{-1}, respectively (ICRAF, 2003). In this trial we selected a design of single, double and triple sets with an intermediate tree planting density of 1600 plants ha^{-1}.

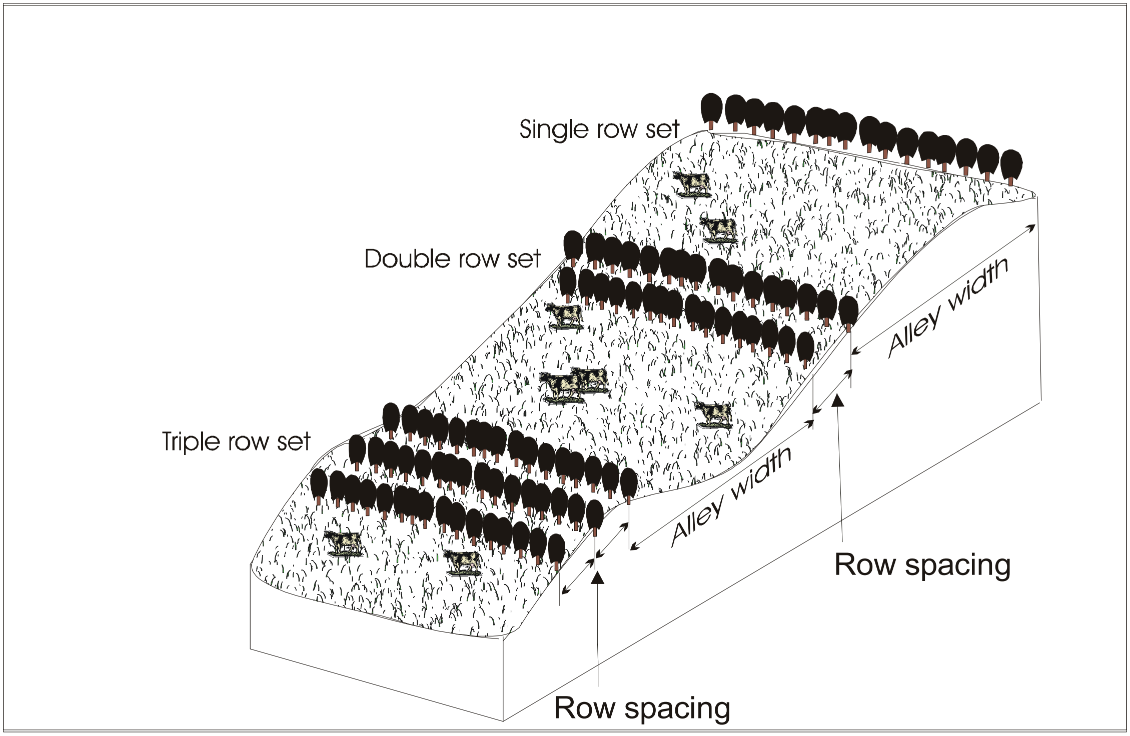
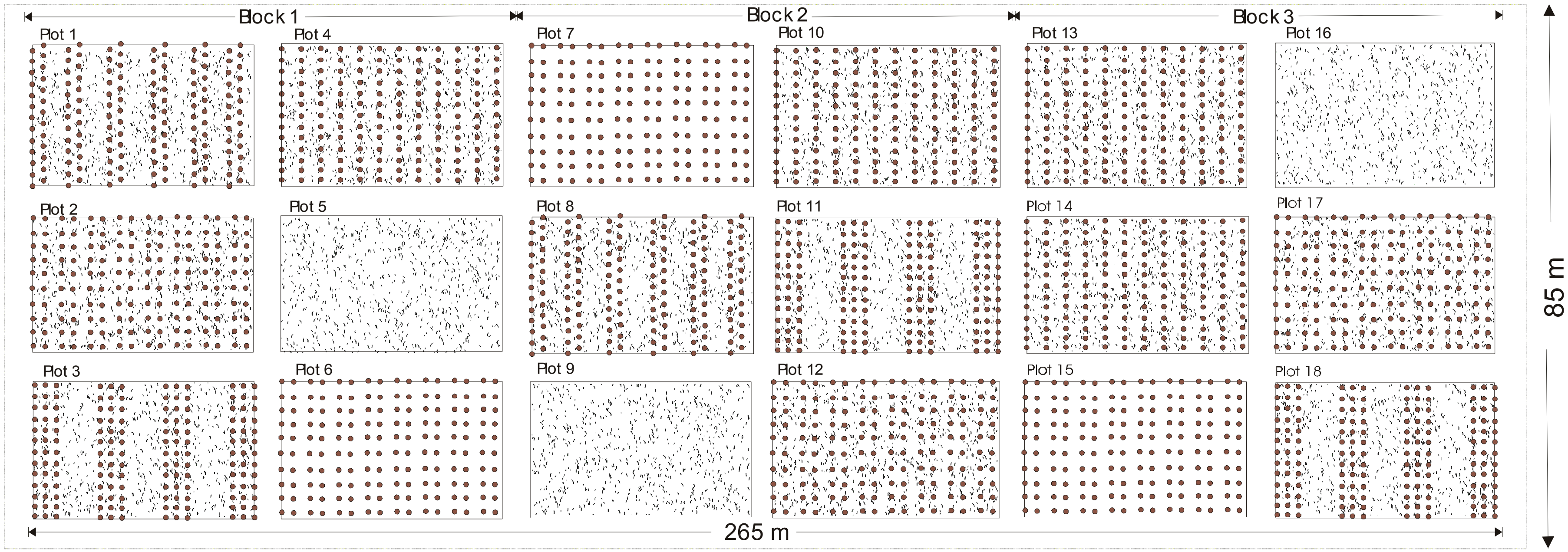


Figure 7.1 Typical layout diagram showing alley width, row spacing, and tree sets for establishing a silvopastoral system

The trial was a randomised block design (3 blocks) with six treatments per block, i.e. 3 replicates per treatment) (Figure 7.2). A large plot size of 40 m x 25 m (0.1 ha) was selected to enable the use of certain micrometeorological techniques and for grazing by livestock. The trial was 265 m long x 85 m wide (an area of 22 525 m^2 or 2.25 ha).

The following are the selected treatments:

1. Kikuyu only (control)
2. *Jatropha* only (control)
3. Normal: 2.5 X 2.5 m spacing + Kikuyu. 16 rows each with 10 trees (160 trees).
4. Single set + Kikuyu: 12 sets of trees (13 trees per set, ~2.0 m inter plant distance), 3.3 m alleys (156 trees).
5. Double set: 6 sets (2.5 m x 2.5 m spacing-13 trees per row or 26 per set), 3.4 m alleys (156 trees).
6. Triple set: 4 sets (2X2 m spacing-13 trees per row or 39 per set), 8.0 m alleys (156 trees).



Planting Density = 1600 Trees ha^{-1}
Plot Size = 40 X 25 m (0.1 ha)

Treatments:

Treatment	block 1 Plot #.	block 2 Plot #.	block 3 Plot #.
1. Kikuyu only	5	3	4
2. *Jatropha* only	6	1	3
3. Normal 2.5x2.5 spacing	2	6	5
4. Single row; 8 rows x 20 trees spacing 3.3 m	4	4	2
5. Double set: 2.5 + 3.4 space	1	2	1
6.Triple row : 2m wide 8m in between	3	5	6

Figure 7.2 **Plan diagram of the *Jatropha* – *Kikuyu* silvopastoral trail**

7.3 IMPLEMENTATION OF THE *JATROPHA* – *PENNISETUM* SILVOPASTORAL SYSTEM

Originally it was planned to use an intermediate tree planting density of 1600 plants ha^{-1} but following recommendations from the reference group committee held in January 2005 a planting density of 1111 plant ha^{-1} was adopted (planting width 3x3 m).

With regards to its maintenance requirements, there is limited information on the effect neighbouring vegetation will have on the growth and productivity of *J. curcas* plantations (Augustus *et al*., 2002). Gush (2006) observed that early tree growth was reduced in plantations planted with kikuyu (Gush, 2006). Research on other tree crops showed that basal vegetation competes for and reduces soil nitrogen, reduces tree yield and vigour, promotes shallow root development (Malik *et al*., 2001; Marty'nez-Herrera *et al*., 2006) and significantly lowers terminal growth (Haley and Hogue, 1990). Thus, there is a need to determine whether the presence of other plants depletes the available soil nutrient and water levels resulting in decreased *J. curcas* growth and productivity. The silvopastoral trial at Ukulinga was therefore used to assess the impact of competition from kikuyu on the growth of *J. curcas* in this silvopastoral system.

In addition, the susceptibility of *J. curcas* to browsing by herbivores in South Africa has not been determined. There is, however, much anecdotal evidence that animals including cattle (*Bos taurus*) and goats (*Capri hircus*) do not browse the plant most likely due to aversive secondary compounds in the stems and leaves (Heller, 1996; Openshaw, 2000; Augustus *et al*., 2002). Such information is vital to determine the viability of *J. curcas* in silvopastoral systems in communal areas. This information is also necessary for the government to reach a conclusion concerning the production of *J. curcas* in South Africa. The silvopastoral trial at Ukulinga was therefore used to investigate the acceptability of *J. curcas* to indigenous goats.

7.3.1 Site preparation and plant establishment

A suitable 3 ha flat site was located in a previous pasture trial on the University farm. The ground was prepared by ploughing and disking. In November 2004 kikuyu rhizomes were dug from a nearby site (Plate 7.1), chopped and spread across the trial using a muck-spreader (Plate 7.2). The rhizomes were then disked into the soil.

Unfortunately a very dry period following the planting resulted in none of the kikuyu rhizomes surviving. In December 2005 an irrigation system was installed to prevent a second failure and the entire trial was replanted by hand (Plate 7.3). By early January the kikuyu rhizomes had taken root and showed good growth by mid January (Plate 7.4). By mid January the trial was invaded by weeds which were removed by mowing and spraying with selective herbicides.

Once the pasture was established the final position of the 18 plots were demarcated with corner posts.

Plate 7.1 Collection of kikuyu rhizomes using a tractor mounted front loader

Plate 7.2 Planting the kikuyu rhizomes using muck-spreader

Plate 7.3 Planting the kikuyu pasture by hand

Plate 7.4 Growth of the kikuyu plants in January 2005.

Also visible is invasion of the plots by weeds.

Jatropha curcas seeds sourced from the Owen Sithole Agricultural College were tested for viability in November 2004. The results showed that only about 30% of the seed was viable. Four thousand five hundred seeds were planted directly into small plastics bags in a nursery with an automatic watering system. Three seeds were planted per bag in order to obtain the required 2 500 *J. curcas* seedlings. In cases where more than one seed germinated per bag the seedlings were removed to new bags. By the end of January 2005 the seedlings had developed to a stage where they could be moved out of the greenhouse to allow them to harden before planting (Plate 7.5).

Plate 7.5 A one month old *J. curcas* seedling growing in the holding nursery in January 2005

A system of marking the position of the planting pits was developed by using a 25 m rope with the interval distance marked with a different coloured rope (Plate 7.6). At each point a small wire marker with hazard tape was used to mark the planting position (Plate 7.7). Once planted the plots were irrigated to ensure the survival of the newly planted seedlings (Plate 7.8). All the plots were planted up by early February and subsequent growth and survival has been excellent.

Plate 7.6 **The markings on the rope**

Plate 7.7 **Marking the position of the planting pits**

Plate 7.8 **Irrigating a newly planted plot**

7.3.2 Measurements of growth and environmental factors affecting the plant water dynamics and production of *J. curcas* in a silvopastoral trial

This experiment was implemented to conduct appropriate water dynamics, soil fertility/health dynamics and plant productivity measurements at the *J. curcas* on-station trial to understand the production processes with particular reference to the efficient use of water.

7.3.2.1 Weather and environmental monitoring instruments

An automatic weather station was installed at the site for monitoring relative humidity, air temperature, wind speed, solar radiation, rainfall and vapour pressure deficit on an hourly and daily basis.

7.3.2.2 Characterisation of soil physical properties

At the beginning of the study a full soil profile description was carried out. Soil samples were taken using soil augers and core samplers, at representative depths, to the bottom of the 0.6 m deep soil profile. By analysing these samples, soil type and texture, bulk density, volumetric soil water contents at field capacity and permanent wilting point, soil hydraulic conductivity and soil water retention properties were determined.

7.3.2.3 Plant water dynamics

7.3.2.3.1 Heat Pulse Velocity technique (tree transpiration)

Water used by the trees was determined using the heat pulse velocity (HPV) method. The HPV technique is recognised internationally as an accepted method for the measurement of sap flow (transpiration) in woody plants. It has received much attention by researchers in recent years, and a wide variety of systems have been developed (Smith and Allan, 1996). It has also been extensively applied in South Africa (Dye and Olbrich, 1993; Dye *et al.*, 1996; Gush, 2008).

The heat ratio method (Burgess *et al.*, 2001) of the HPV technique requires that a central line heater be implanted into the sapwood portion of the stem. The 60 mm long line-heaters were made from 1.8 mm outside-diameter stainless steel tubing, enclosing a constantan filament. Two additional holes were drilled 5 mm above and 5 mm below the heater probe. Thermocouple (TC) probes (consisting of type T copper-constantan thermocouples embedded in 2 mm outside-diameter PTFE tubing), were inserted into the upper and lower holes to a specific depth below the cambium. All drilling was performed with the drill bit projecting through a drill guide strapped to the tree, to ensure that the holes were as close to parallel as possible (Plate 7.9). The thermocouples were wired to a multiplexer (AM16/32) and data logger (mostly CR10X or CR1000), while the heater probes were connected to a relay control module and 12 V battery (Plate 7.10). Generally, 4-12 sets of probes (each set comprises upper and lower TCs and a heater) were implanted in a tree stem, depending on the size of the tree. The TCs were inserted to different depths below the cambium to sample different regions of the sapwood. Sap flow is generally fastest in the younger xylem closer to the cambium, but slows in the older, deeper xylem. To account for long-term changes in position as a result of stem diameter growth, the TCs were completely removed and repositioned to their correct depths once or twice a year.

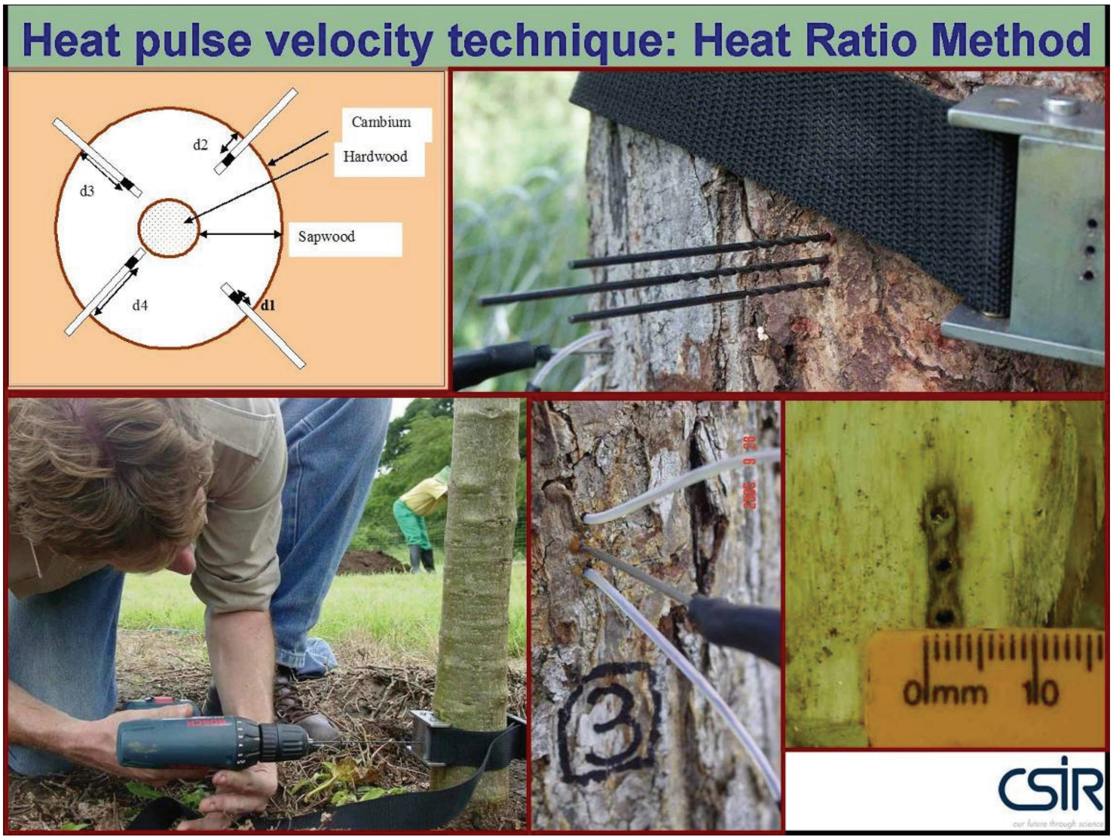


Plate 7.9 Installation of an HPV system to measure sap flow

Plate 7.10 HPV Data logger, multiplexer, relay control module and battery

The data loggers were programmed to initiate measurements at pre-determined intervals (generally hourly). The temperatures in the upper and lower TCs were first measured. The temperature of each TC is measured 10 times and an average of those 10 measurements was calculated to determine the current temperature for each TC. These values were stored in the logger for later calculations. Directly thereafter, a short (e.g. 0.4 second) pulse of heat was released through the entire set of heater probes connected to the relay control module. The heater probes were in groups of four (termed a heater cluster) and each cluster was individually wired to the relay control module. The individual clusters were fired sequentially, and the pulse of heat diffused through the adjacent wood and was taken up by the sap moving upwards through the xylem of the tree. The length of time used for the heat pulse can be varied in the programme but usually ranged from 0.4-0.8 seconds. As the heat pulse is conducted up the tree by the sap, the upper thermocouple begins to warm (generally to a greater extent than the lower thermocouple due to heat transport by the sap, although there is some conduction of heat to the lower thermocouple as well). Logging of the changing heat ratio commenced 60 seconds after the initiation of the heat pulse and was measured continuously (approximately every second, depending on the processing speed of the logger) until 100 seconds after the heat pulse (after Burgess *et al.*, 2001). To determine the heat ratio, first the change in temperature (Δtemp) was measured for each TC. This equated to the current (heated) temperature minus the average pre-pulse temperature determined earlier. The heat ratio (Δtemp upper TC / Δtemp lower TC) was then calculated for each probe set consecutively, and this value changed as the heated sap moved through the xylem. These individual heat ratio values were accumulated for each TC pair, and at the end of the measurement window (e.g. after 100s) the average ratio was calculated for each TC set individually. The heat pulse velocity (for each TC pair) was equal to the natural log of the average heat ratio multiplied by a constant that accounts for the thermal diffusivity of wood and the distance between the heater probe and each TC (after Marshall, 1958). The value of the constant was initially 18, but may vary depending upon wood qualities (Burgess *et al.*, 2001). These hourly heat pulse velocities for each TC set were the final outputs from the logger.

All available HPV data for an individual tree were initially screened to identify periods of missing data. The first step in the patching process was to determine if there were good quality data available from any of the other probes for the period in question. The probes with the highest correlation to the probes being patched were identified through a correlation analysis. A simple linear regression equation was then used to patch the missing data according to the functional probe set. High correlations among different probe sets within the same tree were observed in most cases, giving confidence in the patching technique. Where there were simultaneously missing data for all probe sets in a tree, data from adjacent measured trees were used in a similar manner to correlate and patch. Where there were missing or suspect single hourly values, these were in-filled using an average of the preceding and following values. Unrealistically high spikes or low negative values in the data were each checked for realism. If they were not evident in other probes, and/or did not follow any logical pattern in relation to preceding and following values, or environmental changes, they were assumed to be faulty and patched. Automatic weather station sensors were used to monitor hourly air temperature, air humidity, wind speed, solar radiation and rainfall. These measurements were very useful in interpreting sap flow patterns and assisting in the patching process.

Once the above patching and analysis procedure was completed, it was necessary to confirm the "zero flux" value (i.e. those times of the day when HPV values / transpiration would be expected to be zero). This was necessary because the lowest values in the diurnal HPV trends (e.g. those values between 22h00 and 04h00) did not always stabilise around zero. This was a result of slight misalignment in the position of the thermocouple probes in the tree and was corrected by applying an offset to the data to align the lowest values with zero. Since *J. curcas* is a deciduous species, the “zero flux” value was determined when the trees were completely leafless, and there was no longer any discernable daily trend in sap flow. Under these conditions the data will typically stabilise around a particular "zero flux" value, which, if not exactly at 0, will indicate the offset value necessary to be applied to the data to correct the measured zero flux values to actual zero values.

Once the offset was applied to the HPV data, the final analysis involved the conversion of the hourly HPV values to total daily sap flow (in litres and millimetres). Measurements of sapwood area, moisture content and density, as well as the width of wounded (non-functional) xylem around the thermocouples, were required to convert heat pulse velocities to sap velocities and ultimately sap flow volumes. These sapwood measurements were taken at the conclusion of the experiment due to the destructive nature of the sampling. Firstly the patched and corrected hourly HPV values were corrected for the effects of wound width using wound correction coefficients described by Swanson and Whitfield (1981). These were then converted to sap velocities by accounting for wood density and sapwood moisture content (Marshall, 1958). Finally, the sap velocities were converted to whole-tree total sap flow (litres per hour) by calculating the sum of the products of sap velocity and cross-sectional area for individual tree stem annuli (determined by below-bark individual probe insertion depths and sapwood depth). In this way, point estimates of sap velocity were weighted according to the amount of conducting sapwood in the annulus they represented. Hourly sap flow values were aggregated into daily values.

7.3.2.3.2 Leaf Area Index

A Licor LAI-2000 plant canopy analyser was used to quantify leaf area index and thus leaf area density. Plant dimensions were measured using measuring tapes.

7.3.2.3.3 Evaporation

7.3.2.3.3.1 Eddy Covariance (EC) method

The Eddy Covariance technique is regarded as the standard, most direct method by which evaporation rates can be measured. The Eddy Covariance system is based on very high frequency measurements of water vapour and CO_2 above vegetation canopies (10 Hz). Such frequent measurements describe gas concentrations in eddies of air that are particularly important drivers of gas exchange above aerodynamically rough vegetation. The technique is especially valuable in studies where information on both the water and carbon fluxes are significant indicators of water-use efficiency, and which may be compared to similar data obtained over vegetation in other countries.

In fully turbulent flow the mean vertical flux F of an entity s per unit mass of the fluid is given by

$$F = \overline{\rho_a w s} \qquad 7.1$$

where ρ_a is the density of air, w the vertical wind velocity, and the over bar denotes the average value during a time period of suitable length.

In the surface boundary layer all atmospheric entities exhibit short-period fluctuations about their mean value. Therefore, the instantaneous values of w, s, and ρ_a can be expressed by:

$$w = \overline{w} + w', \qquad s = \overline{s} + s', \qquad \rho_a = \overline{\rho_a} + \rho_a' \qquad 7.2$$

where the prime symbol denotes an instantaneous departure from the mean. These expressions can be substituted into Equation (7.2) and if we neglect fluctuations in density, the mean vertical flux F reduces to:

$$F = \overline{\rho_a w s} + \overline{\rho_a w' s'} \qquad 7.3$$

or by writing ρ_a for $_a$

$$F = \rho_a \overline{w s} + \rho_a \overline{w' s'} \qquad 7.4$$

The first term on the right-hand side of Equation (7.4) represents the flux due to the mean vertical flow or mass transfer. The second term represents flux due to eddying motion or eddy flux. The mass transfer term may arise from a convergence or divergence of air due to sloping surface. For a sufficiently long period of time over horizontally uniform terrain the total quantity of ascending air is approximately equal to the quantity descending and the mean value of the vertical velocity will be negligible. Therefore, Equation (7.4) reduces to

$$F \approx \rho_a \overline{w' s'} \qquad 7.5$$

Based on the above equation, the sensible heat flux (H) and water vapour flux (E) can be expressed as:

$$H = \rho_a C_p \overline{w' T'} \qquad 7.6$$

and

$$E = \frac{\varepsilon}{P} \rho_a \overline{w' e'_a} \qquad 7.7$$

where u', T', and $e_{a'}$ are the instantaneous departures from the mean horizontal velocity, air temperature and vapour pressure; and ε is the ratio of molecular weights of water vapour and air and *P* is the atmospheric pressure.

Two systems were erected on a 3 m mast in two adjacent "*Jatropha* only" plots to maximize the fetch (Plate 7.11). The sensors that comprise our Applied Technologies system were mounted on a cross-arm affixed to the top of the mast, and projected 3 m above the ground.

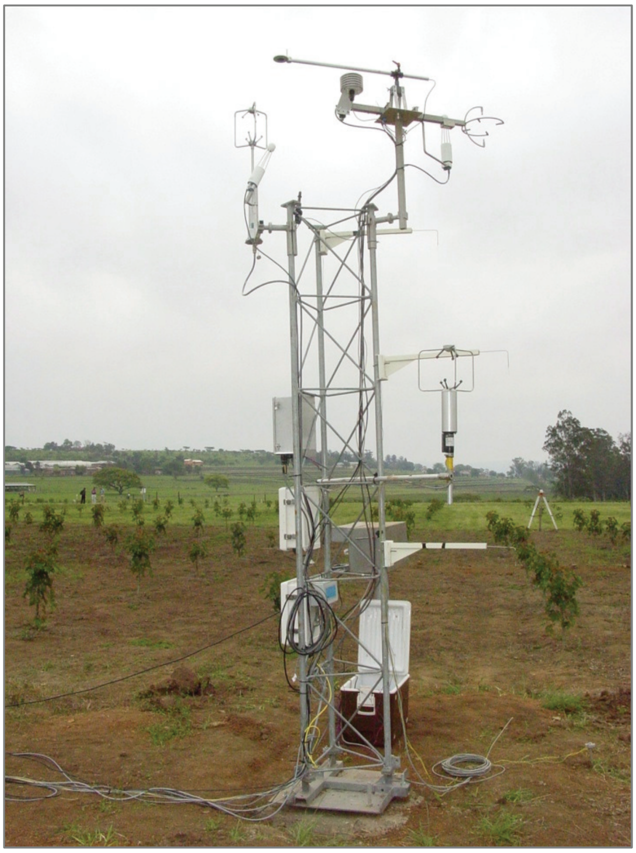


Plate 7.11 The micrometeorological mast with eddy covariance and surface renewal instrumentation

The Eddy Covariance systems included sonic 3-D anemometers, platinum resistance thermometers, open path gas analyzers, data packer, and logger/laptop. The systems recorded changes in air movement, temperature, water vapour and CO_2 concentration every tenth of a second. Where vertical air movement and concentration of water vapour or CO_2 are correlated, there will be a net flux, and these are typically integrated over a period of 30 minutes.

7.3.2.3.3.2 Surface Renewal (SR) Method

The SR method is a simple and relatively inexpensive technique that is based on the principle that an air parcel near the surface is renewed by an air parcel from above (Paw U *et al.*, 1995). This process involves ramp like structures (rapid increase and decrease of a scalar), which are the result of turbulent coherent structures that are known to exhibit ejections and sweeps under shear conditions (Gao *et al.*, 1989; Raupach *et al.*, 1989; Paw U *et al.*, 1992). The theory of heat exchange between a surface and the atmosphere using the SR method is described in detail in Paw U *et al.* (1995), Snyder *et al.* (1996) and Paw U *et al.* (2005). The exchange of heat energy between a surface and the atmosphere is expressed as:

$$H = \alpha \rho_a c_p z \frac{a}{\tau} \qquad 7.8$$

where ɑ is a weighting factor, *a* is amplitude of the air temperature ramps and τ is the total ramping period. The amplitude (*a*) and the ramping period were deduced using analytical solutions of Van Atta (1977) for air temperature structure function:

$$S^n(r) = \frac{1}{m-j} \sum_{i=1+j}^{m} (T_i - T_{i-j})^n \qquad 7.9$$

where *n* is the power of the function, *m* is the number of data points in the time interval measured at frequency *f* (Hz), and *j* is the sample lag between data points corresponding to a time lag $r = j/f$ and T_i is the *i* th temperature sample. Time lags of 0.5 and 1.0 s were used in this study. Second, third and fifth order of the air temperature structure parameter are required to solve for *a* and τ .

The sensible heat flux was finally estimated from the equations above using the measurement height (*z*) and a weighting factor (ɑ) obtained by calibration, using the EC method. The weighting factor ɑ depends on the measurement height, canopy architecture and thermocouple size (Snyder *et al.*, 1996; Spano *et al.*, 1997a,b, 2000). Once determined, it is fairly stable and does not change from site to site regardless of weather conditions unless the surface roughness changes (Snyder *et al.*, 1996; Spano *et al.*, 2000; Paw U *et al.*, 2005).

7.3.2.3.3.3 Surface Layer Scintillometer

A SLS40A surface layer scintillometer (Plate 7.12) was purchased and received in January 2006 for measuring the surface energy balance in the *J. curcas* trial. The Surface Layer Scintillometer measures atmospheric turbulence using the phenomenon of optical scintillation. With the displaced-beam technique, a transmitter emits two parallel and differently polarized laser beams. The radiation is scattered at refractive index inhomogeneities in the air that are caused by turbulent temperature fluctuations. Interference speckle patterns result within the two beams. At the receiver sited 50 to 250 m away from the transmitter, the two beams were identified by their respective polarizations. From the magnitude and the correlation of the intensity modulations, the structure constant Cn^2 and the inner scale Io (microscale) of refractive index fluctuations were derived. These quantities were related to the structure constant of temperature CT^2 and the dissipation rate (epsilon) of turbulent kinetic energy. Application of the dissipation technique finally led to the turbulent fluxes of heat and momentum. Fundamental Advantages: Compared with point measurements of atmospheric turbulence, the line averaging optical technique has significant advantages:

1. Very low statistical noise at high temporal resolution – Since spatial averaging partly replaces time averaging. The temporal resolution achievable with the surface layer scintillometer is one order of magnitude higher than that of point measurements. Typical averaging times are 1 to 5 min for the fluxes and 10 to 60 s for the other turbulence statistics, with virtually no statistical noise.
2. Spatial coverage – Due to the spatial averaging, extended experimental areas can be representatively characterized with a single instrument.
3. No flow distortion – The optical, contact- free access to the medium avoids mechanical interactions as observed with conventional instruments and mountings.
4. High sensitivity and reliability – The surface layer scintillometer accurately responds even to small temperature and wind fluctuations. The measurement principle is based on relative evaluations of the intensity statistics, hence the system is free from long-term drift and does not require calibration.
5. Easy Installation – The surface layer scintillometer is equally well suited to permanent installations and temporary experiments. Semi-conductor laser technology results in low power consumption, permitting battery operation. A built-in interference filter and modulation of the laser light effectively suppress background radiation.

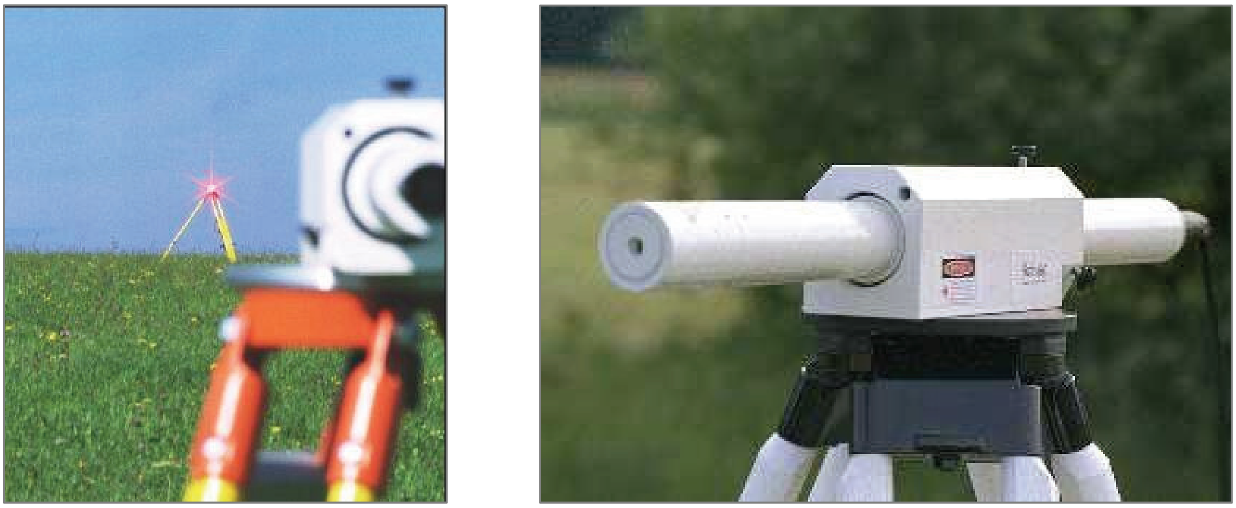


Plate 7.12 The transmitter and receiver of the SLS40A

Scintillometers use a unique optical technique to measure:

- turbulent heat flux
- turbulent momentum flux
- structure constant C_n^2 of refractive index
- inner scale l_0 of refractive index
- dissipation rate of kinetic energy ε
- crosswind.

An OEBMS1 system was purchased to measure surface energy budgets.

Unlike conventional stations, the OEBMS1 uses optical scintillation to obtain the turbulent heat flux. This results in a high accuracy even with short averaging periods: while conventional stations need averaging times of 30-60 min, the OEBMS1 resolves all components in 5 min steps – virtually without statistical scatter and representatively characterizing large experimental areas. For comparison: about 100 eddy correlation sensors mounted on masts along the optical propagation path would be required to achieve a similar performance.

The OEBMS1 consists of one SLS40A scintillometer system with tripods to measure the sensible heat flux, one pyrradiometer (0.3-30 µm) and one pyranometer (0.3-3 µm) to measure the radiation flux balance, and three soil heat flux sensors (new circular design for minimum heat flow disturbance). The latent heat flux is calculated as residuum of the other components. Two ventilated thermometers Pt100 and one pressure sensor provide the auxiliary data for an automatic derivation of the turbulent heat flux from the scintillation measurements (Plate 7.13).

Plate 7.13 The OEBMS1 mast with pyrradiometer, pyranometer, soil heat flux sensors and two ventilated thermometers (PT100) at the Ukulinga site

The OEBMS-SPU1 Signal Processing Unit interfaces with all sensors and communicates with a PC via an RS232 line. The software OEBRUN on the PC outputs the following components:

- Turbulent flux of sensible heat
- Turbulent flux of latent heat (evaporation)
- Incoming solar radiation and net radiation (solar plus thermal)
- Ground heat flux (average over 3 sensors and individual values).

A diagrammatic representation of the equipment as setup at Ukulinga is shown in Figure 7.3.

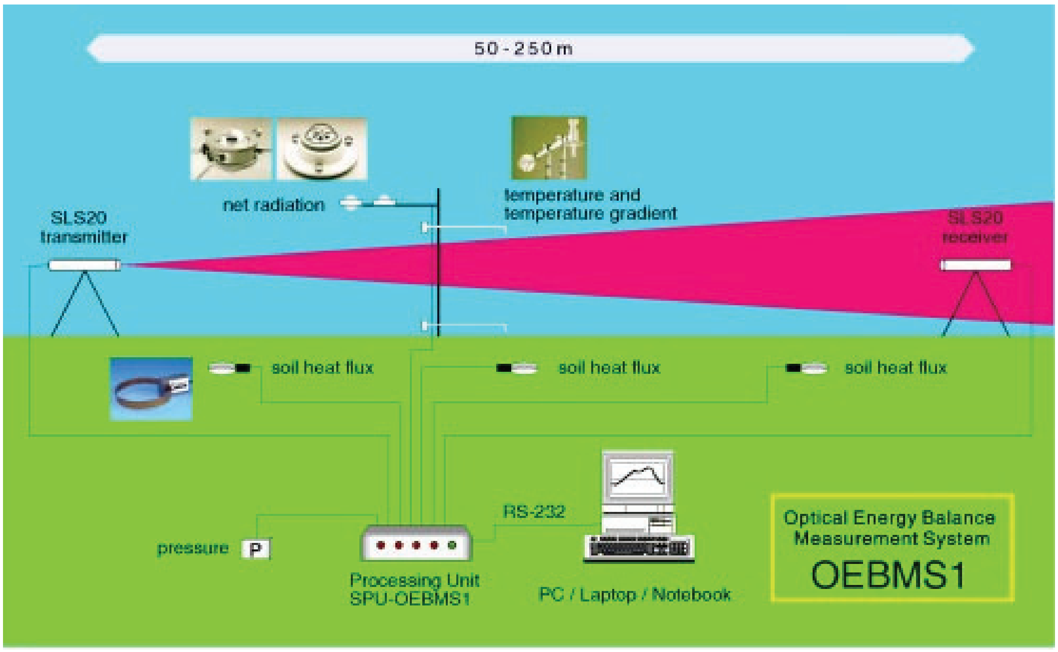


Figure 7.3 **Diagrammatic representation of the OEBMS1 system as setup at Ukulinga in February 2006 (reproduced with permission from Scintek)**

7.3.2.4 Model parameters and variables

The parameters, variables and inputs required for running and validating the soil water balance (SWB) model (full description given in Chapter 9), are outlined in this section.

7.3.2.4.1 <u>Tree Parameters</u>

Distance between tree rows and nodes selected for radiation and soil water measurement as well as tree row orientation were determined. Leaf area index (LAI), leaf area density, crown and tree dimension were measured periodically. Root density distribution in the combination trials were investigated laterally and vertically in the single-row and standard square treatments. This was done by taking soil samples by digging trenches across tree rows and using core samplers.

Destructive sampling of 12 *J. curcas* trees was carried out in order to obtain parameters for a new tree growth routine (Table 7.1) in the SWB mode.

Table 7.1 Parameters of tree growth routine to be incorporated into the SWB model

TREE GROWTH PARAMETERS
A Stem-leaf partitioning factor ($m^2\ kg^{-1}$)
Specific leaf area ($m^2\ kg^{-1}$)
Parameter of dry matter relocation from tree stem to flowering or leaf initiation
Foliage density by mass ($kg\ m^{-3}$)
Leaf area density ($m^{-2}\ m^{-3}$)
Ratio of crown width to crown height (dimensionless)
Allometric coefficients and exponents between biomass and dimensions of J. curcas and basal stem diameter

7.3.2.4.2 Crop Parameters

Grass biomass in one kikuyu-only and two *Jatropha*-kikuyu combination plots were measured periodically. The selected plots were single-row and double-row treatments. Grass samples for biomass determination were taken using a 0.5 m-by-0.5 m quadrant.

7.3.2.4.3 Intensive Monitoring Variables

For this purpose, a *Jatropha*-only, a single-row, a double-row and a kikuyu-only plots were selected.

7.3.2.4.3.1 Water Balance and Dynamics

Soil water content, tree water use and evapotranspiration from grass and soil were monitored to determine water balance and dynamics in the soil-plant-atmosphere system. TDR probes were installed without disturbing the soil section where monitoring was carried out. Two-dimensional nodal arrangements were designed for monitoring soil water by investigating the soil profile and soil water distribution using the Diviner-2000 were used in the *Jatropha*-only, the single-row and the double-row (Plate 7.14). The selected soil depths for TDR probe installations for single-row and double-row trials were: 0.05 m, 0.15 m, 0.25 m, 0.40 m and 0.60 m. For the *Jatropha*-only trial, an additional depth of 0.8 m was also considered. At each soil depth of the single-row, double-row and *Jatropha*-only trials, probes were installed across the tree rows (which are oriented S73^{0}W-N73^{0}E) at distances of:

- *Jatropha*-only: 0 m, 0.75 m and 1.5 m (mid point of alley) on either sides of the tree row
- Single-row: 0 m, 0.83 m, 1.65 m and 2.5 m (mid point of alley) on either sides of the tree row
- Double-row: 0 m (between the tree rows), 1 m, 2 m, 3 m and 4 m on either side of the mid-distance between the tree rows

Soil core samples were taken from the same grid system of TDR placement to determine soil physical properties.

Plate 7.14 Nodal system for TDR probe placement in the *J. curcas* trial

In the treatments containing trees, water use of trees in the soil water monitoring units was monitored using the heat pulse velocity method described in section 7.3.2.3.1. The site had flat land with 0.6 m deep soil underlain by a bed rock. As a result, runoff and drainage were negligible. The following soil water balance equation was used to determine evapotranspiration from grass and soil:

$$\text{Crop evapotranspiration} = \text{Irrigation} + \text{rainfall} - \text{tree water use} - \text{change in soil water}$$

7.3.2.4.3.2 Radiation Interception

Calibrated Delta-T tube solarimeters and pyranometers were placed at uniform spacing across transects of tree row(s) extending between mid-points of two consecutive alleys in the *Jatropha*-only, single-row and double-row treatments. The instruments were placed below the bottom end of the tree crown and above the crop canopy in the selected combination treatments and at the soil surface in the *Jatropha*-only treatment (Plates 7.15, 7.16 and 7.17).

Plate 7.15 Radiation sensors at the *Jatropha*-only treatments

Plate 7.16 **Radiation sensors at the Single-row treatment**

Plate 7.17 **Radiation sensors at the double-row treatment**

7.3.2.4.3.3 Tree and Crop Growth

Lateral and vertical distribution of total root biomass density (grass and tree) was examined by analysing soil core samples taken by digging trenches across the plant rows in the standard-spacing and single-row treatments. The selected depth increments were 0-0.2 m, 0.2-0.4 m and 0.4-0.6 m. Samples were collected at distances of 0 m (under the tree), 0.75 m and 1.5 m in the standard-spacing trial and 0 m (under the tree), 1.25 m and 2.5 m in the single-row treatment (between the mid-points of two adjacent alleys).

Volume of core samples was determined by displacement method. That is, volume of a sample is equal to the volume of displaced water in which the sample is immersed. To isolate roots, each sample was dispersed in water and passed through a 0.5 mm mesh sieve. The root samples were oven-dried until constant mass was obtained. Root biomass was then divided by the volume of the sample to obtained root biomass density. Grass height, leaf area index and biomass were periodically measured. Leaf area index, stem diameter, crown dimensions and total height of sample trees were also measured periodically. Leaf area density of trees was determined as follows (Annandale *et al.*, 2002):

$$LAD = \frac{LAI \times ACB}{V_C} \tag{7.10}$$

Where: *LAI* is leaf area index (m^2 leaf m^{-2} soil), *ACB* is soil area per base unit area of tree foliage (m^2 soil), *Vc* is canopy unit volume (m^3), *a* and *c* denote foliage semi-width (m) and semi-height (m), respectively.

7.3.2.5 Competition trial

7.3.2.5.1 Experimental design

The study used three 50 x 25 m (0.125 ha) plots of uniformly planted *J. curcas* trees. These plots (i.e. plots three, eight and 16) formed part of the existing silvopastoral trial run. The trees were planted three meters apart resulting in a density of 1110 plants ha^{-1} or 136 trees per plot (17 rows of eight). At the onset of this study, the trees were approximately 15 months old. Three treatment levels and a control were applied by manipulating the distance of planted pastures to *J. curcas* individuals:

Control (0): No grass cover removed from under the tree

60: Grass cover manually removed in a 60 cm radius around the tree base

120: Grass cover manually removed in a 120 cm radius around the tree base

300: Grass cover manually removed in a 300 cm radius around the tree base

A randomized block design was used as each treatment and the control was replicated six times in each of the three plots (n = 6 x 3 x 4 = 72). The blocks were located in a homogenous area with similar catenal position and aspect. It is thus expected that the soil type, nutrient and moisture levels as well as incident radiation was homogeneous between the plots, limiting any block effect.

To prevent any confounding influence of initial tree height, only those trees within 10% of the population's mean height were considered suitable. Trees on the periphery of the blocks were disqualified to prevent any influence of edge effect. Trees were randomly assigned treatments using a random number generator. Trees adjacent to individuals receiving treatment '300' were disqualified. Each test tree was individually labelled to enable monitoring of individual trees. The cleared area around the trees was kept free of weeds and grass for the duration of the experiment by using a herbicide (active ingredient glyphosate), which was already used on the silvopastoral trial.

7.3.2.5.2 Data collection and analysis

Tree height, main stem diameter at ground level, number of offshoots and whether these and the main stem experienced leaf abscission were recorded from 21 March to 6 October 2006. Only offshoots within 25 cm of the ground where noted as the trees had a bimodal distribution of side branches, either at the base or near the crown. Percentage abscission was calculated by individually scoring the main stem and branches as either having leaves (0) or not (1). These scores were totalled and added to the decrease in number of offshoots from the previously recorded number. The total was then calculated as a percentage of the total number of previously recorded offshoots.

During the warmer, wetter months (21 March-18 May; 8 August-6 October) measurements were taken approximately every 14 days. From 18 May to 8 August measurements were only taken once a month as growth was expected to be minimal under the colder and dryer winter conditions. Daily minimum and maximum temperatures, precipitation and incident radiation for the study site during the sampling period were obtained from the CSIR.

Analysis of variance (ANOVA) was used to determine the effects of the different treatments on final tree height, basal diameter and number of offshoots. Mann-Whitney U tests were used to determine the effects of the different treatments on percentage leaf abscission on day of year (DOY) 235 (23 August) when leaf drop mostly peaked.

