

A field assessment of the agronomic performance and water use of *Jatropha curcas* in South Africa

C.S. Everson^{a,*}, M.G. Mengistu^a, M. B. Gush^b

^a*School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Private Bag X01, Scottsville, Pietermaritzburg 3209, South Africa.*

^b*CSIR Natural Resources & Environment, PO Box 320, Stellenbosch, 7599.*

*Corresponding author. Tel.: +27332606093; fax: +27332605818.

E-mail address: eversonc@ukzn.ac.za

Abstract

Global attention on biofuels and the potential for *Jatropha curcas* to produce biodiesel from marginal land with low inputs has recently created world-wide interest in this species. This paper reports on the water dynamics and productivity of *J. curcas* in a silvopastoral experiment with *Pennisetum clandestinum* at the Ukulinga research farm of the University of KwaZulu-Natal near Pietermaritzburg, South Africa. 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. High oil yields are unlikely due to the low seed production. The best seed yield was in 2009 (348.8 kg ha⁻¹) in the *J. curcas* only plots. The other treatments (where pasture competition was a factor) ranged between 77.8 and 166 kg ha⁻¹. Data collected on the time taken by labourers to harvest and dehusk the seeds, showed that one kilogram of seed took approximately three hours to process, suggesting that mechanical harvesting would be necessary to make seed production economically viable. *J. curcas* showed a low tolerance to pests and was prone to diseases. This significantly increased the input costs for insecticides and fungicides. The South African results are so unequivocal that *J. curcas* under the experimental conditions does not fulfil the claims that it is a wonderful biodiesel plant.

Key words: Total evaporation, biofuels, *Pennisetum clandestinum*, agroforestry, seed yield

1. Introduction

J. curcas, a species native to Mexico and continental Central America [1,2], is widely promoted as an important income generator for small-scale farmers. The primary potential of *J. curcas* lies in the fact that its seeds can be used to produce biofuels – the global demand for which is increasing dramatically as oil prices increase. A major problem with biofuel production is that it often requires large tracts of land, a resource that is becoming increasingly limited under global population increase [3]. However, *J. curcas* does not require arable land as it is able to grow in infertile, and moderately sodic and saline soils [4]. There are also claims that it is drought-resistant, thus able to grow in arid and semi-arid areas where it tolerates high temperatures and low soil moisture [5]. Because of these characteristics it has been used in land reclamation and soil erosion prevention [6].

Global attention on biofuels and the potential for *J. curcas* to produce biodiesel from marginal land with low inputs has recently created a hyped interest in this species. This has resulted in the planting of large areas of *J. curcas* in Asia, Africa and America. Claims about *J. curcas* include: low water use, grows on marginal and degraded lands, high oil yields, low labour costs and tolerance to pests and diseases. There is some information in the scientific literature on the water use [7-11], on growing conditions [12,13], on growth and yield expectations [14,15] and on the economic performance [16-20] of *J. curcas*. However, there is little scientific evidence to support many of the claims made about this species. In South Africa the government has placed a moratorium on the planting of *J. curcas* due to concerns about possible excessive water use, potential alien invasiveness and lack of knowledge about its' yield and economic potential.

Agroforestry, according to the World Agroforestry Centre, is defined as a system of land use in which harvestable trees or shrubs are deliberately grown among or around crops or on pastureland, as a means of preserving or enhancing the productivity of the land. An agroforestry system that is especially relevant to the South African situation is the farming of livestock alongside trees and crops (silvopasture), as it is applicable to small scale and subsistence farmers. While the benefits of agroforestry are well documented, certain aspects of these systems need to be adapted to suit the areas where they are introduced [21]. These adaptations are primarily to do with selecting the ideal combinations of trees, shrubs and crops that will benefit each other, the environment and the income of small-scale farmers. Traditionally, *J. curcas* was used as a live fence to protect crops, for demarcation of properties or to fence livestock, and as a support plant for vanilla trees [22]. In this study, *J. curcas* was used in a silvopastoral experiment with *Pennisetum clandestinum*. *Pennisetum clandestinum*, commonly known as kikuyu grass is a creeping sub-tropical grass that forms a dense turf and is tolerant to heavy grazing. It is widely used as a highly productive pasture for dairying and as a turf or lawn grass [23].

2. Materials and Methods

2.1 Study Area

The study was conducted at Ukulinga, the research and training farm of the University of KwaZulu-Natal near Pietermaritzburg, South Africa (30°24'S, 29°24'E) (Fig. 1). Ukulinga receives an average of 680 mm over 106 rain days with 23% of the Mean Annual Precipitation falling during the winter months [24]. It is situated at an altitude of 721 m and experiences warm to hot summers and mild winters with occasional frost [25]. The mean annual temperature is 18.4 °C [25]. Although the cooler winter temperatures at Ukulinga may not be ideal for the growth of *J. curcas*, the rainfall is sufficient and is among the lower end of the suitable range [12,13].

2.2. Research design

The trial was a randomised block design (three blocks) with six treatments per block i.e. three replicates per treatment – a total of 18 plots. Each plot had a large area (50m × 25 m or 0.1 ha) to enable the use of certain micrometeorological techniques and for grazing by livestock. The whole trial was 265 m long × 110 m wide (an area of 29 150 m² or 2.915 ha). Trees were planted at a density of 1100 plants ha⁻¹, in single rows and in aggregate rows called “sets” with wide alleys for forage production. The *J. curcas* seeds were imported from Zimbabwe and were supplied by the South African Department of Agriculture.