Repeated measures analysis of variance (RM ANOVA) was used to determine the effects of the different treatments on tree height, basal diameter, number of offshoots and percentage leaf abscission over the sampling period. These growth parameters were averaged to obtain mean measurement values for each sampling day. These were fitted to growth functions to exemplify the growth response to the different treatments and to provide useful tools for managers to predict the growth of *J. curcas* under different management treatments. The models can also be used to determine relative growth rate. This was done with tree height where the growth function was integrated to determine the increase in plant height per unit height per unit time.

The weather conditions were averaged to obtain a mean daily measurement for each month. These values were plotted to show the change in weather conditions throughout the sampling period.

All the assumptions for ANOVA and RM ANOVA were met except for percentage leaf abscission in the latter analysis. The integration was done using Scientific WorkPlace 5.0 (MacKichen Software, Inc. 2003). Growth function analysis, ANOVA and RM ANOVA was done in GenStat 9th Edition (Laws Agricultural Trust 2006). SPSS 11.5 for Windows (SPSS Inc. 2005) was used for the Mann-Whitney U tests and to separate the means using a Scheff Post Hoc test at 95% confidence levels. Microsoft Excel was used to summarise and plot the weather data.

7.3.2.6 Preference trial

7.3.2.6.1 Experimental design

Adult indigenous goats were used in the preference trials as they are common rural livestock of underdeveloped countries and are able to graze and browse a variety of poor quality foodstuffs (Boyazoglu *et al.*, 2005). Goats weigh about 35 kg and are intermediate feeders, browsing 45% of the time (Owen-Smith and Cooper, 1987).
The trials were conducted in a bare 4x4 m pen to ensure that the goats could only eat the test species offered. Goats were kept without food from the previous afternoon to

ensure a sufficient appetite during the trial. They were observed in groups of three as goats most comfortable feeding in herds (Sminia, 2005). Potted *J. curcas* plants and freshly cut *A. karroo, A. nilotica* and *M. alba* branches of similar foliage biomass of were used. The branches were tied at the same height as the *J. curcas* plants. Goats prefer browsing *A. karroo* to most other species including *A. nilotica* (Dziba, Scogings, Gordon and Raats, 2003). This is due to the higher quality, lower tannin content and shorter thorns of *A. karroo* (Sminia, 2005). *M. alba* is also browsed by goats due to its suitable chemical composition and digestibility (Bakshi and Wadhwa, 2006).

Water was supplied ad libitum and the animals were allowed to graze freely once the day's trial was complete. The goats' health was observed for the duration of the trial.

7.3.2.6.2 Two-choice cafeteria trials

The trials were conducted on the 8th and 9th June 2006. Goats were given the option between *J. curcas* and *A. karroo* (trial 1) on the first day and *J. curcas* and *A. nilotica* (trial 2) on the second day. Each trial was replicated four times. Only two of the three goats where observed in each replicate, resulting in a sample size of eight goats per trial. For each trial, the goats were kept in the same groups in the same order to control for any group effect. The goats were observed for 30 minutes each or until either of the plants were depleted to ensure selection was based on preference and not availability. The duration of feeding bouts for each plant species was recorded. A bout began at the first bite of a plant species and ended when the goat stopped chewing. Numerous bites of the same species could be taken during a single feeding bout.

7.3.2.6.3 Three-choice cafeteria trials

The trial was conducted on the 18th August 2006. Goats were offered a choice between *J. curcas, A. karroo* and *M. alba*. The trial was repeated twice. In each trial, all three goats were observed resulting in a sample size of six goats. The goats were observed for 10 minutes each or until any one of the plants were depleted. The number of bites taken of each plant species was recorded.

7.3.2.6.4 Statistical analysis

In the two-choice trials Wilcoxon signed ranks tests were used to analyze the difference in time spent feeding on each plant species in each trial. ANOVA was used to analyze the difference in total time spent feeding between the two trials. All the assumptions for ANOVA were met. A z-test was used to analyse the difference in the proportion of time spent feeding on *J. curcas* between the two trials. SPSS 11.5 for Windows (SPSS Inc. 2005) was used for the first two tests while the z-test was done using Microsoft Excel.

In the three-choice cafeteria trials Chi-squared analysis was used to analyse the difference in the number of bites taken of each species

7.4 RESULTS AND DISCUSSION

7.4.1 Tree Growth

The tree height data for the study period (February 2005-April 2010) showed that the plots with trees only (*J. curcas* only treatment) had the highest growth rates compared to the other treatments. The advantage due to the lack of grass competition was evident in all years. In the second growth season (October-December 2006) the mean difference was approximately 0.25 m (200% greater than the other treatments) (Figure 7.4). By August 2007 the percentage difference had decreased to 125%, showing that the competitive influence of the grasses was reduced as the trees became better established. During the third and fourth years the trees attained heights > 1.75 m, despite being pruned to a height of 1.0 m in the spring of 2006, 2007 and 2009 to maintain them as "hedge-rows" and to stimulate additional branching for increasing seed production. The trees therefore grew approximately 1.0-1.25 m in the 2007, 2008 and 2009 seasons, reaching heights between 1.75 m and 2.25 m (Figure 7.4).

In 2007 and 2008 there was little difference in tree height between the standard square, single row, double row and triple row treatments, the trees having attained an average height of 1.8 m by April 2007 and 2008. This suggests that there was little intra-specific competition between the trees as the planting density increased with the number of row sets (Figure 7.4). The trees in the *J. curcas* only plot reached heights of 2.3 m.

Tree diameter showed similar trends to the height data in the 2006/07 growing season, with mean values of 102 mm recorded in the *J. curcas* only plots compared to approximately 86 mm in the other treatments (Figure 7.5). When the trees were planted in January 2005 they were only 10 mm in diameter and by July 2007 were approximately 100 mm. In 2007 the trees continued to increase in diameter throughout the winter, despite them showing no height increment and being largely leafless during this time (Figure 7.5). Between January 2009 and March 2010, the tree diameter showed an exponential increase in size, jumping for example, from a mean diameter of 150 mm to 480 mm in the *J. curcas* only plots. Also noticeable was the fact that by mid-October the trees had still not come into leaf. These growth adaptations provide some insights as to how *J. curcas* is able to survive in very low and erratic rainfall regions as it appears to accumulate reserves in the dry period (shown by increasing stem diameter) and delays leaf emergence until more regular rains are expected in mid-summer.

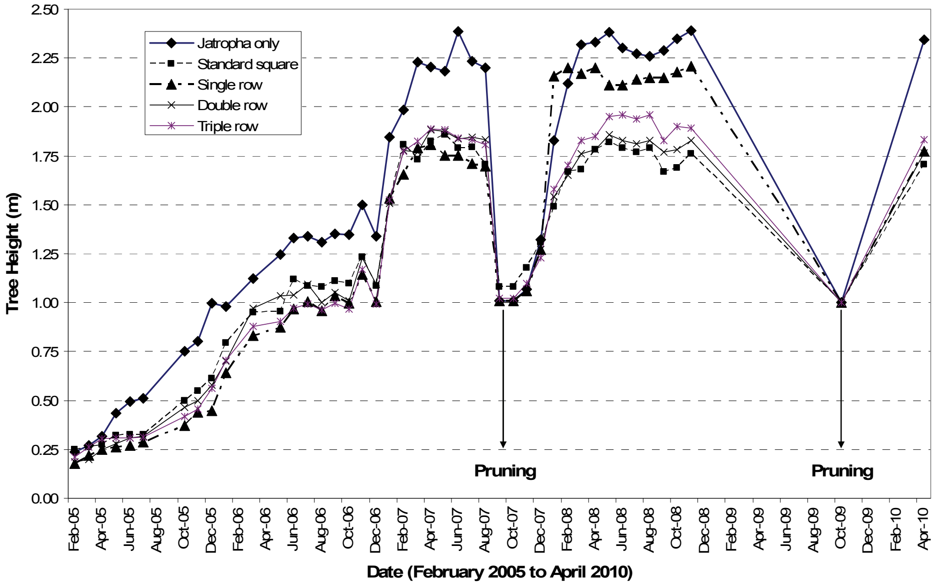


Figure 7.4 Height (m) of *J. curcas* trees in five treatments (*J. curcas* only, Standard Square, Single rows, Double rows and Triple rows) between February 2005 and April 2010

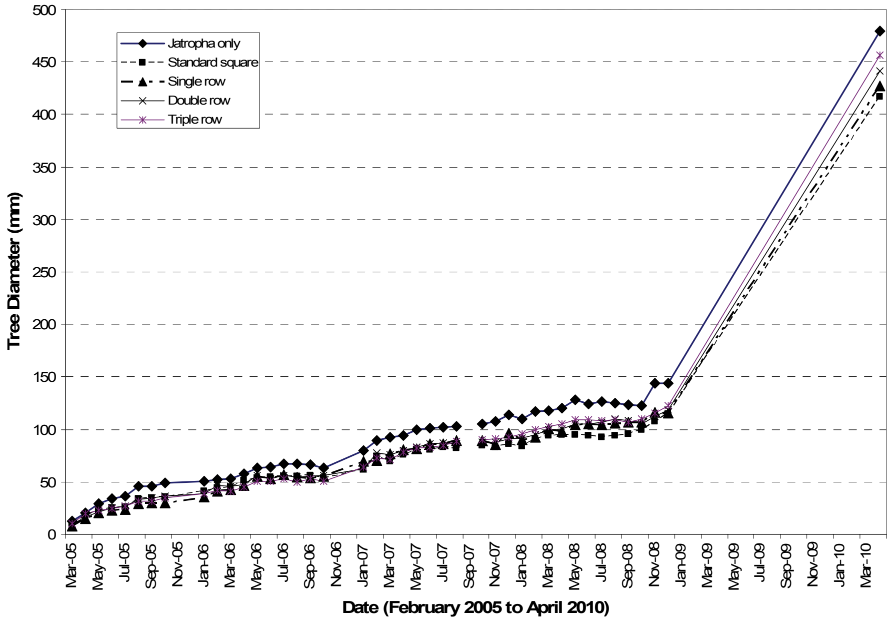


Figure 7.5 Stem diameter (mm) of *J. curcas* trees in five treatments (*J. curcas* only, Standard Square, Single rows, Double rows and Triple rows) between February 2005 and July 2007

The similarity in the tree height and stem diameter curves was reflected in the allometric relationship between basal diameter and tree height (Figure 7.6), where regression analysis showed a strong positive linear relationship (R^2 = 0.976). During the tree pruning in September 2007, data on the relationship between branch diameter and dry weight were collected to provide simple procedures for the prediction of plant production. A good relationship was found using a logarithmic function (R^2 = 0.92) (Figure 7.7). These allometric relationships were developed further to provide a useful tool for both plant growth modelling and carbon sequestration predictions (Ghezehei *et al.*, 2010).

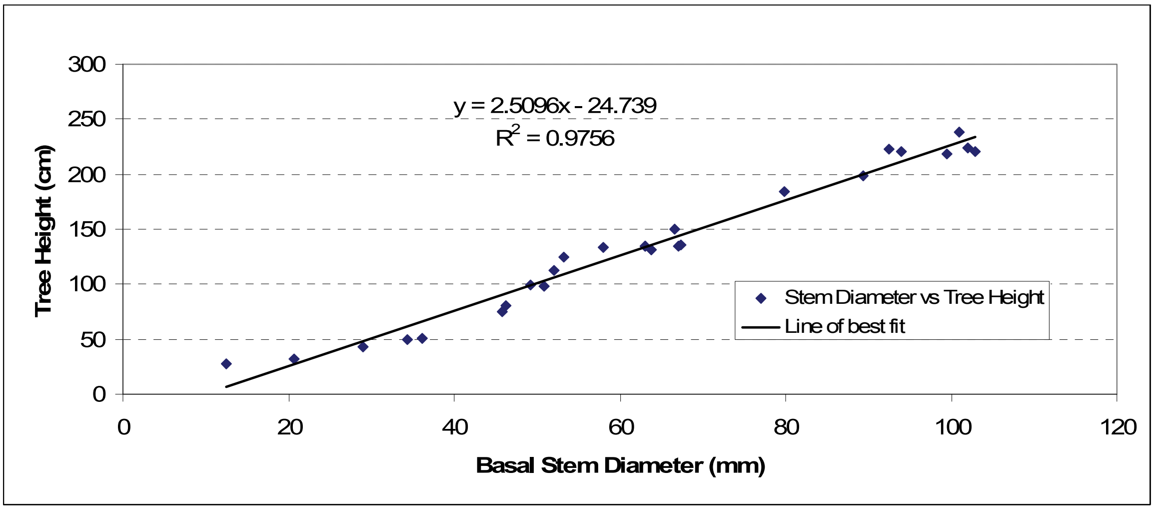


Figure 7.6 The allometric relationship between basal stem diameter (mm) and height (cm) of *J. curcas* trees in the *Jatropha* only treatment

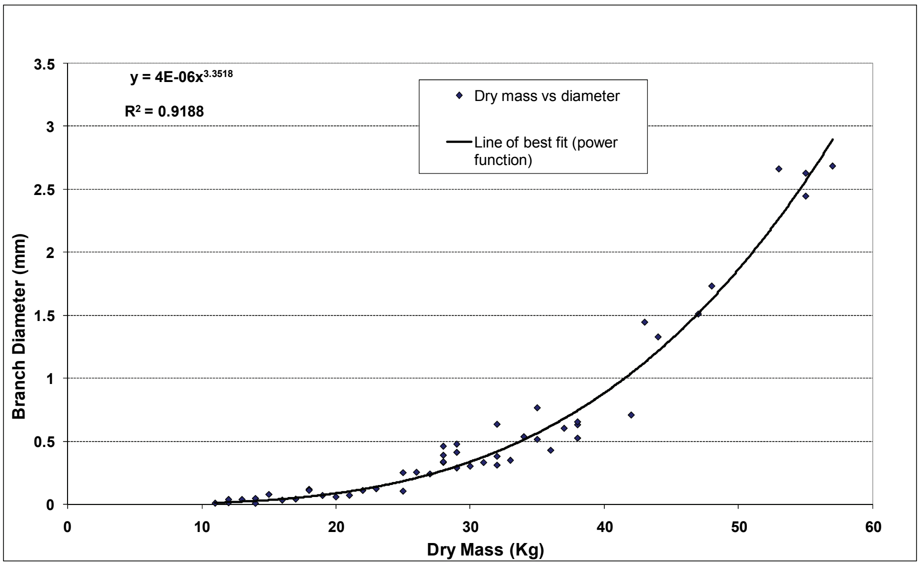


Figure 7.7 The allometric relationship between branch diameter (mm) and dry mass (kg) of *J. curcas* trees in the Ukulinga trial

The most notable effect of the tree growth data was that although tree height levelled off towards autumn and winter, basal diameter continually increased throughout winter. This may be attributed to photosynthetic activity of the stem which was green throughout winter. This suggests that the trees directed all available resources to increasing basal diameter when the growing conditions were poor. The reduced increase in tree height from autumn throughout winter across all treatments can be explained by the decrease in rainfall, ambient temperature and solar radiation over June, July and August at the Ukulinga Farm.

In the competition experiment (section 7.3.2.5) it was shown that tree height and basal diameter were greater with increasing distance of planted pasture species from *J. curcas*. This study concluded that the impact of the pasture grass competition on reducing growth of *J. curcas* may make *J. curcas* silvopastoral systems unviable. However, growth and productivity of *J. curcas* in agroforestry and silvopastoral systems may be increased by implementing some degree of pasture removal and/or ensuring separation of resource utilization in time or space (George *et al.*, 1996; Lehmann *et al.*, 1998) and/or selecting cover or forage crops that are least competitive for nutrients and moisture while still fulfilling their role in the system (Malik *et al.*, 2001). The sensitivity of *J. curcas* to plant competition will require that the surrounding area around the base of *J. curcas* be kept clear of weeds and other plants (approximately 60 cm according to Andersson, 2007). This is an additional management cost that needs to be considered when growing large areas of *J. curcas* for biofuel production.

Claims that *J. curcas* is free of pests and diseases were certainly not evident in this experiment, where the trial was continually threatened by the golden flea beetle (*Apthona* spp.), powdery mildew, leaf spots, insect defoliators and fungal diseases in the soil (*Fusarium* sp, *Fusarium oxysporum*, *Pestalotia* sp, *Alternaria alternata*, *Metarrhizum* sp.), crowns/roots – *Pythium* spp, *Fusarium* spp, *Fusarium oxysporum* and *Phoma* spp and the leaves (*Epicoccum* spp). It would appear that *J. curcas* is highly vulnerable once removed from its natural habitat and grown in a high density plantation situation. Similar observations have also been made in India (Ranga Rao, 2006) and in Kenya (Endelevu Energy, 2009).

Seed production in the *J. curcas* only treatment (the best seed yield) was equivalent to 89.9 kg ha^{-1} for 2007, two and a half years following establishment and only increased to 104.4 kg ha^{-1} in 2008. By year four (2009), the seed yield peaked at 348.8 kg ha^{-1}. Seed yield in all the other treatments (where competition with the kikuyu pasture was a factor) were generally less than half that of the *J. curcas* only treatment. 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, there have been claims by Becker and Makkar (2000) of 2-3000 kg ha^{-1} of seeds ha^{-1} in semi-arid areas, and yields of 5000 kg ha^{-1} under more favourable (wetter) conditions. The annual yields from this experiment were significantly less than the quoted figures. However, in the first year the plants were severely damaged by insects which would have had negative impacts on seed production, but even so the seed production in 2010 (five years post planting) was very poor following the pruning in 2009. Clearly the biodiesel potential of the *J. curcas* trees growing at Ukulinga is very poor. The relationships between seed mass and time of seed harvesting and time to dehusk showed that these factors need to be accounted for in any economic analysis on the farming of *J. curcas* due to the potential high labour costs of seed harvesting.

To date comprehensive studies on the water use of *J. curcas* have been limited to only a few other studies (Gush, 2008; et al., 2009). The results of this study therefore represent substantial new information. Two important facts emerge on the water use of *J. curcas*. Firstly, even at a young age (before canopy closure) total evaporation rates were high. These high rates were associated with the high summer growth rates recorded in the *Jatropha*-only trial. Secondly, there was very low total evaporation during the winter period when the trees were leafless. Because of its deciduous nature when water is limiting, it seems unlikely therefore that *J. curcas* will have a high annual water use in areas characterised by summer rainfall. The relatively low water use was also supported by the fact that the dry-land kikuyu pasture had a higher water use than the *J. curcas* trees. From a South African water planning perspective, *J. curcas* is unlikely to compete for scarce water resources. The water implications of growing trees to produce biodiesel are complex and will vary by region and country. Crops that require no irrigation use little water and provide erosion protection should receive preference when selecting potential biofuel crops. In this respect *J. curcas* is clearly an ideal biofuel crop. The results of this study have shown that it is not a potential streamflow reduction candidate as defined in the National Water Act of 1998 and will not require a water licence. Our findings are consistent with those of Gush (2008), who similarly found low water use of *J. curcas* determined using the heat pulse velocity approach, with peak sap flow rates occurring during the wet summer months and low water use during the dry winter due to its deciduous nature. Scaled-up sap flow measurements resulted in estimates of total annual transpiration of only 147 mm for a 4-year old *J. curcas* tree and 362 mm for a 12-year old tree. The data were comparable to indigenous vegetation types which exhibit seasonal senescence (e.g. grassland) and significantly less than evergreen vegetation capable of transpiring all year-round (e.g. exotic plantation forestry species) (Gush, 2008). There is therefore strong evidence from South African research that *J. curcas* trees are conservative water users when compared with dryland pastures, deciduous indigenous vegetation and exotic plantation forestry species.

The low probability of herbivory makes *J. curcas* a suitable candidate for silvopastoral systems (Andersson, 2007). However, the planted pastures needed to sustain livestock may impose a negative competitive effect on the growth and productivity of 15-month old *J. curcas* trees. Although with some degree of plantation maintenance, *J. curcas* could be a promising component in silvopastoral systems its poor yields and potentially high input costs make it unsuitable as an alternative source of energy in South Africa. Experiences in Kenya among many smallholder farmers growing *J. curcas* have also shown extremely low yields and generally uneconomical costs of production (Endelevu Energy, 2009).The results of the current trial (high costs, together with the low seed production) indicated that *J. curcas* trees do not fulfil the claims that it is a wonder biodiesel plant in South Africa.

7.4.2 Seed production and harvesting

During the 2006/07 season (two years after establishment) the first seeds of *J. curcas* were harvested. Highest seed production was in the *J. curcas* only plots, which yielded a total of 89.9 kg ha^{-1} of seed from March to July 2007 (Table 7.2 and Figure 7.8). The entire seed production for the remaining treatments ranged from 12.3 to 18.0 kg ha^{-1}, highlighting the importance of farming practices to control weeds and grass competition in the early establishment phase to maintain seed production. Reports from Indian research centres and institutes have shown similar poor yields to this study, where the average yields from extensive dry land plantings did not exceed 1 t ha^{-1} yr^{-1} (Ranga Rao, 2006).

In the first flowering season *J. curcas* exhibited "relay flowering" and flowers with varying stages of maturing flowers and nuts were found simultaneously on single trees, necessitating monthly harvests from March to July 2007. In September 2007 the trees were pruned to a height of 1.0 m to stimulate branching to increase seed production and maintain the trees at a convenient height for harvesting without ladders. The logic behind increasing seed production through pruning is that the flowers are produced at the apex of each branch and pruning increases branching. Despite the pruning resulting in many new branches and luxuriant growth in 2008 (plate 7.18) there was no large increase in the seed production from 2007 in any treatment (mean yield in the *J. curcas* only plots = 104.4 kg ha^{-1}, while the other treatments ranged between 13.0-17.8 kg ha^{-1}) (Table 7.2 and Figure 7.8). However, in 2009 the seed production increased to 348.8 kg ha^{-1} in the *J. curcas* only plots and ranged between 77.8 and 166 kg ha^{-1} in the other treatments. The trees were pruned again in September 2009 and despite the good growth exhibited by the plants, a similar drop in seed production in the season subsequent to pruning was recorded in May 2010 ((Table 7.2 and Figure 7.8). The practice of pruning to generate many branches and keep the plants short is therefore questionable, as good yields may only be possible every second year. However, leaving the plants to grow into large trees will create other logistical harvesting problems which will increase the harvesting time and labour costs.

Plate 7.18 A comparison of the number of branches in October 2007 (left) compared with September 2008 (right) following the pruning of the trees to 1.0 m in September 2007. The stimulation of many branches through pruning is clearly demonstrated

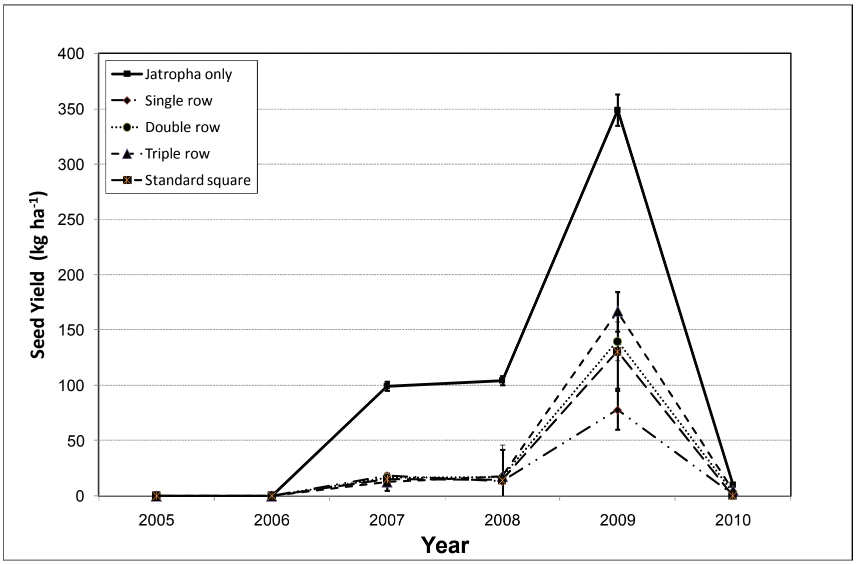


Figure 7.8 Mean seed yield (kg ha^{-1}) from the five *J. curcas* treatments from 2005 to 2010.

Because there is currently no mechanical machine to harvest *J. curcas* seeds, there has been considerable debate on the labour costs of manual harvesting. Therefore data collected in this study, on the mass of the seeds and times taken to harvest and dehusk the seeds were regressed against each other (Figure 7.9). These data showed that to harvest 1 kg of seed (60 minutes) and dehusk the same 1 kg (120 minutes) could take as long as three hours. Wiskerke *et al.* (2010) calculated the estimated harvesting time including dehusking to be 80% of the total time for seed production. This suggests that a mechanical harvesting technique may have to be designed and used for harvesting and dehusking the seed.

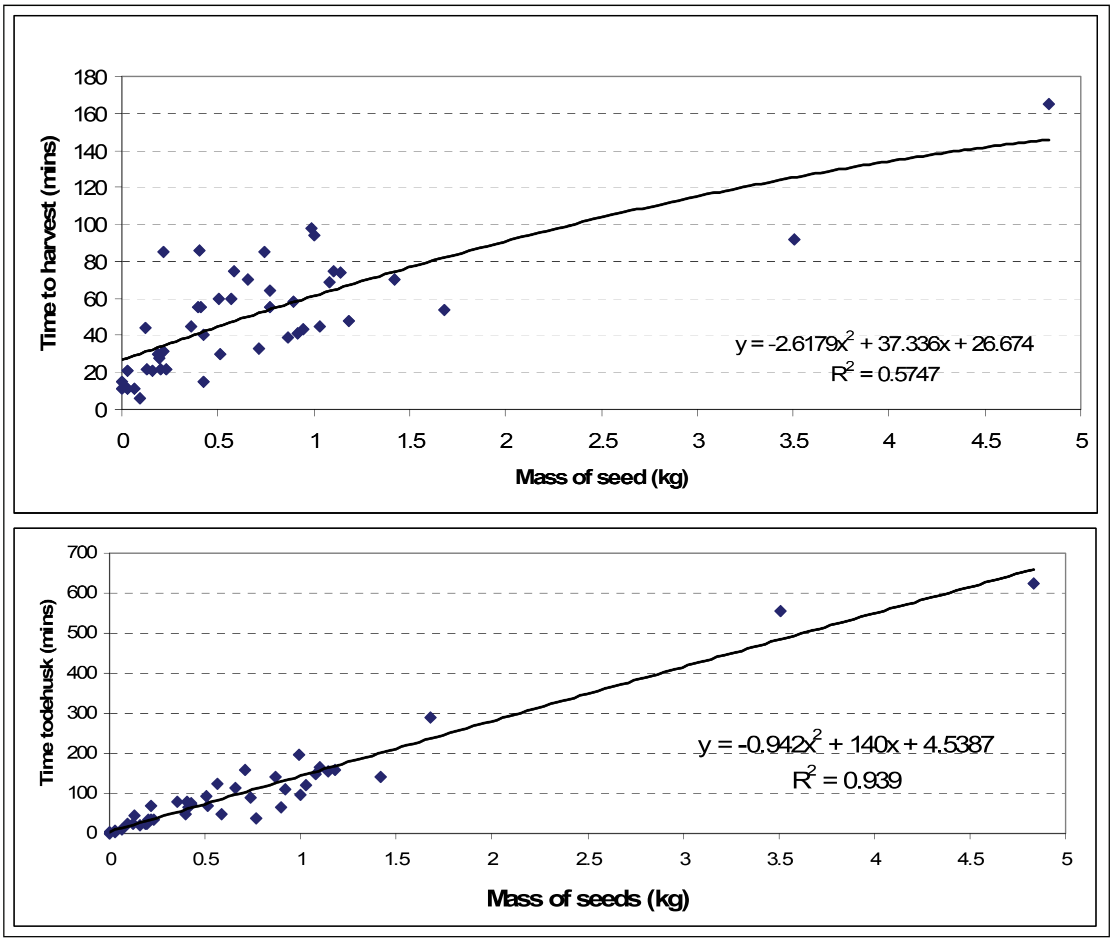


Figure 7.9 The relationship between the mass of *J. curcas* seeds and the time to harvest (above) and the time to dehusk (below)

Table 7.2 Seed production and harvesting time data for *J. curcas* at Ukulinga from 2007-2010

Date	Treatments	Mean time to harvest (mins)	Mean time to dehusk (mins)	Mean number of seeds per plot	Mean mass of seeds (kg ha-1)
06 March 2007	Single row	48	115	1399	6.7
	Double row	65	106	1186	6.1
	Triple row	62	92	1225	4.2
	Jatropha only	61	83	1149	6.2
	Standard square	60	122	1273	4.5
13 April 2007	Single row	42	38	481	2.5
	Double row	15	18	171	0.9
	Triple row	39	16	165	0.9
	Jatropha only	54	100	1067	6.7
	Standard square	39	48	397	2.6
16 May 2007	Single row	42	84	892	6.2
	Double row	54	88	464	3.3
	Triple row	37	78	654	4.3
	Jatropha only	104	490	4551	26.7
	Standard square	36	83	915	5.5
21 June 2007	Single row	-	-	303	1.4
	Double row	-	-	362	1.7
	Triple row	-	-	239	1.2
	Jatropha only	-	-	2681	13.5
	Standard square	-	-	195	1.1
27 July 2007	Single row	-	-	-	1.2
	Double row	-	-	-	3.7
	Triple row	-	-	-	1.8
	Jatropha only	-	-	-	36.9
	Standard square	-	-	-	1.2
Total 2007	Single row	-	-	-	**18.0**
	Double row	-	-	-	**15.7**
	Triple row	-	-	-	**12.3**
	Jatropha only	-	-	-	**89.9**
	Standard square	-	-	-	**15.0**
23 April 2008	Single row	66	194	-	10.9
	Double row	57	153	-	14.3
	Triple row	87	198	-	13.7
	Jatropha only	206	893	-	63.0
	Standard square	78	247	-	10.9
08 June 2008	Single row	48	51	-	2.1
	Double row	36	70	-	2.9
	Triple row	55	120	-	4.1
	Jatropha only	292	832	-	41.4
	Standard square	60	90	-	3.2
Total 2008	Single row	-	-	-	**13.0**
	Double row	-	-	-	**17.2**
	Triple row	-	-	-	**17.8**
	Jatropha only	-	-	-	**104.4**
	Standard square	-	-	-	**14.1**
Total 2009	Single row	-	-	-	**77.8**
	Double row	-	-	-	**140.0**
	Triple row	-	-	-	**166.6**
	Jatropha only	-	-	-	**348.8**
	Standard square	-	-	-	**130.6**
Total 2010	Single row	-	-	-	**1.0**
	Double row	-	-	-	**3.0**
	Triple row	-	-	-	**5.0**
	Jatropha only	-	-	-	**10.0**
	Standard square	-	-	-	**0.0**

7.4.3 Water Use (energy balance)

For brevity only a single representative period of climatic data are presented. Daily average maximum and minimum temperatures are therefore shown for the period January 2007 to September 2007 (9 months) (Figure 7.10). *Jatropha curcas* establishment requires mean annual temperatures between 18 and 28°C and average minimum temperatures of the coldest month above 8°C (Trabucco *et al.*, 2010). As in previous seasons growth conditions were favourable for *J. curcas*, with the lowest recorded temperature being 1.7°C on DOY 144 and the mean minimum temperature 8.0°C (i.e. no frost during the year). Summer maxima were often greater than 35.0°C and the average maximum temperature was 25.6°C. In order to illustrate the atmospheric evaporative demand (an indicator of stress conditions), data and derivatives from the automatic weather station situated at the *Jatropha* trial are represented as a graphical summary from January to mid- September 2007 (DOY 0-250) (Figure 7.11). Regular rains were recorded from January to April, the largest event (53 mm) occurring at the end of February (DOY 57) (Figure 7.11). Very little rain was recorded from May to September. Solar radiation showed typical summer trends with high variability in summer due to the frequent cloudy conditions and more stable conditions in winter when daily maxima were about 15 MJ m^{-2} day^{-1}. Peak summer values in January were 29 MJ m^{-2} day^{-1}. The daily reference evaporation (ET_0) closely tracked the trends in solar radiation (Figure 7.11). Reference evaporation varied form highs of 6.5 mm in January to less than 2 mm in winter (Figure 7.11). The vapour pressure deficit (an indicator of the atmospheric evaporative demand) was low in summer (< 2 KPa) when humid conditions were experienced and high (>2 KPa) in late winter during the hot dry conditions experienced in August (DOY 213-250).

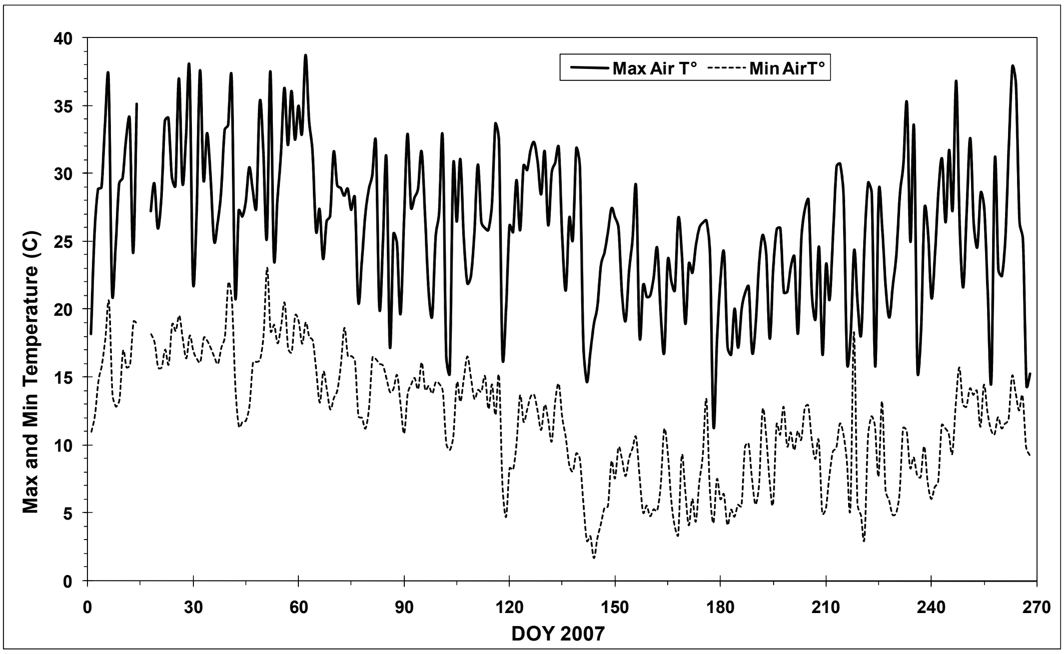


Figure 7.10 The seasonal trends in maximum and minimum air temperature at the Ukulinga study site

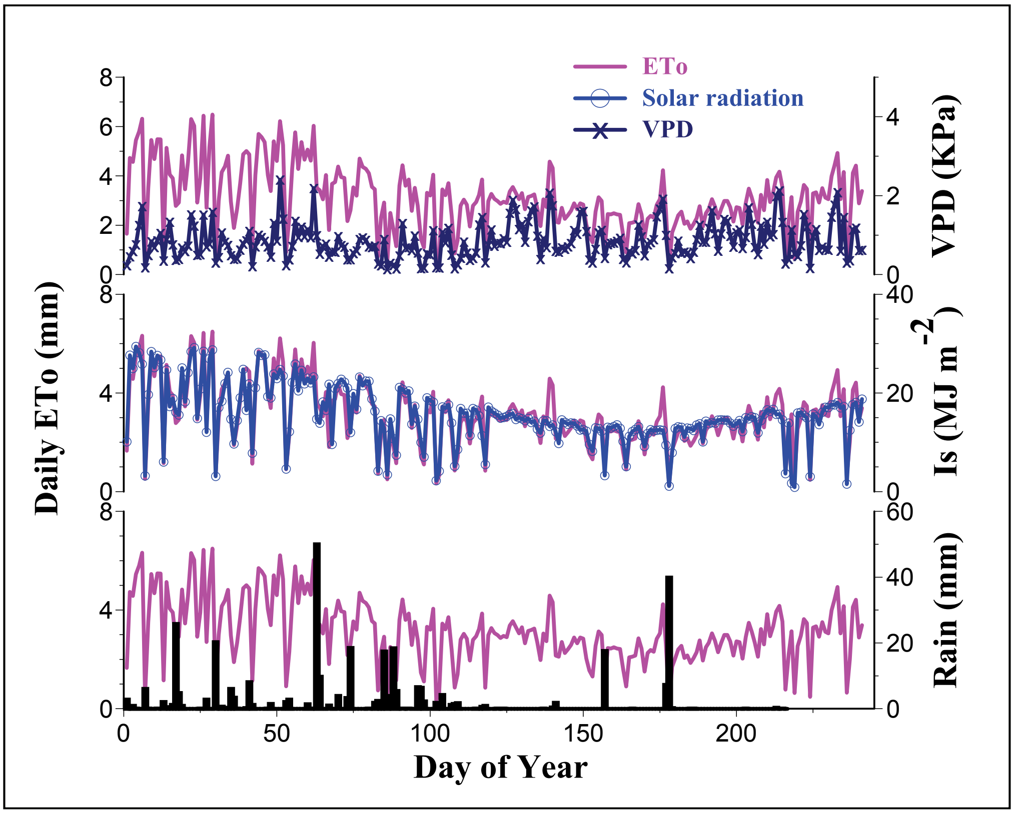


Figure 7.11 Graphical summary of Penman-Monteith grass reference evapotranspiration (ET$_o$), rainfall, solar radiation (Is) and vapour pressure deficit (VPD) for the months January to August 2007 from the AWS station at Ukulinga

Daily estimates of total evaporation (soil evaporation plus plant transpiration) from November 2005 to August 2006 for selected periods together with the daily solar radiation and FAO 56 reference evaporation (representative of a well watered short grass canopy) showed that on clear summer days these two year old plants in the *Jatropha* only plot were using between 3-4 mm day^{-1} (Figure 7.12). The reference evaporation during this period was higher than the total evaporation, varying between 5-7 mm day^{-1} in summer when the daily solar radiation was > 25 MJ day^{-1}. In winter the total evaporation rate averaged only 0.5 mm day^{-1} when the available energy was low. These low values represent the contribution from soil evaporation as the trees were leafless at this time. Our findings are in accordance with previous studies on plant-water relations of *J. curcas* (Maes *et al.*, 2009; Achten *et al.*, 2010). Both studies found water use to be conservative typical of a stem succulent species as *J. curcas* strongly controls its stomatal conductance resulting in relatively high transpiration efficiency.

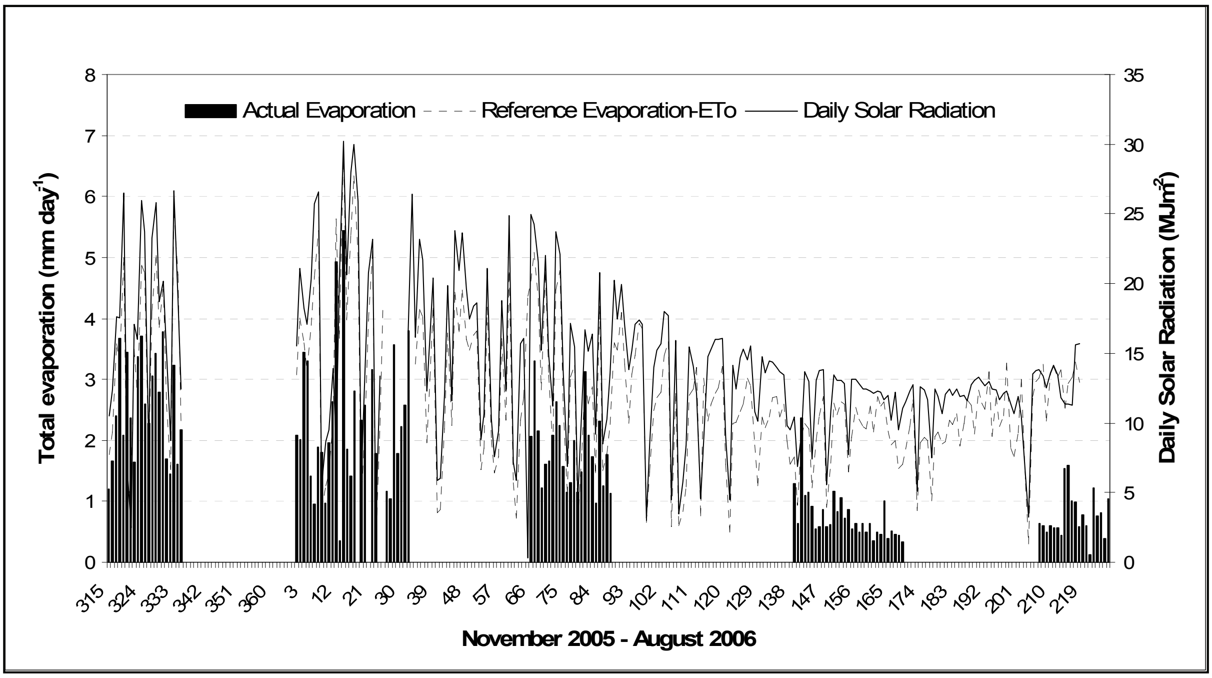


Figure 7.12 Daily total EC evaporation (mm) together with the reference ET$_o$ (mm) and total daily solar radiation (MJ m^{-2} day^{-1})

In 2007 the total evaporation rate in the *Jatropha* only plots was compared with the kikuyu only plots in both winter and summer (Figure 7.13). In the *Jatropha* only treatment the maximum total evaporation rate was about 4 mm day^{-1} compared with 5.5 mm day^{-1} in the kikuyu plots. In winter the *Jatropha* total evaporation dropped to below 1 mm day^{-1} while the kikuyu grass had total evaporation rates between 1-1.5 mm day^{-1}. The higher rates measured in the grass plots may be related to the closed canopy when compared to the more open tree canopy at this time.

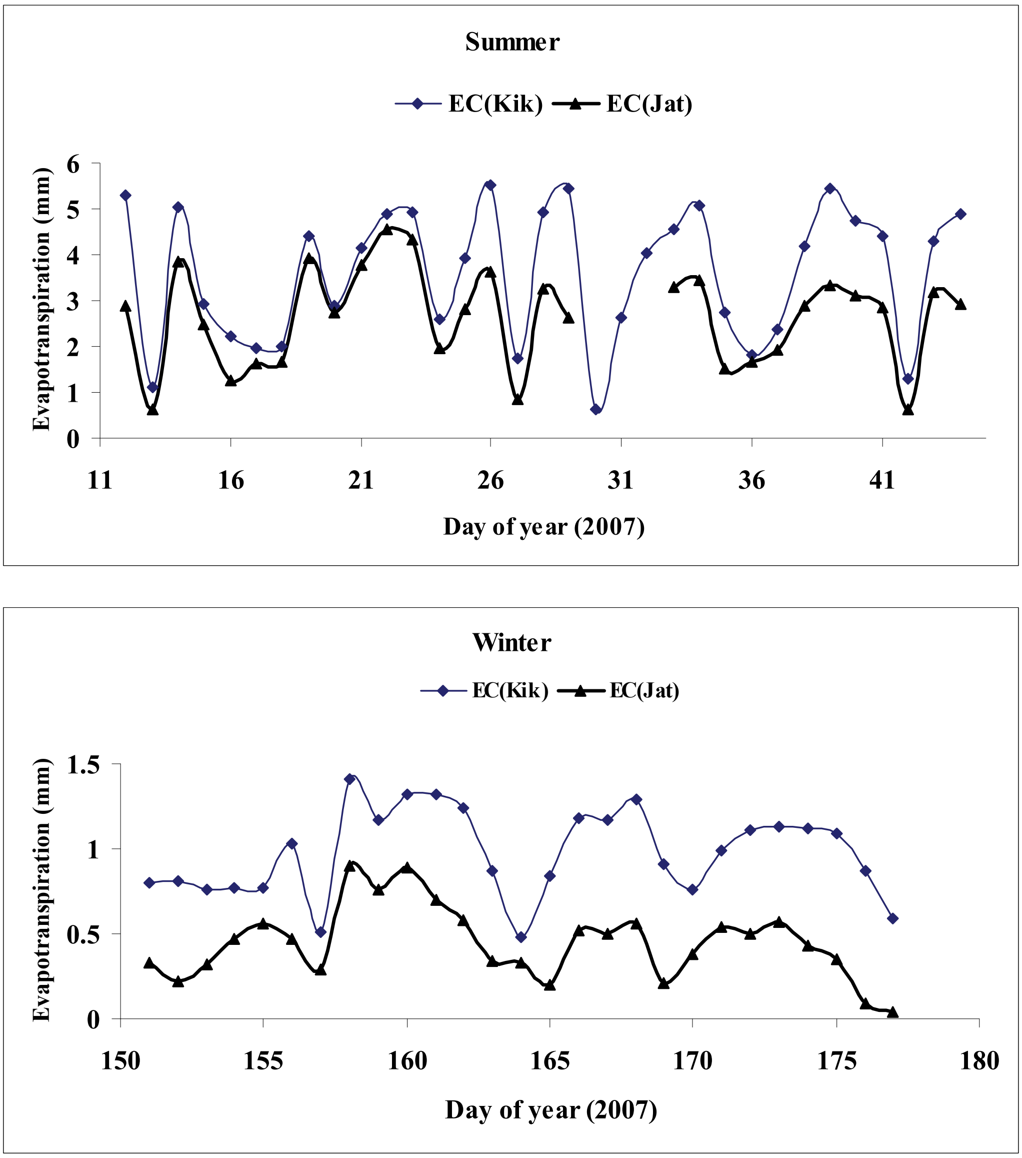


Figure 7.13 Daily total EC evaporation (mm) measured in the *Jatropha* only and Kikuyu treatments in the summer (top graph) and winter (bottom graph) of 2007

7.4.4 Tree water use (Sap flow)

Sap flow of *Jatropha* trees is primarily affected by seasons. As *Jatropha* is deciduous, it remains largely leafless and dormant during very cold and dry seasons. During active transpiration times, its sap flow is dictated by demand and supply of water and its leaf area. Environmental variables relating to demand for water include solar radiation, relative humidity (or vapour pressure deficit) and air temperature, whereas availability of soil water to the trees (via rainfall and irrigation) determines supply.

Hourly and daily trends of heat pulse velocity across all probe sets of the *Jatropha*-only and single-row trials were similar and responded to solar radiation (directly) and relative humidity (inversely) very well (Figures 7.14-.7.17). In both trials, heat pulse velocities measured by the probe sets 2 (20 mm deep) were the highest and that of probe sets 4 (34 mm deep) the lowest. The velocity peaks reduced during cloudy days and after rainy days when relative humidity of the air was still high, which was the case during 03/01/2008 to 10/01/2008 (Figures 7.15 and 7.16). A similar reduction of peaks may also be expected when the soil water content is the limiting factor of sap flow.

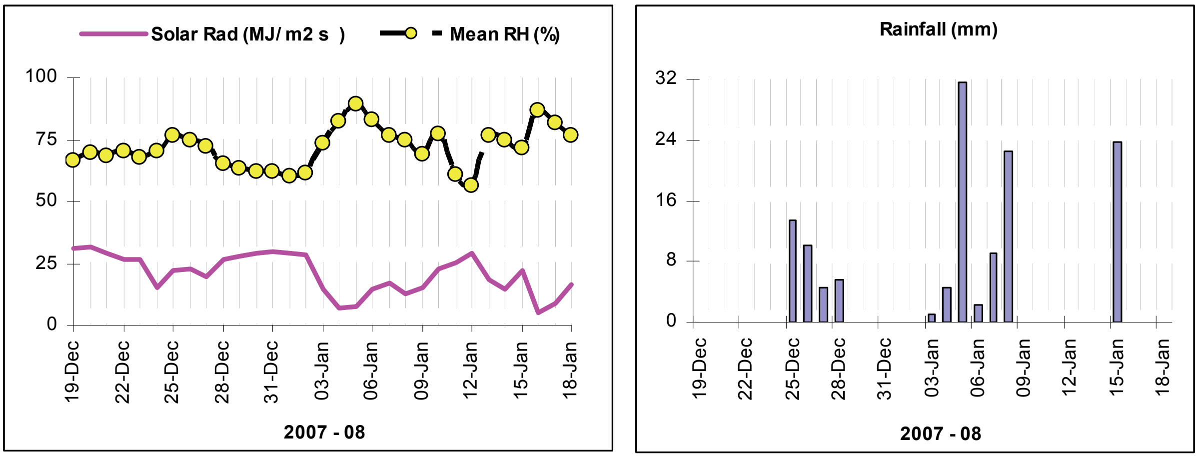


Figure 7.14 Daily solar radiation, average relative humidity and total rainfall for the duration between 19/12/2007 and 18/01/2008, Ukulinga site

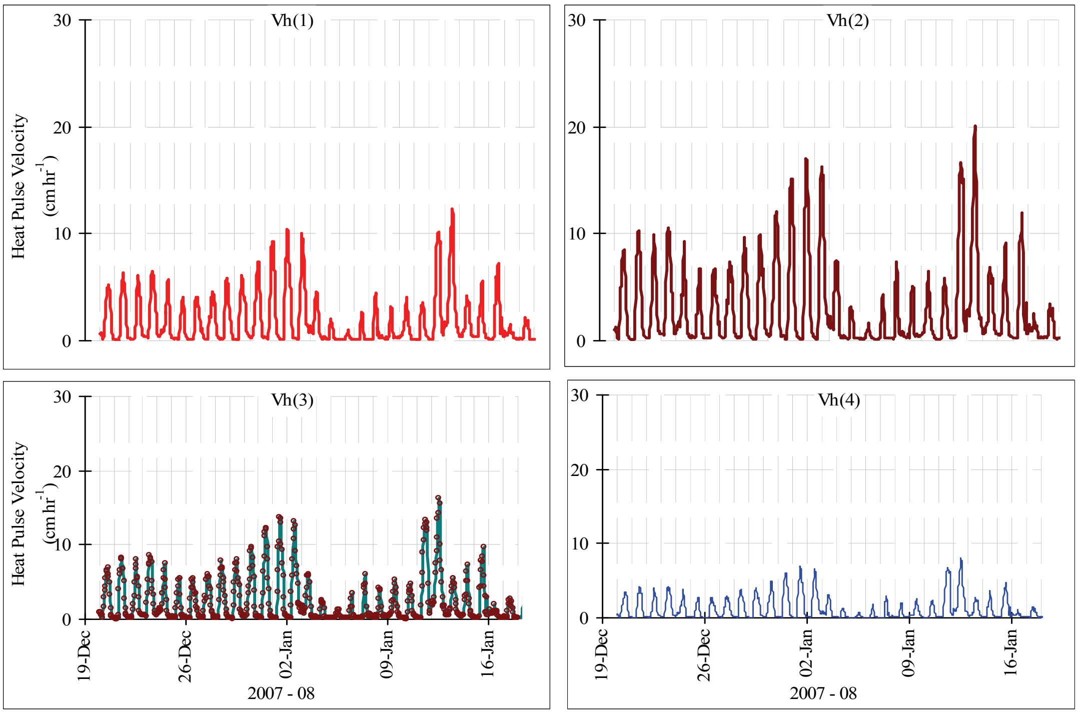


Figure 7.15 Data of heat pulse velocity (cm hr^{-1}) collected from probe sets 1 (13 mm deep), 2 (20 mm deep), 3 (27 mm deep) and 4 (34 mm deep) of the sample tree in the *Jatropha*-only trial at Ukulinga

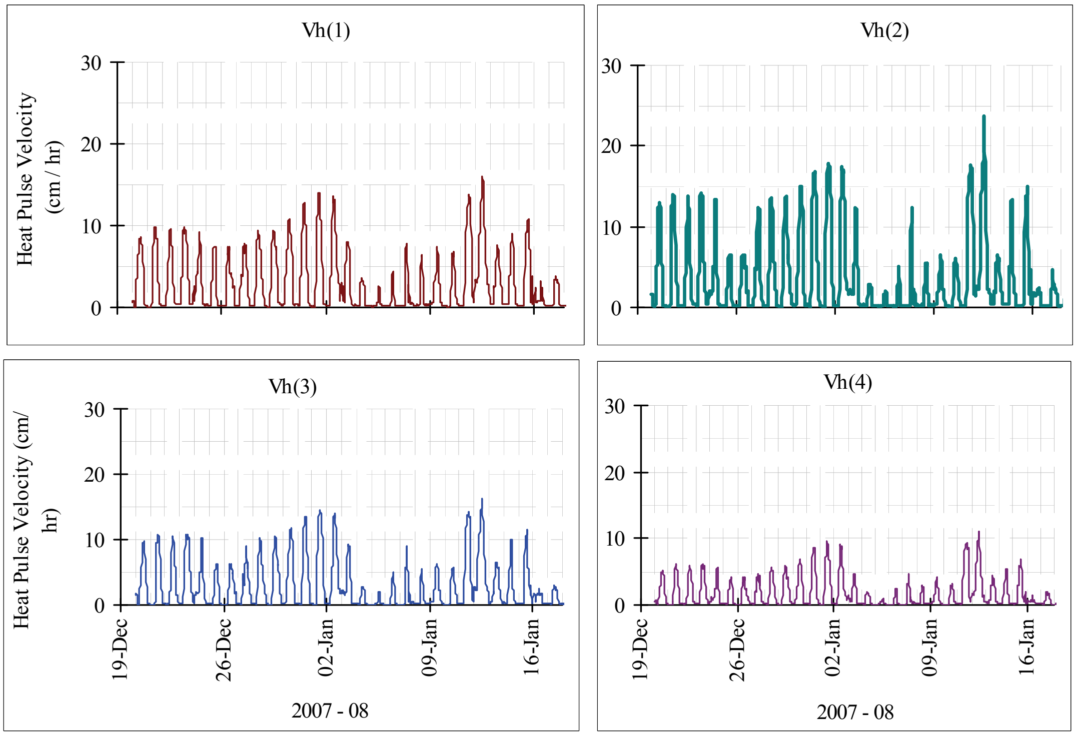


Figure 7.16 Data of heat pulse velocity (cm hr^{-1}) collected from probe sets 1 (13 mm deep), 2 (20 mm deep), 3 (27 mm deep) and 4 (34 mm deep) of the sample tree in the single-row trial at Ukulinga

Heat pulse velocity at all measurement depths of the sample tree in the *Jatropha*-only trial was consistently higher than in single-row samples. Between 18/12/2007 and 20/01/2008, heat pulse velocities were up to 5.12 cm hr^{-1} higher in the *Jatropha*-only sample tree than in the single row sample (at the same sampling depth). The reason for the lower heat pulse velocities in the single-row sample was that the tree has lower leaf area than the *Jatropha*-only sample and had to compete for water with kikuyu.

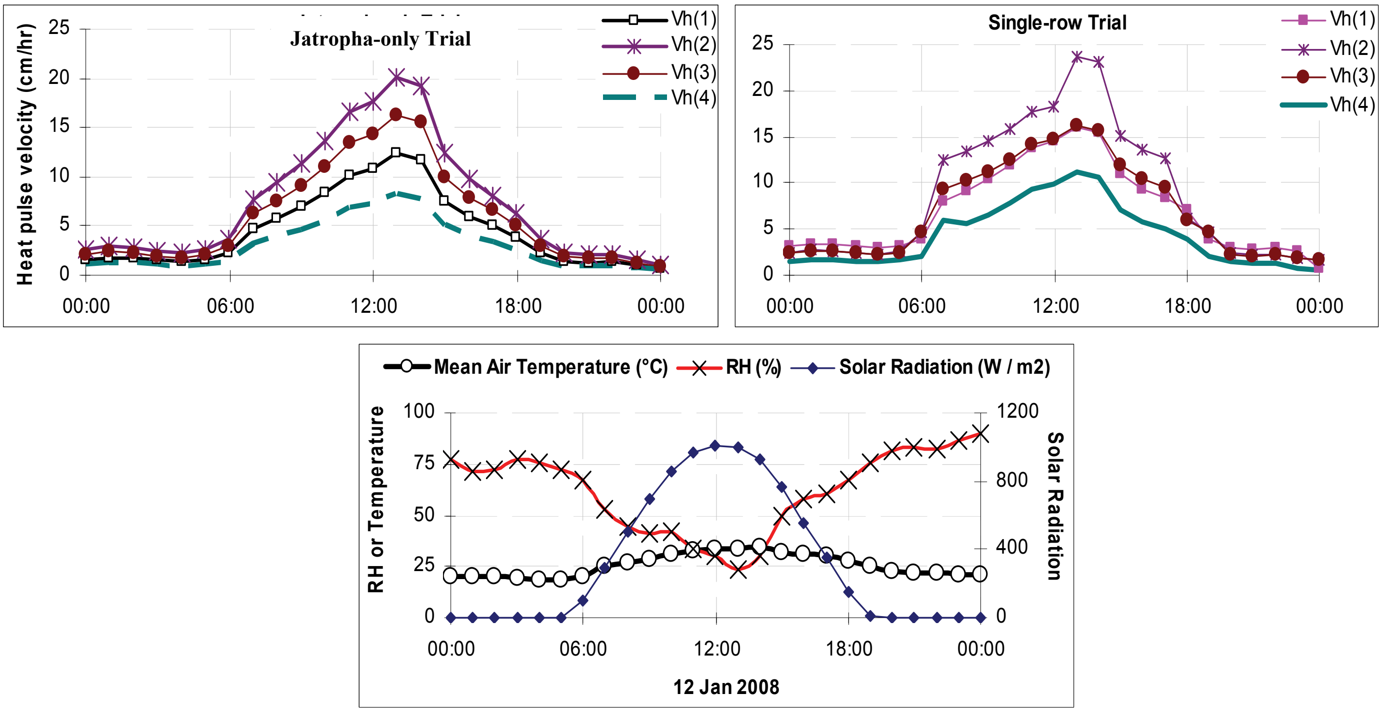


Figure 7.17 Hourly data of heat pulse velocity from the four sampling depths of the sample trees in the *Jatropha*-only and the single-row trials and weather variables (mean temperature, relative humidity and solar radiation) on 12/01/2010, Ukulinga

7.4.5 Soil water

The soil type at Ukulinga is a loam (21.1 % clay, 37.1 % silt and 41.8 % sand) to clay loam (30.2 % clay, 34.5 % silt and 35.3 % sand). Its average bulk density is 1.58 g cm^{-3} (*cv* = 4.74 %). As expected, the highest hydraulic conductivity in the profile (Figure 7.18) is where the percentage of sand (two-third or more of which is coarse sand) is the highest and clay the lowest (Figure 7.19). Clay content of the soil generally increases down the soil profile (Figure 7.19).

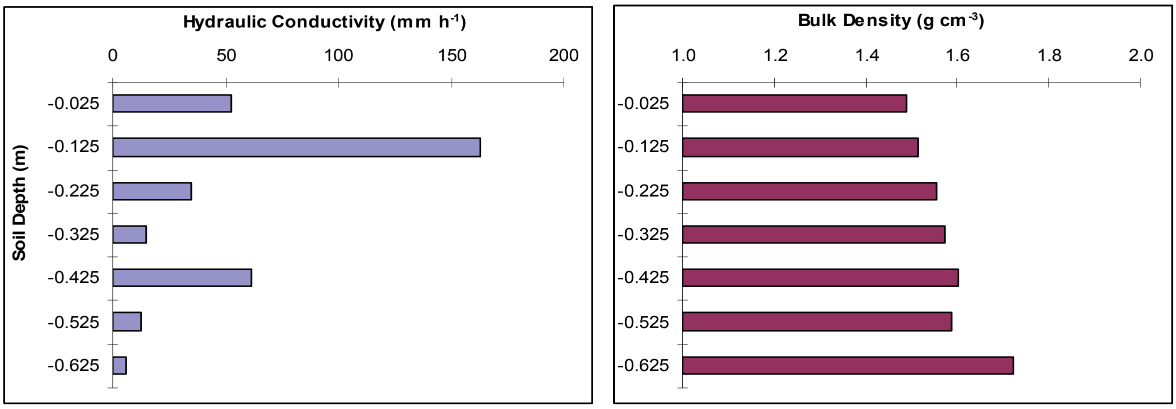


Figure 7.18 Hydraulic conductivity and bulk density of the soil at Ukulinga and their variations with soil depth

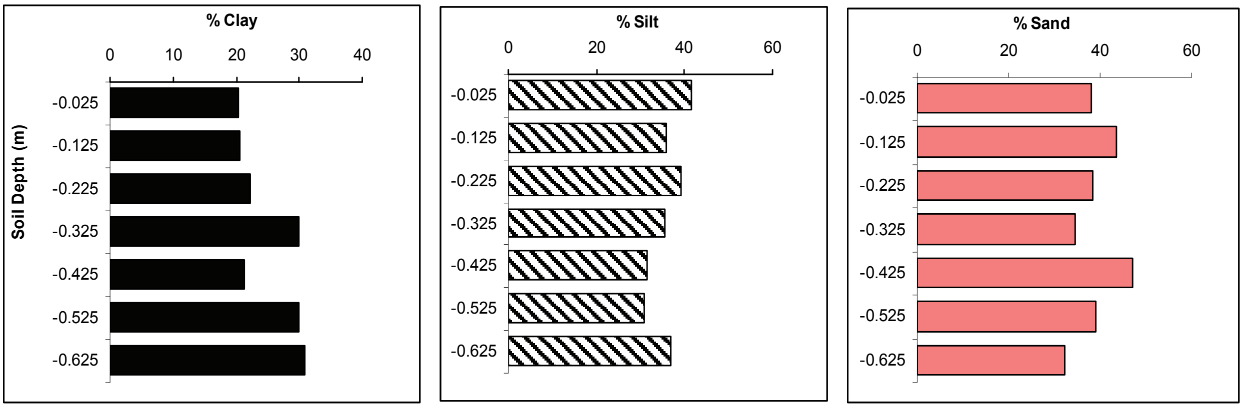


Figure 7.19 Vertical textural profile of the soil profile at Ukulinga

In the *Jatropha*-only trial, soil water generally increased with depth (Figure 7.20-21). Two possible reasons for this are the increase in clay content (Figure 7.19) and decrease in roots and evaporation with depth. The highest increase with depth was right underneath the tree (0 m distance) showing that distance from the tree also affected soil water distribution.

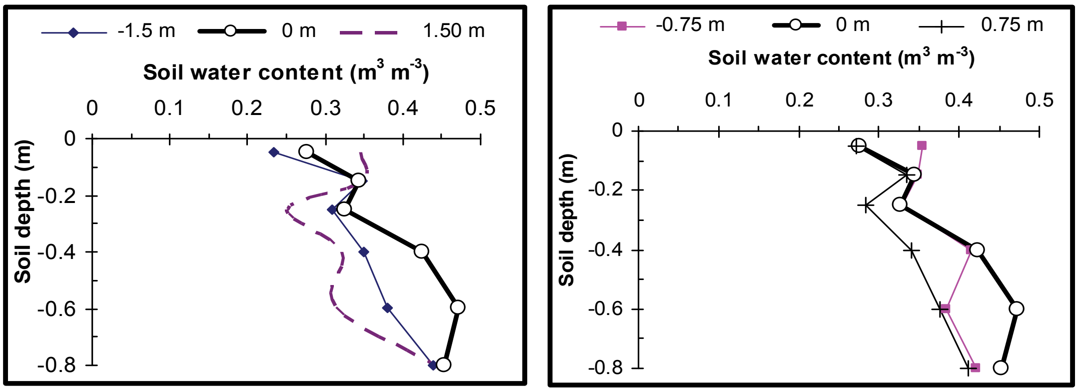


Figure 7.20 Profiles of soil water with depth and distance from the tree row (oriented S73^{0}W-N73^{0}E) in the *Jatropha*-only trial (negative distances indicate distances on the south-western side of the tree)

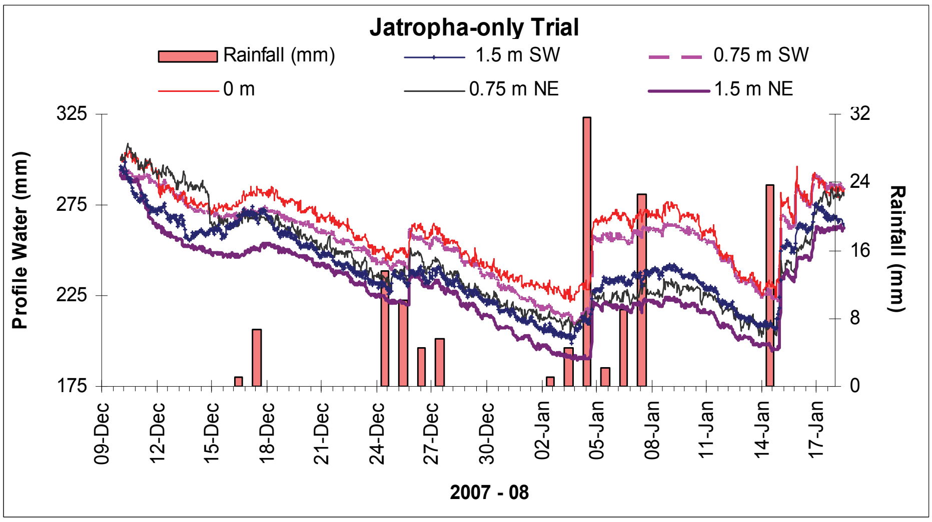


Figure 7.21 Hourly profile water content at selected distances from a tree row (oriented S73^{0}W-N73^{0}E) on a *Jatropha*-only trial, with rainfall, at Ukulinga (SW and NE indicate south-western and north eastern sides of the tree row, respectively)

Distribution of profile water content across the tree row was not symmetrical (Figure 7.23). Soil water content on the south western side of the tree was significantly higher than the north eastern side. This was despite a symmetrical distribution of solar energy across the tree row, shown in Figure 7.22. Water content was significantly the highest right under the tree (0 m distance), as shown in Figures 7.23.

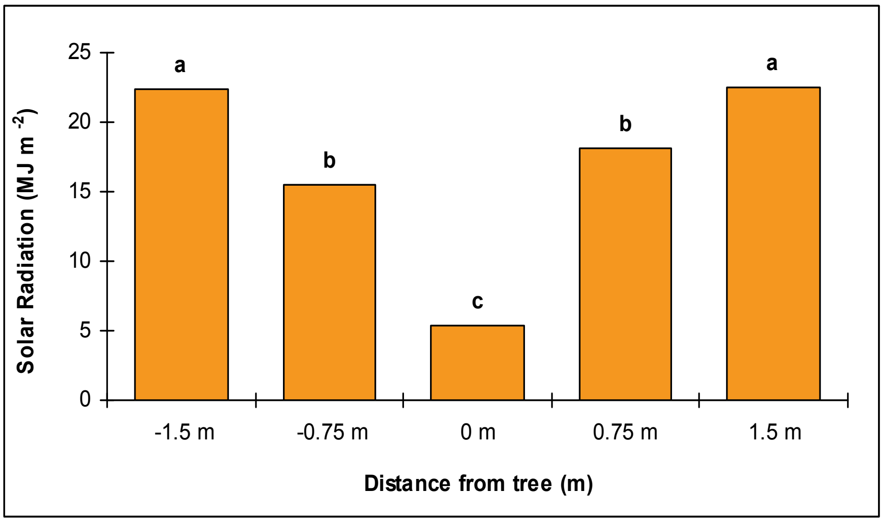


Figure 7.22 Results of significance analysis on effects of distances from tree row (oriented S73^{0}W-N73^{0}E) on the distribution of solar energy in the *Jatropha*-only trial, Ukulinga (negative distances indicate distances on the south-western side of the tree)

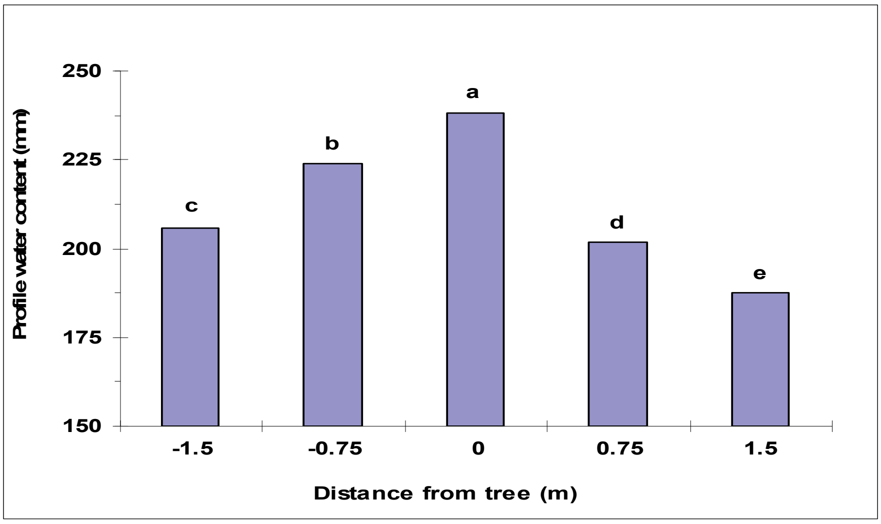


Figure 7.23 Results of significance analysis on distances from tree row (oriented S73^{0}W-N73^{0}E) versus distribution of the profile water content at the soil surface in the *Jatropha*-only trial on 17/12/2007 (negative distances indicate distances on the south-western side of the tree)

This is in agreement with the observation that evaporative energy was least available at that distance (Figure 7.22). It can be inferred that tree root growth is slightly skewed towards the north eastern side of the row.

Distribution of soil water in the single row trial was also affected by depth and distance from the tree (Figures 7.24-7.28). There was asymmetrical distribution of profile water content across the tree, with the south western side of the tree having significantly higher water content that the north eastern side.

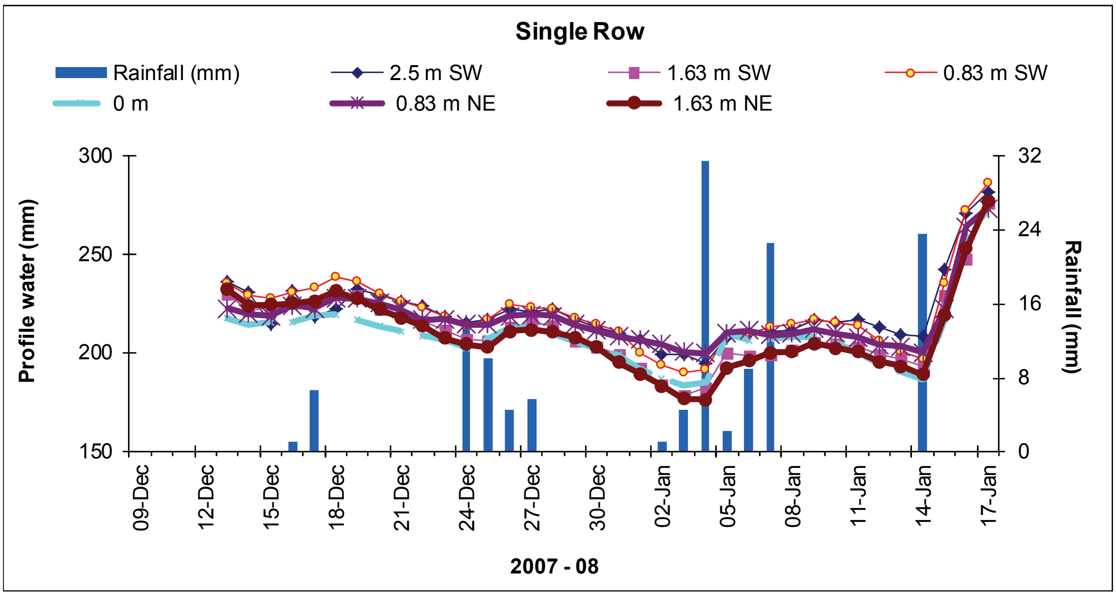


Figure 7.24 Profiles of soil water with depth and distance from the tree row (oriented S73^{0}W-N73^{0}E) in the single-row trial (negative distances indicate distances on the south-western side of the tree)

Unlike in the Jatropha-only trial, though, the increase of soil water with depth is not as pronounced (Figure 7.21) and that the water content underneath the tree row (at 0 m distance) was rather the lowest (Figures 7.22 and 7.23).

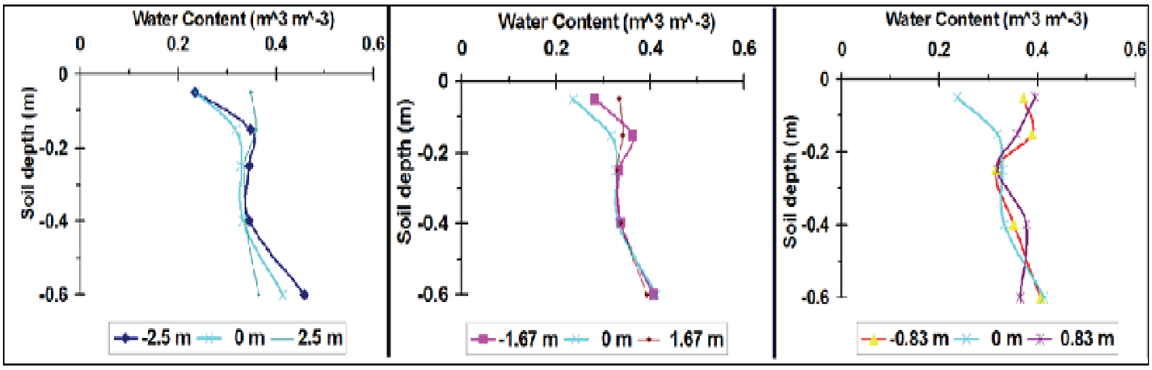


Figure 7.25 Profile water content at selected distances from a tree row (oriented S73^{0}W-N73^{0}E) in the single row trial, with rainfall, at Ukulinga (SW and NE indicate south-western and north eastern sides of the tree row)

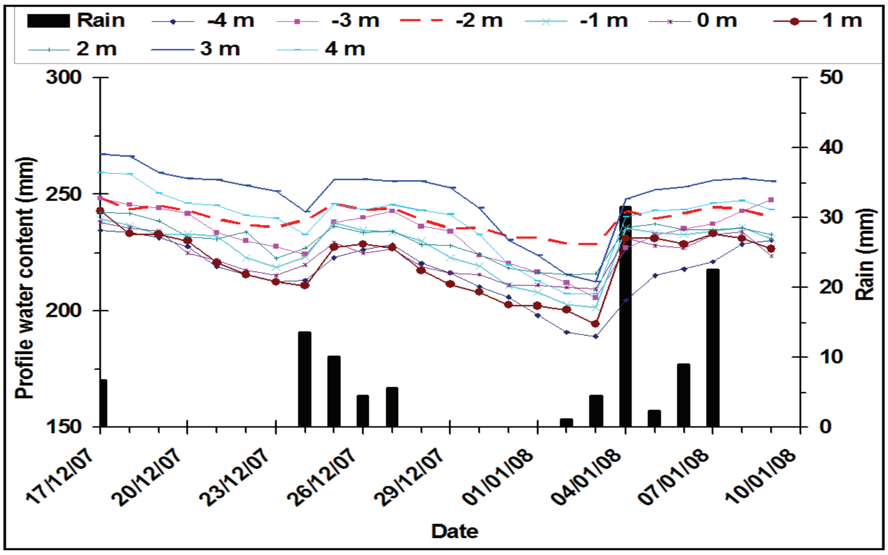


Figure 7.26 Profile water content at selected distances from the tree rows (oriented S730W-N730E) in the double-row trial, with rainfall, at Ukulinga (SW and NE indicate south-western and north eastern sides of the tree rows)

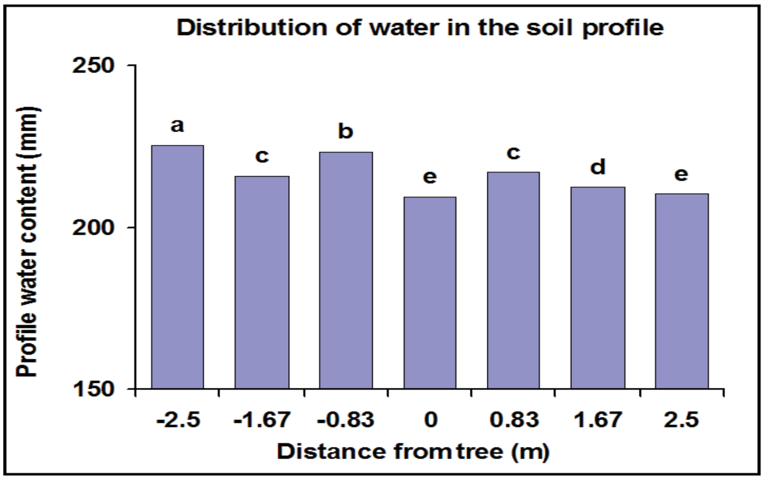


Figure 7.27 Results of significance analysis on effects of distances from tree row (oriented S73^{0}W-N73^{0}E) on the distribution of profile water content in the single-row trial, Ukulinga (negative values indicate distances on the south-western side of the tree)

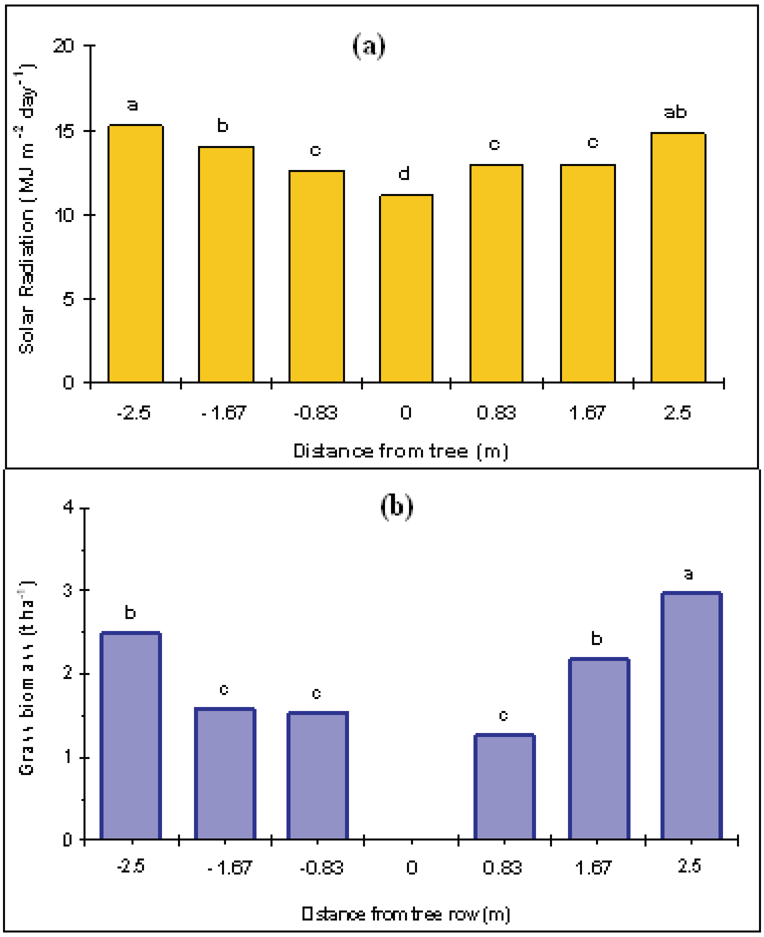


Figure 7.28 Results of significance analyses on how (a) distribution of solar energy at the soil surface (b) kikuyu growth in the single-row trial changes with distance from tree row, oriented S73^{0}W-N73^{0}E, (negative distances indicate distances on the south western side of the tree)

Figure 7.28 shows that distribution of solar radiation and grass growth across the tree row were asymmetrical and generally similar. The figure explains some features of the soil water distribution in the trial (Figure 7.30). The fact that the lowest soil water content was where irradiation was also the lowest (distance of 0 m) indicates high tree root concentration and evaporation. The effect of evaporation was evident due to the absence of grass cover and relatively small tree canopy compared to that in the *Jatropha*-only trial. At the 0.83 m distance, despite significantly low irradiation and grass growth, soil water content was significantly high. This may imply tree roots and grass water use were relatively low and but the grass provided the soil with some cover against evaporation. Finally, at the 2.5 m distance on the north eastern side, profile water content was the lowest mainly due to high grass water use as evidenced by the highest grass growth.

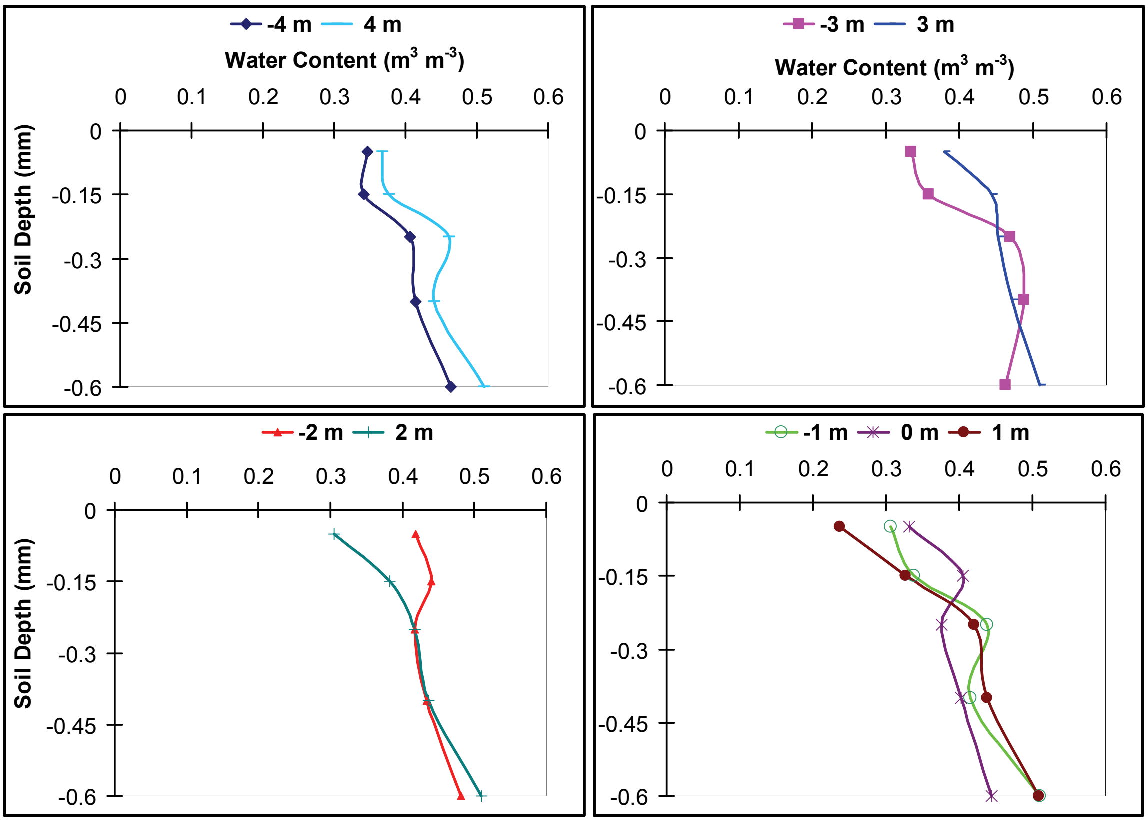


Figure 7.29 Profiles of soil water with depth and distance from the tree row s (oriented S73^{0}W-N73^{0}E) in the double-row trial (negative distances indicate distances on the south-western side of the tree rows)

Distribution of soil water in the double-row trial showed similar characteristics to that of single-row and *Jatropha*-only trials, in that both depth (Figure 7.29) and distance from the tree (Figures 7.30 and 7.31) affected soil water distribution. There was also asymmetrical distribution of profile water content across the tree. The difference between the double-row and the other trials was that soil water on the south western side was significantly higher than the north eastern side closer to the tree rows but the reverse was true towards the centre of the alleys. The lowest soil water content was observed under and between the tree-row pair.

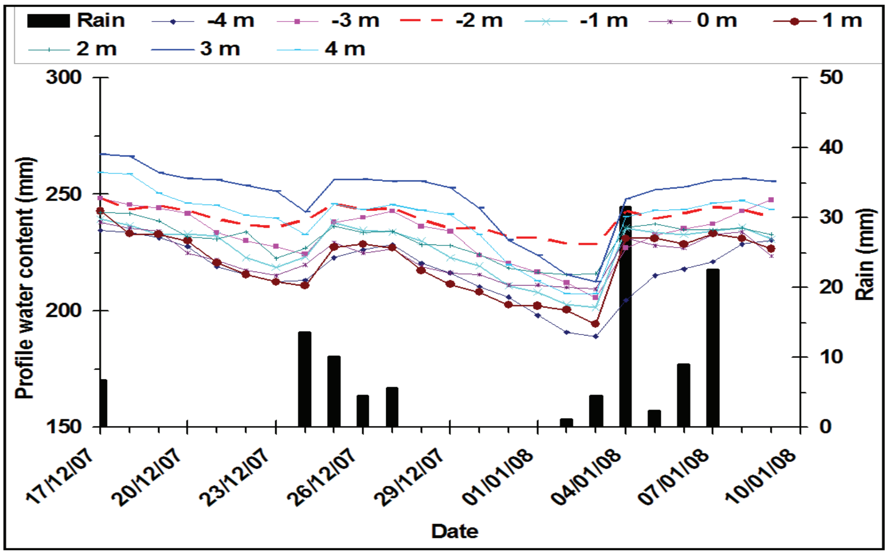


Figure 7.30 Profile water content at selected distances from the tree rows (oriented S73^{0}W-N73^{0}E) in the double-row trial, with rainfall, at Ukulinga (SW and NE indicate south-western and north eastern sides of the tree rows)

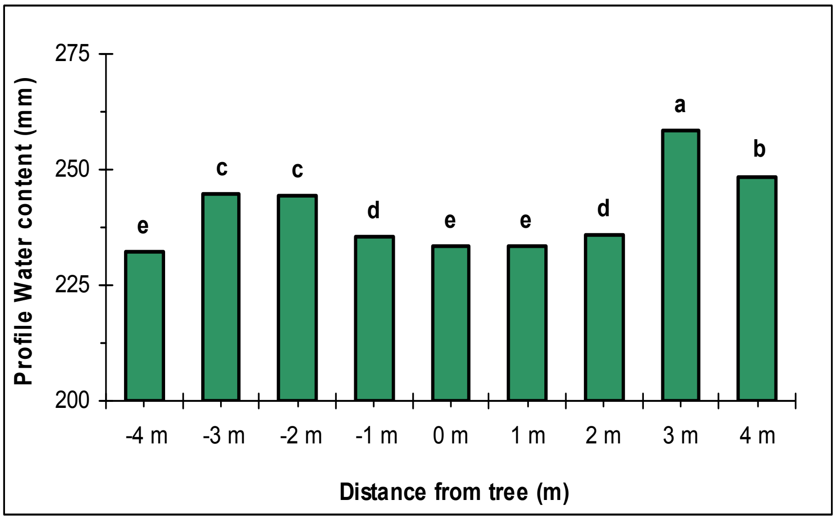


Figure 7.31 Results of significance analysis on effects of distances from the tree rows (oriented S73^{0}W-N73^{0}E) on the distribution of profile water content in the double-row trial, Ukulinga (negative values indicate distances on the south-western side of the trees)

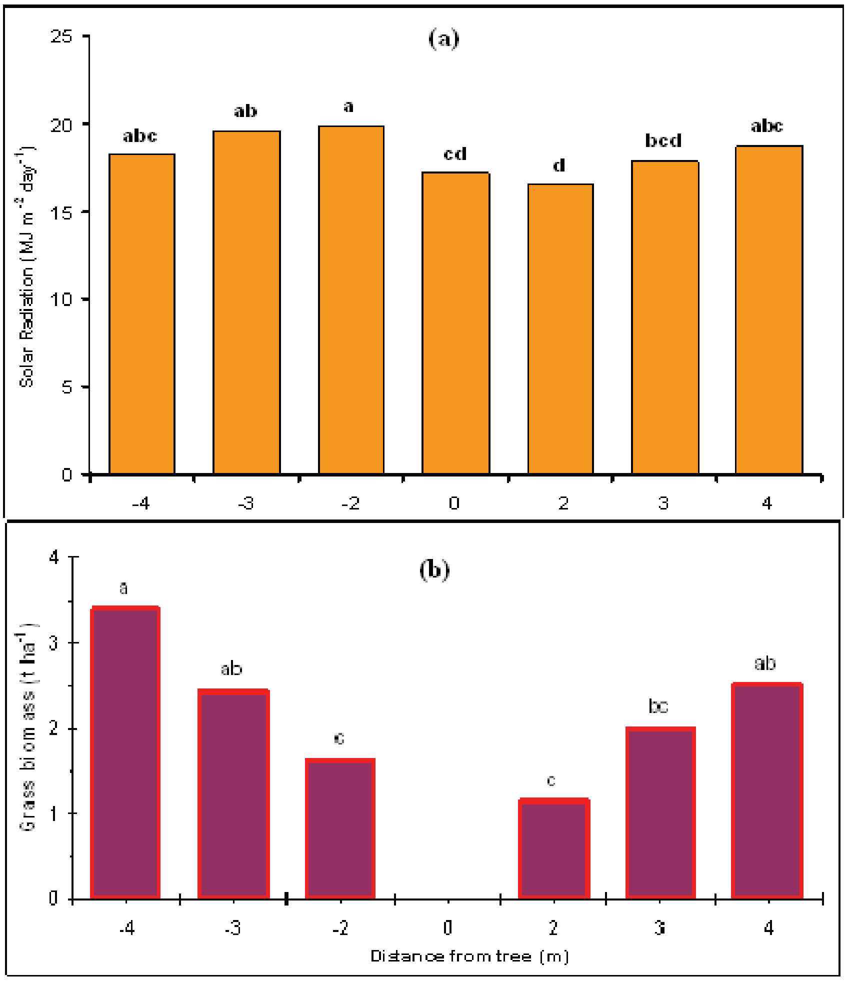


Figure 7.32 Results of significance analyses on how (a) distribution of solar energy at the soil surface (b) kikuyu growth in the double-row trial varied with distance from tree row, oriented S73^{0}W-N73^{0}E, (negative distances indicate distances on the south-western side of the tree)

Spatial distributions of profile water content and solar radiation across the tree row were asymmetrical and generally similar (Figures 7.31 and 7.32). Grass growth across the tree row, on the other hand, was symmetrical. The lowest profile water content underneath the tree (distance of 0 m) was probable due to high tree root activity and evaporation. At the 4 m distance on the south western side, however, profile water content was the lowest mainly due to high water use by kikuyu, as the grass growth at this distance was the highest.