The following treatments were established:

1. Kikuyu only (control)
2. *Jatropha* only (control)
3. Standard square: 3.0 × 3.0 m spacing + Kikuyu. 17 rows each with 8 trees (136 trees).
4. Single row + Kikuyu: 11 sets of trees (13 trees per set, ~2.0 m inter plant distance), 5 m alleys (143 trees).
5. Double row: 6 sets (2.5 m × 2.0 m spacing-11 trees per row or 22 per set), 6.0 m alleys (132 trees).
6. Triple row: 4 sets (3.0 m × 2.0 m spacing - 9 trees per row or 27 per set), 7.0 m alleys (135 trees).

2.3 Tree growth

The tree heights and diameters (0.20 m from ground level) were measured every 2nd week in the early growth phase (February-April 2005) and thereafter at monthly intervals until December 2008 using an extendable tree height rod measurer. Two additional measurements were recorded in November 2009 and April 2010. The measurements were recorded from 30 randomly selected trees in each of the plots planted with trees (15 plots) and averaged for each treatment.

2.4 Seed production

During the 2006/07 season the first seeds of *J. curcas* were harvested. Data on the seed production of *J. curcas* (number and mass of seeds per plot) and time taken to harvest and dehusk the seeds (labour costs) were collected from March 2007 to July 2009. These are important variables relevant to the economic viability of farming with *J. curcas*.

2.5 Weather and Environmental Monitoring Instruments (Climate)

A Campbell Scientific automatic weather station, comprising a Vaisala CS500 (Helsinki, Finland) sensor for measuring relative humidity and temperature, a RM Young Wind Sentry Set (Model 03002, Traverse city, Michigan, USA) - for measuring wind speed and direction, a LI-200X pyranometer (LI-COR, Lincoln, Nebraska, USA) for measuring solar radiation, a TE525 tipping bucket raingauge (Texas electronics Inc., Dallas, Texas, USA) and a CR10X data-logger (Campbell Scientific, Logan, Utah, USA) were used to collect climatic data for the study site. Stored data were downloaded weekly using a laptop computer. The data-logger also calculated saturated vapour pressure, ambient vapour pressure, vapour pressure deficit and reference evaporation.

2.6 Water use

The water use of the *J. curcas* only and Kikuyu only treatments were estimated using the eddy covariance (*EC*) technique using an *InSitu* flux system (directly using a LI-7500 IRGA and Gill 3-D sonic anemometer) and an RM Young 3-D ultrasonic anemometer (Model 81000, Traverse city, Michigan, USA). The RM Young 3-D ultrasonic anemometer was used as an indirect measure of total evaporation by determining H and estimating λE by subtraction using the shortened energy balance equation:

$$R_n = H + \lambda E + G \quad (1)$$

where R_n is the net irradiance, H is the sensible heat flux, λE is the latent heat energy and G is the soil heat flux. This equation defines an energy component, apart from R_n , to be positive when directed away from the surface and negative when directed towards the surface. Closure of the energy balance is said to be met when independently measured components satisfy Equation 1. The total evaporation (λE) above the *J. curcas* canopy was calculated directly using the *InSitu* flux system (Equation 2) and indirectly above the Kikuyu grass plot by rearranging Equation 1 and assuming closure. In each treatment the net irradiance was measured using a NR-LITE net radiometer (Kipp and Zonen, Delft, The Netherlands) and soil heat flux was measured using two soil heat flux plates (HFT-S, REBS, Seattle, WA) placed at a depth of 80 mm below the soil surface. A system of parallel thermocouples at depths of 20 and 60 mm were used for measuring the soil heat stored above the soil heat flux plates, and volumetric soil water content in the top 60 mm was also measured using a CS615 time domain reflectometer (TDR).

The *EC* method provides a direct measure of the vertical turbulent flux of a scalar entity of interest (*s*) across the mean horizontal stream lines [26] providing fast response sensors (Hz) for the wind vector and scalar entity of interest [27]. For example the sensible heat flux can be described as:

$$H = \rho c_p \overline{w'T'} \dots\dots\dots (2)$$

where ρ is the density of air (1.19 kg m^{-3}), c_p the specific heat capacity of air at constant pressure ($1056 \text{ J kg}^{-1} \text{ K}^{-1}$), w' is the vertical wind speed and T' is the concentration of the scalar of interest. The primes in Equation 2 indicate fluctuations from a temporal average. The vertical wind speed is responsible for the flux across a plane above a horizontal surface.

The *InSitu* flux system¹ estimated the fluxes of momentum, sensible heat, and latent heat by applying the eddy covariance method to measurements of atmospheric conditions above the canopy surface. The system consisted of a Gill R3 three-dimensional sonic anemometer, data collection unit and open path infrared gas analyser (Li-7500). The sonic anemometer sampled orthogonal wind speeds and calculated the virtual temperature from the speed of sound. Information about wind speed, temperature, carbon dioxide, and water vapour density were transmitted to the data collection unit at 10 Hz. Internal to the data collection unit was the data acquisition software, a multi-tasking, protected mode software system designed to accomplish data collection and storage of raw data, calculation and storage of mean fluxes, variances, co-variances, wind direction and wind speed, stability and friction velocity. The software made all necessary corrections, filtering and co-ordinate rotations that were needed for accurate measurements.

3. Results and Discussion

3.1. 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) (Fig. 2). 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 m – 1.25 m in the 2007, 2008 and 2009 seasons, reaching heights between 1.75 m and 2.25 m (Fig. 2).

¹ Use of trade names does not imply endorsement of the product.

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 (Fig. 2). 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 (Fig. 3). 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 (Fig. 3). 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.

The similarity in the tree height and stem diameter curves was reflected in the allometric relationship between basal diameter and tree height (Fig. 4), 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 ($R^2 = 0.92$) (Fig. 5). These allometric relationships were developed further to provide a useful tool for both plant growth modelling and carbon sequestration predictions [28].

3.2 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 1 and Fig. 6). 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. In this 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 1) 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 1 and Fig. 6). 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 1 and Fig. 6). 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.

Reports from Indian research centres and institutes have shown similar poor yields to this study, where the average yields from extensive dry land plantings were not expected to exceed 1 t ha⁻¹ yr⁻¹ [29].

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 (Fig. 7). 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.* [20] 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.

3.3 Water Use

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) (Fig. 8). *Jatropha* establishment requires mean annual temperatures between 18 and 28 °C and average minimum temperatures of the coldest month above 8 °C [13]. 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) (Fig. 9). Regular rains were recorded from January to April, the largest event (53 mm) occurring at the end of February (DOY 57) (Fig. 9). 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 (ET₀) closely tracked the trends in solar radiation (Fig. 9). Reference evaporation varied from highs of 6.5 mm in January to less than 2 mm in winter (Fig. 9). 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).

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 (Fig. 10). 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* [9,15]. 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.

In 2007 the total evaporation rate in the *Jatropha* only plots was compared with the Kikuyu only plots in both winter and summer (Fig. 11). 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.

4. Conclusions

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 a competition experiment in the same Ukulinga trial [30], it was shown that tree height and basal diameter were greater with increasing distance of planted pasture species from *J. curcas*. The 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 [31,32] and/or selecting cover or forage crops that are least competitive for nutrients and moisture while still fulfilling their role in the system [33]. 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 0.6 m according to Andersson [30]). 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*, *Metarrhizium* 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 [29] and in Kenya [18].

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. According to the literature, 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 a yield of 2000 kg ha⁻¹ - 3000 kg ha⁻¹ of seeds can be achieved in semi-arid areas, although yields of 5000 kg ha⁻¹ are routinely achievable under more favourable (wetter) conditions [34]. 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 [7,9]. 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 *Jatropha* 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 [35] and will not require a water licence. Our findings are consistent with those of Gush [7], who similarly found low water use of *J. Curcas* determined using the heat pulse velocity approach [36,37],

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 147mm for a 4-year old *J. curcas* tree and 362mm 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) [7]. 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 [30]. 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 [18].

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 under trial conditions (and from earlier South African work) the wonder of *Jatropha* is a fiction.

Acknowledgements

Project funding from the Water Research Commission of South Africa is greatly acknowledged and without whom this project would not have been possible. Colleagues Dr Caren Jarman, Alistair Clulow and Lelethu Sinuka provided valuable technical assistance towards the field-work components. The land for the trial was kindly provided by the University of KwaZulu-Natal. The CSIR and University of KwaZulu-Natal provided the instrumentation for the water use measurements.

References

- [1] Heller J. Physic nut - *Jatropha curcas* L. - Promoting the conservation and use of underutilized and neglected crops. PhD dissertation, Institute of Plant Genetic and Crop Plant Research, Gatersleben, Germany & International Plant Genetic Resource Institute; 1996. <http://www.ipgri.cgiar.org/Publications/pdf/161.pdf>
- [2] Sujatha M, Reddy TP, Mahasi M. Role of biotechnological interventions in the improvement of castor (*Ricinus communis* L.) and *Jatropha curcas* L. *Biotechnol Adv* 2008;26:424-435.
- [3] Parfit M. Future Power: Where will the world get its next energy fix? *National Geographic* 2005;208:2-31.
- [4] Mohibbe Azam M, Waris A, Nahar NM. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. *Biomass Bioenerg* 2005;29:293-302.
- [5] Augustus GDPS, Jayubalan M, Seiler GJ. Evaluation and bioinduction of energy components of *Jatropha curcas*. *Biomass Bioenerg* 2002;23:161-164.
- [6] Openshaw K. A review of *Jatropha curcas*: an oil plant of unfulfilled promise. *Biomass Bioenerg* 2000;19:1-15.
- [7] Gush M. Measurement of water use by *Jatropha curcas* L. using the heat pulse velocity technique. *Water SA* 2008;34(5):579-583.
- [8] Jongschaap REE, Blesgraaf RAR, Bogaard TA, van Loo EN, Savenije HHG. The water footprint of bioenergy from *Jatropha curcas* L. *P Natl Acad Sci USA* 2009;106:E92.
- [9] Maes MH, Achten WMJ, Reubens B, Samson R, Muys B. Plant-water relationships and growth strategies of *Jatropha curcas* L. saplings under different levels of drought stress. *J Arid Environ* 2009;73:877-884.
- [10] Maes, WH, Achten WMJ, Muys B. Use of inadequate data and methodological errors lead to an overestimation of the water footprint of *Jatropha curcas*. *P Natl Acad Sci USA* 2009;106:E91.
- [11] Silva EN, Ribeiro RV, Ferreira-Silva SL, Viégas RA, Silveira JAG. Comparative effects of salinity and water stress on photosynthesis, water relations and growth of *Jatropha curcas* plants. *J Arid Environ* 2010;74:1130-1137.
- [12] Maes WH, Trabucco A, Achten WMJ, Muys B. Climatic growing conditions of *Jatropha curcas* L. *Biomass Bioenerg* 2009;33:1481-1485.