7.4.6 Root distribution

The highest total root density in the standard spacing was underneath the tree (distance of 0 m), as shown in Figure 7.33. This was due to the presence of high woody roots and root hairs of the tree. The reason for the lowest root density at 0.75 m was the decrease in tree roots with distance (especially the woody roots) and that the contribution of the grass roots was also limited as grass cover was also low. Towards the middle of the alleys, root density increased. This increase was higher on the south western side, resulting in an asymmetrical root distribution.

Distribution of the total root density in the single-row was also asymmetrical (Figure 7.34). The highest total root density within the top 0.2 m depth increment was at 0 m distance (underneath the tree). Root length distribution across the tree row was very similar to that of the standard-spacing trial. Root density within 0.2-0.6 m was very low below the tree and higher on the north eastern side of the tree row than the south western side.

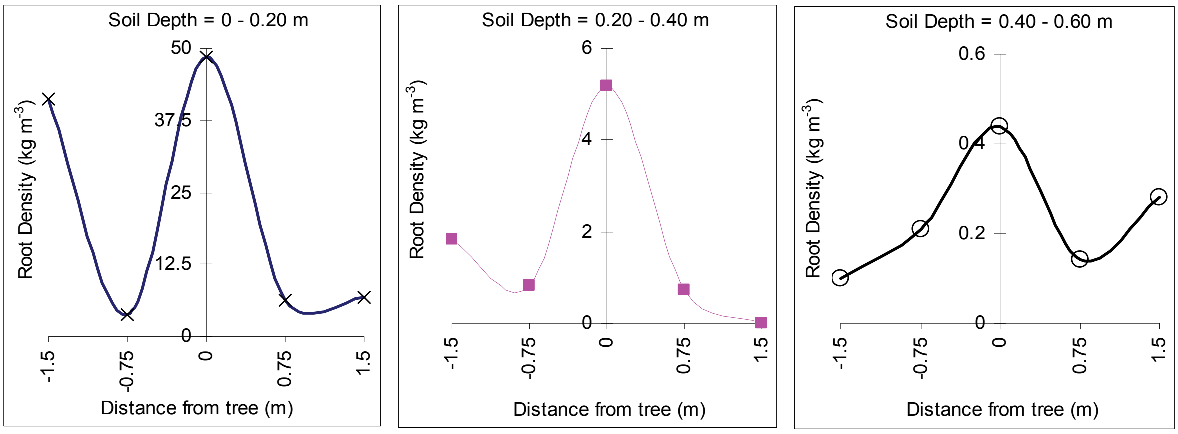


Figure 7.33 Vertical and lateral root biomass density distribution across the tree row (oriented S73^{0}W-N73^{0}E) in the standard-spacing trial (negative distances indicate distances on the south-western side of the tree row). Note that different scales are used for the Y-axis (root density)

Distribution of the total root density in the single-row was also asymmetrical (Figure 7.34). The highest total root density within the top 0.2 m depth increment was at 0 m distance (underneath the tree). Root length distribution across the tree row was very similar to that of the standard-spacing trial. Root density within 0.2-0.6 m was very low below the tree and higher on the north eastern side of the tree row than the south western side.

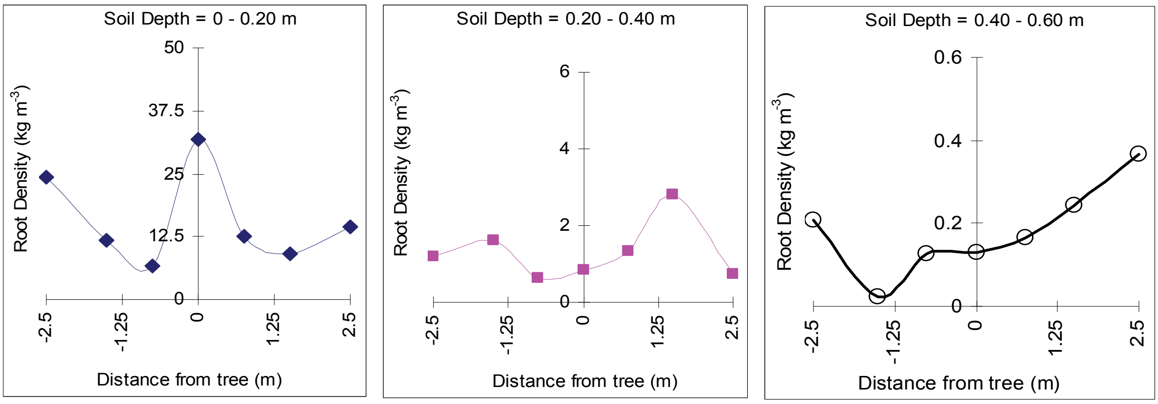


Figure 7.34 Vertical and lateral root biomass density distribution across the tree row (oriented S73^{0}W-N73^{0}E) in the single-row trial (negative distances indicate distances on the south-western side of the tree row). Note that different scales are used for the Y-axis (root density)

7.4.7 Competition Trial

7.4.7.1 Tree Height

The rank order of the final heights by treatment was 300>120>60>control (Table 7.3). After correcting for block effect, the average final tree height of the trees under treatment '300' (117.97 cm) was significantly greater than that of the control trees (107.28 cm) (ANOVA, $F_3 = 3.098$, $P = 0.33$) (Table 7.3). In fact, trees under treatment '300' were able to grow on average 9.97% taller than the control (Table 7.3). Final tree height for both treatment '60' and '120' did not differ significantly from either the control or treatment '300' (Table 7.3).

The asymptotic growth response of height (Figure. 7.35) differed significantly between the different treatment levels over time (RM ANOVA, $F_{33} = 5.43$, $P < 0.001$, Greenhouse-Geisser epsilon (correction factor for the d.f.) = 0.1525). Thus four different Gompertz models were necessary to adequately explain the response to the different treatment levels.

The relative growth rate for trees under treatment '60' increased steeply at first until 6 April (DOY 96) (Figure 7.36). Such an increase was also observed under treatment '300' but was not as marked. After the 6 April the relative rate of increase in plant height for all treatments generally decreased over time until it became minimal (i.e. close to zero) (Figure 7.36). This occurred around 24 June (DOY 175) for the control plants, 29 July (DOY 210) for treatment '60' and 13 August (DOY 225) for both treatment '120' and '300'.

7.4.7.2 Basal diameter

The rank order of the final basal diameter by treatment was 300>120>60>control (Table 7.3). The final basal diameter data had to be transformed to the power of –2 to meet the assumptions of parametric tests. After correcting for block effect, the mean final basal diameter of the control trees (55.14 mm) was significantly less than that of the trees under treatment '300' (61.58 mm) (ANOVA, F_3 = 3.15, P = 0.031) (Table 7.3). In fact, the final basal diameter of trees under treatment '300' was on average 11.7% greater (Table 7.3). Final basal diameter for both treatment '60' and '120' did not differ significantly from either the control or treatment '300' (Table 7.3).

Table 7.3 Effect of clearing (0, 60, 120, 300 cm) on growth parameters of *J. curcas*

		Average additional increase from control	
	Mean final measurement ± S.D.*	**Absolute**	**Relative (%)**
Height (cm)			
Control (0)	107.28 ± 9.16^{a}	-	-
60	111.95 ± 9.27^{ab}	4.7	4.36
120	115.27 ± 13.98^{ab}	8	7.45
300	117.97 ± 13.54^{b}	10.7	9.97
Basal diameter (mm)			
Control (0)	55.14 ± 4.14^{a}	-	-
60	59.86 ± 7.77^{ab}	4.72	8.6
120	60.92 ± 8.65^{ab}	5.78	10.5
300	61.58 ± 6.67^{b}	6.44	11.7
Leaf abscission (%)			
Control (0)	79.07 ± 34.68 ^{a}	-	-
60	13.15 ± 23.30^{b}	-	-
120	18.94 ± 24.98^{b}	-	-
300	14.35 ± 23.36^{b}	-	-
Number of offshoots			
Control (0)	1 ± 0.97^{a}	-	-
60	2 ± 1.07^{a}	-	-
120	2 ± 1.36^{a}	-	-
300	1 ± 0.70^{a}	-	-

**S.D.: Standard deviation*

Treatments: Control (0) – no pasture removed; 60 – pasture removed in 60 cm radius; 120 – pasture removed in 120 cm radius; 300 – pasture removed in 300 cm radius

a,b: Significantly different groups for each growth parameter

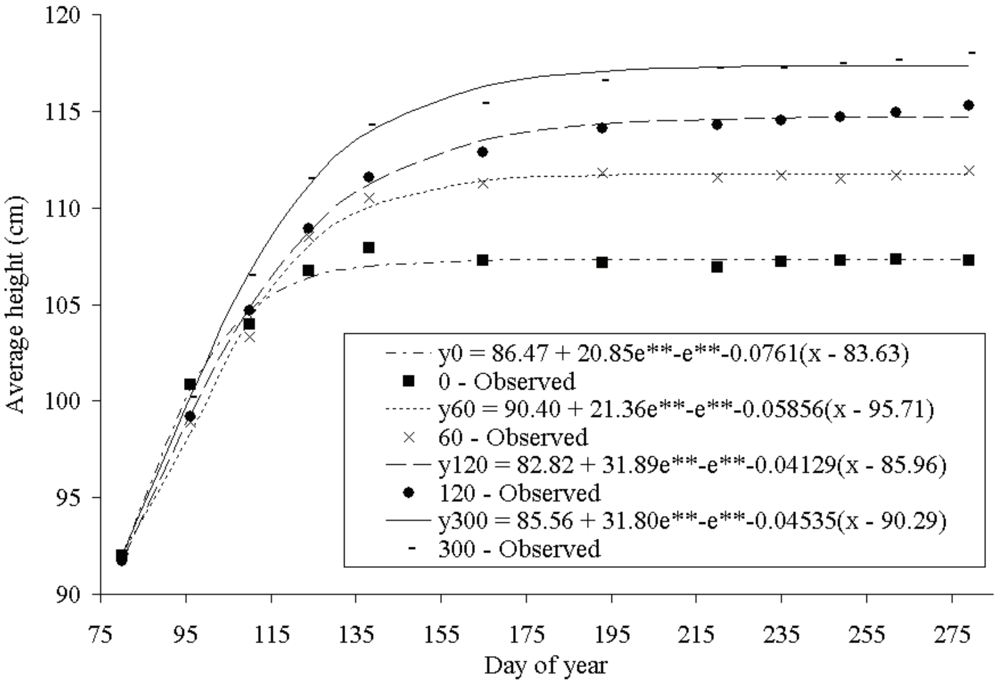


Figure 7.35 Average tree height (symbols; n = 12) fitted to Gompertz growth functions (y = a + ce**-e**-b(x – m); R2 = 99.6; lines) from late March to early October. (Treatments: 0 = control – no grass removed; 60 = grass removed in a 60 cm radius; 120 = grass removed in a 120 cm radius; 300 = grass removed in a 300 cm radius)

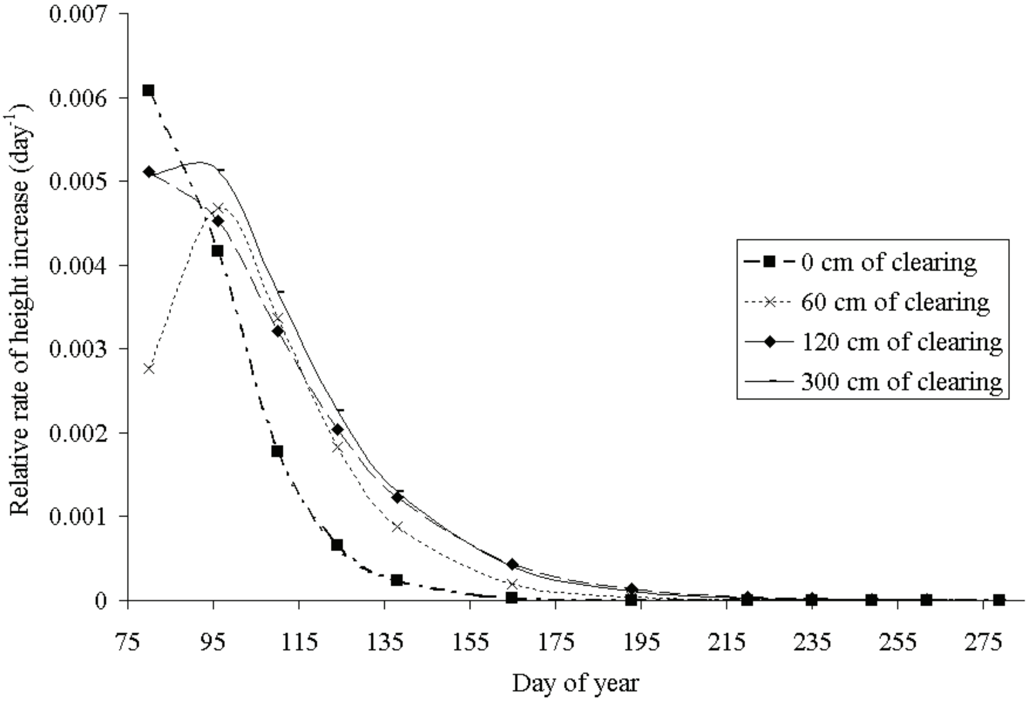


Figure 7.36 Relative growth rate in terms of tree height for trees under different clearing treatments from late March to early October. (Treatments: 0 = control – no grass removed; 60 = grass removed in a 60 cm radius; 120 = grass removed in a 120 cm radius; 300 = grass removed in a 300 cm radius)

The linear growth response of basal diameter (Figure 7.37) differed significantly between the different treatment levels over time (RM ANOVA, F_{33} = 2.55, P = 0.009, Greenhouse-Geisser epsilon (correction factor for the d.f.) = 0.2625). Thus four different exponential models were necessary to adequately explain the response to the different treatment levels. The growth rate was lower for the control and treatment '60' than for treatments '120' and '300'.

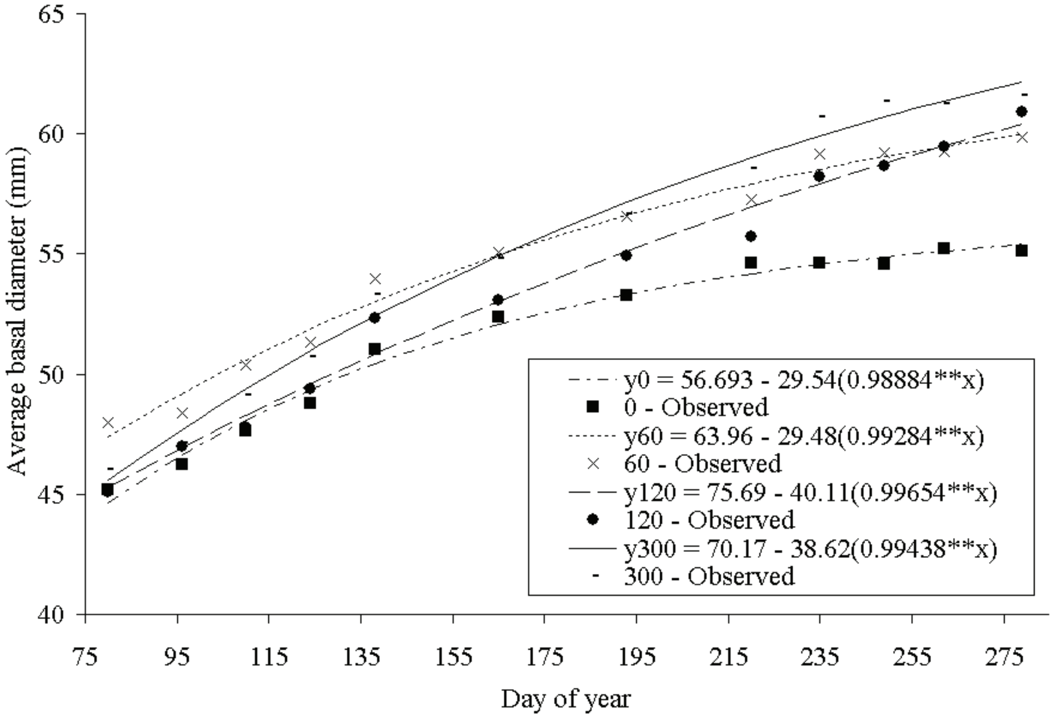


Figure 7.37 Average basal diameter (symbols; n = 12) fitted to exponential growth functions (y = a + b(r^x); R^2 = 98.5; lines) from late March to early October. (Treatments: 0 = control – no grass removed; 60 = grass removed in a 60 cm radius; 120 = grass removed in a 120 cm radius; 300 = grass removed in a 300 cm radius)

7.4.7.3 Number of offshoots

One of the trees under treatment '120' in block three was removed from the analysis as it produced an exceptionally high number of offshoots. The remaining data had to be square root transformed to meet the assumptions of parametric tests. After accounting for block effect, there was no significant difference in final number of offshoots between the treatments (ANOVA, F_3 = 1.22, P = 0.309) (Table 7.3).

The growth response was not affected by the different treatment levels (RM ANOVA, F_{33} = 1.2, P = 0.284, Greenhouse-Geisser epsilon (correction factor for the d.f.) = 0. 3442). Nevertheless, four different quadratic-by-quadratic models were needed to adequately explain the response under the different treatments (Figure 7.38). Thus the response was considered worthy of further investigation.

There was a non-synchronized peak in the number of offshoots earlier in the sampling period (Figure 7.38). Trees under treatment '300' obtained their maximum average number of offshoots (<3) the earliest (around 25 April, DOY 115). This was followed by treatment '120' which produced the greatest maximum number of offshoots overall (<4) around 15 May (DOY 135). Trees under treatment '60' peaked at no more than three offshoots on 18 May (DOY 138). A peak in number of offshoots for the control trees was barely noticeable (an average of two offshoots) although there was a decline after the 4 June (DOY 155).

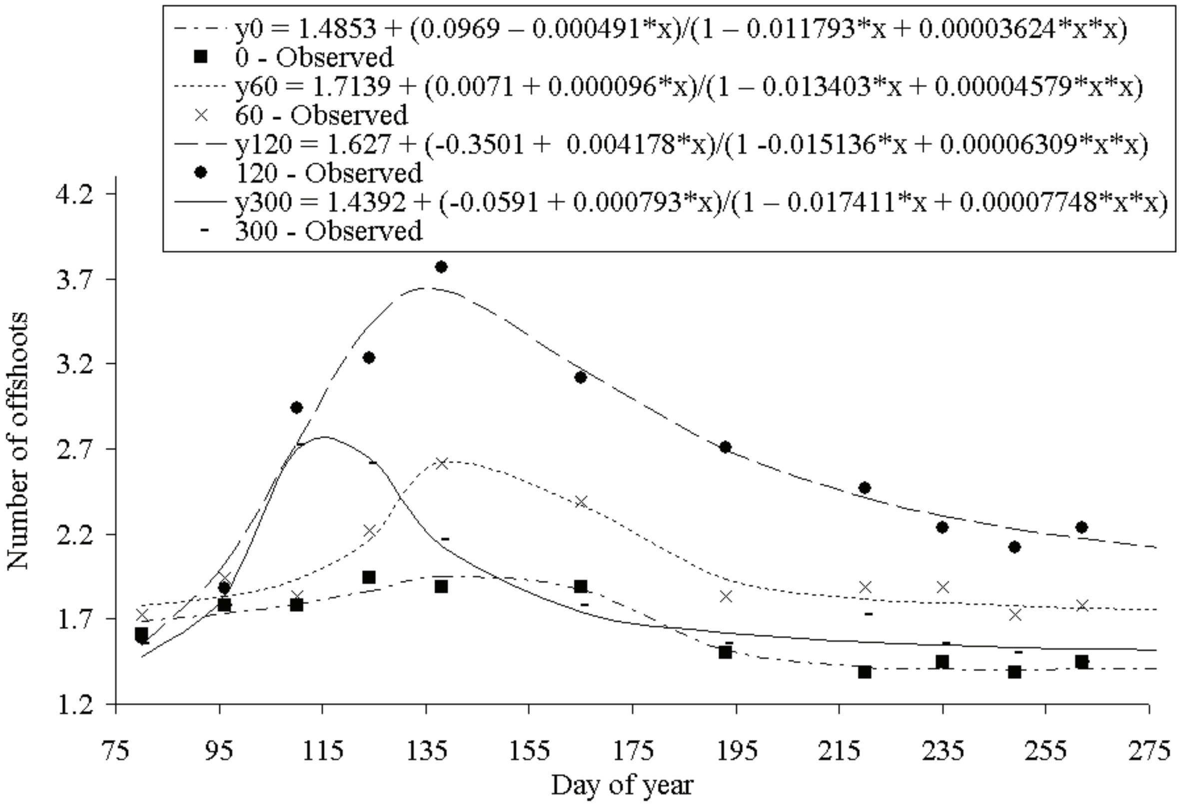


Figure 7.38 Average number of offshoots (symbols; n = 12) fitted to quadratic-by-quadratic growth functions (y = a + (b + c*x)/(1 + d*x + e*x*x); R^2 = 96.5; lines) from late March to early October. (Treatments: 0 = control – no grass removed; 60 = grass removed in a 60 cm radius; 120 = grass removed in a 120 cm radius; 300 = grass removed in a 300 cm radius)

7.4.7.4 Percentage leaf abscission

Percentage leaf abscission generally peaked around the 23 August (DOY 235) thus leaf drop was only analysed up to this point. On this day, percentage leaf abscission was significantly greater in the control than under treatment '300' (Mann-Whitney U = 31.0; $P < 0.001$), '120' (Mann-Whitney U test = 30.5; $P < 0.001$) and '60' (Mann-Whitney U = 32.0; $P < 0.001$) (Table 7.3).

There was also a significant difference in the response to the different treatment levels over time (RM ANOVA, $F_{24} = 7.15$, $P < 0.001$. Greenhouse-Geisser epsilon (correction factor for the d.f.) = 0.7025). Leaf-drop in the control and treatment '300' increased right up to day 235, although, the latter did so at a much-reduced rate (Figure 7.39). Treatments '60' and '120' showed a similar response to the treatments over time including a decline in leaf-drop shortly before DOY 235 (Figure 7.39). Thus four different critical exponential models were necessary to adequately explain the response to the different treatment levels. It must be reiterated that these data did not meet the assumptions of parametric tests so caution must be taken when interpreting the results of the RM ANOVA.

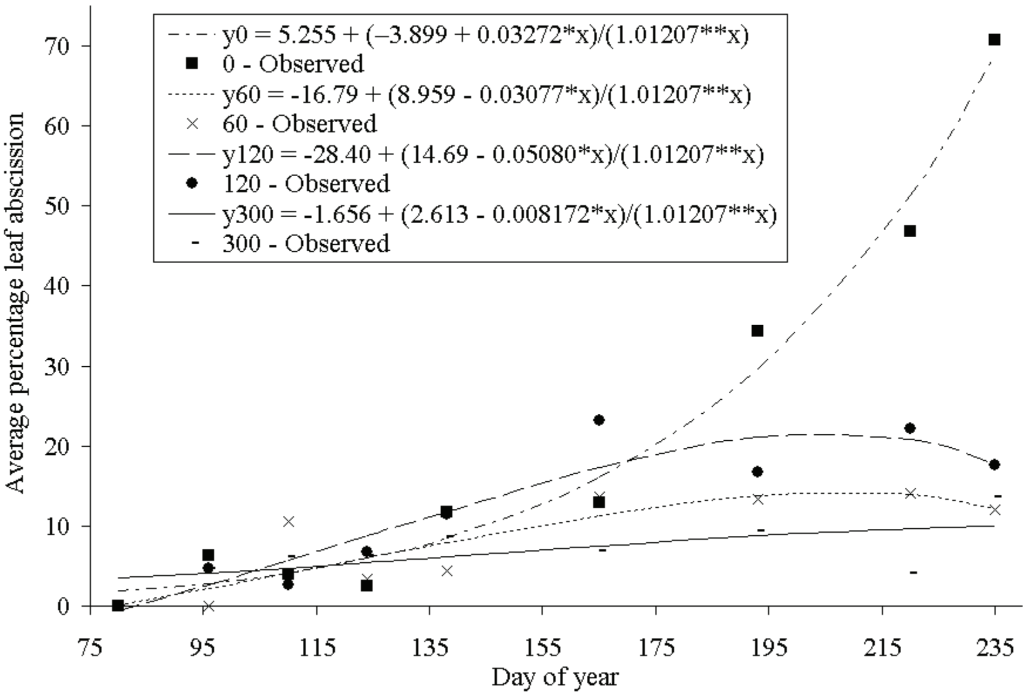


Figure 7.39 Average percentage leaf abscission (symbols; n = 12) fitted to critical exponential growth functions (y = a + (b + c*x*)(R^x); R^2 = 93.2; lines) from late March to 23rd August (235th day of the year). (Treatments: 0 = control – no grass removed; 60 = grass removed in a 60 cm radius; 120 = grass removed in a 120 cm radius; 300 = grass removed in a 300 cm radius)

7.4.7.5 Weather data

During the sampling period, average daily rainfall reached a minimum in the winter months of June and July (Figure 7.40). Average daily maximum and minimum temperatures for each month began declining from February and reached the lowest values during May and June (Figure 11.36). The average daily solar radiation for each month also declined from February, reaching the lowest levels from May through to July (Figure 7.40).

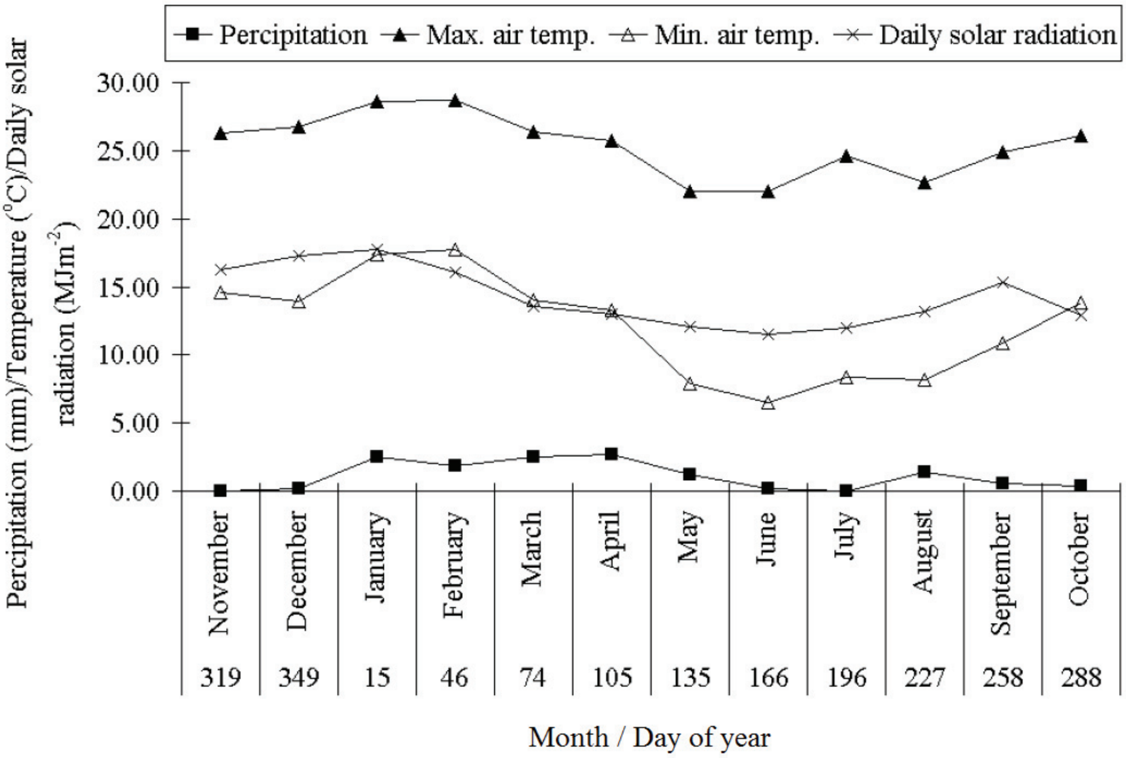


Figure 7.40 Average daily minimum and maximum temperatures, precipitation and solar radiation for each month at the Ukulinga study site from 1 November 2005 to 31 October 2006

7.4.7.6 Discussion and Conclusions – Competition Trial

The clear increase in final tree height and basal diameter with increasing distance of planted pasture species from *J. curcas* supports the hypothesis of increased tree growth with increasing distance of neighbouring vegetation. Reduced tree growth in the presence of basal vegetation has been recorded in many studies (e.g. Malik *et al.*, 2000; Malik *et al.*, 2001). For example, tree height, basal diameter and tree volume of *Liquidambar styraciflua* (sweetgum), a bioenergy hardwood, was significantly reduced in the presence of *Festuca arundinacea* (tall fescue) and *Lespedeza cuneata* (lespedeza) (Malik *et al.*, 2001).

This reduced growth in the presence of forage and cover crops is often attributed to more efficient competition for nutrients and water by the latter (Malik *et al.*, 2000). Since the control plants, with no separation between them and the planted pastures, showed the least amount of growth, they most likely experienced the greatest level of competition. Those plants under treatment '300', with the maximum distance of pasture removal, experienced the greatest amount of growth and therefore the least amount of competition.

The level of competition not only affected final tree height, basal diameter and degree of leaf abscission but also their growth response. In addition, competition in general affected the growth response of these growth parameters differently. While basal diameter continually increased, tree height levelled off towards autumn and winter and percentage abscission peaked in late winter.

The reduced increase in tree height from autumn throughout winter across all treatments can be explained by the decrease in rainfall, ambient temperature and solar radiation over June, July and August at Ukulinga Farm (Figure 7.40). Such conditions induce dormancy in *J. curcas* (Heller, 1996). Of more interest is that full competition reduced the rate of height increase to a minimum approximately 35 days before that of trees with pastures removed up to 60 cm away and approximately 50 days before those with pastures removed up to 120 and 300 cm away (Figure 7.36). The resultant 9.97% height advantage of trees under the least amount of competition, over those under full competition, could have important implications on the productivity of *J. curcas*.

Most studies on J*. curcas* productivity relate yield to tree age and not height. A study on *J. curcas* in Paraguay, found a rapid increase in productivity in years three to five followed by a less rapid increase in later years (Matsuno *et al*., 1985). Since height is, to a certain degree, a function of tree age (Thomas, 1996) and the increase of *J. curcas* height is also most rapid in earlier years (Openshaw, 2000), the increase in productivity could possibly be influenced by both maturity and height. In fact, Mansur *et al*. (1996) found that there was a significant correlation of height and maturity with seed yield of *Glycine max* (soybean).

While tree height levelled off, basal diameter continued increasing through winter. This suggests that the trees direct all available resources to increasing basal diameter when growing conditions were poor. Trees under less competition (i.e. treatments '300' and '120') were able to increase at a greater rate than those experiencing higher levels competition (Figure 7.37). As a result the main stems were on average 11.7 and 10.5% thicker than those of trees under full competition.

This lead may give trees experiencing less competition an advantage of increased biomass and seed production. Basal diameter has been shown to correlate positively with total flower production, seed number, and seed biomass in *Heracleum lanatum* (cow parsnip) (Hendrix, 1984), cone production in *Pinus sylvestris* (Scots pine) (Karlsson, 2000) and tree height in a number of different tree species (Thomas, 1996).

Competition did not have a significant effect on the number of offshoots within 25 cm of the ground. Despite this, personal observations were that trees under the greatest amount of competition had the least total amount of side branches and offshoots per plant. In fact, the study did show that trees under the most amount of competition produced the least amount of offshoots throughout the sampling period. This could influence seed production as the flowers and therefore the fruit of *J. curcas* are borne on the ends of branches (Heller, 1996). Interestingly, trees with the greatest amount of ground cover removed also had a relatively low number of offshoots. Although the relationship between number of offshoots and competition was not significant, it could imply that under low levels of competition trees direct most of their resources to increasing height and basal diameter. At intermediate levels of competition (i.e. treatment '120'), trees direct an increased proportion of resources to increasing the number of offshoots. The peak in the number of offshoots was most probably caused by an accumulation of leaves during the growing season, followed by their loss as a consequence of unfavourable winter conditions.

Although, unlike the number of offshoots, the effect of competition on tree height and basal diameter was undoubtedly significant, competition had the greatest effect on leaf abscission. Trees under full competition experienced the highest degree of leaf drop (Figure 7.39). Many reports have noted leaf fall in *J. curcas* during the winter and correlate abscission to times of water scarcity (Openshaw, 2000; Gush, 2006; Marty'nez-Herrera *et al*., 2006). Leaf abscission during these times is beneficial as it reduces water loss through transpiration (Tainton, 1999).

High levels of leaf abscission under full competition may, however, disadvantage *J. curcas* individuals. Indeed the increase in basal diameter of trees under the greatest degree of competition almost levelled off from around 23 August (DOY 235) when the trees experienced the greatest level of leaf abscission. A study on foliage loss in six Costa Rican tree species by Rockwood (1973) found that total seed number and weight was substantially less for individuals that were experimentally defoliated. In fact 80% did not produce fruit at all. The results therefore gave further support to studies showing growth and reproduction as functions of leaf area. A defoliation experiment on *Rhododendron lapponicum* showed similar results including a 70% decrease in dry weight of reproductive support tissues (Karlsson, 1994). A study by Karnosky *et al*. (1996) found that premature abscission of mature *Populus* leaves on the lower stem would substantially reduce root growth as those leaves allocate most of their carbon to below ground growth. Other recently mature *Populus* leaves were shown to transport most of their carbon to the developing leaf zone, resulting in a decrease in new leaf production following leaf loss.

The high level of leaf abscission in the control suggests that water is the limiting resource restricting *J. curcas* growth. Many studies have found that low soil moisture reduces *J. curcas* growth and productivity. In arid and semi-arid conditions *J. curcas* can take three years to grow three to four meters (Augustus *et al*., 2002) and produce a seed yield of only 0.4t $ha^{-1}yr^{-1}$ at maturity (Openshaw, 2000). Under wetter conditions, *J. curcas* can grow four meters in two to three years (Augustus *et al*., 2002), start producing seeds after only 12 months (Becker and Makkar, 2000) and generate seed yields of 12t $ha^{-1}yr^{-1}$ at maturity (Openshaw, 2000). Plants experiencing one rainy season a year will only have one annual fruiting where as plants under irrigation may have three fruiting events a year (Openshaw, 2000).

Reduced tree growth in the presence of planted pastures may also be due to a reduced availability of soil nutrients (Openshaw, 2000). Low nutrient levels (especially nitrogen) may result in decreased flower production followed by increased flower abortion and failure of seed development in *J. curcas* (Openshaw, 2000).

The observed reduction in *J. curcas* growth in the presence of neighbouring vegetation may make *J. curcas* silvopastoral systems unviable. However, growth and productivity of *J. curcas* in agroforestry and silvopastoral systems may be increased by implementing some degree of pasture removal and/or ensuring separation of resource utilization in time or space (George *et al*., 1996; Lehmann *et al*., 1998) and/or selecting cover or forage crops that are least competitive for nutrients and moisture while still fulfilling their role in the system (Malik *et al*., 2000).

The results suggest that the optimal distance of pasture removal is 60 cm. Final height, basal diameter and percentage leaf abscission of trees with pasture removed up to 60 and 120 cm away did not differ significantly from treatments with the greatest and least amount of competition (Table 7.3). Therefore, removing up to 60 cm will allow for growth similar to that of trees with 300 cm of pastures removal while still providing sufficient pasture for grazing.

The spatial separation of resource utilization requires the use of plants that obtain resources from different soil depths through different rooting depths (Lehmann *et al.,* 1998). Unfortunately, *J. curcas* has a shallow root system (Henning, 1996) and will therefore compete with neighbouring vegetation for surface water. Therefore further research could be directed at finding suitable winter annuals that grow and use resources when the tree is mostly dormant thus allowing for the temporal separation of resource utilization (Lehmann *et al.*, 1998).

The direct effect of competition on seed productivity and the change in the competition effect as the trees grow and mature may also be interesting avenues of further research. Noting the total number of side branches may also give a more clear understanding on the effect of competition on tree growth.

7.4.8 Preference trial

7.4.8.1 Two-choice cafeteria trials

When offered a choice between *J. curcas* and *A. karroo* (trial 1) the goats spent significantly less time feeding on *J. curcas* (only 0.19% of the time) (Wilcoxon signed ranks test, $Z = -2.521$, d.f. = 1, $P = 0.012$) (Table 7.4). When offered a choice between *J. curcas* and *A. nilotica* (trial 2) the goats also spent significantly less time feeding on the former (only 3.77% of the time) (Wilcoxon signed ranks test, $Z = -2.521$, d.f. = 1, $P = 0.012$) (Table 7.4).

The proportion of time spent feeding on *J. curcas* did not differ significantly between the two trials (z-test for differences in proportions, $Z = 2.504$, d.f. = 1, $P = 0.99$) and although the goats fed for less in the second trial (525 vs. 285s), the difference was not significant after correcting for any group effect (ANOVA, $F_1 = 2.202$, $P = 0.176$) (Table 7.4).

Table 7.4 Average feeding time of the goats in the two-choice cafeteria trials

	Average time (s) ± S.D.*	**Percentage (%)**
Trial 1: J. curcas vs. *A. karroo*		
J. curcas	1 ± 2^a	0.19^e
A. karroo	524 ± 401^b	99.81
Total	**525**	**100**
Trial 2: J. curcas vs. *A. nilotica*		
J. curcas	10 ± 22^a	3.77^e
A. nilotica	255 ± 192^b	96.23
Total	**265**	**100**

**S.D.: Standard deviation*
a,b: Significantly different groups for each trial
e: Significantly similar groups

7.4.8.2 Three-choice cafeteria trials

All bites taken by the goats were of similar size irrespective of plant species. The goats took significantly less bites of *J. curcas* than *A. karroo* ($\chi^2 = 437.01$, $df = 1$, $P < 0.001$) and *M. alba* ($\chi^2 = 129.09$, $df = 1$, $P < 0.001$) (Table 7.5). In fact, only one bite of *J. curcas* was taken out of the total of 573 bites throughout the entire study (Table 3). Additionally, the goats significantly preferred *A. karroo* to *M. alba* ($\chi^2 = 175.25$, $df = 1$, $P < 0.001$) (Table 7.5).

Table 7.5 Total number of bites taken by the goats in the three-choice cafeteria trial

	Total number of bites	Percent of total (%)
J. curcas	1^a	0.17
M. alba	132^b	23.04
A. karroo	440^c	76.79
Total	**573**	**100**

a,b,c: Significantly different groups

7.4.8.3 Discussion and Conclusions – Preference trial

Throughout the trials, the goats spent significantly less time browsing *J. curcas* than *M. alba*, *A. karroo* and even *A. nilotica* even though the latter is not preferentially browsed by goats. This suggests that the aversion of goats to *J. curcas* may be independent of the quality of the other species available. However, caution must be taken when interpreting the two-choice trials due to the large standard deviations making the mean feeding time less reliable. Nevertheless, the results support the hypothesis that the goats will avoid *J. curcas*, spending significantly more time browsing other plant species irrespective of their palatability.

The acceptability of foliage to herbivores can be influenced by factors including nutrient content, physical structures (e.g. thorns), growth stage of the plant and its leaves, resource availability (e.g. light and nutrients), previous defoliation history, appetite and secondary metabolites with harmful post-ingestive consequences (Owen-Smith and Cooper, 1987). Research by Jansen *et al.* (2005) found that diet selection in goats is best explained by the minimization of negative plant compounds. Studies have shown that herbivores including goats, sheep and cows learn to avoid plants containing such compounds through conditioned taste aversions (CTA) where animals associate the sensory properties of the food with the negative post-ingestive consequences (Ginane *et al.*, 2005). In the future, when the animal is confronted with a similar smell, flavor or texture (but not necessarily the same food) it will avoid the plant (Ginane *et al.,* 2005).

Cows and sometimes sheep avoid browsing *Euphorbia esula* L. (also a member of the Euphorbiaceae family) due to a CTA to diterpenes (Kronberg and Walker, 1993; Halaweish *et al.*, 2002), a secondary metabolite also found in *J. curcas* (Matsuse *et al.,* 1999). Although the exact toxicity of *J. curcas* leaves is uncertain, diterpenes have been known to cause severe gastroenteritis, vomiting and diarrhoea in animals (Frohne and Pfander, 2005). Another toxic constituent, hydrogen cyanide (HCN) can lead to neuropathies (deafness, paralysis and myelopathy), hyperglycaemia and cretinism (Frohne and Pfander, 2005). Such negative side effects make it very likely that goats will develop CTAs to diterpenes and HCN and therefore avoid browsing *J. curcas* since it contains such toxins.

Incidents of limited browsing of *J. curcas*, particularly by a younger, inexperienced male could be explained by feeding naivety where the individual has not yet sampled a wide variety of unfavourable foodstuffs. Although no negative side effects where noted in any of the goats that sampled *J. curcas*, Van Wyk *et al.* (2002) warn that such situations where the animal is exposed to novel foods may lead to incidences of poisoning.

Situations where the only available forage is *J. curcas* may also result in browsing by animals. Such situations could arise due to drought and fire, which often force animals to eat foods they would normally avoid (Van Wyk *et al.*, 2002). In fact animals have been known to feed on *J. curcas* during times of drought when vegetation in sparse (Abdel Gadir *et al.*, 2003). Animals have also been known to browse young *J. curcas* plants (Jøker and Jepsen, 2003). In fact, Jøker and Jepsen (2003) recommend that young trees be protected from herbivory before they reach the age of three months after which the plant develops a repellent smell to ward off browsers.

Likewise, newly emerged leaves may also be at risk to herbivory (Owen-Smith and Cooper, 1987). This has been noted in other unpalatable tree species, possibly due to lower levels of toxic compounds in freshly formed leaves (Owen-Smith and Cooper, 1987). The ingestion of young shoots may, therefore, not be entirely detrimental especially since the young leaves are considered fit for human consumption after steaming or stewing (Pratt *et al.*, 2002). As leaves mature, palatability may decline through the season due to increased dryness, toughness and an accumulation of toxins (Goralka *et al.*, 1999). If this is the case with *J. curcas*, conducting the preference trials late in the growing season may not be a true reflection of the plants palatability. Of additional concern is that the nut and seed cake of the non-toxic variety can be used as animal feed without detoxification (Openshaw, 2000). This suggests that the leaves of the non-toxic variety may also have reduced levels of toxic compounds and, if cultivated in unfenced areas, maybe at risk to defoliation.

Further research should be directed at determining the palatability of the non-toxic variety, young plants, new and recently matured leaves and the effect such herbivory would have on plant growth and productivity. The aversion to *J. curcas* when no other forage is available as well as the physiological effects of foliage ingestion should also be assessed.

Nevertheless, the results suggest that, as long as other forage is available, goats will not browse mature *J. curcas* leaves irrespective of the quality of the other foodstuffs. Although it should be tested, other livestock most likely have a similar if not greater aversion, as previously mentioned, goats are often better able to graze and browse a variety of poor quality foodstuffs when compared to the former (Boyazoglu *et al.*, 2005).

8 DEVELOPMENT OF ALLOMETRIC RELATIONSHIPS FOR J. *CURCAS*

8.1 INTRODUCTION

Harvesting-and-weighing is the best approach of determining growth and biomass of trees (Ketterings *et al.,* 2001). It is, however, time-consuming, expensive and destructive (Telenius and Verwijst, 1995). Additionally, research projects running for extended periods involve continuous monitoring of trees under study. These necessitate the use of less destructive techniques (Verwijst and Telenius, 1999), one of which is allometry (St. Clair, 1993).

Allometry is the most common and the easiest approach of estimating growth and biomass of trees and forests. Equations are developed by relating biomass of tree components as dependent variables with easily measured variables, such as stem diameter, as independent variables (Pastor *et al.,* 1984). This method is non-destructive (St. Clair, 1993) and accurate (Crow and Laidly, 1980). It is, however, site-specific, species-specific and empirical (Campbell *et al.,* 1985). 'Generalised' allometric equations (non site-specific) can be developed from site-specific data or equations (Pastor *et al.,* 1984*;* Campbell *et al.,* 1985*;* Ter-Mikaelian and Korzukhin, 1997). Equations developed elsewhere may be considered for use at a site in the absence of site-specific or 'generalised' equations (Pastor *et al.,* 1984). Tritton and Hornbeck (1981) found similarities among most allometric equations developed for the same species in different sites. Significant differences are expected among sites with considerable differences in productivity (Koerper and Richardson, 1980).