- [13] Trabucco A, Achten WMJ, Bowe C, Aerts R, van Orshoven J, Muys B. Global mapping of *Jatropha curcas* yield based on response of fitness to present and future climate. *Glob Change Biol Bioenerg* 2010;2:139-151.
- [14] Achten WMJ, Verchot L, Franken YJ, Mathijs E, Singh VP, Aerts R et al. *Jatropha* biodiesel production and use. *Biomass Bioenerg* 2008;32:1063-1084.
- [15] Achten WMJ, Maes W, Reubens B, Mathijs E, Singh V, Verchot L et al. Biomass production and allocation in *Jatropha curcas* L. seedlings under different levels of drought stress. *Biomass Bioenerg* 2010;34(5):667-676.
- [16] Francis G, Edinger R, Becker K. A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: need, potential and perspectives of *Jatropha* plantations. *Nat Resour Forum* 2005;29:12-24.
- [17] Messemaker, L. The Green Myth? Assessment of the *Jatropha* value chain and its potential for pro-poor biofuel development in Northern Tanzania. M.Sc. dissertation, Utrecht University; 2008.
- [18] Endelevu Energy. *Jatropha* Reality Check: A field assessment of the agronomic and economic viability of *Jatropha* and other oilseed crops in Kenya; 2009: p.146. <http://www.worldagroforestry.org/downloads/publications/PDFs/B16599.PDF> [Accessed 21 February 2011]
- [19] Mulugetta Y. Evaluating the economics of biodiesel in Africa. *Renew Sust Energ Rev* 2009;13:1592-1598.
- [20] Wiskerke WT, Dornburg V, Rubanza CDK, Malimbwi RE, Faaij APC. Cost/benefit analysis of biomass energy supply options for rural smallholders in the semi-arid eastern part of Shunyanga Region in Tanzania. *Renew Sust Energ Rev* 2010;14:148-165.
- [21] Esterhuyse CJ. Agroforestry. Issued by the Forestry and Environmental Conservation Branch of the Department of Environmental Affairs, Pretoria, South Africa; January 1989: Pamphlet 412.
- [22] Wahl N, Jamnadass R, Baur H, Munste C, Iiyama M. Economic viability of *Jatropha curcas* L. plantations in Northern Tanzania – Assessing farmers’ prospects via cost-benefit analysis. ICRAF Working Paper no. 97. Nairobi. World Agroforestry Centre; 2009.
- [23] Moore G, Sanford P, Wiley T. Perennial pastures for Western Australia. Department of Agriculture and Food Western Australia, Bulletin 4690, Perth; 2006.
- [24] Gush M. *Jatropha curcas* in South Africa – Trial Establishment Report. CSIR, Natural Resources and the Environment, Pietermaritzburg; 2006, p. 1-66.

- [25] Camp KG. The Bioresource Groups of KwaZulu-Natal. KZN Department of Agriculture. Cedara Report No. N/A/97/6;1997.
- [26] Swinbank WC. Measurement of vertical transfer of heat and water vapour by eddies in the lower atmosphere. *J Meteorol* 1951;8:135-145.
- [27] Meyers TP, Baldocchi DD. Current micrometeorological flux methodologies with applications in agriculture. In: Hatfield JL, Baker JM (Eds.), *Micrometeorology in Agricultural Systems Agronomy Monograph no. 47*; 2005, p. 381-396.
- [28] Ghezehei SB, Annandale JG, Everson CS. Shoot allometry of *Jatropha curcas* L. *Southern Forests* 2010;71(4):279-286.
- [29] Rao VR. The *Jatropha* Hype: Promise and Performance. In: Singh B, Swaminathan R, Ponraj V (Eds). *Biodiesel conference towards energy independence – focus on Jatropha*. Papers presented at the Conference Rashtrapati Nilayam, Bolaram, Hyderabad, 9-10 June; 2006, p. 16-19.
- [30] Andersson CEF. Management of oil producing *Jatropha curcas* (Euphorbiaceae) silvopastoral systems: risk of herbivory by indigenous goats and competition with planted pastures. Unpublished Honours report, Discipline of Rangeland Ecology, School of Biological and Conservation Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa; 2007.
- [31] George SJ, Kumar BM, Wahid PA, Kamalam NV. Root competition for phosphorus between the tree and herbaceous components of silvopastoral systems in Kerala. *India Plant Soil* 1996;179: 189-196.
- [32] Lehmann J, Peter I, Steglich C, Gebauer G, Huwe B, Zech W. Below-ground interactions in dryland agroforestry. *Forest Ecol Manag* 1998;111:157-169.
- [33] Malik RK, Green TH, Brown GF, Beyl CA, Sistani KR, Mays DA. Biomass production of short-rotation bioenergy hardwood plantations affected by cover crops. *Biomass Bioenerg* 2001;21:21-33.
- [34] Becker K, Makkar HPS. *Jatropha* and *Moringa*: Sources of renewable energy for fuel, edible oil, animal feed and pharmaceutical products – ideal trees for increasing cash income. Hand-out from presentation given at the "Daimler Chrysler / The World Bank Environment Forum", Magdeburg;1999. Available online: <http://www.uni-hohenheim.de/~www480/docs/se990720/jatr-opha.htm> [Accessed 16 March 2006].
- [35] National Water Act. National Water Act, RSA *Government Gazette* No. 36 of 1998, Cape Town, South Africa; 26 August 1998, No 19182.
- [36] Dye PJ, Olbrich BW. Estimating transpiration from 6-year-old *Eucalyptus grandis* trees: development of a canopy conductance model and comparison with independent sap flux

measurements. *Plant Cell Environ* 1993;16:45-53.

- [37] Dye PJ, Soko S, Poulter AG. Evaluation of the heat pulse velocity method for measuring sap flow in *Pinus patula*. *J Exp Bot* 1996;47:975-981.

Fig. Captions

Fig. 1

Location of the *Jatropha curcas* study site near Pietermaritzburg, South Africa.

Fig. 2

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.

Fig. 3

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.

Fig. 4

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

Fig. 5

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

Fig. 6

Mean seed yield (kg ha^{-1}) from the five *J. curcas* treatments from 2005 to 2010. Vertical bars represent the standard error.

Fig. 7

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

Fig. 8

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

Fig. 9

Graphical summary of Penman-Monteith grass reference evapo-transpiration (ET_o), rainfall, solar radiation (I_s) and vapour pressure deficit (VPD) for the months January to August 2007 from the AWS station at Ukulinga.

Fig. 10

Daily total EC evaporation (mm) together with the reference ET_o (mm) and total daily solar radiation ($MJ\ m^{-2}\ day^{-1}$).

Fig. 11

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

Table 1

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

Plate 1

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.

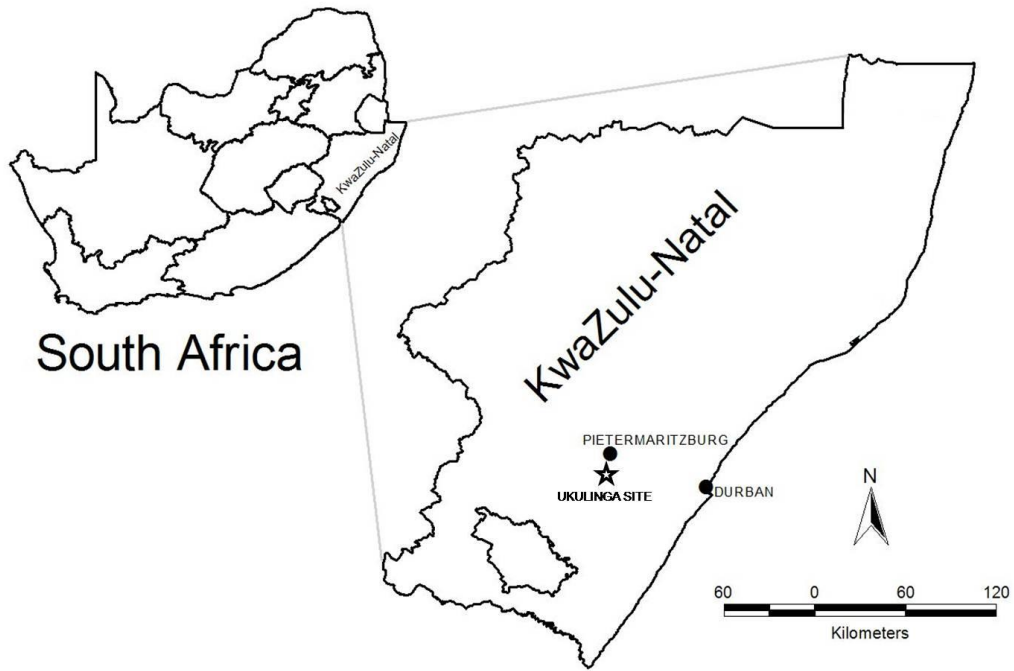


Fig. 1. Location of the *Jatropha curcas* study site near Pietermaritzburg, South Africa.

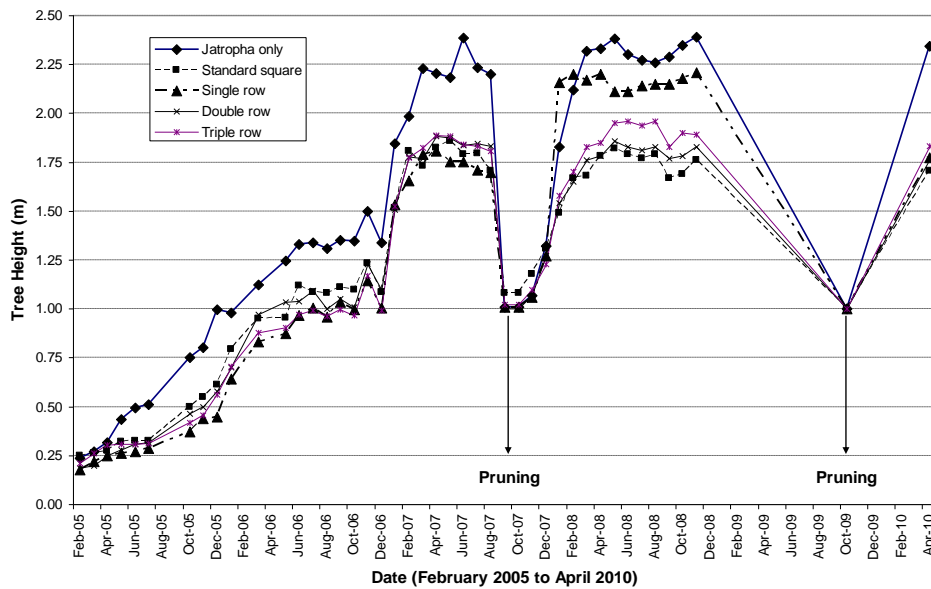


Fig. 2. Height (m) of *J. curcas* trees in five treatments (*J. curcas* only, Standard Square, Single rows, Double rows and Triple rows) between February 2005 and April 2010.