Several authors have reported strong allometric relationships in many species, at tree level (Young *et al.,* 1980*;* Perala and Alban, 1994; Wang *et al.,* 2000; Samba *et al.,* 2001; Ong *et al.,* 2004; Salis *et al.,* 2006; Levia, 2008) and branch level (Vann *et al.,* 1998; Xioa and Ceulemans, 2004). On the contrary, Cole and Ewel (2006) warn about challenges of allometry in dicotyledonous trees, a group that *J. curcas* belongs to, arising from their complex form-function relationships. They found poor allometry for leaf biomass of small *Cordia* and *Cedrela* trees. This was due to defoliation and variation in their leaf phenology during dry seasons to which younger trees are more prone.

This chapter addresses questions regarding the following: reliability (strength) of allometric relationships in *J. curcas*; effects of interspecies competition for nutrients and water and tree spacing on allometric relationships; and validity of site-specific allometric relationships for applications in a range of growing and (non-destructive) tree management conditions at a site. The objectives were to examine: reliability of above-ground allometry of *J. curcas* using basal diameter and crown depth as predictor variables; effects of below-ground interspecies competition and tree spacing on allometry; and validity of these relationships with independent data.

8.2 MATERIALS AND METHODS

8.2.1 Definition

Allometric equations are usually defined as:

$$Y = aD^b \qquad 8.1$$

Where: Y is tree biomass (g); D is tree diameter (mm) at breast height (DBH) or at the base of the stem (BD); a and b are constants (Ter-Mikaelian and Korzukhin, 1997). The dry mass component of the equation (Y) may be replaced by tree dimensions such as tree height (m), leaf area (m^2), crown depth (m), crown width (m) and crown volume (m^3). Other easily measured attributes of tree such as tree height or canopy dimensions may also be used as "*D*". The linear form of equation (1) is given by:

$$\log Y = b \log D + \log a \qquad 8.2$$

With b the slope and log a intercept of the linear equation. ("$\log_{10}$" yields a lower sum of squares than the natural logarithm "ln").

Transforming data using log-transformation techniques subjects the antilog values of the predicted outputs to systematic biases. Such biases are corrected by multiplying the antilog of the outputs by a 'correction factor', *cf*: (Ong *et al.,* 2004):

$$cf = \text{antilog}\left[0.5\left(\frac{\sum(\log Y - \log Y_{Predicted})^2}{n-2}\right)\right] \qquad 8.3$$

Where: Y is the value of a sampled dependent variable; $Y_{Predicted}$ is the predicted value of the dependent variable and n is the sample size.

In this study, diameter at stem base was used instead of the more popular diameter at breast height (DBH). This was because the stem of *J. curcas* hardly grows as high as the DBH before it forms branches.

8.2.2 Study Site

Data were collected from the Ukulinga Research Farm. Figure 8.1 shows intra-row tree spacing (T), alley width (I) and inter-row spacing (R) of the trials, namely: *Jatropha*-only (3 m x 3 m); standard-spacing (3 m x 3 m); single-row (5 m x 2 m); double-row (6 m x 2 m x 2.5 m); and triple-row (7 m x 2.0 m x 3.0 m).. All trials but the *Jatropha-only* had kikuyu planted in their alleys (the widest spacing).

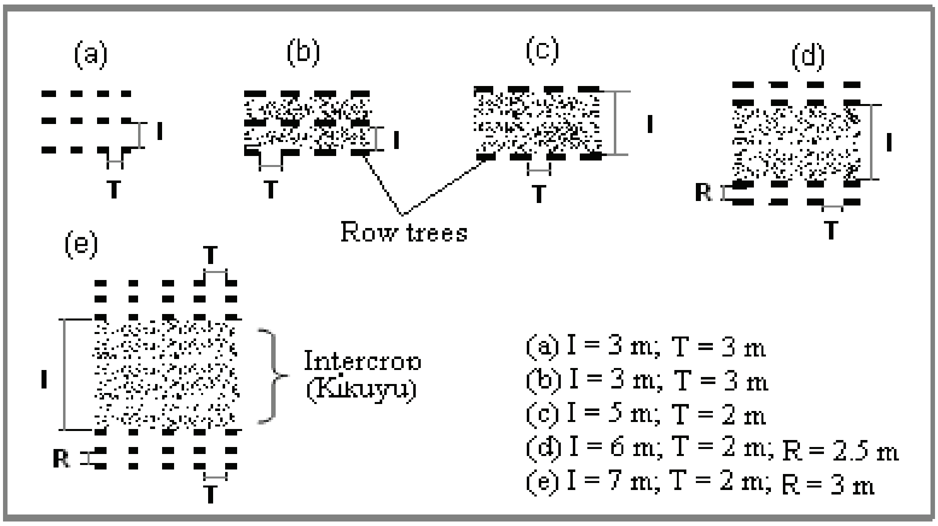


Figure 8.1 Illustration of intra-row tree spacing (T) and alley width (I) of the (a) *Jatropha*-only, (b) standard-spacing, (c) single-row, (d) double-row and (d) triple-row trials and inter-row spacing (R) in the double row and the triple row trials

8.2.3 Sampling

8.2.3.1 Allometry between basal diameter and above-ground variables of J. curcas

A *Jatropha*-only trial containing 16 to 26 month-old trees, which were 0.48 to 2.22 m tall, was selected. The age range enabled a wide range of tree sizes to be studied. The trial was divided into three height classes, namely: shorter than 1.2 m; between 1.2 m and 2 m; and taller than 2 m. From each class, four trees were sampled randomly and destructively between the 4th and 13th March 2008.

Just before cutting, tree height, crown depth (tree height minus bare stem height), maximum crown width along and across tree rows and basal stem diameter were measured. Basal diameter, total length, crown length and mean crown width (geometric mean of two perpendicular crown diameters) of 13 random branches were also determined from an upright branch position. Leaf area was measured using a belt driven leaf area meter (Licor LI 3000). Leaf, branch and stem samples were oven dried at 73°C, until constant mass. Finally, dry masses were obtained with an electronic balance.

8.2.3.2 Allometry between crown depth and above-ground variables of J. curcas

The destructive sampling used in the study of allometry between basal diameter and above-ground biomass and dimensions of *J. curcas* was used.

8.2.3.3 Effects of interspecies competitions and tree spacing on allometry

(1) Effects of below-ground interspecies competitions on allometry

A standard-spacing trial, containing 15 months-old *J. curcas* trees planted with kikuyu grass was used. The interactions between these species were for water and nutrients (below-ground) only, as the grass was too short to have any above-ground effects on the trees. Effects of the interspecies interactions on the above-ground allometry of *J. curcas* were investigated using four treatments, based on radial distances (from base of the trees) where no kikuyu was allowed to grow. They were: 0.6 m; 1.20 m; 3.0 m; and a control where no grass was removed from under the trees (0 m). Tree height and basal stem diameter were measured bi-weekly from 21st March to 18th May 2006 and 8th August to 6th October 2006 and monthly between 18th May and 8th August 2006. The latter measurement period was chosen due to slower growth of *J. curcas* during winter.

(2) Effects of tree spacing on allometry
Jatropha-only, standard-spacing, single-row, double-row and triple-row trials were used. These trials had the same planting density (1100 trees ha^{-1}) but different spacing. Tree height and basal stem diameter were measured monthly during March 2005 to April 2007.

8.2.3.4 Validation of allometric relationships using independent data

Tree height and basal stem diameter measurements taken from all trials between March 2005 and April 2007 (a total of 158) were pooled for validating the height-diameter equation developed by destructive sampling.

8.2.4 Data analyses

8.2.4.1 Allometry between basal diameter and above-ground variables of J. curcas

All sample data were used to calculate various above-ground tree parameters including: total leaf area, total branch dry mass, total leaf dry mass, woody above-ground dry matter and total above-ground dry mass. Geometric mean of maximum crown width ($\overline{\mathrm{CW}}$) was determined from maximum crown diameters along and across the tree rows. Crown volume (at tree level and branch level) was computed as:

$$CV = \frac{4}{3}\pi\left(\frac{CH\ (\overline{CW})^2}{8}\right) \qquad 8.4$$

Where: CV (m^3) is crown volume, CH (m) is depth and $\overline{\mathrm{CW}}$ (m) is mean maximum width (m) of the half ellipse crown respectively.

Data set of basal diameter (BD) was paired with data sets of total above-ground dry mass; woody above-ground dry mass; dry masses of stem and branch; leaf dry mass and leaf area; tree height; and crown volume, depth and mean maximum width. Similarly, basal branch diameter (BBD) was paired with the various branch level variables. All pairs of data were subjected to a $\log_{10}$–$\log_{10}$ transformation method (Giordano *et al.,* 2003). Regression analyses were carried out on the transformed data sets to decide between the hypotheses:

Null hypothesis H_0: $b = 0$ (No relationship between regression variables.)
Alternative hypothesis H_1: $b \neq 0$ (Regression variables are related.)
Where: b is the slope of the regression (eq. 2).

8.2.4.2 Allometry between crown depth and above-ground variables of J. curcas

The data were analysed in the same way as in the study of tree level allometry between basal diameter and above-ground variables, using crown depth as the predictor variable and excluding allometry of crown volume.

Effects of interspecies competitions and tree spacing on allometry

Analysis of covariance (ANCOVA) was used to examine equivalences of the linearized allometric equations between basal diameter and tree height across the competition treatments and the tree spacing treatments.

Validation of the allometric relationships using independent data

The measured basal diameters were used in the height-diameter equation developed by destructive sampling. Predicted and measured values of tree height were plotted against each other and their relationship examined.

8.3 RESULTS

Allometry between basal diameter and above-ground variables

At tree level, the allometric regressions were highly significant, with high and positive correlation coefficients. Results of the regression analyses, 'correction factors' and the corrected allometric equations are presented in Table 8.1. All 'correction factors' were very low (close to one). Hence, basal stem diameter has a highly significant relationship with the above-ground variables. The relationship between total above-ground dry mass and basal stem diameter (before log-transformation) is presented in Figure 8.2 (a).

Table 8.1 Results of regression analyses of the linearized allometric relationship (log Y = b log *BD* + log a) of basal diameter with various above-ground variable of *J. curcas* and corrected allometric equations (Y = a *BD* ^{b})

Tree parameter	b	log a	*r*	P > *F*	*cf*	Corrected equations (Y = a *BD* ^{b})
Tree height (m)	1.044	-1.714	0.98	0.0001	1.002	$Y = 0.0193\ BD^{1.044}$
Crown volume (m^3)	3.243	-5.798	0.97	0.0001	1.013	$Y = 0.000002\ BD^{3.243}$
Crown depth (m)	1.114	-1.907	0.98	0.0001	1.017	$Y = 0.0126\ BD^{1.114}$
Mean crown width (m)	1.065	-1.805	0.95	0.0001	1.005	$Y = 0.0157\ BD^{1.065}$
Leaf area (m^3)	2.734	-4.463	0.97	0.0001	1.004	$Y = 0.000035\ BD^{2.734}$
Foliage dry mass (g)	3.017	-2.921	0.97	0.0001	1.021	$Y = 0.00126\ BD^{3.017}$
Stem dry mass (g)	2.469	-2.273	0.99	0.0001	1.015	$Y = 0.00541\ BD^{2.469}$
Branch dry mass (g)	3.391	-3.386	0.97	0.0001	1.029	$Y = 0.000423\ BD^{3.391}$
Total above-ground dry mass (g)	3.354	-3.053	0.98	0.0001	1.025	$Y = 0.000907\ BD^{3.354}$
Woody above-ground dry mass (g)	3.529	-3.549	0.99	0.0001	1.002	$Y = 0.000283\ BD^{3.529}$

n = 12; Unit of BD is mm.

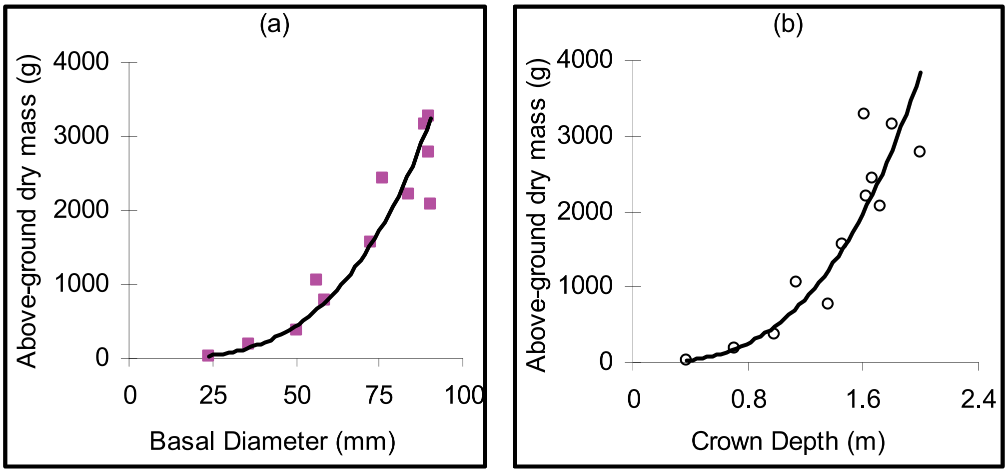


Figure 8.2 **Relationship of above-ground dry mass with (a) basal stem diameter and (b) crown depth before log-transformation**

Partitioning of above-ground biomass of *J. curcas* into wood and foliage showed a very strong linear relationships (r = 0.91) with basal stem diameter (without log-transformation of the data). Percentage of branch biomass also exhibited a highly significant linear relationship with basal diameter ($r > 0.95$). Table 8.2 presents results of statistical analyses of the relationships. With increasing stem diameter, the proportion of woody biomass increased at the expense of leaf biomass (Figure 8.3 (a)). This increase is due to increased biomass allocation to branches, which was from 39.4 % to 59.7 %.

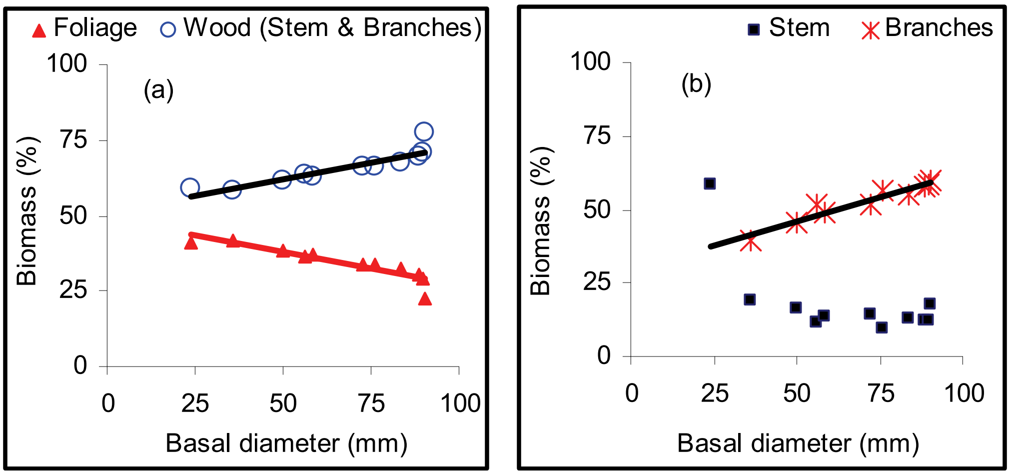


Figure 8.3 **Partitioning of above-ground components of *J. curcas,* expressed as a percentage of total above-ground biomass**

Table 8.2 Results of regression analyses of the linear relationships between basal stem diameter and percentages of above-ground wood and leaf biomasses of *J. curcas*

Percentage	Slope	Intercept	*r*	P > *F*
Wood	0.223	50.998	0.91	0.0001
Leaf	-0.223	49.002	0.91	0.0001
Branch[a]	0.322	29.898	0.95	0.0001

n = 12; For Branch[a], n = 11 (one sample tree had no branches).

Results of regression analyses of branch level allometry are summarised in Table 8.3. Basal branch diameter was of highly significant value in explaining variations in the branch level variables of *J. curcas*. The systematic biases resulting from log-transformation were very low (Table 8.3).

Allometry between crown depth and above-ground variables

Above-ground allometric relationships using crown depth as a predictor variable were highly significant. The correlation coefficients were very high and the 'correction factors' very low, as shown in Table 8.4. Figure 8.2 (b) shows the relationship between above-ground dry mass and crown depth before log-transformation.

Table 8.3 Results of regression analyses of the linearized allometric relationship ($\log Y = b \log BBD + \log a$) of basal branch diameter with various branch level variables of *J. curcas* and resulting corrected allometric equations ($Y = a\ BBD^{b}$)

Branch parameter	b	log a	r	P > F	cf	Corrected equations ($Y = a\ BBD^{b}$)
Branch dry mass (g)	2.737	-2.207	0.99	0.0001	1.009	$Y = 0.00626\ BBD^{2.737}$
Branch height (m)	0.952	-1.385	0.96	0.0001	1.004	$Y = 0.0414\ BBD^{0.952}$
Leaf dry mass (g)	1.726	-0.902	0.95	0.0001	1.019	$Y = 0.128\ BBD^{1.726}$
Branch leaf area (m^2)	1.533	-2.63	0.95	0.0001	1.014	$Y = 0.00238\ BBD^{1.533}$
Branch and foliage dry mass (g)	2.361	-1.42	0.99	0.0001	1.007	$Y = 0.0383\ BBD^{2.361}$
Crown volume (m^3)	1.647	-3.277	0.91	0.0001	1.032	$Y = 0.000544\ BBD^{1.647}$
Crown length (m)	0.547	-0.872	0.92	0.0001	1.003	$Y = 0.135\ BBD^{0.547}$
Mean crown width (m)	0.554	-1.068	0.89	0.0001	1.005	$Y = 0.0859\ BBD^{0.554}$

n (number of branches) = 13; Unit of BBD is mm.

Effects of below-ground interspecies competition and tree spacing on allometry

Below-ground interspecies competition had no effect on allometry. Table 8.5 shows the results of the statistical analysis proving that the linearized height-diameter equations developed under the various competition treatments were equivalent.

The slopes of the regressions between stem diameter and tree height developed for the tree spacing treatments were also homogenous, as were the intercepts. The results of the statistical analysis showing the homogeneity of the regressions are presented in Table 8.6. Tree spacing, therefore, had no effect on allometry.

Validation of the allometric relationships using independent data

The relationship between predicted and measured values of tree height was linear (Figure 8.4). The coefficient of correlation (r) was very high and positive (> 0.97). The outcome strongly confirms the validity of the height-diameter equations as the independent data sets represented diverse management and growth conditions at the site.

Table 8.4 Results of regression analyses of the linearized allometric relationship ($\log Y = b \log CD + \log a$) of crown depth with various above-ground variables of *J. curcas* and corrected allometric equations ($Y = a\ CD^{b}$)

Tree parameter	b	log a	*r*	P > *F*	*cf*	Corrected equations ($Y = a\ CD^{b}$)
Tree height (m)	0.931	0.074	0.99	0.0001	1.001	$Y = 1.185\ CD^{0.931}$
Mean crown width (m)	0.931	0.020	0.94	0.0001	1.006	$Y = 1.054\ CD^{0.931}$
Leaf area (m^2)	2.424	0.219	0.97	0.0001	1.017	$Y = 1.683\ CD^{2.424}$
Foliage dry mass (g)	2.679	2.246	0.97	0.0001	1.024	$Y = 180.155\ CD^{2.679}$
Stem dry mass (g)	2.125	1.962	0.97	0.0001	1.017	$Y = 93.062\ CD^{2.125}$
Branch dry mass (g)	3.301	2.366	0.96	0.0001	1.024	$Y = 237.797\ CD^{3.301}$
Total above-ground dry mass (g)	2.955	2.694	0.98	0.0001	1.018	$Y = 503.312\ CD^{2.955}$
Woody above-ground dry mass (g)	3.100	2.499	0.98	0.0001	1.018	$Y = 320.936\ CD^{3.100}$

$n = 12$; Unit of CD is mm.

Table 8.5 Results of analysis of covariance (ANCOVA) to examine effects of below-ground interspecies competition on the allometry between basal diameter and tree height ($\log Y = b \log BD + \log a$)

Contrast	Mean Square	F Value	P > *F*
Slopes (b)	0.00068165	0.58	0.4507
Intercepts (log a)	0.00058344	0.50	0.4851

Table 8.6 Results of analysis of covariance (ANCOVA) to examine effects of tree spacing on the allometry between basal diameter and tree height ($\log Y = b \log BD + \log a$)

Contrast	Mean Square	F Value	P > *F*
Slopes (b)	0.00422389	0.11	0.7462
Intercepts (log a)	0.00553091	0.14	0.7112

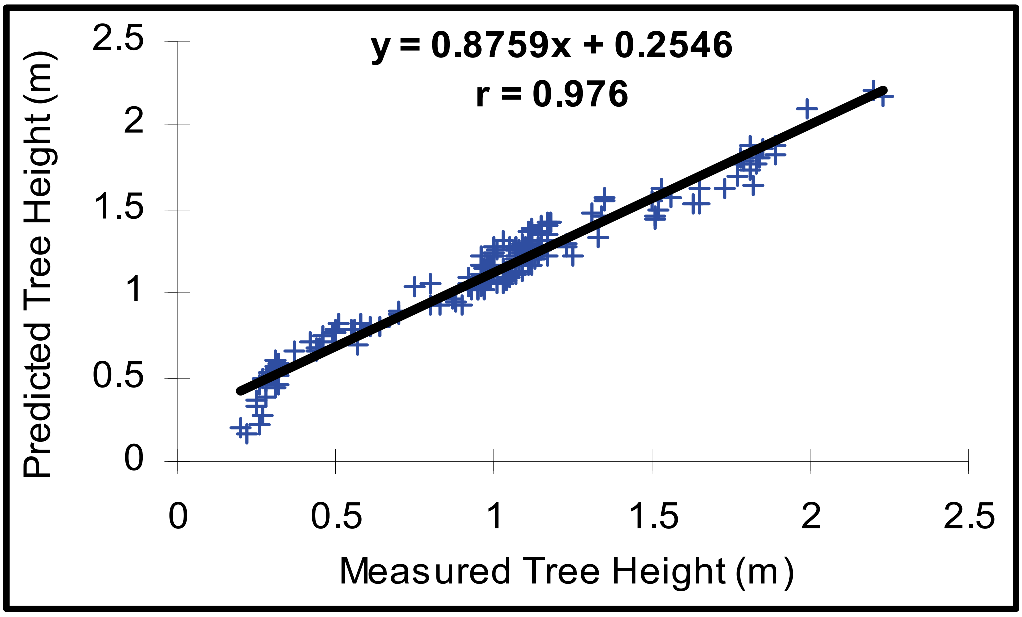


Figure 8.4 **Relationships between predicted and measured tree height of *J. curcas***

The relationship between predicted and measured values of tree height was linear (Figure 8.4). The coefficient of correlation (r) was very high and positive (> 0.97). The outcome strongly confirms the validity of the height-diameter equations as the independent data sets represented diverse management and growth conditions at the site.

8.4 DISCUSSION

Power regressions represent tree allometry satisfactorily (Clough and Scott, 1989). Upon log-transformation, they enable implementation of standard least squares regression analyses and provide uniformity of the variance over the sampled range (Ong *et al.,* 2004). Different independent variables have been used in these regressions (Ter-Mikaelian and Korzukhin, 1997), of which the most common is stem diameter. Contradicting results have been reported on performance of equations that use tree height as an added predictor variable (Kumar *et al.,* 1998; Montagu *et al.,* 2005). Use of such equations is compromised due to a high level of error, and time and cost demands of measuring tree height (Montagu *et al.,* 2005).

The allometric relationships vary among species significantly (Clough and Scott, 1989). Their strength has been established in several species, at tree level (Lott *et al.,* 2000; Wang *et al.,* 2000; Samba *et al.,* 2001; Salis *et al.,* 2006; Levia, 2008) and at branch level (Nygren *et al.,* 1993; Vann *et al.,* 1998; Xioa and Ceulemans, 2004). The outcomes of the current study are in agreement with these results. Above-ground allometry is justified, as the growing above-ground tree parts are biomechanically supported by stem (Montagu *et al.,* 2005), which has to grow proportionally (King, 1986).

In the current study, crown depth (as a predictor variable) showed consistent and strong allometric relationship with the above-ground variables. This was contrary to previously reported results. As cited in Ter-Mikaelian and Korzukhin (1997), Ker (1980) found inconsistency in the performances of allometric equations using crown dimensions as independent variables.

Tree foliage is affected by growing conditions and browsing animals (Cole and Ewel, 2006). Although *J. curcas* is not suitable for consumption by herbivores (Heller, 1996), it is cold-deciduous (Openshaw, 2000). It is, therefore, recommended that the equations of foliage developed here be used for estimating leaf area and biomass of *J. curcas* under non-winter conditions.

The low values of 'correction factors' obtained in this study are indicative of very low systematic biases resulting from log-transformations, as a value equal to one indicates the absence of bias. High coefficient of correlation is another indicator of the presence of very low bias (McArdle, 1988). It should be noted that these factors correct biases resulting from data processing (Ong *et al.,* 2004) and not the source of data (site). They cannot have values less than one as they are calculated as antilogarithms.

Depending on species, some trees have a greater proportion of stem than branch (Montagu *et al.,* 2005; Cole and Ewel, 2006), while in species like *Hevea,* belonging to the same sub-family as *J. curcas,* the contrary is true (Cannell, 1984). The result of the current study was in agreement with the latter. The most dynamic phase of tree biomass partitioning is at a very young age (Cole and Ewel, 2006). The drastic decline in the percentage of stem biomass during early emergence of branches (Figure 12.3 (b)) signals such dynamics of allocation in *J. curcas.*

The result of this study on effects of tree spacing on allometry coincides with reports by Pinkard and Neilsen (2003) and Fownes and Harrington (1992). The current results on competition were in contrast to a report by O'Brien *et al.* (1995). As in Malik *et al.* (2001), competition treatments of the current study affected tree growth. The height-diameter allometric equations were, however, not significantly different from one another suggesting proportional effects of the treatments on tree height and stem diameter.

The most reliable way of evaluating the predictive performance of allometric equations is by comparing their estimations with independent data (Haywood, 2009). Site-specific equations are accurate at the site or under the conditions they are developed. It is, however, very crucial to establish their validity under various management and growing conditions. This was, in part, achieved by the finding that below-ground competition and spacing of trees had no effect on allometry of *J. curcas*. Full validation of the height-diameter allometry using all the data, confirmed that the equations hold under non-pruning conditions at the site. The validation data range was wider than that of the destructive sampling data used to develop the equation. This implies that although the destructively sampled trees were young, the equation showed high potential within and outside the sampled range.

Allometry is an accurate, easy-to-use and non-destructive method of predicting tree growth and biomass, requiring limited and readily available inputs. Allometric equations are, however, site-specific and empirical. Equations developed here will be used for validating a two-dimensional tree growth and biomass allocation model under various growing environments, without the need for destructive sampling. With the help of carbon content of tree biomass, which is assumed to be a fixed proportion of the biomass (Montagnini and Porras, 1998) or determined directly (Kraenzel *et al.,* 2003), they can be used to estimate carbon storage in trees and forests (Losi *et al.,* 2003) and their wood and foliage (Specht and West, 2003). Allometric relationships can also be used for: estimating carbon fluxes (Chambers *et al.,* 2001) and implications of large scale deforestation and carbon sequestration on carbon cycle and carbon balance (Ketterings *et al.,* 2001); monitoring growth and partitioning of above-ground dry matter; and estimating of above-ground interactions when trees are used for agroforestry purposes. The equations developed in this study also contribute to the development of generalised allometry for *J. curcas*. The generalised equations can be developed by relating biomass and dimension variables with basal stem diameter of tree samples from additional sites representing a wide range of growing environments.

8.5 CONCLUSION

The results of this study reveal that tree level and branch level allometric relationships of *J. curcas* using basal stem diameter and crown depth as predictor variables were very reliable. Stem diameter is, however, easier to measure. It had linear and direct proportionality with wood and branch percentages and inverse proportionality with foliage percentage. Neither below-ground interspecies competition nor tree spacing had any significant effects on allometry. Site-specific allometric equations are, therefore, valid for accurate, non-destructive and quick predictions of tree growth under various growing and (non-destructive) tree management conditions at a given site. They can be developed into generalised allometric relationship for *J. curcas*. They are also valuable for comparative evaluation of suitability of sites for growing *J. curcas*, which is relevant because the species has attracted global attention for its high potential as a source of biodiesel.

9 COMPUTERIZED MODEL TO SIMULATE THE PRODUCTION PROCESS AND EXTRAPOLATE FROM ON-STATION TO ON-FARM

The model presented here is developed by integrating well established, quantitatively validated, user-friendly models and components that are based on sound biophysical principles. The approach used in the development of the current model was:

- It takes the two-dimensional energy interception and water balance model for hedgerow tree crops (SWB-2D) as a basis and main framework. The reason for this is the model is accurate in simulating solar radiation interception and soil water balance in a system of tree hedgerows, which is fundamental in two-dimensional agroforestry.
- The crop growth routine of the soil water balance model is adopted to predict growth of alley-crops due to its accuracy, generic and mechanistic features as well as sound biophysical principles.
- The crop growth routine of the SWB is adapted as the tree growth model.
- Additional model components of tree root growth and distribution, tree canopy growth, solar radiation interceptions by alley crops and the soil are developed.

9.1 TREE GROWTH MODEL

The tree growth model presented here is essentially an adaptation of the crop growth routine of the Soil Water Balance (SWB) model (Annandale *et al.*, 1999). These adjustments include:

- Use of stem translocation of assimilates approach to initiate leaf growth in deciduous trees; and
- Priority of biomass allocation to plant parts depending on which resource (between solar radiation and water) is more limiting.

Additional subroutines and features are developed and included (from other models), namely:

- Fraction of biomass allocated to tree roots;
- Litter-fall for evergreen and deciduous trees
- Tree height and diameter growth
- Tree root growth and distribution
- Tree canopy growth

At the start of the simulation, the tree growth model reads input values listed in Table 9.1 below and assigns parameters presented in Appendix 1. Figure 9.1 illustrates the tree dimensions given in Table 9.1.

Table 9.1 List of inputs for the tree growth model

Input Details
Canopy dimensions (initial or after pruning to a smaller ellipse): Canopy width (2a), height (2c), depth (2b, which is equal to intra-row tree spacing),; height of canopy centre from the soil surface (Z_0)
Base-pruned tree canopy: Width of tree canopy base after pruning (2ap); the height of the pruned part of the canopy (cp); height of the canopy base from the soil surface (Z_b)
Management: Depth of pruning of tree root (pd) or tillage of the alley zone (td); soil fertility rating (FR); tree row spacing (h); orientation (from North)
Initial values: Root biomass (RDM); stem diameter (D); lateral & vertical root extent
Daily weather data: Solar radiation; rainfall; minimum & maximum temperatures or average temperatures and vapour pressure deficit;
Location: Latitude, standard meridian, longitude

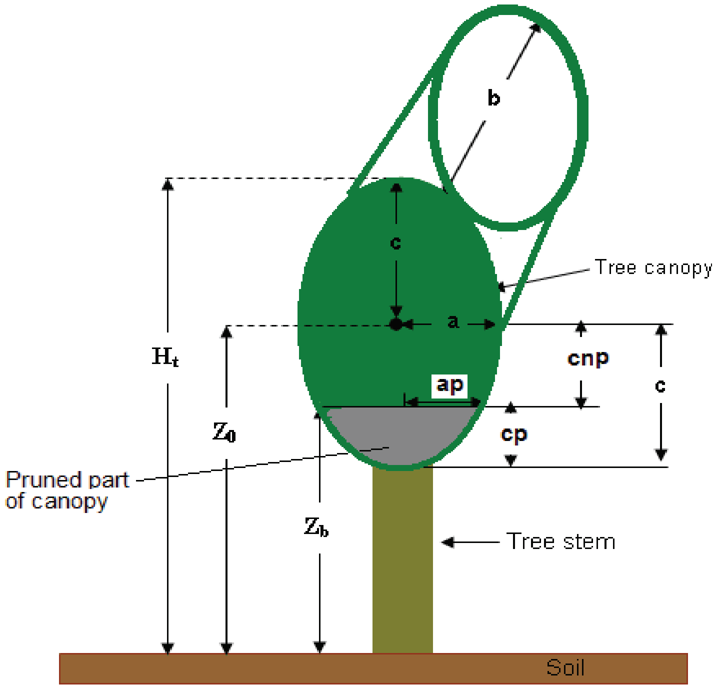


Figure 9.1 A diagrammatic representation of the dimensions of a tree in three-dimensions

a is half canopy width; b is half canopy depth (assumed to b half of intra-row spacing); c is half canopy height; ap is half of the width of the canopy base after pruning; cp is the reduction in the tree canopy height due to pruning; cnp is the part of the lower half of the canopy that is not pruned; H_t is tree height; Z_0 the height of the centre of canopy from the soil surface; and Z_b the height of the canopy base from the soil surface.

9.1.1 Biomass production and allocation

Initially, the leaf area index (LAI) of the tree is calculated using the equation:

$$LAI = LDM\ SLA \tag{9.1}$$

Where: LAI is in m^2 of leaf m^{-2} of soil; LDM is initial biomass of the tree foliage (kg m^{-2}) and SLA is mean specific leaf area ($m^2\ kg^{-1}$).

On the first day of simulation or first day after pruning, LDM is determined as:

$$LDM = \rho_{F(mass)}\ V_F \tag{9.2}$$

Where: $\rho_{F(mass)}$ is tree foliage density by mass (kg m^{-3}), which is a tree parameter and V_F is canopy volume (m^3), calculated for an ellipsoid canopy as:

$$V_F = \pi\ a\ b\ c \tag{9.3}$$

Where: a, b and c are half canopy width (m), half canopy depth (m and assumed to be equal to half of intra-row tree spacing) and half canopy height (m) respectively (Figure 9.1).

A flow chart of the tree growth model showing major processes of biomass production and allocation is presented in Figure 9.2.

Branch biomass of trees is calculated using the allometric relationship (Ghezehei *et al.,* 2009):

$$BDM = a_b \cdot D^{n_b} \tag{9.4}$$

Where: D is stem diameter (m); a_b and n_b are parameters.

Following canopy pruning, the model computes the ratio of the canopy volume after pruning to the canopy volume prior to pruning (f_{cv}). The branch biomass is assumed to be reduced by the factor "f_{cv}" due to pruning. In other words, the branch biomass (BDM) after pruning is determined as:

$$BDM_{new} = f_{cv}\ BDM_{old} \tag{9.5}$$

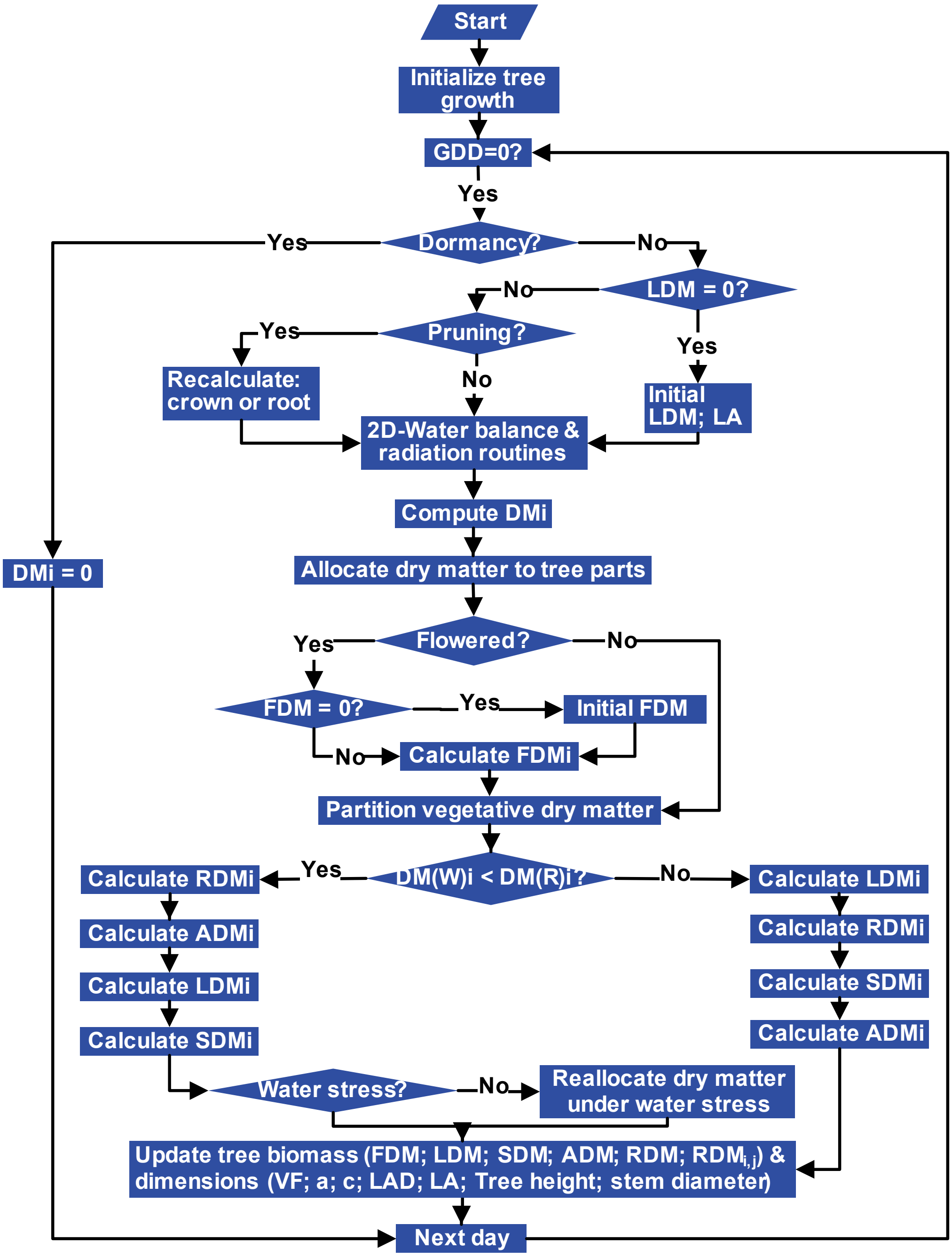


Figure 9.2 Flow chart of daily growth and biomass allocation in trees

ADMi is daily above-ground dry matter increment; DMi is daily dry matter increment; DMRi is radiation limited daily dry matter increment; DMWi is water limited daily dry matter increment; FDM is fruit biomass; FDMi is daily fruit biomass increment; FLDD is growing degree days required for flower initiation; GDD is cumulative total growing degree days; LAD is leaf area density; LA is leaf area per tree; LIDD is growing degree day requirement for leaf initiation; LDM is foliage biomass; LDMi is daily increment of tree foliage biomass; RDMD is root biomass density; RDMi is net daily increment of tree root biomass; SDMi is daily stem biomass increment; and VF is foliage volume.

Daily net primary production, DMi, (kg m^{-1}) is determined as follows:

- When water is the limiting growth resource, net primary production (DMWi) is (Tanner and Sinclair, 1983):

$$DMWi = DWR\ (T\ /\ VPD) \qquad 9.6$$

Where: DMWi is water limited net primary production (kg m^{-1}); DWR is dry matter-water ratio (Pa); VPD is vapour pressure deficit (Pa); and T – tree transpiration (mm)

- When solar radiation limits growth, net primary production (DMRi) is calculated by (Monteith, 1977):

$$DMRi = E_c\, T_f\, FI_{transp}\, R_s \qquad 9.7$$

Where: E_c denotes radiation conversion efficiency (kg MJ^{-1}); FI_{transp} is fractional radiation interception by the canopy for photosynthesis and transpiration; R_s is solar radiation

(MJ m^{-2} day^{-1}); T_f is an index ($0 \leq T_f \leq 1$) showing effect of temperature for radiation-limited plant growth, given by:

$$T_f = (T_{ave} - T_b)\ /\ (T_{lo} - T_b) \qquad 9.8$$

Where: T_{ave} is average air temperature (^oC); T_b is base temperature (^oC); and T_{lo} is the most favourable temperature for growth (^oC) when radiation limits growth.

Actual daily net primary production (DM_i) is equal to the lower of water-limited (DMWi) and radiation-limited DMRi net primary productions:

The model then checks whether the growing degree days required for flowering has been reached. When flowering starts, initial fruit biomass (FDM) is given by:

$$FDM = Transl\ SDM \qquad 9.9$$

Where: FDM is in kg m^{-2}; Transl is a dimensionless parameter of stored assimilate relocation from tree stem for fruit production; SDM is updated tree stem biomass (kg m^{-2}).

Daily increment of fruit biomass (FDMi) is computed using:

$$FDMi = rpf\ DMi \qquad 9.10$$

rpf is the reproductive partitioning fraction, which is the fraction of daily biomass increment allocated to flower/fruit production. It s calculated as:

$$rpf = (GDD - FLDD)\ /\ TransDD \qquad 9.11$$

Where: GDD is total growing degree days (d ^{o}C); FLDD is cumulative growing degree days (d ^{o}C) for flowering initiation; and TransDD denotes cumulative growing degree days (d ^{o}C) the tree needs to switch from the vegetative stage to flowering.
Growing degree days are incremented and summed using the following equations:

$$GDD_i = (T_{ave} - T_b) \tag{9.12}$$

$$GDD_i = 0 \qquad \text{if} \qquad T_{ave} < T_b \tag{9.13}$$

$$GDD_i = (T_{cutoff} - T_b) \qquad \text{if} \qquad T_{ave} > T_{cutoff} \tag{9.14}$$

$$GDD_t = GDD_{t-1} + GDD_i \tag{9.15}$$

Where: GDD is in d ^{o}C; T_{cutoff} (^{o}C) is the maximum temperature for the development of a plant species.

The lowest value of rpf (0) is used before flowering starts whereas its highest value (1) implies all of the daily net primary production is used to for flower/fruit production.

Daily vegetative dry matter increment (VDMi), which is the biomass left after fruit biomass increment is apportioned, is available to be partitioned to tree root, canopy and stem and calculated as:

$$VDMi = DMi - FDMi \tag{9.16}$$

For deciduous tree, leaf initiation after winter is modelled in the same way as the start of flower/fruit production. The model does this when the cumulative growing degree days since the end of the previous fruit stage is equal to the growing degree day requirement for leaf initiation (LIDD). The model assigns an initial biomass for leaf production from stored assimilates from stem using the equation:

$$LDM = Transl \quad SDM \tag{9.17}$$

Where: LDM is leaf dry matter in kg m^{-1} and Transl is a parameter of relocating assimilates stored in stem for fruit production.

The model decides priority of biomass allocation to root and foliage based on whether growth is limited more by water or radiation. When growth is limited by radiation, biomass is allocated first to leaf growth so that more foliage is available for radiation interception and photosynthesis. During water-limited growth, on the other hand, root growth is given priority in order for the tree to grow more roots to reach wider and deeper in the soil profile. Under water stress conditions, biomass allocation prioritises root growth and what would be allocated for leaf production is divided up between root and stem. As a result, more assimilate is available for root growth and transpiration is also limited, as there would be no foliage growth. Tables 9.2 and 9.3 summarise the alternative procedures.

Table 9.2 Equations for calculating biomass allocation to foliage, root and stem of the tree when growth is limited by radiation

Step	If DMi = DMRi		Equation
1	$LDMi = f_f\ VDMi$	(Based on Sands, 2004)	*9.18*
2	$RDMi = f_R\ (VDMi - LDMi)$	(Based on Sands, 2004)	*9.19*
3	$SDMi = (1 - f_f - f_R + f_f\ f_R)\ VDMi$		*9.20*
4	$ADMi = LDMi + SDMi$		*9.21*

Table 9.3 Equations for calculating biomass allocation to foliage, root and stem of the tree when growth is limited by availability of water

Step	If DMi = DMWi	Equation
1	$RDMi = f_R\ VDMi$	*9.22*
2	$ADMi = (1 - f_R)\ VDMi$	*9.23*
3	$LDMi = f_f\ ADMi$	*9.24*
4	$SDMi = (1 - f_f)\ ADMi$	*9.25*

Where: RDMi is net daily increment of root dry matter (kg m^{-2}); VDMi is vegetative dry matter increment; f_R is the proportion of net primary production apportioned to tree roots; ADMi is daily above-ground dry matter increment; f_f is the proportion of net primary production to tree foliage; f_R LDMi denotes net daily increment of tree foliage biomass (kg m^{-2}); and SDMi is daily increment of stem biomass (kg m^{-2}).

The fraction of net primary production apportioned to tree root (f_R) is calculated as (Landsberg and Waring, 1997):

$$f_R = 0.8 / (1 + (2.5\ m\ T_f)) \qquad 9.26$$

Where: T_f is an index ($0 \leq T_f \leq 1$) showing effect of temperature for radiation-limited plant growth; m is a factor representing effects of soil fertility on biomass allocation to tree root and is calculated as:

$$m = m_0 + (1 - m_0)\ FR \qquad 9.27$$

Where: m_o is the magnitude of the factor for infertile soil (FR = 0) and FR is the *fertility rating* of the soil. From equations 9.26 and 9.27, the lowest biomass allocation to roots occurs when the soil is highly fertile (FR = 1).