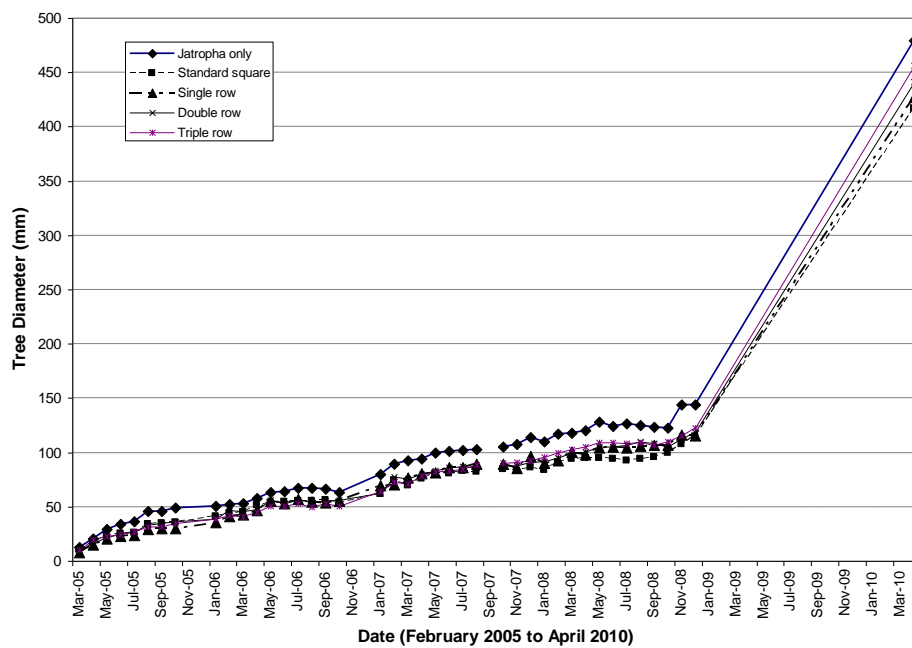


Fig. 3. Stem diameter (mm) of *J. curcas* trees in five treatments (*J. curcas* only, Standard Square, Single rows, Double rows and Triple rows) between February 2005 and July 2007.

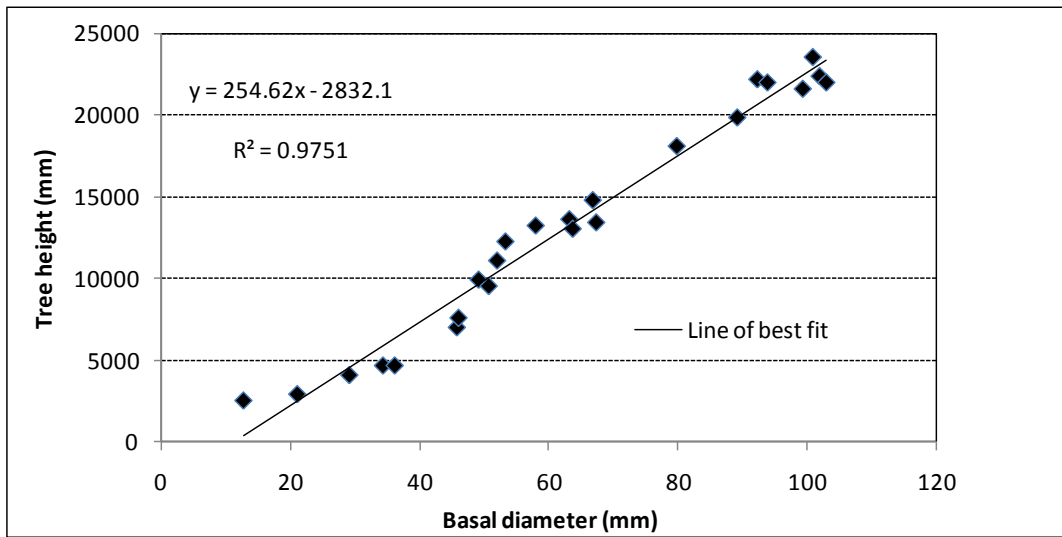


Fig. 4. The allometric relationship between basal stem diameter (mm) and height (mm) of *J. curcas* trees in the *Jatropha* only treatment.