The proportion of net primary production to tree foliage (f_f) is determined using the following equation:

$$f_f = 1 / (1 + PART\ \ ADM)^2 \qquad 9.28$$

Where: PART is a constant for biomass allocation to stem and leaves; and ADM is the total aerial (vegetative) dry matter of the tree, and is computed as:

$$ADM = ADM_{t-1} + ADMi \qquad 9.29$$

According to the model, there is no leaf growth for water-stressed trees (when their threshold stress index is higher than calculated stress index, SI). Hence, the daily leaf biomass increment (eq. 9.24) is equally re-partitioned between roots and stem. The daily water stress index (SI) is calculated as (Annandale *et al.,* 1999):

$$SI = T / (FI\ PET) \tag{9.30}$$

Where: FI is fractional interception of solar radiation by the tree for transpiration, and PET is potential evapotranspiration of the tree (mm), as calculated by:

$$PET = ETo\ Kc_{max} \tag{9.31}$$

Where: ETo is FAO reference evapotranspiration (Allen *et al.,* 1996, Smith *et al.,* 1996, Allen *et al.,* 1998) and Kc_{max} is the maximum crop coefficient of the tree.

ETo is calculated by:

$$ETo = [0.408\ \Delta\ (R_n - G) + \gamma\ 900 / (T_{avg} + 273)\ U_2\ VPD] / [\Delta + \gamma\ (1 + 0.34\ U_2)] \tag{9.32}$$

Where: Δ is slope of the saturation vapour pressure curve (kPa $°C^{-1}$), determined by:

$$\Delta = 4098\ e_s / (T_a + 237.3)^2 \tag{9.33}$$

G is heat flux of the soil (MJ m^{-2} day^{-1}), calculated as:

$$G = 0.38\ [T_{avg}(DOY) - T_{avg}(DOY-1)] \qquad \text{(Wright and Jensen, 1972)} \tag{9.34}$$

T_{avg} - Mean daily ambient temperature (°C) given by:

$$T_{avg} = (T_{max} + T_{min}) / 2 \tag{9.35}$$

γ - Psychrometer constant (kPa $°C^{-1}$) calculated as

$$\gamma = 0.00163\ P_a / \lambda \tag{9.36}$$

Where: λ is latent heat of vaporization (MJ kg^{-1}) and equal to:

$$\lambda = 2.501 - 2.361\text{x}10^{-3}\ T_{avg} \tag{9.37}$$

U_2 is wind speed as measured at 2 m height (m s^{-1})

Maximum tree crop coefficient is computed by (Allen *et al.,* 1996):

$$Kc_{max} = Max\ \{ Kc_{max\ (1)}, Kc_{max\ (2)}\} \le 1.45 \tag{9.38}$$

$$\text{Where: } Kc_{max(1)} = 1.2 + [\ 0.04\ (U_2 - 2) - 0.004\ (RH_{min} - 45)\ ]\ (H_t / 3)^{\ 0.3} \tag{9.39}$$

$$Kc_{max(2)} = Kcb + 0.05 \qquad 9.40$$

Where: H_t is height of the tree (m); Kcb is the FAO basal crop coefficient.

On the first day of simulation, stem biomass is estimated from the allometry between stem diameter and stem biomass as (Ghezehei *et al.,* 2009):

$$SDM = a_s\, D^{n_s} \qquad 9.41$$

Where: D is stem diameter (m); a_s and n_s are parameters.

Total tree stem biomass is updated by adding daily stem increment to the initial stem biomass. The model then updates stem diameter and height of the tree from allometric relationships, as:

$$D = \left(SDM / a_s \right)^{\frac{1}{n_s}} \qquad 9.42$$

$$H_t = a_H\, D^{n_H} \qquad 9.43$$

Where: H_t (m) is the updated tree height at time "t"; a_H and n_H are species specific parameters.

Stem diameter is plotted against stem dry matter and tree height and a power function is fitted to obtain the parameters of the stem diameter-stem biomass and stem diameter-tree height relationships respectively.

9.1.2 Tree root growth and distribution

In alley-cropping, there are continuous below-ground interactions among component species for nutrients and water uptake. Therefore, growth and distribution of tree and crop roots are crucial for the nature and intensity of these (below-ground) interactions.
Trees, as the perennial component in two-dimensional agroforestry systems, have well-established root systems. Their roots are more developed than the roots of the alley crops, extending more in depth and across the tree-crop interface. Additionally, tree roots also re-grow and redevelop after damage resulting from root pruning and/or tillage in the alley zone between cropping seasons. Growth of tree roots is affected, among others, by soil and profile characteristics, and contents and distributions of soil water and oxygen. Variations in these factors within the soil, result in differential vertical and horizontal growth of tree roots.

The tree root modelling presented here estimates two-dimensional root growth and distribution in the soil; i.e. with vertical and horizontal distances from the base of the tree stem. It also allows tree roots to re-grow following root pruning and tillage of the alley zone.

Root biomass is updated daily using the equation:

$$RDM_t = RDMi + (1 - \gamma_R)\, RDM_{t-1} \qquad 9.44$$

Where: γ_R is root turnover rate, estimated as half of leaf fall rate, γ_f (Landsberg and Waring, 1997), which is calculated in section 9.1.3.

According to the model, tree root biomass is allocated to soil control volumes as a function of soil matric potential, soil oxygen content and fraction of tree root system, based on the approach by Zhang and Dawes (1998). Root biomass increment is allocated to each soil control volume ($RDMi_{(i,j)}$) by:

$$RDMi_{(i,j)} = RDMi\, (p_{(i,j)} / P) \qquad 9.45$$

Where: $RDMi_{(i,j)}$ denotes the increment of root biomass in soil control volume "i,j" ("i" indicating vertical position and "j" horizontal position of soil nodes); $p_{(i,j)}$ is a dimensionless index of '*favourability*' of the control volume "i,j" for tree root growth and P is the summation of $p_{(i,j)}$, calculated to enable allocation of root biomass in the soil according to the proportional '*favourability*' of control volumes.

The parameters $p_{(i,j)}$ and P are calculated by (Zhang and Dawes, 1998):

$$p_{(i,j)} = (1 - (\psi_{(i,j)} / \psi_{wilt}))\, (1 - (Z_i / R_j))\, froot_{(i,j)\,(t-1)} \qquad 9.46$$

$$P = \Sigma\, p_{(i,j)} \qquad 9.47$$

Where: $\psi_{(i,j)}$ is the sum of matric and gravitational potential in control volume "i,j" (J kg^{-1}); ψ_{wilt} is the soil matric potential at permanent wilting point (J kg^{-1}); Z_i is the depth of control volume "i,j" (m); R_j is the maximum vertical distance the tree roots have reached (m); $froot_{(i,j)\,(t-1)}$ is the fraction of the total root biomass in control volume "i,j" at the previous time step and is calculated as:

$$froot_{(i,j)\,(t-1)} = RDM_{(i,j)(t-1)} / RDM_{(t-1)} \qquad 9.48$$

Where: $RDM_{(i,j)(t-1)}$ is tree root biomass in control volume "i,j" (g) at the previous time step; and $RDM_{(t-1)}$ represents the total root biomass of the tree at the previous time step (g).

The term $(1 - (Z_i / R_i))$ serves as an implicit indicator of soil oxygen content, which decreases with soil depth. All soil nodes at the same soil depth are assumed to have the same amount of oxygen. The value of $(1 - (Z_i / R_i))$ is set to zero, when depth of a soil node (Z_i) exceeds root depth (R_i).

Vertical and horizontal extents of un-pruned root system are calculated from tree height (Mobbs *et al.*, 1999):

$$R_j = f_j H_t \tag{9.49}$$

$$R_i = f_i H_t \tag{9.50}$$

Where: R_j is the horizontal root extent (m); f_j is a parameter in the tree height and horizontal root growth relationship; R_i is the vertical root extent (m); f_j is a parameter in the tree height and vertical root growth relationship; and H_t is tree height (m).

As long as horizontal root growth (R_j) is less than the maximum horizontal rooting extent of the tree ($R_{j.max}$, species-specific) or half of the alley width, the adjacent (farther) soil node (horizontally) is considered for root biomass allocation. Vertical root growth also continues until the current root depth (R_i) reaches the maximum rooting depth of the tree ($R_{j.max}$, species-specific) or maximum soil depth. Once maximum vertical and horizontal root growth limits are reached, root is allocated to control volumes for replacing dead roots and increasing root density.

The model converts root biomass increment of each control volume ($RDMi_{(i,j)}$) to root biomass density ($RDMDi_{(i,j)}$) using:

$$RDMDi_{(i,j)} = RDMi_{(i,j)} / V_{(i,j)} \tag{9.51}$$

Where: $RDMD_{(i,j)}$ is in g m^{-3} and $V_{(i,j)}$ is the volume of a control volume "i,j", calculated for a unit breadth of the control volume "i,j" using (Annandale *et al.,* 2002):

$$V_{(i,j)} = ¼ \ [(\Delta X_{j-1}\, \Delta Z_{j-1}) + (\Delta X_{j-1}\, \Delta Z_j) + (\Delta X_j\, \Delta Z_j) + (\Delta X_j\, \Delta Z_{j-1})]\ \Delta Y \tag{9.52}$$

Where: ΔX and ΔZ denote width and thickness of control volumes respectively (m) and ΔY is the breadth of the control volume, which is 1 (i.e. per unit breadth of control volume).

The model allows tree roots to re-grow following root pruning and tillage of the alley zone. Root pruning is tree management practice and tillage is a soil management practice. Nevertheless, in agroforestry, both are intended to make a favourable growing medium available for the understory components and compromise root system of trees. No root pruning or tillage is allowed on the soil control volumes beneath the tree (j=6). The model user selects the depth of tillage/root pruning in the alley zone. In other words, roots may not be pruned all the way to the bottom of the soil profile. The first day after root pruning or tillage, the model sets the root biomass densities of the soil control volumes beyond where pruning/tillage takes place to zero, That is,

$$RDMD_{(i,j)} = 0 \tag{9.53}$$

Where: "j" represents horizontal position of the control volume (except j=6, which is right beneath the tree) where pruning or tillage is carried out; pd is the depth of root pruning; and td is the depth of tillage of the alley zone.

Biomass allocation for root re-growth in the control volumes where pruning or tillage takes place is determined by using $froot_{(i,j)}$ to calculate $p_{(i,j)}$ (instead of equation 9.48):

$$froot_{(i,j)} = Max\ (froot_{(i,j)}{}^{0};\ froot_{(i,j)(t-1)}) \tag{9.54}$$

Where: $froot_{(i,j)}$ is the maximum fraction of root biomass in control volume "i,j" (assuming that no root pruning or tillage occurred); $froot_{(i,j)}^{0}$ is the fraction of root biomass in control volume "i,j" on the last day before root pruning or tillage and is updated every time there is root pruning or tillage in the control volume.

Finally, root biomass densities of the control volume in which root pruning or tillage takes place are updated using equations 9.51 and 9.52.

9.1.3 Tree canopy growth

Tree foliage is updated using the equation (Based on Annandale *et al.,* 1999: Sands, 2004)

$$LDM_t = LDMi + (1 - \gamma_f)\ LDM_{t-1} \qquad 9.55$$

Where: LDM_t is the updated tree foliage biomass at time "t" (kg m^{-2}), γ_f is the rate of leaf-fall (day^{-1}) and LDM_{t-1} is the tree foliage biomass from the previous day (kg m^{-2}).
The leaf fall rate (day^{-1}) of evergreen trees is calculated as:

$$\gamma_f = 1 / (365\ LL) \qquad 9.56$$

Where: LL is the life span of the leaves in the canopy in years (Mäkelä, 1986).
Leaf-fall rate of a deciduous tree is calculated in the manner described by Annandale *et al.*, 1999. The model tracks ages of daily increments of leaf dry matter as LDMagei (in d °C). Once the maximum age ($LDMage_{max}$) of the leaf increment, which is a species-specific input, is reached, an equal quantity of leaf biomass is considered dead leaf and deducted from the total leaf dry mass (LDM). LDMagei (d °C) is affected by water stress and is determined as:

$$LAIagei = (1 / SI)\ GDDi \qquad 9.57$$

Where: GDDi is daily increment of growing degree days; and the ratio 1 / SI denotes effect of water stress on leaf fall, with values between 1 and 2.

The model calculates leaf area index (LAI_t in $m^2\ m^{-2}$) as:

$$LAI_t = LDM_t\ SLA \qquad 9.58$$

If no value of initial foliage biomass is available, for instance on the first day of simulation or first day after pruning, equation 9.55 is replaced by:

$$LDM_t = \rho_{F(mass)}\ V_F \qquad 9.59$$

Where: $\rho_{F(mass)}$ is tree foliage density by mass (kg of foliage m^{-3} canopy volume), which is a tree parameter; and V_F is canopy volume (m^3), which is calculated using equation 9.3 or as:

$$V_F = LDM_t / \rho_{F(mass)} \quad 9.60$$

The model calculates leaf area density (ρ_f) as follows (Annandale *et al.,* 2002):

$$\rho_f = LAI\ (2\ b\ h / V_F) \quad 9.61$$

Where: h is tree row spacing (m).

Trees in two-dimensional agroforestry systems, such as alley-cropping, are planted in hedgerows forming a continuous (closed) canopy along the tree row. The model assumes such as canopy have the shapes of elliptical cylinders and that intra-row spacing is used in the place of canopy depth for calculating canopy volume. If the base of the canopy is pruned, the volume of the canopy, V_F (m^3), is calculated by subtracting the volume of the pruned part of the canopy, which is assumed to be half of an elliptical canopy with dimensions ap, cp and b, from the volume of the un-pruned canopy (Figure 9.1). That is:

$$V_F = [\pi\ a\ b\ c] - [(1/2)\ \pi\ ap\ b\ cp] \quad 9.62$$

Where: a and c represent dimensions of the un-pruned canopy; b is equal to half of the intra-row tree spacing; ap is half of the width of the canopy base after pruning (m); cp denotes the height (m) of the pruned part of the canopy; and 1/2 indicates that the pruned part of the canopy is equal to half of a canopy with dimensions ap and cp.
The vertical extent (m) of the pruned part of the tree canopy (cp) is calculated as follows:

$$cp = c - cnp \quad 9.63$$

The ratio (q) of canopy width (a) to canopy height (c) is calculated and kept constant for updating canopy height and canopy width once the canopy volume is updated. That is:

$$q = a / c \quad 9.64$$

Canopy volume is updated using foliage density by mass ($\rho_{F(mass)}$) and updated foliage biomass (LDM_t), as in equation 9.60. Using canopy depth (known and equal to the intra-row tree spacing) and q and by rearranging the equation of the volume of an elliptical cylinder (to solve for "a"), canopy dimensions are updated as follows:

$$V_F = \pi\ a\ b\ c = \pi\ a\ b\ (a / q) \quad 9.65$$

$$a = [(VF\ q) / (\pi\ b)]^{0.5} \quad 9.66$$

$$c = a / q \quad 9.67$$

Canopy height increment (Δc_t) is equal to:

$$\Delta c_t = c - c_{t-1} \quad 9.68$$

Where C is the updated height of half of the tree canopy (from equation 9.67); and c_{t-1} is half of the canopy height at previous time step

The part of the lower half of the canopy that is not pruned (cnp) increases by Δc_t and should not grow more than the canopy height (c). In other words, the canopy grows downward to replace the pruned part.

$$cnp_t = cnp_{t-1} + \Delta c \qquad 9.69$$

The model updates the height of the missing (pruned) part of canopy as follows:

$$cp = c - cnp \qquad 9.70$$

Finally, the height of the centre of the canopy from the soil surface (Z_0), the height of the canopy base from the soil surface (Z_b) and half the width of the canopy ap are updated as follows:

$$Z_o = Ht - c \qquad 9.71$$

$$Z_b = Z_o - cnp \qquad 9.72$$

$$ap = q\ cp \qquad 9.73$$

The model simulates the re-growth of the tree canopy after pruning. There are two canopy pruning options: pruning to a smaller and elliptical shape (maintaining the original shape) and base pruning. The required inputs for both options are given in Table 9.1. When the base pruning option is selected, the width of the canopy base after pruning (ap) is equal to:

$$ap = q\ cp \qquad 9.74$$

Table 9.4 Parameters of tree growth routine to be incorporated into the SWB model

Parameter	Values for *J. curcas*
Coefficient in stem diameter – tree height equation (dimensionless)	26.172
Coefficient in stem diameter – stem mass equation (dimensionless)	10912
Exponent in height-stem diameter equation (dimensionless)	1.0349
Exponent in stem diameter – stem mass equation (dimensionless)	3.5288
A Stem-leaf partitioning factor ($m^2\ kg^{-1}$)	5.5722
Specific leaf area ($m^2\ kg^{-1}$)	9.046
Temperature for optimum light-limited growth (°C)	24 (20 -28)
Foliage density by mass ($kg\ m^{-3}$)	0.296
Ratio of crown width to crown height (dimensionless)	1.025

9.2 OVERVIEW OF THE MODELS OF TWO-DIMENSIONAL RADIATION INTERCEPTION, WATER BALANCE AND CROP GROWTH

Solar radiation is a prime plant growth resource. It affects plant growth and development by taking part in several aspects of plant morphology and physiology (Berlyn & Cho, 2000). Indirectly, radiation affects plant use of other growth resources (Huxley, 1999). Quantity, quality and duration of radiation plants intercept is dictated by: canopy structure, duration and optical features; clouds; time of day and year; location (Berlyn & Cho, 2000); and amount of incident solar energy (Ong *et al.*, 1996).

In agroforestry, there are interspecies competitions for radiation (Nair, 1993; Ong *et al.*, 1996). Radiation reaching understorey crops is a function of: closeness to trees; nature and structure of tree canopy (sparse or dense); solar positions; management aspects including, timing of tree canopy pruning (Ong *et al.*, 2000) and planting geometry of component species (Ong *et al.,* 1996; Berlyn & Cho, 2000). Heterogeneity and constant variation of canopy structures and architecture makes the distribution of radiation in agroforestry complex (Ong *et al.,* 1996). Overestimation of light capture by a component implies over-growth and resource over-utilizations at the expense of the other component (Mobbs *et al.,* 1999). Reid and Ferguson (1992) highlighted that detailed modelling of spatial radiation distribution under the tree canopy, in agroforestry, is crucial to determine light availability to understory crops.

Two-dimensional agroforestry systems, (hedgerow intercropping systems) involve a symmetrical geometry of planting trees and crops, which ensures homogeneity along the tree rows and within crop rows. The interactions across tree-crop interfaces result in a characteristic crop growth profiles. the approaches of many of the radiation-driven models developed so far and applicable to hedgerow intercropping may be over-simplified or lack a full account of different solar positions; differentiation of radiation distribution with distance from trees and partitioning radiation transmitted through trees canopies to understory crop absorption and transmission to soil surfaces.

A mechanistic, real-time, generic, crop growth and soil water balance model, called the Soil water Balance (SWB) model was developed by Annandale *et al*. (1999), as an irrigation management tool. Using soil, weather and crop inputs, it simulates crop growth and provides an insightful account of the biophysical links among the atmosphere (environment), plant and the soil system. The model has been calibrated and tested under a range of conditions and crops. It has proven to be very helpful, with reliable correctness.

A model that performs energy interception and water balance modelling in two dimensions, by trees planted in hedgerows (SWB-2D), was developed as an extension of the SWB model and authenticated (Annandale *et al.*, 2002). The model applies Beer's principle of radiation attenuation and makes use of position of the sun, tree row orientation, dimensions and leaf area density of the tree canopy. It has four components, namely: tree canopy radiation interception simulator, soil evaporation simulator, tree transpiration simulator and simulator of water redistribution in the soil. These components were evaluated independently and altogether and have shown that the model and its components are accurate. Subsequently, the two-dimensional model was incorporated into the SWB model (Annandale *et al.*, 1999; Annandale *et al.*, 2002; Annandale *et al.*, 2003; Annandale *et al.*, 2004).

In the model, Beer's law is rearranged to determine radiation transmittance through an ellipsoidal tree canopy from the path length of rays through the canopy and leaf area density. The path length of the ray through the tree canopy is a function of zenith angle of the sun. It shows how far the ray travels in a canopy of constant foliage density. Leaf area density of an ellipsoidal canopy with a spherical leaf distribution is a parameter that shows the total leaf area that a unit of the canopy volume contains. The model recognises the differences in the interaction of the plant canopies with the direct and diffuse components of solar radiation. The model tackles this by computing direct radiation interception separate from that of the diffuse component of radiation using the method described by Weiss and Norman (1985).

The SWB model and the two-dimensional energy interception and water balance model for hedgerow tree crops (SWB-2D) were developed to be user-friendly. Their accuracies have been demonstrated in several trials. Due to the mechanistic approaches followed, these models form powerful components to an integrated two-dimensional agroforestry system model.

The modelling approach used here is as follows:

- Radiation routine of the SWB-2D simulates radiation interception by trees and radiation reaching at 11 distances across a tree hedgerow, referred to as soil surface nodes. An illustration of this is shown in Figure 9.3.
- The water balance routine of the model simulates two-dimensional soil water balance. Figure 9.4 illustrates the two-dimensional nodal system employed and how the component species of the hedgerow intercropping systems are integrated into the water balance system.
- Each surface node but the one beneath tree row represents mid-point of a crop row, grown as a single plant ('crop column') using radiation estimated at the node and soil water available in the soil volumes (called control volumes) that lie beneath the crop column. The highlighted and magnified section of Figure 9.5 represents the focus of simulation of the hedgerow model. The Figure also shows set up details of the hedgerow intercropping system model user can change.

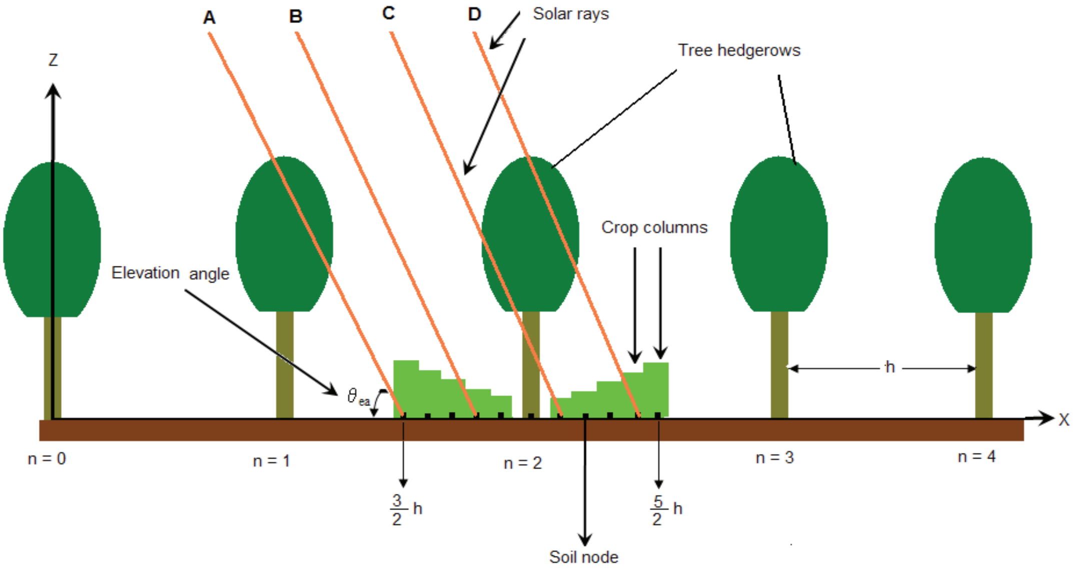


Figure 9.3 Schematic illustration of two-dimensional radiation distribution in a two-dimensional agroforestry system drawn on the Cartesian coordinates x and z. Radiation interception by intercrops and transmission to soil nodes are determined at distances of 3/2 and 5/2 of the inter-row spacing (h) from the origin at n = 0. Two rows of trees on either side of the centre tree (at n = 2) are taken into account for radiation modelling. Cases A through D represent possible interactions of the solar rays with canopies of trees under consideration, alley crops and soil nodes (between 3/2 h to 5/2 h from the origin)

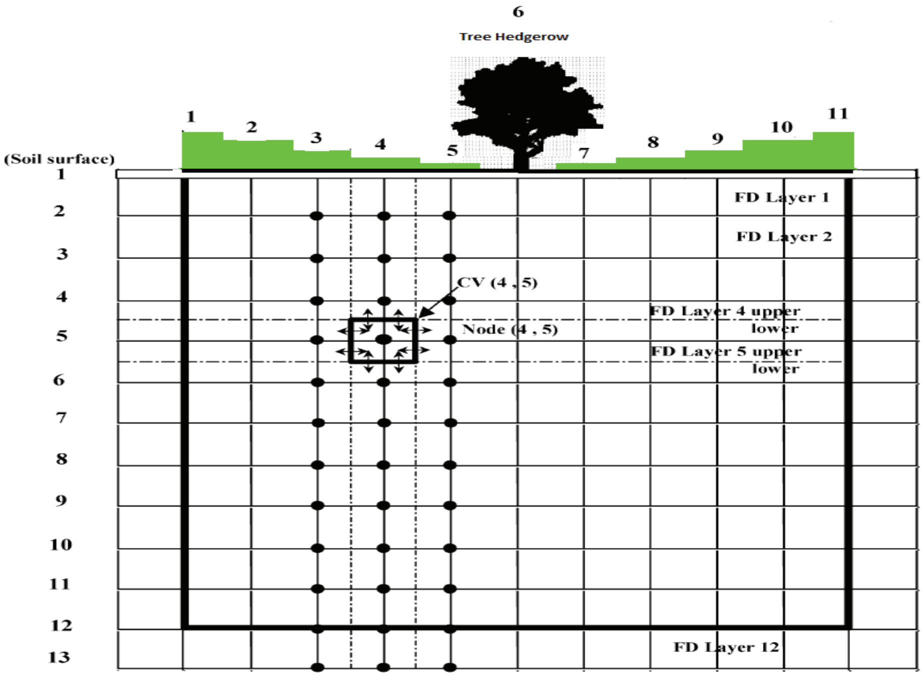
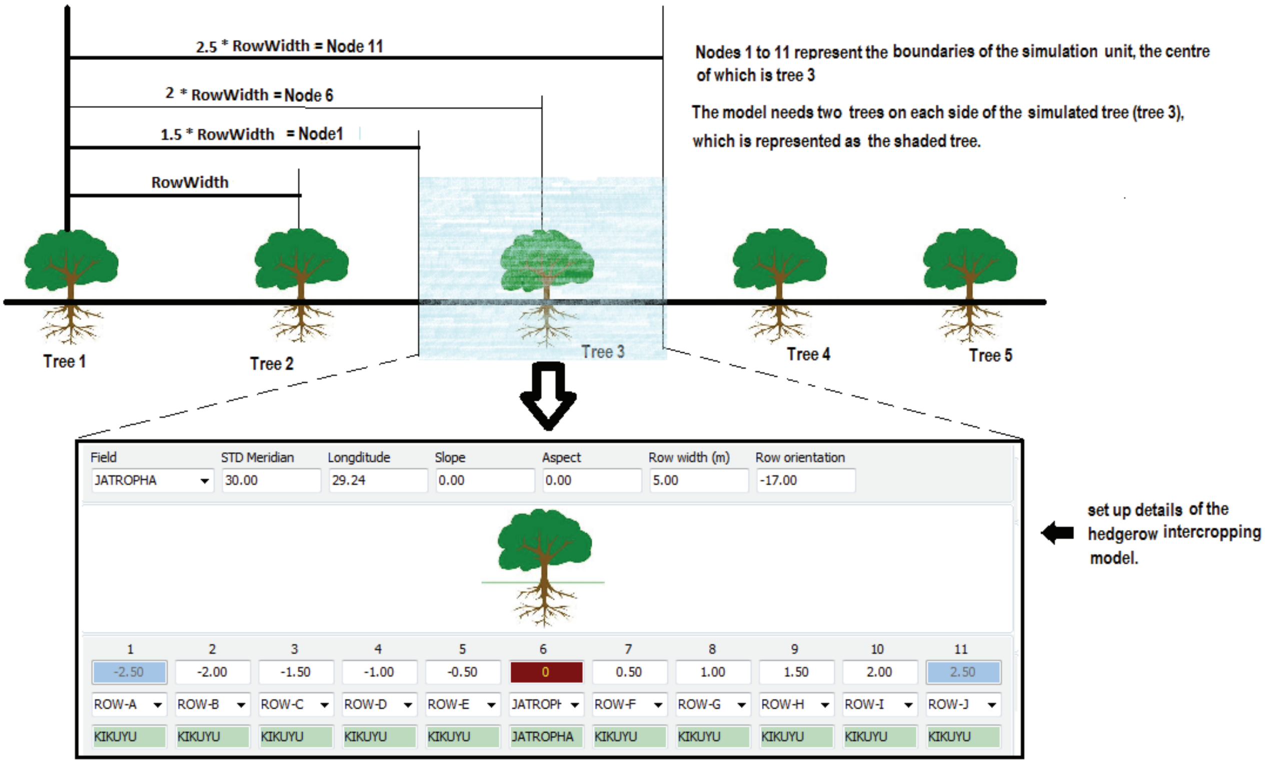


Figure 9.4 Nodal grid system showing symmetry planes and tree hedgerow and crop rows in a typical hedgerow intercropping system. Horizontal numbers (1 to 11) represent plant rows. They also represent lateral nodes within the soil profile that make up unit soil volumes (referred here as control volumes or CV) together with the vertical numbers (1 to 13) representing vertical nodes for water balances and redistribution modelling



Nodes 1 to 11 represent the boundaries of the simulation unit, the centre of which is tree 3

The model needs two trees on each side of the simulated tree (tree 3), which is represented as the shaded tree.

set up details of the hedgerow intercropping model.

Field	STD Meridian	Longditude	Slope	Aspect	Row width (m)	Row orientation
JATROPHA	30.00	29.24	0.00	0.00	5.00	-17.00

1	2	3	4	5	6	7	8	9	10	11
-2.50	-2.00	-1.50	-1.00	-0.50	0	0.50	1.00	1.50	2.00	2.50
ROW-A	ROW-B	ROW-C	ROW-D	ROW-E	JATROPH	ROW-F	ROW-G	ROW-H	ROW-I	ROW-J
KIKUYU	KIKUYU	KIKUYU	KIKUYU	KIKUYU	JATROPHA	KIKUYU	KIKUYU	KIKUYU	KIKUYU	KIKUYU

Figure 9.5 Schematic representation of the set-up of tree and understory crop components in the hedgerow intercropping model. Trees 1 and 2 as well as trees 4 and 5 represent the neighbouring trees required for radiation modelling

9.3 MODEL TESTING AND VERIFICATION

This section presents the results of the evaluation of the hedgerow intercropping model. Data collected from a single-row treatment at the Ukulinga research site (described in Chapter 4) were compared to model predictions. Selected statistical parameters were used to evaluate the model predictions, namely (Annandale *et al.*, 2002):

- Number of observations (N)
- Coefficient of determination (r^2)
- Index of agreement of Willmott (1982) (D); and
- Mean absolute error (MAE)

Kikuyu Growth and Productivity

Periodic cuttings of kikuyu from different distances from a tree row in single-row treatment were compared to simulated yields. Simulated and measured cumulative harvests for the durations of the growing season 2006/07 and 2007/08 were also compared. The selected distances at which the model was tested are given in Table 9.5. Crop specific parameters used for the selected intercrop (kikuyu) are also provided in Table 9.6.

Table 9.5 Details of the positions of the kikuyu rows considered in the calibration and validation of the model

Kikuyu row	Distance from tree hedgerow (m)	Side with respect to tree hedgerow
Row B	2	South-western (SW)
Row D	1	South-western (SW)
Row G	1	North-eastern (NE)
Row I	2	North-eastern (NE)

Table 9.6 Specific parameters of kikuyu used for calibrating and validating the crop growth component of the hedgerow intercropping model

Parameter	Value	Unit
Canopy extinction coefficient for solar radiation	0.5	-
Dry matter water ratio	4	Pa
Radiation conversion efficiency	0.0013	kg MJ^{-1}
Base temperature	10	°C
Temperature for optimum growth	25	°C
Cut off temperature	30	°C
Emergence day degrees	0	d °C
Day degrees at the end of vegetative growth	5000	d °C
Day degrees for maturity	5400	d °C
Transition period day degrees	300	d °C
Day degrees for leaf senescence	600	d °C
Maximum crop height	0.4	m
Maximum root depth	1.0	m
Fraction of total dry matter translocated to heads	0.01	-
Leaf water potential at maximum transpiration	-1500	kPa
Maximum transpiration	9	mm d^{-1}
Specific leaf area	15	m^2 kg^{-1}
Leaf-stem partition parameter	0.7	m^2 kg^{-1}
Fraction of total dry matter partitioned to roots	0.2	-
Root growth rate	4	m^2 kg^{-1}
Stress index	0.95	-
Total dry matter at emergence	0.0025	kg^{-1} m^2
TDM after cut	1.0	t ha^{-1}

Data from 2006/07 were used to calibrate the model. The first part of the calibration was to check the model predictions under periodic cuttings (Figure 9.6). The model predictions at various distances were generally acceptable. Both measured and simulated were slightly less in the south-western side (rows B and D) than the north-eastern (rows G and I) side of the tree rows. Kikuyu growth was also less towards the tree row. At the beginning of the season, the model tended to overestimate the harvestable yield. Towards the end of the season, however, measured yields were higher than simulated yields.

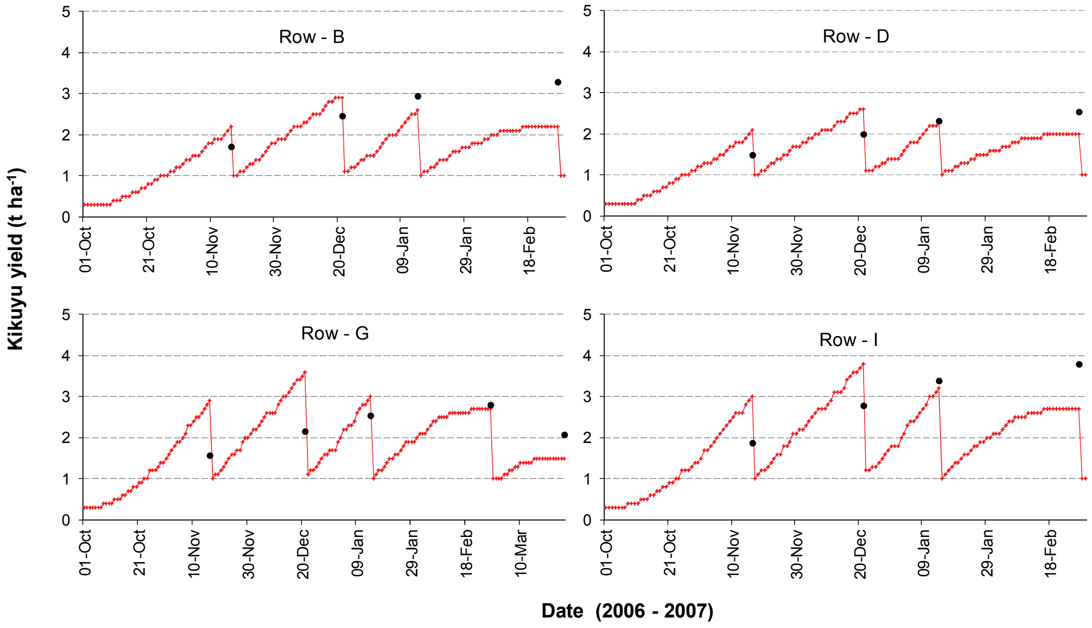


Figure 9.6 **Simulated (lines) and measured (symbols) above-ground dry matter of kikuyu at various distances from a selected tree row for model calibration during various growth cycles of the 2006/07 growing season at Ukulinga**

Simulated cumulative kikuyu yields were less affected by distance from the tree row than the position (side) of the kikuyu rows with respect to the tree row (NE or SW). Figure 9.7 presents measured and simulated cumulative kikuyu yields on SW and NW sides of the tree. Though the SW side (rows B and D) had less simulated and measured yields than the NE side (rows G and I), the model predictions were better on the SW side than the NE side where the model overestimated yield. The statistical parameters of model performance confirming this are presented in Table 9.7.

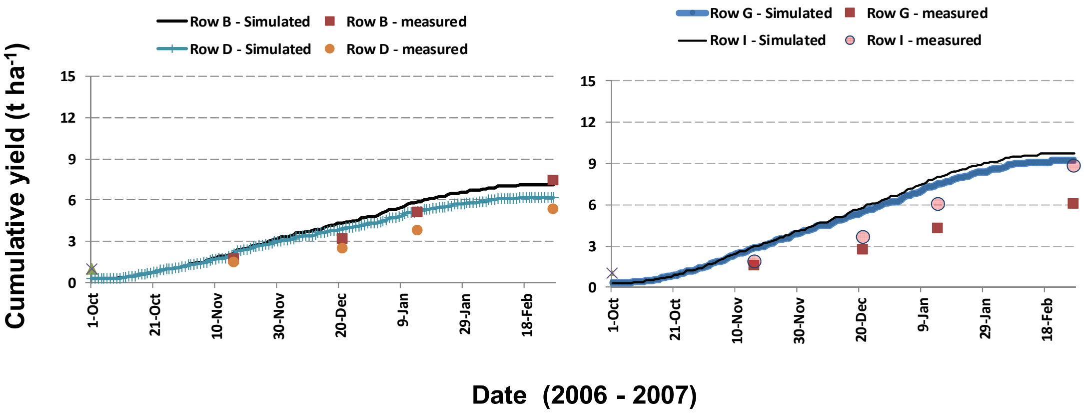


Figure 9.7 **Simulated (lines) and measured (symbols) cumulative above-ground dry matter of kikuyu during the 2006/07 growing season at Ukulinga**

Independent yield data from 2007/08 growing season were used to validate model predictions at the distances considered in the calibration process. As far as periodic harvesting is concerned (Figure 9.8), the outcomes were similar to those observed in the model calibration. The difference between predicted and measured cumulative yields, on the other hand, were more pronounced during the 2007/08 season on both the NE and SW sides (Figure 9.9), resulting in lower model accuracy (Table 9.7).

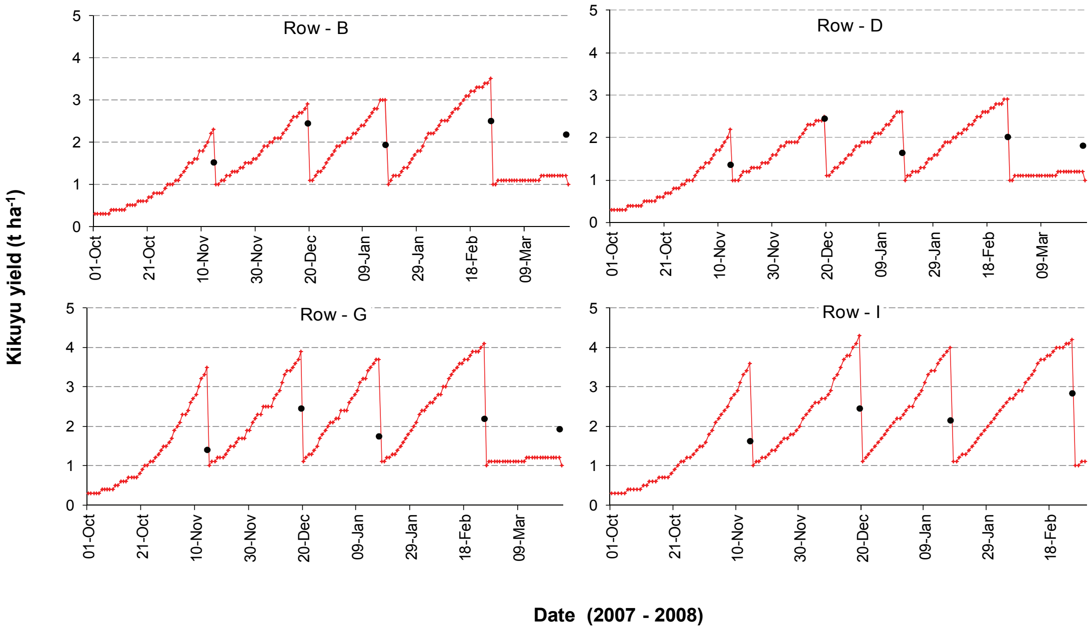


Figure 9.8 Simulated (lines) and measured (symbols) above-ground dry matter of kikuyu for model validation during various growth cycles of the 2007/08 season at Ukulinga

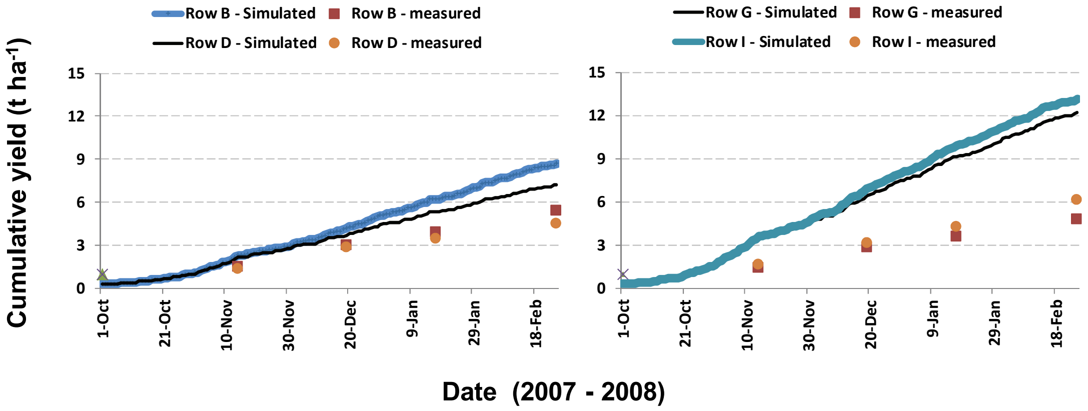


Figure 9.9 Simulated (lines) and measured (symbols) cumulative above-ground dry matter of kikuyu during the growing season of the 2007/08 at Ukulinga

Table 9.7 Values of the statistical performance quantifiers of model to predict cumulative yield of kikuyu during the 2006/07 (calibration) and 2007/08 (validation)

Parameter name	Parameter value				
	Expected	2006/07		2007/08	
		SW	NE	SW	NE
n	-	8	8	8	8
r^2	> 0.8	0.93	0.88	0.98	0.97
D	> 0.8	0.93	0.82	0.75	0.46
MAE (%)	< 20	22.57	46.88	53.02	132.57

Tree water use

The two-dimensional energy interception and water balance model of the soil water model (SWB) was proven accurate for hedgerow applications. In this project, therefore, the tree water transpiration is validated in the context of hedgerow intercropping. The tree parameters provided in Table 9.8 were used to run the model.

Table 9.8 Tree parameters used for validating the hedgerow intercropping model using *J. curcas*

Parameters	Value				Parameters	Value
	Initial	Development	Mid	Late		
Period (days)	15	60	90	45	Stem height (m)	0.3
Canopy height (m)	1.8	-	2.1	-	Base height (m)	0.2
Canopy width (m)	1.8	-	2.0	-	Absorptivity	0.5
LAI (m^2 m^{-2})	0.3	-	1.6	-	Extinction coefficient	0.5
Root depth (m)	0.6	-	0.6	-	Stress index	0.9

The validation results of tree water use are presented in Figure 9.10 and Table 9.9. Simulated water use became less than measured amount towards the end March. The results show that the model has a good potential to simulate tree water use in hedgerow intercropping systems.

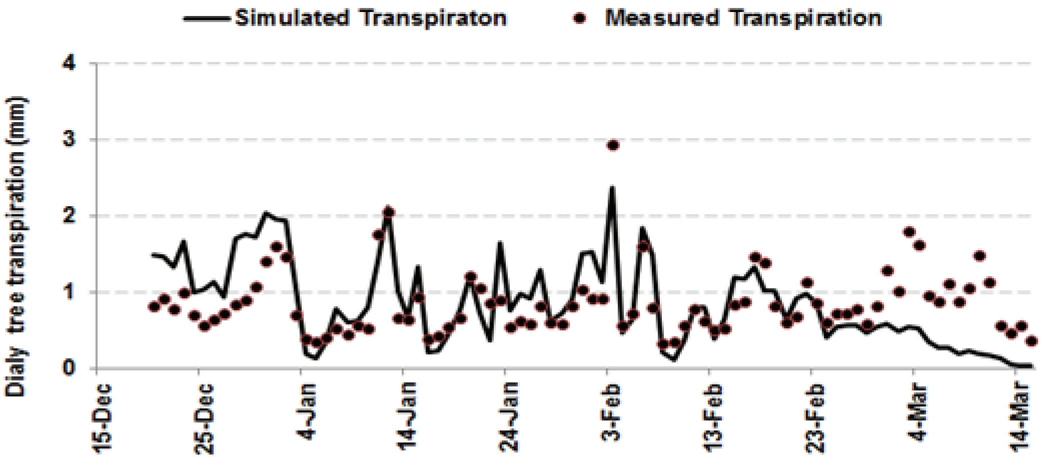


Figure 9.10 Measured symbols) and simulated (lines) daily transpiration by *J. curcas* during the period 20/12/2007 to 15/03/2008 in the single-row treatment at Ukulinga

Table 9.9 Statistical parameters for evaluating model performance of predicting tree transpiration in the single-row treatment during 2007-08 season at Ukulinga

Parameter name	Parameter value	
	Expected	Obtained
n	-	87
r^2	> 0.8	0.69
D	> 0.8	0.59
MAE (%)	< 20	6.29

Soil water and radiation distribution

The model underestimated profile water contents at the various distances (Figure 9.11). The evaluation result is presented in Table 9.10. Considering high spatial variability of soils, the results presented in Table 9.10 are fairly acceptable.