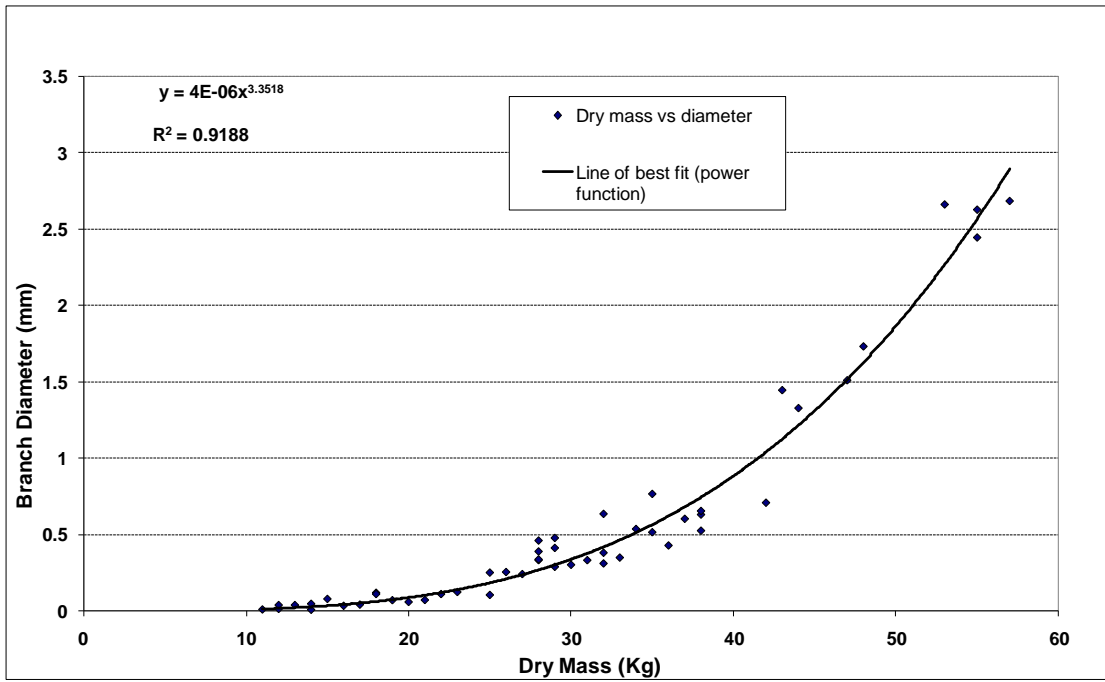


Fig. 5. The allometric relationship between branch diameter (mm) and dry mass (kg) of *J. curcas* trees in the Ukulinga trial.



Plate 1. 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.

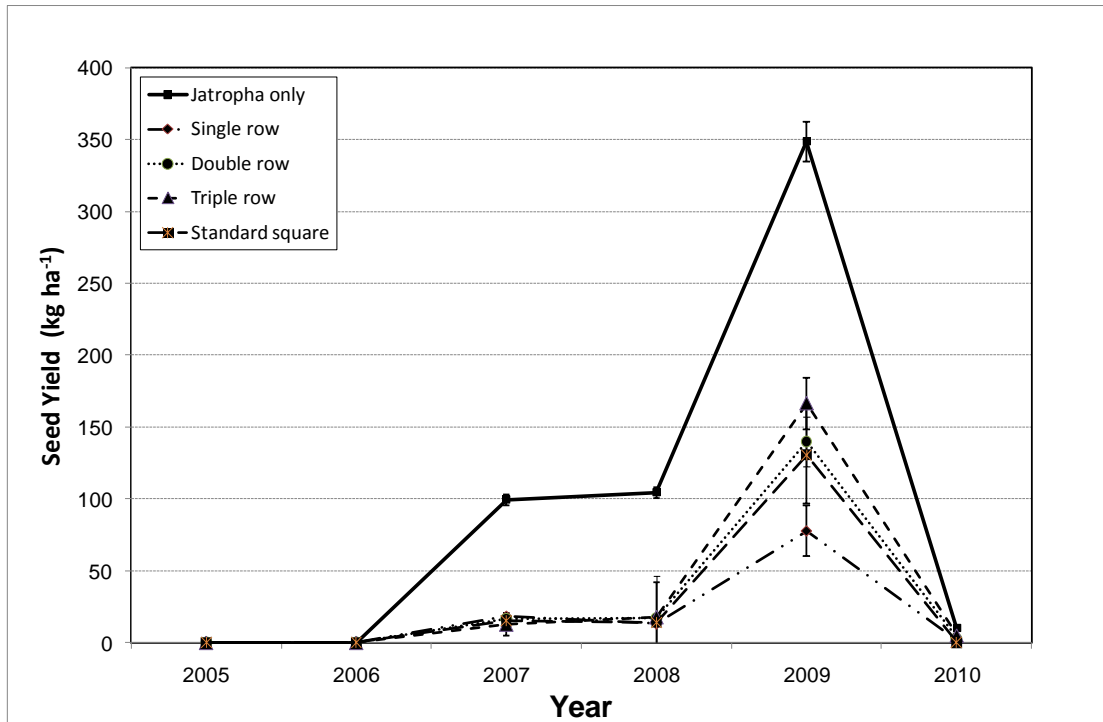


Fig. 6. Mean seed yield (kg ha^{-1}) from the five *J. curcas* treatments from 2005 to 2010. Vertical bars represent the standard error.