Table 9.10 Statistical parameters for evaluating model predictions of soil water distribution in the single-row treatment between 15/12/2007 to 10/01/2008 (Ukulinga)

Parameter name	Parameter value				
	Expected	Row B	Row D	Row G	Row I
n	-	24	24	24	24
r^2	> 0.8	0.5	0.63	0.64	0.52
D	> 0.8	0.36	0.4	0.37	0.42
MAE (%)	< 20	17.82	13.93	14.26	13.12

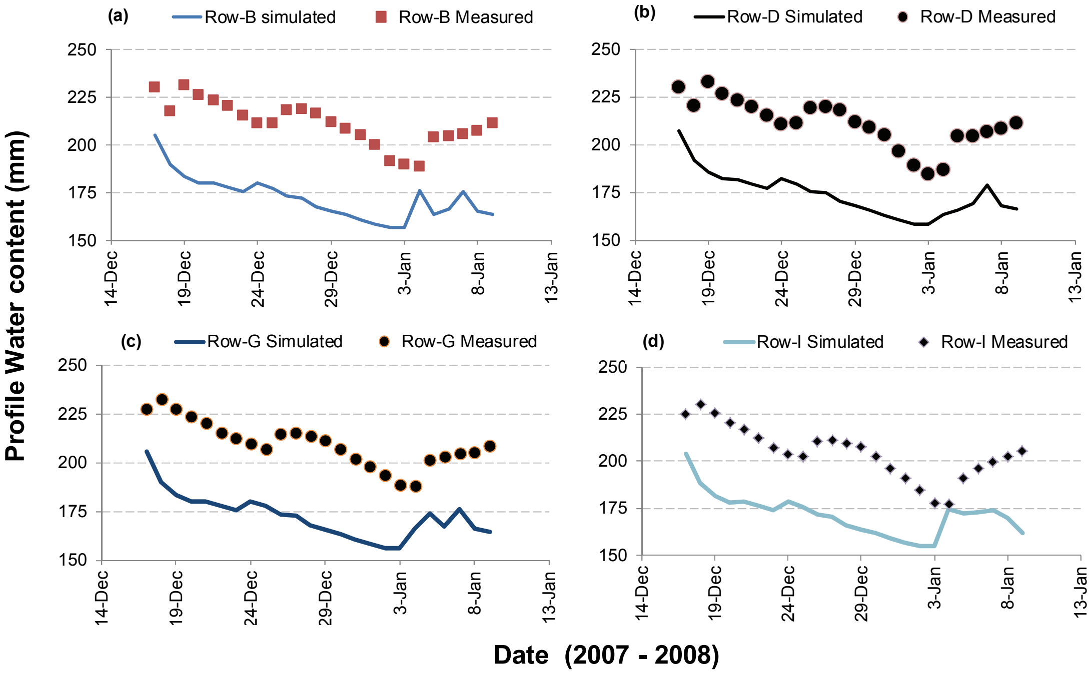


Figure 9.11 Simulated (lines) and measured (symbols) distribution of soil profile water content with distance during between 15/12/2007 to 10/01/2008 in the single-row treatment (Ukulinga)

Simulated solar radiation incident at various distances were different. Figure 9.12 shows the radiation absorbed by crops at 2 m (rows B and I) and at 1 m (rows D and G) on SW and NE sided of the tree rows. The simulate radiation on the SW side is slightly lower than the NE side and as expected, for both sides, radiation intercepted by the kikuyu rows close to the tree (at 1 m distance) was lower that farther from the tree.

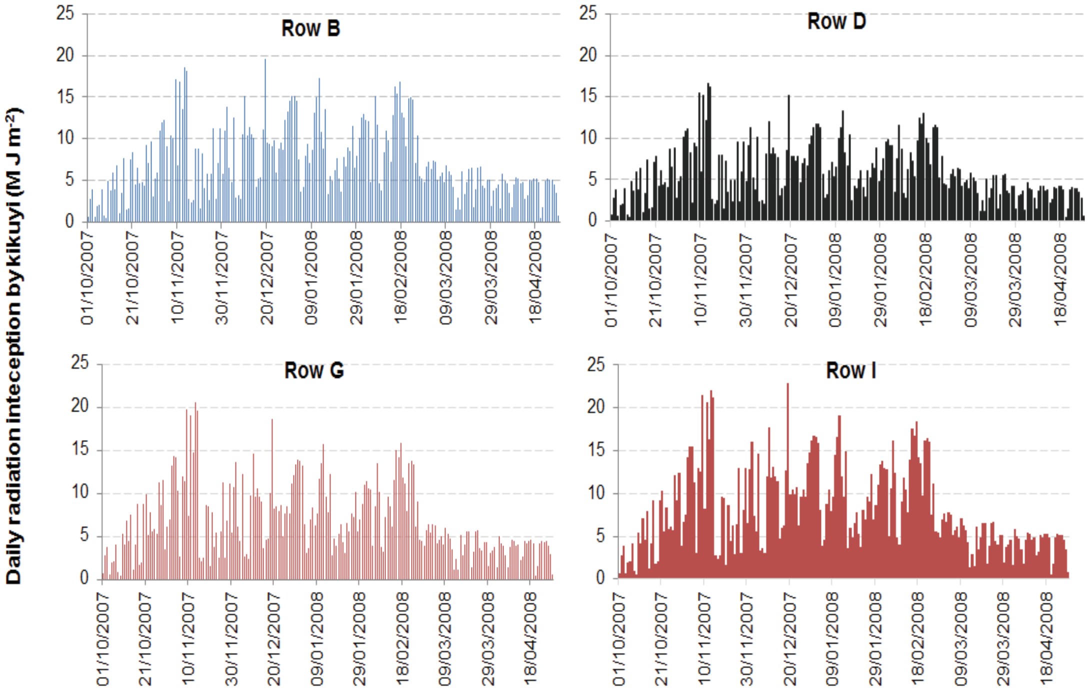


Figure 9.12 **Simulated radiation intercepted by kikuyu at different distances during between 15/12/2007 to 18/04/2008 in the single-row treatment (Ukulinga)**

9.4 CONCLUSIONS

The hedgerow intercropping model developed in this project offers a lot of potential as it is based on well-established, robust and reliable models and meets important aspects of silvopastoral systems and alley-cropping systems. Calibration and validation results conducted so far have confirmed its potential. However, it needs to be evaluated for more crop and tree species. Another important aspect that needs improvement on the current version is tree growth. It is recommended that the mechanistic tree growth approach presented in this report (Section 9.1 and 9.2) be incorporated to the current version.

10 GENERAL CONCLUSIONS AND RECOMMENDATIONS

On 27 August 2009, 1200 participants of the 2nd World Congress of Agroforestry held in Nairobi, Kenya, recognized the significant progress made in the development of agroforestry as a science-based land-use discipline during the past three decades. Participants signed a declaration recognizing the demonstrable role of agroforestry in sustaining crop yields, diversifying farm production, ensuring environmental integrity and realizing ecosystem services that can lead to improved livelihoods for smallholder farmers. In spite of this global consensus on the benefits of agroforestry, the implementation of agroforestry systems in South Africa has been relatively slow. At a government level this may be due to poor development of cross-sectoral policy at regional and national levels. In South Africa, the past focus has been on intensive production of individual sectors (agriculture and forestry), as opposed to integrated agroforestry practices to improve farming systems, restore degraded environments and supplement incomes. The development of policy on agroforestry in South Africa has been neglected as the two departments involved in agroforestry (agriculture and forestry) were in separate directorates. Previously the directorate of forestry (including agroforestry) resided in the Department of Water Affairs and Forestry, while agriculture fell under the Department of Agriculture. In 2009 Forestry was incorporated into the Department of Agriculture, Forestry and Fisheries. This incorporation of agriculture and forestry into the same department should provide the consolidated support for the development of new agroforestry policy. It is therefore recommended that there is an urgent need to review South Africa’s agroforestry policy and legislation.

At farmer level, lack of adoption may be attributed to lack of farmer knowledge on applicable crop and tree combinations that benefit the people and the environment. The aim of this project was to implement on-station agroforestry systems to determine their impact on water and plant production in order to facilitate the adoption of agroforestry locally. With the approval of the reference group the study focused on a single bioclimatic region, the Coast Hinterland Thornveld. The study was carried out from 2005 to 2012. The objectives of the project outlined in section 1.2 were all met.

The potential species examined in this study will enable farmers to diversify their operations to improve overall production while conserving water and soil resources. The range of species that were tested in this trial together with the source of planting material will give farmers a number of options for agroforestry systems depending on their specific objectives. The species selected can provide a variety of services such as water and soil conservation, fertilization, fodder and food production, as well as products for additional income such as firewood, oil, fence posts and bark.

On-farm trials of different species combinations selected by farmers need to be implemented and documented to promote the potential effectiveness of agroforestry practices. The results from the alley cropping trials in this study clearly demonstrate that benefits of agroforestry are generally not realized in the first two seasons after establishment. This may be another reason for poor uptake of agroforestry by rural farmers. Thus realistic timeframes for potential benefits need to be given to rural farmers before they establish agroforestry systems. The failure of *A. xanthophloea* and

P. maximum to establish in the on-station alley cropping trial highlights the importance of testing species before promoting them to rural farmers. The results from this study indicated that a good potential tree species for use in alley cropping practices is *L. leucocephala*. Even during the dry periods that occurred in the second season of the trial *L. leucocephala* recovered well after harvesting and produced high fodder yield (1715 kg ha-1) compared to *A. karroo* and *M. alba* (<1140 kg ha-1). Throughout the three agroforestry systems tested, one of the main lessons learnt for farmers is that good agronomic practices (e.g. weeding, irrigation) are critical for the success of crop and tree species.

To date comprehensive studies on the water use of *J. curcas* have been limited to only a few other studies (Gush, 2008; Maes *et al.*, 2009). The results of this study have therefore provided valuable new information for policy implementation on the introduction *J. curcas* in South Africa. Two principal facts emerge on the water-use of *J. curcas*. Firstly, even at a young age (before canopy closure) total evaporation rates were high. These high rates were associated with the high summer growth rates recorded in the *Jatropha* only trial. Secondly, there was very low total evaporation during the winter period when the trees were leafless. Because of its deciduous nature when water is limiting, it seems unlikely therefore that *J. curcas* will have a high annual water use in areas characterised by summer rainfall. The relatively low water use was also supported by the fact that the dry-land Kikuyu pasture had a higher water use than the *J. curcas* trees. From a South African water planning perspective, *J. curcas* is therefore unlikely to compete for scarce water resources.

The long term nature of agroforestry systems necessitates the use of models to facilitate the planning and optimisation from the wide range of species and tree spacing options available for implementation. The agroforestry systems established in this study enabled the development of a hedgerow intercropping model. This was achieved by merging two well-established, robust and reliable models, namely: the Soil Water Balance Model (SWB) and the two-dimensional energy interception and soil water balance model (SWB-2D). The model is applicable to two-dimensional agroforestry systems including silvopastoral and alley-cropping systems.

Data collected from a hedgerow intercropping system (single-row treatment) at Ukulinga experimental farm were used to evaluate performance of the hedgerow intercropping model on:

- Understorey crop growth: Including how crop growth changes with distance from tree rows; an option of periodic pasture harvesting as well as seasonal productivity;
- Tree water use; and
- Profile water distribution and variability with distance from tree rows.

Although *J. curcas* was used in the model, it must be emphasized that the model applies to any potential agroforestry species. The performances of the model were encouraging. There is room for improvement of model performance through a more intensive and thorough calibration process. It also needs to be evaluated for the full-account of hedgerow intercropping systems. In order to take full advantage of its capabilities as a management and planning tool for hedgerow intercropping systems, the model evaluations should take into account systems with different row widths, row orientations and crop and tree species.

Model performances related to soil water predictions are bound to be affected by high soil variability and soil disturbance during installation of measurement sensors. In the current model, the soil water balance models used for crops and trees have different principles. The latter is based on more sound physical principles yet needs more inputs. The cascading water balance approach employed by the crop growth model has been validated for several crops and works very well. However, when it is used in conjunction with the finite difference approach employed by SWB-2D, as in the current model, errors may rise to due to difference in soil layering between the two approaches. If the resultant errors are significant, a finite difference approach can be used for crops as well (an option which is already available). The current model needs to incorporate tree growth and productivity predictor. The mechanistic approach of tree growth developed in the current project and fully described in this report could be used for this purpose. It needs to be evaluated for various crop and tree types (field, cash, shade-loving crops; evergreen and deciduous trees);

An economic return estimator that takes into account values of crop and tree outputs and estimates system return needs to be included in the current model. This makes the model not only a field-level management and planning tool but also a decision-making tool from economic return point of view (by manipulating the row width and orientation; tree and crop selection). An optimisation program was recommended for the two-dimensional energy interception and soil water balance model (SWB-2D) component of the current model. This is believed to have a positive contribution to the current model.

One of the potential agroforestry systems implemented in this study was the silvopastoral agroforestry system. In this system *J. curcas* trees, which have potential to produce biodiesel, were planted in different alley rows with kikuyu, a valuable pasture fodder species. The low probability of herbivory makes *J. curcas* a suitable candidate for silvopastoral systems. However, the planted pastures needed to sustain livestock may impose a negative competitive effect on the growth and productivity of 15-month old *J. curcas* trees. It is recommended that a 60 cm radius around the base of individuals be kept clear of pasture species to enhance *J. curcas* growth. Therefore with some degree of plantation maintenance, *Jatropha curcas* could be a promising component in silvopastoral systems. However, the highest seed yield, which was achieved in 2009 in the *J. curcas* only plots, was very low (348.8 kg ha^{-1}). In the other treatments (where pasture competition was a factor) seed yield was significantly lower, ranging between 77.8 and 166 kg ha^{-1}. High oil yields are therefore unlikely due to the low seed production. The potential of *J. curcas* as a suitable alternate source of energy in South Africa is therefore questionable. The results of this study support the stand taken by the government to ban the widespread planting of *J. curcas* until the potential impact of the species could be evaluated through a comprehensive research programme. While the results of this study provide valuable insight into the water-use, seed production, palatability and competitive effects of *J. curcas*, further research needs to be carried out before it can be used effectively for agroforestry purposes.

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APPENDIX 1: CAPACITY BUILDING AND TECHNOLOGY TRANSFER

Technology transfer is a process by which science and technology is transferred from one party to another through practical applications of the results of the scientific research. This report describes the transfer of preliminary results of the *J. curcas*/ Kikuyu agroforestry trial to the public and scientific community. The technology transfer activities included a workshop on biodiesel fuel production, scientific papers delivered at regional and local conferences, numerous informal study group sessions by local and international visitors to the trial, user training and registration of the project on the World Wide Web.

The building of research capacity is a key objective of all WRC projects. In this project four PhD and two MSc projects were registered as part of the research programme. To date three PhD's have been published and one MSc. The fourth PhD involved the development of the two dimensional agroforestry models and is nearing completion. The uncompleted MSc by Ignacio Nhancale is an excellent piece of work and we are actively encouraging the student (who is currently employed at a high level in the Mozambican Government) to finalise the work. In addition a number of undergraduate students carried out research projects. In the following section the thesis titles and summary of each and publications are listed. Clearly this project is not able to document the large amount of work this entailed within a single report. We have therefore focused the report on the main theme and summarise the ancillary research here. The interested reader is thus able to access this work through the relevant published theses and scientific publications which have emanated from this project.

The following is a list of publications and conference activities emanating from the project:

Peer reviewed scientific publications

1. SB Ghezehei1, JG Annandale and CS Everson (2009) Shoot allometry of *Jatropha curcas* L. Southern Forests: a Journal of Forest Science, Vol 71. pg:279-286.

2. Savage, M.J., Odhiambo G.O., Mengistu M.G., Everson C.S., and Jarmain, C. 2010. Measurement of grassland evaporation using a surface-layer scintillometer. Water SA 36 (1) 1-8.

3. Everson, C.S., Mengistu, M.G., and M. B. Gush (in press) A field assessment of the agronomic performance and water use of *Jatropha curcas* in South Africa. Biomass and Bioenergy.

4. Andersson C.E.F., Everson T.M. and Everson C.S. (in press). Management of oil producing *Jatropha curcas* (Euphorbiaceae) silvopastoral systems: risk of herbivory by indigenous goats and competition with planted pastures.

5. Abraha, M.G. and M.J. Savage, 2011. Energy and mass exchange over incomplete vegetation cover. Accepted for publication by Crit. Rev. Plant Sci.

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THESIS ABSTRACTS

The following section comprises the abstracts and summaries from the theses of the PhD and MSc candidates:

HEAT AND ENERGY EXCHANGE ABOVE DIFFERENT SURFACES USING SURFACE RENEWAL

By

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Thesis submitted in partial fulfilment of the requirement for the award of degree of

PhD

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ABSTRACT

The demand for the world's increasingly scarce water supply is rising rapidly, challenging its availability for agriculture and other environmental uses, especially in water scarce countries, such as South Africa, with mean annual rainfall is well below the world's average. The implementation of effective and sustainable water resources management strategies is then imperative, to meet these increasingly growing demands for water. Accurate assessment of evaporation is therefore crucial in agriculture and water resources management. Evaporation may be estimated using different micrometeorological methods, such as eddy covariance (*EC*), Bowen ratio energy balance (*BR*), surface renewal (*SR*), flux variance (*FV*), and surface layer scintillometry (*SLS*) methods. Despite the availability of different methods for estimating evaporation, each method has advantages and disadvantages, in terms of accuracy, simplicity, spatial representation, robustness, fetch, and cost. Invoking the shortened surface energy balance equation for which advection and stored canopy heat fluxes are neglected, the measurement of net irradiance, soil heat flux, and sensible heat flux allows the latent energy flux and hence the total evaporation amount to be estimated.

The SR method for estimating sensible heat, latent energy, and other scalars has the advantage over other micrometeorological methods since it requires only measurement of the scalar of interest at one point. The SR analysis for estimating sensible heat flux from canopies involves high frequency air temperature measurements (typically 2 to 10 Hz) using 25 to 75 µm diameter fine-wire thermocouples. The SR method is based on the idea that parcel of air near a surface is renewed by an air parcel from above. The SR method uses the square, cube, and fifth order of two consecutive air temperature differences from different time lags to determine sensible heat flux. Currently, there are three SR analysis approaches: an ideal SR analysis model based on structure function analysis; an SR analysis model with finite micro-front period; and an empirical SR analysis

model based on similarity theory. The SR method based on structure function analysis must be calibrated against another standard method, such as the eddy covariance method to determine a weighting factor α which accounts for unequal heating of air parcels below the air temperature sensor height. The SR analysis model based on the finite micro-front time and the empirical SR analysis model based on similarity theory need the additional measurement of wind speed to estimate friction velocity.

The weighting factor α depends on measurement height, canopy structure, thermocouple size, and the structure function air temperature lag. For this study, α for various canopy surfaces is determined by plotting the SR sensible heat flux H_{SR} against eddy covariance H_{EC} estimates with a linear fit forced through the origin.

This study presents the use of the SR method, previously untested in South Africa, to estimate sensible heat flux density over a variety of surfaces: grassland; Triffid weed (*Chromolaena odorata*); Outeniqua Yellow wood (*Podocarpus Falcatus*) forest; heterogeneous surface (*Jatropha curcas*); and open water surface. The sensible heat flux estimates from the SR method are compared with measurements of sensible heat flux obtained using eddy covariance, Bowen ratio, flux variance, and surface layer scintillometer methods, to investigate the accuracy of the estimates. For all methods used except the Bowen ratio method, evaporation is estimated as a residual using the shortened energy balance from the measured sensible heat and from the additional measurements of net irradiance and soil heat flux density.

Sensible heat flux H_{SR} estimated using the SR analysis method based on air temperature structure functions at a height of 0.5 m above a grass canopy with a time lag r = 0.5 s, and $\alpha = 1$ showed very good agreement with the eddy covariance H_{EC}, surface layer scintillometer H_{SLS}, and Bowen ratio H_{BR} estimates. The half-hourly latent energy flux estimates obtained using the SR method λE_{SR} at 0.5 m above the grass canopy for a time lag r = 0.5 s also showed very good agreement with λE_{EC} and λE_{SLS}. The 20-minute averages of λE_{SR} compared well with Bowen ratio λE_{BR} estimates.

Sensible heat and latent energy fluxes over an alien invasive plant, Triffid weed (*C. odorata*) were estimated using SR, EC, FVand SLS methods. The performance of the three SR analysis approaches were evaluated for unstable conditions using four time lags r = 0.1, 0.4, 0.5, and 1.0 s. The best results were obtained using the empirical SR method with regression slopes of 0.89 and root mean square error (RMSE) values less than 30 W m^{-2} at measurement height z = 2.85 and 3.60 m above the soil surface for time lag r = 1.0 s. Half-hourly H_{SR} estimates using r = 1.0 s showed very good agreement with the FV and SLS estimates. The SR latent energy flux, estimated as a residual of the energy balance λE_{SR}, using time lag r = 1.0 s provided good estimates of λE_{EC}, λE_{FV}, and λE_{SLS} for z = 2.85 and 3.60 m.

The performance of the three SR analysis approaches for estimating sensible heat flux above an Outeniqua Yellow wood stand, were evaluated for stable and unstable conditions. Under stable conditions, the SR analysis approach using the micro-front time produced more accurate estimates of H_{SR} than the other two SR analysis approaches. For unstable conditions, the SR analysis approach based on structure functions, corrected for α using EC comparisons produced superior estimates of H_{SR}. An average value of 0.60 is found for α for this study for measurements made in the roughness sublayer. The SR latent energy flux density estimates λE_{SR} using H_{SR} based on structure function analysis gave very good estimates compared with eddy covariance (λE_{EC}) estimates, with slopes near 1.0 and RMSE values in the range of 30 W m^{-2}. The λE_{SR} estimates computed using the SR analysis approach using the micro-front time also gave good estimates comparable to λE_{EC}.

The SR and EC methods were used to estimate long-term sensible heat and latent energy flux over a fetch-limited heterogeneous surface (*J. curcas*). The results show that it is possible to estimate long-term sensible heat and latent energy fluxes using the SR and EC methods over *J. curcas*. Continuous measurements of canopy height and leaf area index measurements are needed to determine α. The weighting factor α was approximately 1 for placement heights between 0.2 and 0.6 m above the *Jatropha* tree canopy. The daily sensible heat and latent energy flux estimates using the SR analysis gave excellent estimates of daily EC sensible heat and latent energy fluxes.

Measurements of sensible heat and estimates of the latent energy fluxes were made for a small reservoir, using the SR and EC methods. The SR sensible heat flux H_{SR} estimates were evaluated using two air temperature time lags r = 0.4 and 0.8 s at 1.0, 1.3, 1.9, 2.5 m above the water surface. An average α value of 0.175 for time lag r = 0.4 s and 0.188 for r = 0.8 s was obtained. The H_{SR} and H_{EC} estimates were small (-40 to 40 W m^{-2}). The heat stored in water was larger in magnitude (-200 to 200 W m^{-2}) compared to the sensible heat flux. The SR and EC latent energy fluxes were almost the same in magnitude as the available energy, due to the small values of the sensible heat fluxes. The daily evaporation rate ranged between 2.0 and 3.5 mm during the measurement period.

The SR method can be used for routine estimation of sensible heat and latent energy fluxes with a reliable accuracy, over a variety of surfaces: short canopies, tall canopies, heterogeneous surface, and open water surface, if the weighting factor α is determined. Alternatively, the SR method can be used to estimate sensible heat flux which is exempt from calibration using the other two SR analysis approaches, with additional measurement of wind speed for estimating friction velocity iteratively. The advantages of the SR method over other micrometeorological methods are the relatively low cost, easy installation and maintenance, relatively low cost for replicate measurements. These investigations may pave the way for the creation of evaporation stations from which real-time and sub-hourly estimates of total evaporation may be obtained relatively inexpensively.

General conclusions and recommendations for future research

Conclusions

The main aim of this research is to estimate sensible heat flux density over a range of representative surfaces using the surface renewal (*SR*) method and make comparison with measurements obtained using the eddy covariance (*EC*) method. The SR method for estimating sensible heat flux and the shortened energy balance equation allows the latent energy flux to be estimated as a residual term, using additional measurement of net irradiance and soil heat flux density. For this calculation, advection fluxes, canopy stored heat, and the energy fluxes associated with photosynthesis and respiration are ignored. Surface renewal analysis for estimating sensible heat flux from canopies involves high frequency air temperature measurements using fine-wire thermocouples. Other methods used for comparison purposes are the Bowen ratio (*BR*), flux variance (*FV*), and surface layer scintillometry (*SLS*) methods. The FV method is also based on high frequency air temperature measurements.

There are three SR analysis approaches: an ideal SR analysis model based on structure function analysis; SR analysis model with a finite micro-front period; and empirical SR analysis model based on similarity theory. The ideal SR analysis model based on structure function analysis must be calibrated against another standard method, such as the EC method to determine the correction or weighting factor α, to account for unequal heating or cooling of air parcels below the air temperature sensor height. The weighting factor α, depends on measurement height above the soil surface z, canopy structure and on thermocouple size. Therefore, the weighting factor α should be known for a specific canopy. For this study, the SR method was used over a range of representative surfaces, such as grassland, Triffid weed (*Chromolaena odorata*), Outeniqua Yellow wood forest (*Podocarpus Falcatus*), *Jatropha curcas*, and open water surface, and α is determined for each surface. The other two SR analysis methods, are exempt from calibration, but they need the extra measurement of wind speed to estimate the friction velocity iteratively.

To meet the specific objectives of this research, high frequency air temperature data were collected at four measurement heights over an open and mixed grassland, to estimate sensible heat flux density using the SR analysis for time lags r = 0.25 s and r = 0.50 s, during unstable atmospheric conditions at four measurement heights: z_1= 0.5 m, z_2= 0.8 m, z_3= 1.0 m, and z_4 = 1.5 m above grass canopy surface. The ideal SR analysis model based on structure function analysis technique from Van Atta (1977) was used to estimate sensible heat flux H_{SR}. The correction factor α was close to 1.0 at 0.5 m above the canopy and decreased for the other three measurement heights. The measurements show very good agreement between the surface renewal sensible heat flux density H_{SR} estimates at 0.5 m above the canopy and the eddy covariance sensible heat flux density H_{EC} estimates. Good agreement for the other three heights (0.8, 1.0, 1.5 m) between H_{SR} and H_{EC} is also obtained with a coefficient of determination greater than 0.8, but there was bias with the slopes different from 1. The H_{SR} measurements at 0.5 m above the canopy also showed good agreement compared to the sensible heat flux density obtained using the Bowen ratio H_{BR} and surface layer scintillometer H_{SLS} estimates. The H_{SR} estimates at 0.5 m above the grass canopy provided accurate estimates of latent energy flux density λE_{SR} when used with measured net irradiance and soil heat flux density.

The performance of the three SR analysis approaches were evaluated for unstable conditions using four time lags r = 0.1, 0.4, 0.5, and 1.0 s over alien invasive plant, Triffid weed (*C. odorata*) at 2.30, 2.85, and 3.60 m above the soil surface. The SR sensible heat flux H_{SR} computed using r = 0.1 and 0.4 s provided poor estimates of sensible heat flux with bias. The SR sensible heat flux closest to the canopy top, at 2.30 m above the soil surface underestimated the EC sensible heat flux estimates. The best results were obtained using the empirical SR method with regression slopes of 0.89 and root mean square error (RMSE) values less than 30 W m^{-2} at 2.85 and 3.60 m using time lag r = 1.0 s.

The empirical SR analysis based on similarity theory is also compared with two MOST based methods, FV and SLS methods in the roughness sublayer over *C. odorata*. Generally, MOST effectively predicts mean and turbulent statistics in the inertial sublayer where fluxes are approximately constant. For this experiment, all measurements were made in the roughness sublayer where the applicability of MOST fails. However, turbulent fluxes can be normalized for the roughness sublayer. Sensible heat and latent energy flux estimates obtained using the empirical SR method were compared with the FV and SLS estimates in the roughness sublayer under unstable conditions and free convection limit. The FV and SLS measurements normalized for the roughness sublayer performed well in estimating the sensible heat and latent energy fluxes at 2.85 and 3.60 m above the soil surface. The free convection limit of the empirical SR analysis also performed very well in estimating the sensible heat flux. The use of the free convection limit of the empirical SR method under slightly unstable conditions has an advantage, since it only requires the high frequency air temperature data. Generally, the results show that there is good agreement between the SR sensible heat and latent energy fluxes using a time lag, r = 1.0 s and the EC, FV and SLS measurements.

To test the performance of the SR analysis over tall canopies, three sets of experiments were carried out for estimating sensible heat and latent energy flux over 10-m high Outeniqua Yellow wood stand at three measurement heights above the canopy using the SR and EC methods. The performance of the three SR analysis approaches in estimating the sensible heat flux density is also evaluated for stable and unstable atmospheric conditions using four time lags r = 0.1, 0.4, 0.5, and 1.0 s. The weighting factor α was determined by plotting H_{SR} against H_{EC} estimates. An average value of 0.60 is obtained for α over Outeniqua Yellow wood forest for measurements made in the roughness sublayer. Under stable conditions, the SR analysis model with finite micro-front period produced better estimates of H_{SR}. For unstable conditions, the SR analysis model based on structure function analysis corrected for α produced superior estimates of H_{SR}, using a time lag r = 1.0 s. The SR latent energy flux estimates λE_{SR} based on structure function analysis gave very good estimates of λE_{EC}. In general, the agreement between the SR sensible heat and latent energy flux estimates and EC estimates are good.

The SR and EC methods were used to estimate sensible heat and latent energy flux over *J. curcas* (Physic nut) trees planted in rows. The objective was to test the SR method over a heterogeneous surface and to investigate the applicability of the SR analysis for a long-term sensible heat and total evaporation estimation. The results show that it is possible to estimate long-term sensible heat and latent energy fluxes using the SR and EC methods over heterogeneous canopies. Continuous measurements of canopy height and leaf area index measurements are needed, especially for long-term studies over fast growing trees to determine the weighting factor α, for the SR method. The weighting factor, α was approximately 1 for heights between 0.2 and 0.6 m above the Jatropha tree canopy. The daily sensible heat and latent energy flux estimates using the SR analysis gave excellent estimates of daily EC sensible heat and latent energy fluxes. Seasonal estimates of total evaporation using the EC and SR methods were investigated, spanning a period of almost two years. Total evaporation (*ET*) estimates tracked the trend of fluctuation of the available energy. The available energy and ET varied with time throughout the day and from day to day. Total evaporation estimates were at peak in summer (with an average daily amount of greater than 3 mm). In summer, ETestimates were mainly dictated by the available energy flux, often varying from one day to the next due to the influence of clouds. In winter, the daily ET estimates from the *Jatropha* trees were very low, with an average daily amount of less than 1 mm.

A footprint analysis was made to investigate the relative contribution of upwind surface sources to the measured downwind sensible heat and latent energy fluxes, as the measurements were made in a plot with limited fetch. The estimated footprint, peak location of the footprint, and the cumulative fraction of the measured flux to surface source flux ratio were calculated. The results showed that 81 % of the measured flux was coming from the upwind fetch distance of 40 m for a cloudy day, and 90 % for a clear day. The high ratio of the measured flux F to surface source flux S_0 values – generally close to 80 % for the fetch-limited *J. curcas* site, is surprising. Therefore, an important recommendation for future research is that these footprint calculations should be confirmed using other footprint models for this site.

The use of the SR method for estimating sensible heat flux and open water evaporation from a shallow dam was also investigated. The SR method, to the author's knowledge, has not been tested over open water surfaces. The aim of this study is therefore to calibrate the sensible heat flux obtained using the SR method against measurements obtained using the EC method. The calibration factor, α for each height and time lag was determined from the slope of linear regression forced through the origin of measured H_{EC} values *vs* H_{SR}. Average α values of 0.175 for time lag, r = 0.4 s and 0.188 for r = 0.8 s were obtained for open water surface from this study. The sensible heat flux values were extremely small for all days during the measurement period. The stored heat in water was much larger in magnitude compared to the sensible heat flux values. Therefore, the stored heat in water plays an important role in the energy balance and evaporation estimation of shallow water bodies. The SR and EC latent energy fluxes were almost the same in magnitude as the available energy flux, due to the small values of the sensible heat fluxes. The daily total evaporation ranged between 2.0 and 3.5 mm.

The study has confirmed that the SR method can be used for routine estimation of sensible heat and latent energy fluxes with a reliable accuracy, over a variety of surfaces: short canopies, tall canopies, heterogeneous surface, and open water surface. The SR method offers a relatively simple, low cost, and accurate estimate of sensible heat and, together with net irradiance and soil heat flux, the latent energy flux, if the weighting factor α is determined. The weighting factor α, once determined, is unlikely to change with weather conditions unless there are significant changes in the vegetation canopy structure. If there is a change in canopy structure, recalibration of the SR method is needed. However, this can be done easily since measurements can be replicated inexpensively. Alternatively, the SR method can be used to estimate sensible heat flux which is exempt from calibration using the other two SR analysis approaches, with the additional measurement of wind speed for estimating friction velocity iteratively. Short time lags (r < 0.5 s) are recommended for short canopies while for tall canopies longer time lags (r > 0.5 s) should give good estimates of sensible heat and latent energy fluxes. The advantages of the SR method over other micrometeorological methods are the relatively low cost, easy installation and maintenance, relatively low cost for replicate measurements, and the SR method is less dependent on fetch since it is based on the theory of short-term heat transfer between a surface and air parcels passing through the surface.

Recommendations for future research

The search for methods for estimating sensible heat and latent energy flux (evaporation) using simple, inexpensive, and portable methods, has been the subject of interest in the past few decades. The SR method has the advantage over other micrometeorological methods since it requires only measurement of the scalar of interest at one point. Therefore, the SR method can offer a relatively simple, low-cost, and accurate estimate of sensible heat flux. The SR method has been mostly used for estimating sensible heat flux over different surfaces, and the latent energy flux is obtained as a residual of the energy balance equation. Most of the studies have focused on the determination of the weighting factor α, and analysing the performance of the SR sensible heat flux.

The SR analysis can be applied to other scalars such as water vapour, carbon dioxide, and other gases. However, there has been little research on the application of the SR analysis to estimate the flux of other scalars. Therefore, further studies should focus on the use of the SR method to estimate fluxes of water vapour, carbon dioxide, and other scalars. Also, the *SR* method applied here does not allow real-time estimation of sensible heat flux and further research on this aspect would be valuable.

SENSIBLE HEAT FLUX AND EVAPORATION FOR SPARSE VEGETATION USING TEMPERATURE-VARIANCE AND A DUAL-SOURCE MODEL

by

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ABSTRACT

The high population growth rate and rapid urbanization that the world is experiencing today has aggravated the competition for the already scarce resource – water – between the agricultural sector and the other economic sectors. Moreover, within the agricultural sector, water is increasingly being used for commercial plantations as opposed to growing food crops, threatening food security. Therefore, it is very important that this scarce resource is managed in an efficient and sustainable manner, for now and future use. This requires understanding the process of evaporation for accurate determination of water-use from agricultural lands. In the past, direct measurements of evaporation have proven difficult because of the cost and complexity of the available equipments, and level of expertise involved. This justifies a quest for relatively simple, accurate and inexpensive methods of determining evaporation for routine field applications. Estimation of sensible heat flux (H) from high frequency air temperature measurements and then calculating latent energy flux (λE) and hence evaporation as a residual of the shortened surface energy balance equation, assuming that closure is met, is appealing in this sense. Concurrent net irradiance (R_n) and soil heat flux (G) measurements can be conducted with relative ease for use in the energy balance equation. Alternately, evaporation can also be mathematically modelled, using single- or multi-layer models depending on vegetation cover, from less expensive routine meteorological observations. Therefore, the ultimate objective of this study is to estimate and model H and λE, and thereby evaporation, accurately over sparsely vegetated agricultural lands at low cost and effort.

Temperature-variance (TV) and surface renewal (SR) methods, which use high-frequency (typically 2 to 10 Hz) air temperature measurements, are employed for estimation of H. The TV method is based on the Monin and Obukhov Similarity Theory (MOST) and uses statistical measures of the high frequency air temperature to estimate H, including adjustments for stability. The SR method is based on the principle that an air parcel near the surface is renewed by an air parcel from above and, to determine H, it uses higher order air temperature differences between two consecutive sample measurements lagged by a certain time interval. Single- and double-layer models that are based on energy and resistance combination theory were also used to estimate evaporation and H from sparse vegetation. Single- and double-layer models that were extended to include inputs of radiometric temperature in order to estimate H were also used. The transmission of solar irradiance to the soil beneath in sparse canopies is variable and depends on the vegetation density, cover and apparent position of the sun. A three-dimensional radiation interception model was developed to estimate this transmission of solar irradiance and was used as a sub-module in the double-layer models. Estimations of H from the TV (H_{TV}), SR (H_{SR}) and double-layer models were compared against H obtained from eddy covariance (H_{EC}), and the modelled λE (single- and double-layer) were compared with that obtained from the shortened energy balance involving H_{EC}. Besides, long-term λE calculated from the shortened energy balance using H_{TV} and H_{SR} were compared with those calculated using H_{EC}.

Unshielded and naturally-ventilated fine-wire chromel-constantan thermocouples (TCs), 75 μm in diameter, at different heights above the ground over sparse *Jatropha curcas* trees, mixed grassland community and bare fallow land were used to measure air temperature. A three-dimensional sonic anemometer mounted at a certain height above the ground surface was also used to measure virtual temperature and wind speed at all

three sites. All measurements were done differentially at 10-Hz frequency. Additional measurements of R_n, G and soil water content (upper 60 mm) were also made.

The Jatropha trees were planted in a 3-m plant and inter-row spacing in a 50 m × 60 m plot with the surrounding plots planted to a mixture of Jatropha trees and kikuyu grass. Average tree height and leaf area index measurements were taken on monthly and bimonthly basis respectively. An automatic weather station about 10 m away from the edge of the Jatropha plot was also used to obtain solar irradiance, air temperature and relative humidity, wind speed and direction and precipitation data. Soil water content was measured to a depth of 1000 mm from the surface at 200 mm intervals. Soil and foliage surface temperatures were measured using two nadir-looking infrared thermometers with one mounted directly above bare soil and the other above the trees.

The three-dimensional solar irradiance interception model was validated using measurements conducted on different trees and planting patterns. Solar irradiance above and below tree canopies was measured using LI-200 pyranometer and tube solarimeters respectively. Leaf area density (*LAD*) was estimated from *LAI*, canopy shape and volume measurements. It was also determined by scanning leaves using either destructive sampling or tracing method.

The performance of the TV method over sparse vegetation of *J. curcas*, mixed grassland community and fallow land was evaluated against H_{EC}. Atmospheric stability conditions were identified using (i) sensor height (z) and Obukhov length (L) obtained from EC and (ii) air temperature difference between two thermocouple measurement heights. The H_{TV} estimations, adjusted and not adjusted for skewness (actual and estimated) of air temperature (s_k), for unstable conditions only and for all stability conditions were used. An improved agreement in terms of slope, coefficient of determination (r^2) and root mean square error (*RMSE*), almost over all surfaces, was obtained when the temperature difference rather than the z/L means of identifying stability conditions was used. The agreement between the H_{TV} and H_{EC} was improved for estimations adjusted for actual s_k than not adjusted for s_k. Improved agreement was also noted when H_{TV} was adjusted using estimated s_k compared to not adjusting for s_k over *J. curcas*. The TV method could be used to estimate H for surfaces with varying homogeneity with reasonable accuracy.

Long-term water-use of a fetch-limited sparse vegetation of *J. curcas* was determined as a residual of the shortened surface energy balance involving H_{TV} and H_{SR} and compared with those estimated using H_{EC}. Concurrent measurements of R_n and G were also performed. The long-term water-use of *J. curcas* trees calculated from the shortened surface energy balance involving H_{TV} and H_{SR} agreed very well when compared with those obtained from H_{EC}. The seasonal H_{TV} and H_{SR} also agreed very well when compared with H_{EC}. Changes in structure of the canopy and environmental conditions appeared to influence partitioning of the available energy into H and λE. The seasonal total evaporation for the EC, TV and SR methods amounted to 626, 640 and 674 mm respectively with a total rainfall of 690 mm. Footprint analysis also revealed that greater than 80% of the measured flux during the day originates from within the surface of interest. The TV and SR methods, therefore, offer a relatively low-cost means for long-term estimation of H, and λE, hence the total evaporation, using the shortened surface energy balance along with measurements of R_n and G.

Evaporation and biomass production estimations from tree crops requires accurate representation of solar irradiance transmission through the canopy. A relatively simple three-dimensional, hourly time-step tree-canopy radiation interception model was developed and validated using measurements conducted on isolated trees, hedgerows and tree canopies arranged in tramline mode. Measurements were obtained using tube solarimeters placed 0.5 m from each other starting from the base of a tree trunk in four directions, along and perpendicular to the row up to mid-way between trees and rows. Model-simulations of hourly radiant transmittance were in good agreement with measurements with an overall r^2 of 0.91; Willmott's index of agreement of 0.96; and general absolute standard deviation of 17.66%. Agreement between model-estimations and measurements, however, was influenced by distance and direction of the node from the tree trunk, sky conditions, symmetry of the canopy, and uniformity of the stand and leaf distribution of the canopy. The model could be useful in planning and management applications for a wide range of tree crops.

Penman-Monteith (PM) equation and the Shuttleworth and Wallace (SW) model, representing single- and dual-source models respectively, were used to determine the total evaporation over a sparse vegetation of *J. curcas* from routine automatic weather station observations, resistance parameters and vegetation indices. The three-dimensional solar irradiance interception model was used as a sub-module in the SW model. The total evaporation from the sparse vegetation was also determined as a residual of the shortened surface energy balance using measurements of R_n, G and H_{EC}. The PM equation failed to reproduce the 'measured' daily total evaporation during periods of low *LAI*, with improved agreement with increased *LAI*. The SW model, however, produced total evaporation estimates that agreed very well with the 'measured' with a slope of 0.96, r^2 of 0.91 and *RMSE* of 0.45 mm for a *LAI* ranging from 0 (no leaves) to 1.83 m^2 m^{-2}. The SW model also estimated soil evaporation and plant transpiration separately, and about 66 % of the cumulative evaporation was attributed to soil evaporation. These findings suggest that the PM equation should be replaced by the SW model for surfaces that assume a range of *LAI* values during the growing season.

The *H* was estimated using (i) SW model that was further developed to include surface radiometric temperature measurements; (ii) one-layer model, but linked with a two-layer model for estimation of excess resistance, that uses surface radiometric temperature; and (iii) the SW model (unmodified). The agreement between modelled and measured *H*, using 10-min data, was in general reasonably good with *RMSE* (W m^{-2}) of 45.11, 43.77 and 39.86 for the three models respectively. The comparative results that were achieved from (iii) were not translated into the daily data as all models appeared to have a tendency to underestimate *H*. The resulting *RMSE*s for the daily *H* data for the three models were (MJ m^{-2}) 1.16, 1.17 and 1.18 respectively. It appears that similar or better agreement between measured and estimated *H* can be forged without the need for surface radiometric temperature measurements.

The study showed, in general, that high frequency air temperature measurements can be used to estimate *H* with reasonable accuracy using the simple and relatively low-cost TV and SR methods. Moreover, these methods can be used to calculate λE, hence *ET*, as a residual of the shortened surface energy balance equation along with measurements of R_n and G assuming that energy balance closure is met. The simple and low-cost nature of these methods makes replication of measurements easier and their robust nature allows long-term measurements of energy fluxes. The study also showed that *H* and λE can be modeled using energy and resistance combination equations with reasonable accuracy. It also reiterated that the SW-type models, which treat the plant canopy and soil components separately, are more appropriate for estimation of H and λE over sparse vegetation as opposed to the PM-type models.

GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

CONCLUSIONS

The main focus of the work was on estimating and modelling sensible heat flux (H) and latent energy flux (λE), and hence total evaporation (ET), accurately using simple low-cost methods. The temperature-variance (TV) and surface renewal (SR) methods that use high frequency (typically 2 to 10 Hz) air temperature measurements, without the need for turbulent wind velocity measurements, were used for estimation of H. From this λE, and hence ET, was calculated as a residual of the shortened surface energy balance involving H from TV (H_{TV}) and SR (H_{SR}) and measurements of net irradiance (R_n) and soil heat flux (G), assuming energy balance closure is met. Single- and double-layer models were also used to estimate ET from routine meteorological observations. Extended versions of these models were used to estimate H using additional inputs of radiometric surface temperature. All estimations of H were compared against H obtained from eddy covariance (H_{EC}); and λE, and hence ET, were compared with those calculated using the residual surface energy balance from measurements of R_n, G and H_{EC}.

The TV method estimated H, using universal constants, over sparse vegetation of *Jatropha curcas*, mixed grassland community and bare fallow land, without and with adjustments for skewness (actual and estimated) of air temperature (s_k) under different atmospheric stability conditions. The atmospheric stability conditions were identified using sensor height (z) and Obukhov length (L) obtained from EC and air temperature difference between two thermocouple measurement heights. Improved agreement in terms of slope, coefficient of determination (r^2) and root mean square error ($RMSE$), over almost all surfaces used, was noted when air temperature difference between two measurement heights rather than the z/L criterion of identifying stability conditions was used. The near-neutral H_{TV} values were not reproduced very well. The H_{TV} estimates adjusted for actual s_k resulted in better agreement in terms of slope and $RMSE$ for almost all surfaces compared to those not adjusted or adjusted using estimated s_k within the respective means of identifying stability condition of the atmosphere when compared with H_{EC}. The r^2 barely changed whether adjustments for s_k were made or not. Also, H_{TV} adjusted for estimated s_k showed an improved agreement over the unadjusted estimates. This suggests that H_{TV} estimates should be adjusted for actual s_k when available, and for estimated s_k in the absence of actual s_k. The TV method offers a reasonably accurate and relatively low-cost means of estimating H over variety of different surfaces.

Season-long high frequency air temperature data collected over *J. curcas* allowed estimation of seasonal H using the TV and SR methods. This enabled seasonal λE, and hence ET, to be calculated as a residual of the shortened surface energy balance equation along with measurements of R_n and G. The seasonal estimates of H and ET from the TV and SR methods agreed reasonably well with those obtained from EC. The SR method needs calibration but gives more accurate estimates, and hence is less suitable for routine applications; whereas the TV method can use universal constants which give less accurate estimates – but is more suitable for routine application compared to SR method. Overall, the seasonal ET total for the EC, TV and SR methods were 626, 673 and 640 mm respectively with a total rainfall of 690 mm. Energy flux and rainfall thorough the season also revealed that ET is governed by the available energy, rainfall amount and vegetation canopy structure. The ET increased with increases in R_n and leaf area index (LAI) and vice versa. A footprint analysis also indicated that greater than 80% of the measured *H* under most atmospheric stability conditions originated from the surface of interest. These findings ensure that *H* can routinely be estimated over vegetation surfaces with reasonable accuracy from high frequency air temperature measurements using the relatively low-cost TV and SR methods. Long-term water-use can then be calculated as a residual of the shortened surface energy balance along with measurements of R_n and *G* assuming that energy balance closure is met.

The Penman-Monteith (PM) equation and the Shuttleworth and Wallace (SW) model, representing single- and double-layer models respectively, were used to determine evaporation from sparse vegetation of *J. curcas*. Routine meteorological observations, vegetation indices and/or soil water content were used as inputs in both cases. The double-layer SW model used a three-dimensional solar irradiance interception as sub-model to determine the available energy above and below the plant canopy. Model estimates of evaporation were compared with those obtained as a residual of the energy balance equation from measurements of R_n, *G* and H_{EC}. The PM equation significantly underestimated total evaporation during the stages when the trees had small or zero *LAI*, with improved agreement with increased *LAI*. This was because of lack of appropriate representation of soil surface resistances in the PM equation. The total evaporation from the SW model, however, agreed very well with measurements with a slope of 0.96, r^2 of 0.91 and *RMSE* of 0.45 mm for the range of *LAI* encountered during the experiment. The explicit representation of surface resistance parameters also allowed the SW model to estimate the soil evaporation and plant transpiration separately. The model results indicated that soil evaporation was the sole contributor at low *LAI* and continued to contribute significantly to the total evaporation as long as the soil was not fully covered covered by the vegetation. About 66% of the modelled cumulative evaporation for the study period was attributed to soil evaporation. For the time period when the trees had no leaves until they attained a *LAI* of approximately 1.4 m^2 m^{-2}, the modelled soil evaporation was about 84% of the total evaporation. For a *LAI* ranging between 1.4 and 1.83 m^2 m^{-2}, the modelled soil evaporation accounted for about 52% of the total evaporation. As the canopy starts to close the SW model aligns more closely with the PM equation, hence the difference in total evaporation between the PM equation and the SW model at the latter stages of the experiment was smaller. The findings of this study suggest that the PM-type models should be superceded by the SW-type models for long-term modelling of evaporation over sparse vegetation surfaces.

Extended versions of the SW model were also used to estimate *H* and/or its component parts over sparse *J. curcas* trees. The *H* was determined using (i) double-layer SW model requiring either separate or composite additional surface temperature input, (ii) linked one- and two-layer model, requiring additional composite surface radiometric temperature input and (iii) double-layer SW model without the need for surface radiometric temperature measurement. The models in (ii) and (iii) required a three-dimensional solar irradiance interception as a sub-model to estimate the available energy above and below the plant canopy in order to estimate *H*.

Using model (i), the modelled and measured *H* agreed reasonably well with *RMSE* of 45 W m^{-2} for 10-min and 1.16 MJ m^{-2} for daily data. There was no significant difference in the modelled *H* whether separate or composite surface temperature inputs were used. In fact, it was found that using the composite surface temperature as input based on the soil and foliage area coverage had no bearing on the outcome of the total *H*. It was the temperature difference between the soil surface and reference height as corrected by the temperature difference between the soil and foliage that was important in estimating *H*.

Model (ii) required an excess resistance in the form of r_r due to the replacement of the aerodynamic temperature by radiometric temperature in the classic flux-gradient equation. The results achieved from this model were similar to those achieved from (i) both in terms of the scatter-plots and statistics with *RMSE* of 44 W m^{-2} for 10-min and 1.17 MJ m^{-2} for daily data. Both models underestimated higher values of *H* when the *LAI* was small, with improved agreement for higher values of *H* when the *LAI* was larger. The additional complexity of model (ii) was not translated into improved agreement compared to results achieved from model (i).

Using model (iii), the agreement between modelled and measured *H* for the 10-min data was better (*RMSE* of 40 W m^{-2}) than for the other two models which used surface radiometric temperature measurements, but this was not reflected in the daily data (*RMSE* of 1.18 MJ m^{-2}). The daily trend also exhibited, contrary to the models that used additional surface temperature inputs, a good agreement when leaves were absent or the *LAI* was small, but underestimation when *LAI* was relatively larger.

In general, all three models showed a tendency to underestimate *H*. This will have the opposite effect (overestimate) in *λE*, and hence *ET*, calculated as the residual term of the shortened surface energy balance equation. The model which did not use extra surface temperature measurements also produced similar or better agreement between modelled and measured *H* compared to models that used surface temperature measurements.

Evaporation and biomass production from sparse vegetation requires accurate estimation of the available energy above and below the canopy. This was needed to be addressed in the double-layer SW models so far used (except for the one that estimated *H* using additional surface temperature inputs). A relatively simple three-dimensional solar irradiance model was developed and validated using data sets comprising different canopy characteristics (canopy size and leaf area density), row orientations, row and tree spacing and sky conditions for use in the double-layer SW models.

Measurements of solar irradiance above and below the canopy were made using LI-200 and tube solarimeters respectively. The tube solarimeters were placed 0.5 m from each other starting from the base of a tree trunk in four directions, along and perpendicular to the row up to mid-way between trees and rows. Comparison of modelled and measured hourly transmitted solar irradiance was performed for each node. In general, the model reproduced the spatial and temporal variation of hourly solar irradiance transmission of the tree crops for each node for a range of model input parameters very well. An overall average of r^2 = 0.91, Willmott's index of agreement, *d* = 0.96 and general absolute standard deviation, *GASD* = 17.66% was obtained for measurements conducted on isolated tree crowns, hedgerows and tree canopies arranged in tramline mode. An improved agreement between modelled and measured values was noted for nodes located further from than near to the tree trunk and in north than in the south side of the tree trunk (in southern hemisphere). The agreement was also improved for overcast than for clear sky conditions when same node locations under similar canopy characteristics were compared. Tree trunks (especially for trees with low *LAI*), leaves and branches in close proximity with tube solarimeters, asymmetrical canopy shapes, and non-uniform tree canopy sizes and leaf distribution violate the basic assumptions of the model and hence affected its performance negatively. The model was successfully used as a sub-module in the double-layer SW model for estimating *ET* and *H*.

Competition

The toxicity of the plant's vegetative structures has not been thoroughly investigated (Abdel Gadir *et al*., 2003) although phorbol esters (Giibitz *et al*., 1999; Matsuse *et al*., 1999) and cyanogenic glycosides that liberate hydrogen cyanide (HCN) (Frohne and Pfander, 2005) are thought to be the major toxic components. Although the leaves and stems have been found poisonous to fish (Watt and Breyer-Brandwijk, 1962), no examples of conditions suffered by other animals, which ingested the vegetative plant parts, were found in the covered literature.

RECOMMENDATIONS FOR FUTURE RESEARCH

Most H_{TV} estimations are performed for unstable atmospheric conditions. Hence identification of atmospheric stability is of utmost importance. Therefore, more rigorous means of identifying stability conditions, other than through the air temperature difference between two heights that is used in this study, that do not involve complex measurements is still needed. In this regard, air temperature structure function that is employed in the surface renewal method might be a viable option. This study has also shown that estimates under stable and neutral conditions are promising and hence future research should concentrate on finding appropriate constants or refining the existing ones.

Future studies should also concentrate on the right height of air temperature sensor/s deployment above the ground and/or vegetation for H_{TV} computations. Theoretically, H_{TV} estimations should be conducted from sensors mounted in the inertial sublayer as the method is MOST based, but equally good or better results have been obtained from sensors mounted in the roughness sublayer. The issue of identifying the heights of the roughness and inertial sublayers for a given surface has also a huge effect on H_{TV} estimations, and hence requires due attention.

High frequency air temperature measurements, ranging from 2 to 10 Hz, are traditionally used for H_{TV} estimations. H_{TV} estimations from different air temperature measurement frequencies should be conducted to establish the minimum data frequency required for H_{TV} estimation without compromising accuracy.

The mathematical computations that are involved in the SR equation have prohibited its adoption by the agricultural community for determination of *H* and λE, and therefore, the equations involved need to be simplified to be of use to the average agriculturalist. Besides, the equations that are involved sometimes fail to find a real solution resulting in a loss of data. Iterative procedures that are promising in this regard are developed and should be used in place of the traditionally used program or spreadsheet (M J Savage, pers. comm., 2009). More importantly future studies should concentrate on elimination of the need for calibration of the SR method against standard measurements.

In terms of estimating water-use, research should focus on using the TV and SR methods to determine evaporation directly from high frequency water vapour measurements. Moreover, the usefulness of these methods for estimation of other fluxes or trace gases like carbon dioxide and methane should be explored.

It is established here that the SW-type models should be used for sparse vegetation. However, these models require more detailed knowledge of the resistance parameters and simple means of acquiring these resistance parameters should be developed in the future. Adequate representation of the combined soil and plant resistance also poses a challenge in using the PM-type equations successfully for sparse vegetation, and hence deserves some attention. The applicability of the Priestley-Taylor equation for such vegetation cover should also be evaluated in line with the PM equation and SW model.

The challenge in using a one dimensional radiation interception model in sparse vegetation is in finding an extinction coefficient that adequately accounts for the leaf grouping and clumping that are inherent to such vegetation surfaces. Future radiation interception models should consider developing a simple methodology that adequately determines the extinction coefficient for sparse vegetation.

The estimated (TV and SR methods) and modelled evaporation in this study were compared with total evaporation obtained as a residual of the shortened surface energy balance equation, assuming closure is met, from measurements of R_n, G and H_{EC}. In the future, comparisons of estimates should be made against more direct measurements of evaporation. Solving the issues surrounding the surface energy balance closure and underestimation of surface fluxes by the EC method would also be invaluable in validating the TV and SR methods, and the SW model. Moreover, the soil evaporation and plant transpiration partitioned using the double-layer SW model should be tested further using independent measurements, for example – microlysimetric and sap-flow methods respectively. Finally, the feasibility of coupling, integrating or linking the double-layer SW and the three-dimensional radiation interception models with soil water balance and growth models to create a complete tree growth model should be investigated.

A SIMPLE THREE-DIMENSIONAL SOLAR RADIATION INTERCEPTION MODEL FOR TREE CROPS

M.G. Abraha and M.J. Savage

ABSTRACT

Solar radiation is a fundamental parameter in estimating evapotranspiration and dry matter production from agricultural fields. A three-dimensional, hourly time-step canopy radiation interception model which considers the earth-sun relationship, the geometry of the plant canopy, planting pattern, row orientation and solar radiation transfer equations to simulate canopy radiant transmittance through tree crops is developed. The model assumes that trees are elliptical in shape with uniform leaf distribution, and that radiation attenuation within the canopy follows Beer's law. Transmittance of direct and diffuse radiation is calculated separately. In order to determine the solar radiation at a certain point, the model calculates the path length traversed through the tree canopy. Radiation can be obstructed by neighbouring trees, so five rows of trees with five trees within each row with the tree of interest at the centre were considered. Inputs of geographic location, altitude, row orientation, row and tree spacing, canopy size, extinction coefficient and incident solar radiation are required. Tube solarimeters were placed 0.5 m from each other starting from the base of a tree trunk in four directions, along and perpendicular to the row up to mid-way between trees and rows. Model validation was carried out for each node using a wide range of input parameters. Planting patterns encompassing isolated trees, hedgerows and tree canopies arranged in tramline mode were used. Model-simulations of hourly radiant transmittance were in good agreement with measurements with an overall coefficient of determination, r^2 = 0.91; Willmott's index of agreement, *d* = 0.96; and general absolute standard deviation, *GASD* = 17.66%. Agreement between measurements and model-simulations, however, appeared to be influenced by distance and direction of the node from the tree trunk, sky conditions, symmetry of the canopy, and uniformity of the stand and leaf distribution of the canopy. This three-dimensional solar radiation interception model could be used in planning and management applications for a wide range of tree crops.

Keywords: Model; Canopy; Solar radiation interception/transmission; Leaf area density

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ENERGY AND MASS EXCHANGE OVER INCOMPLETE VEGETATION COVER

Abraha, M.G. and M.J. Savage

ABSTRACT

Competition for fresh water between agriculture and domestic and industrial uses is increasing worldwide. This is forcing subsistence and commercial agriculture to produce more with less water. Consequently, it is crucial to properly and efficiently manage water resources. This requires accurate determination of crop water loss into the atmosphere, which is greatly influenced by the exchange of energy and mass between the surface and the atmosphere. Measurement of these exchange processes can best be accomplished by micrometeorological methods. However, most micrometeorological methods are very expensive, difficult to set-up, require extensive post-data collection corrections and/or involve a high degree of empiricism. This review discusses estimation of evapotranspiration using relatively inexpensive micrometeorological methods in temperature-variance (TV), surface renewal (SR) and mathematical models. The TV and SR methods use high frequency air temperature measurements above a surface to estimate sensible heat flux (*H*). The latent heat flux (λE), and hence evapotranspiration, is calculated as a residual of the shortened surface energy balance using measured or estimated net radiation and soil heat flux, assuming surface energy balance closure is met. For crops with incomplete cover, the disadvantage of these methods is that they do not allow separation of evapotranspiration into soil evaporation and plant transpiration. The mathematical models (single- and dual-source) involve a combination of radiation and resistance equations to determine evapotranspiration from inputs of automatic weather station observations. Single-source models (Penman-Monteith type equations) are used to determine evapotranspiration over homogeneous surfaces. The dual-source models, basically an extension of single-source models, determine soil evaporation and plant transpiration separately over heterogeneous or sparse vegetation. These mathematical models have also been modified to accommodate inputs of remotely-sensed radiometric surface temperatures that enable estimation of evapotranspiration on a regional and global scale.

KEY WORDS: micrometeorology, temperature-variance, surface renewal, Penman-Monteith, dual-source models, surface energy balance, sensible heat flux, evapotranspiration, latent heat flux, eddy covariance, Bowen ratio energy balance, crop water-use, remote sensing

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STRATEGIES TO IMPROVE SEED PRODUCTION IN *JATROPHA CURCAS* – A POTENTIAL SEED OIL CROP FOR BIODIESEL

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ABSTRACT

Interest in planting *Jatropha curcas* L. for the production of biodiesel is growing exponentially. The properties of the crop and its oil have persuaded investors to consider *J. curcas* oil as a substitute for fossil fuels. However, this plant is still undomesticated, basic agronomic properties are not thoroughly understood and the environmental effects on growth have not been investigated. This thesis investigated different approaches that may contribute to improving the productivity of this plant.

Seed germination and methods of propagation are usually the first consideration in any plant development programme. The effects of aerosol smoke, smoke water, potassium nitrate, naphthalene acetic acid and indole-3-butyric acid on germination and seedling growth of *J. curcas* were investigated. Seed coat removal accelerated water imbibition and germination occurred within 48 h. Seeds exposed to aerosol smoke failed to germinate over the whole study period of three months. There were no significant differences in total germination between the treatments and the untreated control (intact- and shelled-seed). However, shelled-seeds had a shorter mean germination time. The seedlings were subsequently sown in trays under shade house conditions and different seedling growth traits measured after three months. Smoke water, potassium nitrate and naphthalene acetic acid produced significantly heavier seedlings with longer stems and roots, wider stems and a higher vigour index compared to the control treatments. Smoke water, potassium nitrate and naphthalene acetic acid stimulated seedling growth and vigour of *J. curcas*. This opens the possibility of applying these treatments to produce quality seedlings for large scale planting and accelerated plant establishment in production orchards.

Effective pollination is a prerequisite for many crops to increase seed-set and fruit production. Experiments were conducted to determine factors that could influence seed production in this potential biofuel seed crop. Controlled pollination experiments showed that plants required pollinator visits for seed production and were genetically self-compatible. Pollen-supplementation did not lead to increased fruit set, suggesting that seed production in the study population was not pollen-limited. Both male and female flowers produced nectar and were highly attractive to honeybees. These insects were effective pollinators of *J. curcas*, as shown by experiments in which flowers exposed to single or multiple visits by honeybees set significantly more fruit than those from which visits were precluded. Pollinator-mediated self-pollination led to marginally lower levels of seed production relative to cross-pollination. Progeny from selfed plants had significantly shorter roots than progeny of outcrossed plants. However, in general, there was little evidence of inbreeding depression. The present results provide empirical evidence that honeybees are effective pollinators of *J. curcas*. Fruit arising from self-pollination were almost as numerous and as large as those arising from cross-pollination, suggesting that promotion of cross-pollination does not have to be a priority in orchard management for fruit yield.

Manipulation of pollen development and function is of vital importance for crop development and improvement. Experiments were conducted to investigate pollen viability, *in vitro* pollen germination and *in vivo* pollen tube growth in *J. curcas*. Light and fluorescence microscopy were employed to examine the different developmental stages. It was possible to determine pollen viability and distinguish between fresh and dead pollen using 2,3,5-triphenyltetrazolium chloride (TTC). Pollen germination was

significantly higher in an agar-based medium composed of sucrose, boric acid and calcium nitrate compared with the control treatment (distilled water). Supplementation of IAA to the different media significantly increased pollen germination and pollen length compared with the control treatment. Pollen from hermaphrodite flowers had a lower viability, lower germination rates and shorter pollen tubes, with abnormal shapes, compared to the pollen from male flowers. Pollen tubes from both self- and cross-pollinated flowers entered the ovary within 8 hours after pollination (HAP). However, at 6 HAP, the pollen tube length and growth rate were significantly higher in cross- compared to self-pollinated pollen. Our results suggest that TTC is a reliable test for pollen viability; boric acid, calcium nitrate, sucrose and addition of IAA are essential and beneficial for pollen germination in this plant. Pollen germination and pollen tube growth were not inhibited, nor interfered with, as a result of self-pollination treatments. During, both types of pollination, fertility is maintained as evidenced by ovule penetration by pollen tubes. This suggests that type of pollination has no influence on the success of fertilization in *J. curcas.*

Manual pruning is one of the major management practices in commercial plantations of *J. curcas*, resulting in production of more branches and thus increased potential for more inflorescences leading to a higher seed yield. Experiments were conducted to determine the response of *J. curcas* plants to manual pruning under summer and winter conditions. The results showed that manual pruning under both conditions significantly increased the number of branches per plant. However, there were no significant differences in number of branches between winter and summer manual pruning. Winter pruning, however, had a significantly wider crown diameter compared to the control and summer pruning. Both treatments produced significantly less fruits/per plant in the subsequent season compared to the un-pruned control. This study revealed that winter and summer manual pruning may be suitable practice to promote branching.

Manual pruning, however, is time consuming, labour intensive and expensive. A study was conducted to determine the potential of different plant growth regulators (PGRs) to increase the number of lateral branches of *J. curcas* plants. A single foliar application of BA (benzyladenine) at 12 mmol l^{-1} significantly increased branches in both the pot (4) and field (13.2) trials compared to manual pruning (MP) (1.8 and 5.7 respectively) and control (no new branches) plants. In the field, treatment with TIBA (2,3,5-triiodobenzoic acid) (1 mmol l^{-1}) significantly increased the number of branches (15.9) after seven months from application. Of all the PGRs examined, DK (Dikegulac) (2,3:4,6-di-*O*-isopropylidene-2-keto-L-gulonic acid) at 2 mmol l^{-1} produced the maximum number of branches (18) in the field seven months after application. Concentrations of 2 and 3 mmol I^{-1} of MH (Maleic hydrazide) (1,2-dihydro-3,6-pyridazinedione, coline salt) significantly increased the number of branches, four and seven months after spraying in both the pot trial in the shade house and field respectively. Under field conditions *J. curcas* plants responded better to all the PGRs (DK < TIBA < BA < MH) when treated once, with insignificant variations of other growth parameters. This study indicates that a single foliar application of PGRs under field conditions can be an alternative method to MP for increasing the number of lateral branches of *J. curcas* plants.

The field chemical pruning experiment was continued to determine the potential subsequent effects of the different PGRs on seed production. In the subsequent year following the single foliar application, the parameters of flowering, fruit set, fruit characteristics, total oil content and free fatty acid (FFA) content were evaluated. Number of flowers per plant and number of fruits per bunch were significantly affected by the different treatments. However, there were no variations in the degree of fruit set. A single foliar application of BA (6-benzylaminopurine) produced more flowers per plant, more fruits per bunch, heavier and bigger fruits and seeds with more oil compared to MP (manual pruning). TIBA (2,3,5-Triiodobenzoic acid) produced significantly more flowers per plant and heavier fruits compared to the control and MP treatments. However, it produced significantly bigger fruits with more seeds and a higher oil content than MP. DK (Dikegulac) (2,3:4,6-di-*O*-isopropylidene-2-keto-L-gulonic acid) produced more flowers per plant and seeds with high oil content compared to the control and MP. However, it produced more fruit per bunch and more seeds per fruit compared to MP. MH (Maleic hydrazide) produced more flowers per plant, heavier and bigger fruits with numerous, heavier and oil rich seeds compared to the control and MP. This study indicates that foliar application of PGRs can be used in *J. curcas* to increase seed production and improve fruit quality.

LIST OF PUBLICATIONS AND ABSTRACTS:

(A) Publications in peer-reviewed / refereed journals:

(1) Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Pollinator effectiveness, breeding system, and tests for inbreeding depression in the biofuel seed crop, *Jatropha curcas. Journal of Horticultural Science & Biotechnology,* 84, 319-324.

Abstract

Effective pollination is a prerequisite for many crops to increase seed-set and fruit production. Experiments were conducted to determine factors that could influence seed production in this potential biofuel seed crop. Controlled pollination experiments showed that plants required pollinator visits for seed production and were genetically self-compatible. Pollen-supplementation did not lead to increased fruit set, suggesting that seed production in the study population was not pollen-limited. Both male and female flowers produced nectar and were highly attractive to honeybees. These insects were effective pollinators of *J. curcas*, as shown by experiments in which flowers exposed to single or multiple visits by honeybees set significantly more fruit than those from which visits were precluded. Pollinator-mediated self-pollination led to marginally lower levels of seed production relative to cross-pollination. Progeny from selfed plants had significantly shorter roots than progeny of outcrossed plants. However, in general, there was little evidence of inbreeding depression. The present results provide empirical evidence that honeybees are effective pollinators of *J. curcas*. Fruit arising from self-pollination were almost as numerous and as large as those arising from cross-pollination, suggesting that promotion of cross-pollination does not have to be a priority in orchard management for fruit yield.

(2) Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Promoting branching of a potential biofuel crop *Jatropha curcas* L. by foliar application of plant growth regulators. *Plant Growth Regulation*, 58, 287-295.

Abstract

Jatropha curcas L. (Euphorbiaceae) has the potential to become a key biofuel crop. Manual pruning (MP) is one of the major management practices in commercial plantations of this crop, resulting in production of more branches and thus increased potential for more inflorescences leading to a higher seed yield. However, this method is time-consuming, labour-intensive and expensive. This study was conducted to determine the potential of different plant growth regulators (PGRs) to increase the number of lateral branches of *J. curcas*. A single foliar application of N6-benzyladenine (BA) at 12 mM significantly increased branches in both the pot (4.0) and field (13.2) trials compared to MP (1.8 and 5.7, respectively) and control (no new branches) plants. In the field, a single foliar application of 1.0 mM 2,3,5-triiodobenzoic acid
(TIBA) resulted in a significant increment in the number of branches (15.9) after 7 months. Of all the PGRs examined, 2,3:4,6-di-O-isopropylidene-2-keto-L-gluconic acid (dikegulac; DK) at 2.0 mM produced the maximum number of branches (18.0) in the field 7 months after application. Concentrations of 2.0 and 3.0 mM of 1,2-dihydro-3,6-pyridazinedione (maleic hydrazide; MH) significantly increased the number of branches, 4 and 7 months after spraying in both the pot trial in the shade house and field, respectively. Under field conditions, *J. curcas* plants responded better to all the PGRs

(DK\TIBA\BA\MH) when treated once, with insignificant variations in other growth parameters. This study indicates that a single foliar application of PGRs under field conditions can be an alternative method to MP for increasing the number of lateral branches of *J. curcas*.

(3) Abdelgadir, H.A., Jäger, A.K., Johnson, S.D., Van Staden, J., 2010. Influence of plant growth regulators on flowering, fruiting, seed oil content, and oil quality of *Jatropha curcas*. *South African Journal of Botany*. 76, 440-446.

Abstract

Field experiments were conducted to determine the effects that plant growth regulators (PGRs) have on seed production of *Jatropha curcas* when they are used for chemical pruning. In the subsequent year, following a single foliar application of PGRs, flowering, fruit set, fruit characteristics, seed total oil content and oil free fatty acid (FFA) content were evaluated. The number of flowers per plant, number of fruits per bunch, fruit- and seed characteristics and seed oil content were significantly affected by the different treatments. However, there were no variations in the degree of fruit set or oil FFA content. A single foliar application of N6-benzyladenine produced more flowers per plant, more fruits per bunch, heavier and bigger fruits and seeds with more oil compared to manual pruning. Treatment with 2,3,5-triiodobenzoic acid yielded more flowers per plant and heavier fruits with a higher oil content than the control and manually pruned plants. Treatment with 2,3:4,6-di-O-isopropylidene-2-keto-L-gulonic acid yielded similar results. More fruits per bunch and more seeds per fruit were also produced. Maleic hydrazide treatment yielded more flowers per plant, heavier and bigger fruits with more, heavier, oil rich seeds compared to the control and manual pruning. This study indicates that foliar application of PGRs as chemical pruners in *J. curcas* may have a sequential effect in boosting seed production, seed oil content and improves fruit quality.

(4) Abdelgadir, H.A., Kulkarni, M.G., Arruda, M.P., Van Staden, J., 2011.. Enhancing seedling growth of *Jatropha curcas* – A potential oil seed crop for biodiesel. *South African Journal of Botany*. doi: 10.1016/j.sajb.2011.05.007.

Abstract

The effects of aerosol smoke (AS), smoke-water (SW), potassium nitrate (KNO3), naphthalene acetic acid (NAA) and indole-3-butyric acid (IBA) on germination and seedling growth of *Jatropha curcas* were investigated. Seed coat removal accelerated water imbibition and germination occurred within 48 h. Seeds subjected to AS failed to germinate over a 90 day period. There were no significant differences in germination percentage between the treatments and untreated control (intact- and shelled-seed). However, shelled-seeds had the shortest mean germination time (MGT). Seedlings developed from treated seeds were planted in trays under shade house conditions and growth traits measured after 3 months. Soaking intact-seeds in SW, KNO3 and NAA (24 h) produced significantly heavier and longer seedlings, which resulted in higher vigour indices (VI) compared to the control treatments. These results provide empirical evidence of the stimulatory effect of SW, KNO3 and NAA on *J. curcas* seedling growth and vigour and the continuation of the effect over time. The approach of treating intact-seeds of *J. curcas* with plant growth substances prior to planting will help in producing healthy seedlings and possibly improve crop productivity.

(5) **Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2011. Pollen viability, pollen germination and pollen tube growth in the biofuel seed crop *Jatropha curcas*. *South African Journal of Botany*. (Accepted).**

Abstract

The fate of pollen and pollen tubes can have a profound effect on fruit and seed production. Experiments were conducted to investigate pollen viability, *in vitro* pollen germination and *in vivo* pollen tube growth in the biofuel seed crop *Jatropha curcas*. It was possible to distinguish between fresh and dead pollen using 2,3,5-triphenyltetrazolium chloride (TTC). Pollen germination was significantly higher in an agar-based medium composed of sucrose, boric acid and calcium nitrate compared with the control and indole-3-acetic acid (IAA) treatments. Pollen from hermaphrodite flowers had lower viability, lower germination rates and shorter pollen tubes, with abnormal shapes, compared to the pollen from male flowers. Pollen tubes from both self- and cross-pollinated flowers entered the ovary within 8 h after pollination, thus confirming earlier reports of self-compatibility in this species*.*

(B) Oral conferences' presentations and poster published in peer-reviewed / refereed journals:

1. **Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Pollen viability, pollen germination and pollen tube growth in *Jatropha curcas* -- A potential oil seed crop for biodiesel. *South African Journal of Botany*, 75, 391.**

Abstract

Experiments were conducted to investigate pollen viability, in vitro pollen germination and in vivo pollen tube growth in *Jatropha curcas*. Light and fluorescence microscopy were employed to examine the different developmental stages. It was possible to determine pollen viability and distinguish between fresh and dead pollen using 2,3,5-tryphenyltetrazolium chloride (TTC). Pollen germination was significantly higher in agar-based medium composed of sucrose, boric acid and calcium nitrate compared to the control treatment (distilled water). Supplementation of IAA to the different media significantly increased pollen germination and pollen length compared to the control treatment. Pollen from hermaphrodite flowers had a lower viability, lower germination rates and shorter pollen tubes, with abnormal shapes, compared to the pollen from male flowers. Pollen tubes from both self- and cross-pollinated flowers entered the ovary within 8 HAP (8 h after pollination). However, at 6 HAP, the pollen tube length and growth rate were significantly higher in cross- compared to self-pollinated pollen. Our results suggest that TTC is a reliable test for pollen viability; boric acid, calcium nitrate, sucrose and addition of IAA are essential and beneficial for pollen germination in this plant. Pollen germination and pollen tube growth were not inhibited, nor interfered with, as a result of self-pollination treatments. During both types of pollination, fertility is maintained as evidenced by ovule penetration by pollen tubes. This suggests that type of pollination has no influence on the success of fertilization in *J. curcas*.

2. **Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Effect of foliar application of plant growth regulators on flowering and fruit set in *Jatropha curcas* -- A potential oil seed crop for biodiesel. *South African Journal of Botany,* 75, 391.**

Abstract

Experiments were conducted to determine the potential of different plant growth regulators (PGRs) to increase seed production in *Jatropha curcas* plants. In the subsequent year following a single foliar application, the parameters of flowering, fruit set, fruit characteristics and total oil content were evaluated. Number of flowers per plant and number of fruits per bunch were significantly affected by the different treatments. However there were no variations in percentage of fruit set. A single foliar application of BA (6-benzylaminopurine) produced more flowers per plant and more fruits per bunch with heavier weight and bigger size compared to MP (manual pruning) treatment. TIBA (2,3,5-Triiodobenzoic acid) at all concentrations produced heavier and more fruits compared to the control and MP treatments. Dikegulac (2,3:4,6-di-O-isopropylidene-2-keto-L-gulonic acid) at 2, 4, and 6 mmol l-1 produced more seeds per fruit compared to MP. Maleic hydrazide (1,2-dihydro-3,6- pyridazinedione, coline salt) produced heavier and bigger fruits with numerous and heavier seeds compared to the control and MP. This study indicates that foliar application of PGRs can be used in *J. curcas* to increase seed production and improve fruit quality.

3. **Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Promotion of seedling growth in *Jatropha curcas* – a potential oil seed crop for biodiesel. *South African Journal of Botany,* 75, 391.**

Abstract

The effects of aerosol smoke, smoke water, potassium nitrate, naphthalene acetic acid and indole-3-butyric acid on germination and seedling growth of *Jatropha curcas* were investigated. Seed coat removal accelerated water imbibitions and germination occurred within 48 h. Seeds exposed to aerosol smoke failed to germinate over the whole study period of three months. There were no significant differences in total germination between the treatments and the untreated control (intactand shelled-seed). However, shelled-seeds had a shorter mean germination time. The seedlings were subsequently, sown in trays under shade house conditions and different seedling growth traits measured after three months. Smoke water, potassium nitrate and naphthalene acetic acid produced significantly heavier seedlings with longer stems and roots, wider stems and a higher vigour index compared to the control treatments. Smoke water, potassium nitrate and naphthalene acetic acid stimulated seedling growth and vigour of *J. curcas*. This opens the possibility of applying these treatments to produce quality seedlings for large scale planting and accelerated plant establishment in production orchards.

4. **Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2008. Approaches to improve seed production of *Jatropha curcas* L. *South African Journal of Botany,* 74, 359.**

Abstract

Jatropha curcas L. (Euphorbiaceae) potentially can become one of the world's key energy crops. The seeds can produce crude vegetable oil that can be refined into high quality biodiesel. Low numbers of female flowers, limited branching and inadequate pollination are the major factors that limit seed production and thus oil yield of *J. curcas*. To understand the breeding system of *J. curcas*, bagged vs. open and self vs. cross pollination were studied. Fruits from open-pollinated flowers were significantly more numerous, larger and heavier than those produced from autogamous self-pollinated flowers. Cross-pollinated flowers had significantly higher fruit set than self-pollinated flowers. However, supplemental cross- and self-pollination did not significantly increase fruit set. Flowers exposed to single and multi visits by honeybees set significantly more fruits than those which received no visits, indicating that honeybees are effective pollinators. Benzyladenine and hand-pruning produced significantly more branches than the control and other treatments (TIBA, Dikegulac and MH) after 90 days. Dikegulac, BA and TIBA treatments significantly increased shoot length. These results suggest that fruit production in *J. curcas* can be boosted by manipulating biological processes of pollination and growth.

LIST OF PUBLICATIONS:
Publications in peer-reviewed / refereed journals:

1. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2011. Pollen viability, pollen germination and pollen tube growth in the biofuel seed crop *Jatropha curcas*. *South African Journal of Botany*. (Accepted).

2. Abdelgadir, H.A., Kulkarni, M.G., Arruda, M.P., Van Staden, J., 2011.. Enhancing seedling growth of *Jatropha curcas* – A potential oil seed crop for biodiesel. *South African Journal of Botany*. doi: 10.1016/j.sajb.2011.05.007

3. Abdelgadir, H.A., Jäger, A.K., Johnson, S.D., Van Staden, J., 2010. Influence of plant growth regulators on flowering, fruiting, seed oil content, and oil quality of *Jatropha curcas*. *South African Journal of Botany*. 76, 440-446.

4. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Promoting branching of a potential biofuel crop *Jatropha curcas* L. by foliar application of plant growth regulators. *Plant Growth Regulation*, **58,** 287-295.

5. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Pollinator effectiveness, breeding system, and tests for inbreeding depression in the biofuel seed crop, *Jatropha curcas. Journal of Horticultural Science & Biotechnology,* **84,** 319-324.

Oral presentations and poster published in peer-reviewed / refereed journals:

5. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Pollen viability, pollen germination and pollen tube growth in *Jatropha curcas* -- A potential oil seed crop for biodiesel. *South African Journal of Botany*, **75,** 391.

6. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Effect of foliar application of plant growth regulators on flowering and fruit set in *Jatropha curcas* -- A potential oil seed crop for biodiesel. *South African Journal of Botany,* **75,** 391.

7. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Promotion of seedling growth in *Jatropha curcas* – a potential oil seed crop for biodiesel. *South African Journal of Botany,* **75,** 391.

8. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2008. Approaches to improve seed production of *Jatropha curcas* L. *South African Journal of Botany,* **74,** 359.

LIST OF PUBLICATIONS:
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9. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Pollen viability, pollen germination and pollen tube growth in *Jatropha curcas* – A potential oil seed crop for biodiesel. *South African Journal of Botany*, **75,** 391.

10. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Effect of foliar application of plant growth regulators on flowering and fruit set in *Jatropha curcas* – potential oil seed crop for biodiesel. *South African Journal of Botany,* **75,** 391.

11. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2009. Promotion of seedling growth in *Jatropha curcas* – a potential oil seed crop for biodiesel. *South African Journal of Botany,* **75,** 391.

12. Abdelgadir, H.A., Johnson, S.D., Van Staden, J., 2008. Approaches to improve seed production of *Jatropha curcas* L. *South African Journal of Botany,* **74,** 359.

1. Workshop on "Biodiesel Fuel Production -Technical And Practical Aspects For Smaller Scale Producers"

A workshop run under the auspices of the BioEnergy Research Group was held in August and over 60 participants visited the trial at Ukulinga. A presentation on the WRC project was given by Prof. C. Everson. The details of this workshop are given below as well as a copy of an article published in Farmers weekly in August 2007.

Workshop Report on:BIODIESEL FUEL PRODUCTION -TECHNICAL AND PRACTICAL ASPECTS FOR SMALLER SCALE PRODUCERS

A one-day workshop for Engineers, Technicians and interested persons

Date: Thursday, 02 August
Venue: Ukulinga Research Farm, University of KwaZulu-Natal, Pietermaritzburg

Overview:

With the recent rises in fuel costs, there is great deal of interest in alternate sources of energy to fuel equipment in South Africa. One of the most promising alternatives is Biodiesel, which is growing in popularity both in South Africa and abroad. Biodiesel is a chemically-altered form of vegetable oil that can be used to run diesel engines, without any modification to the engines themselves. The benefits of using Biodiesel include reduced dependence on imported petrolium, reduced pollution, and potentially lower operating costs.

The good news is that practically any technically minded person can produce biodiesel fuel using relatively common materials and supplies. However, the procedures for producing this fuel are not widely understood, and the danger of low quality fuel causing damage to an engine is a reality that must be guarded against.

Engineers and technicians who are involved with transport and fuel will gain a great deal of technical and practical knowledge at this workshop that will enable them to make wise and economical decisions with regard to the possible use of Biodiesel fuel.

This workshop will provide a firm grounding in the theory and science of biodiesel production, but will also give practical instruction, including a hands-on demonstration in which biodiesel fuel will be manufactured.

Topics Covered:

Biodiesel Theory
Impacts of Biodiesel on Water Resources
Benefits and Drawbacks
Production Procedures
Quality Testing
Economics of Biodiesel in South Africa

Performance of Biodiesel in Engines
Presenters:
Dr. Daniel Ciolkosz, University of KwaZulu-Natal
Dr. Colin Everson, CSIR
Professor Alan Hansen, University of Illinois (USA)
Mr. Alan Hill, University of KwaZulu-Natal
Dr. George Tivchev, University of KwaZulu-Natal

2. Conference presentations

Results from the project were presented at a number of conferences:

2.1 Everson, CS, Andersson, C., Everson TM & Ghehezi, S (2007). Growth and water use of a *Jatropha* / Kikuyu silvopastoral system for the production of biofuel and fodder. Paper presented at the ICID 2nd African Regional Conference on the 6-9 November 2007 at Glenburn Lodge, Johannesburg. The theme of the conference was Contribution of rainfed and irrigated agriculture to poverty alleviation through increased productivity in Africa.

2.2 Ghezehei, SB, Annandale, JG & Everson, CS (2007). Monitoring two-dimensional soil water distribution of a *Jatroph*a-Kikuyu alley cropping system. Combined Congress of the Soil Science Society of South Africa, the South African Society of Crop Production, the Southern African Weed Science Society and the Southern African Society for Horticultural Sciences, Grahamstown, 21-24 January 2008.

2.3 Mengistu, MG & Savage, MJ (2007). Evapotranspiration measurement for a silvopastoral system consisting of *Jatropha* and Kikuyu grass. Combined Congress 2007. South African Society of Crop Production, Soil Science Society of South Africa, and Southern African Society for Horticultural Sciences. 22-25 January, Badplaas, South Africa.

2.4 Abraha, M & Savage, MJ (2007). A simple three-dimensional solar radiation interception-model for tree crops. . Combined Congress 2007. South African Society of Crop Production, Soil Science Society of South Africa, and Southern African Society for Horticultural Sciences. 22-25 January, Badplaas, South Africa.

3. Study Group Sessions

Information from the trial has been made available to a broad number of agencies through focussed study group sessions at the trial site. These included international agencies, government departments, NGOs, tertiary education institutions and commercial agencies (Table 1).

Table 1. Details of visitors to the *Jatropha* / Kikuyu silvopastoral trial at the UKZN Ukulinga research farm, Pietermaritzburg.

Name	Organisation	Location	Email Address	Contact Number	Date visited
Dr. Johann Breytenbach	Ubukwane	Namibia	ubukwane@mweb.co.za	0837486810	January 2006
Prof. Elsa du Toit	Univ. Pretoria	Pretoria, RSA	elsa.dutoit@up.ac.za	012-4203227	March 2006
Mr. Roy Mottram	Bio Fuels de Mozambique Lda	Hilton, RSA	mottram@iafrica.com	033-3830223 0823217081	March 2006
Mr. Gavin Schafer	Sun Biofuels	E. Cape, RSA	terramap@net4all.co.za	072 298 5300 042 274 2348	April 2006
Dr. Jiregna Gindaba	Sun Biofuels	Addis Ababa, Ethiopia	jgindabadoti@sunbiofuels.com	+251-11 663 6486	April 2006
Mr. John Lapham	Netafim - Vegtech	Zimbabwe	agsystem@mweb.co.zw	082-7420523 011-9745254	May 2006
Prof. Graham Jewitt (and BEEH students)	UKZN	Pietermaritzburg, RSA	jewittg@ukzn.ac.za	033-2605678	September 2006
Mr. Peter Whitehead			pnwd@mweb.co.za		February 2007
Dr. Maurus Decurtins	Tanga Cement	Tanga, Tanzania	mdecurtins@simbacement.co.tz	+255-27 264 4500	November 2007
Dr Motseki Hlatshwayo	Dept. of Agriculture	Directorate Animal and Aquaculture Production	daap@nda.agric.za	+27 12 3197570	February 2008
Dr Fred Kruger	CIC International	Pretoria	fkruger@global.net		February 2008
Aimee Ginsburg	CIC International	Pretoria			February 2008
Kyle Harris	CIC International	Pretoria			February 2008
Mike P. Zachairias Pr Eng	Shell SA	Bryanston	Mike.zacharias@shell.co,	+27 11 3610658	June 2007
Prof P Zacharias: Deputy Vice Chancellor UKZN	UKZN	Pietermaritzburg	zachariasp@ukzn.ac.za		June 2007
Dr Sizwe Mkhize	Dept. of Agriculture	Assistant Director General : Sustainable resources	ADGSRMU@nda.agric.za	+27 12 319 6446	Aug 2007 Jan 2008
Mr Victor Musetha	Dept. of Agriculture	Directorate Animal and Aquaculture Production	Victor2@nda.agric.za	+27 12 3197509	February 2008
Dr At van Coller	ARC				Nov 2007
Dr Stuart Christie	SFM	Johannesburg			February 2008

4. User training

The trial has played a significant role in user training for two students:

Alberto Macucule, an international PhD student from Mozambique, was given on site training at Ukulinga on data logging and the heat pulse velocity technique for agroforestry systems.

Henry Menchero Perez, a third year BSc student from UKZN, was given training on estimating production in agroforestry systems and has initiated a mini project at the trial to investigate this aspect.

5. Information transfer WWW

The technologies developed in this project have been made available to potential implementing agencies through registering the project as a participant in the BioEnergy Research Group at UKZN which is listed on the World Wide Web:

http://www.beeh.unp.ac.za/Bio Energy/index.htm