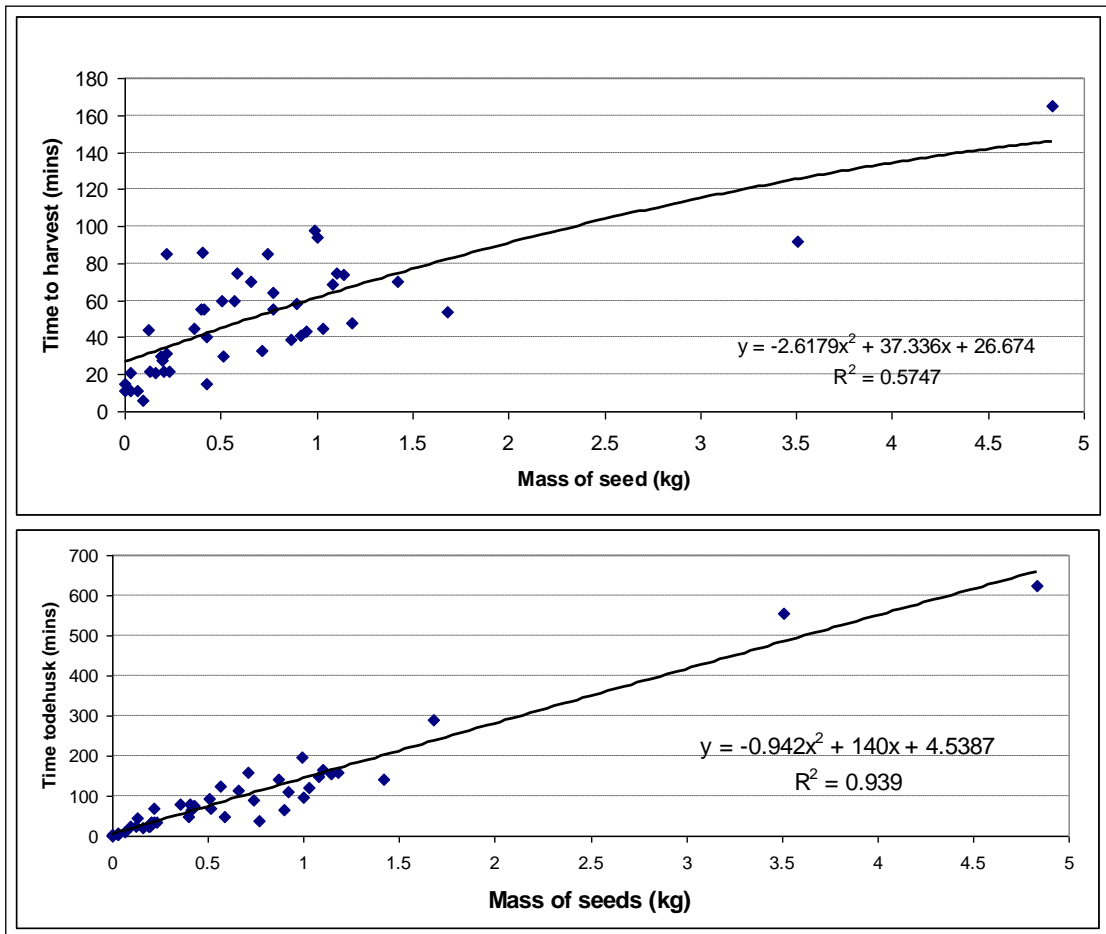


Fig. 7. The relationship between the mass of *J. Curcas* seeds and the time to harvest (above) and the time to dehusk (below).

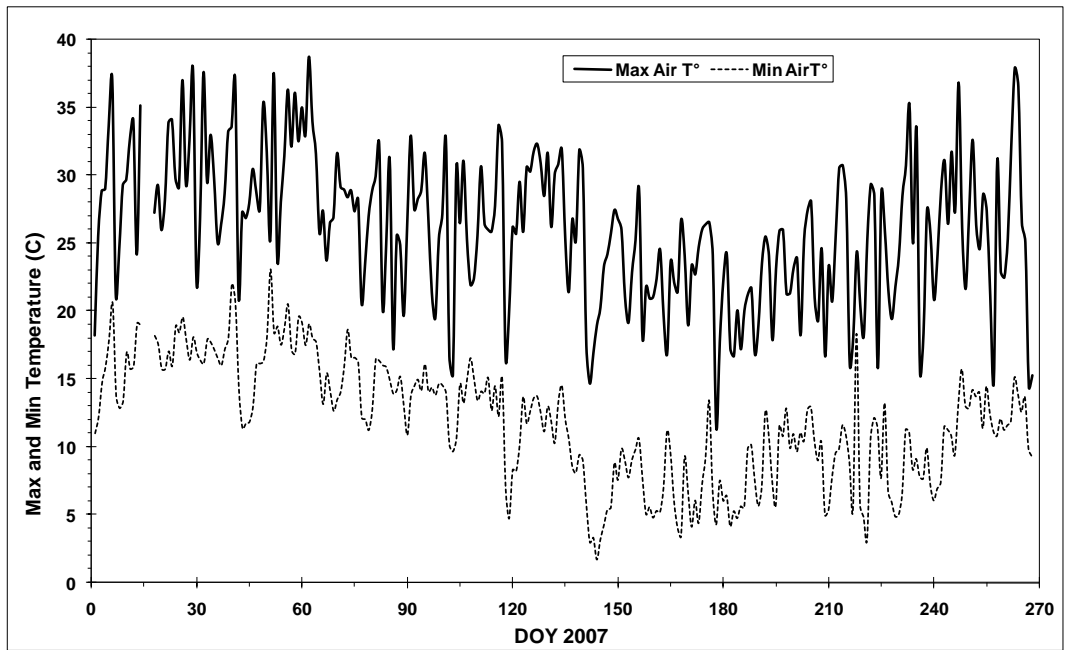


Fig. 8. The seasonal trends in maximum and minimum air temperature at the Ukulinga study site.

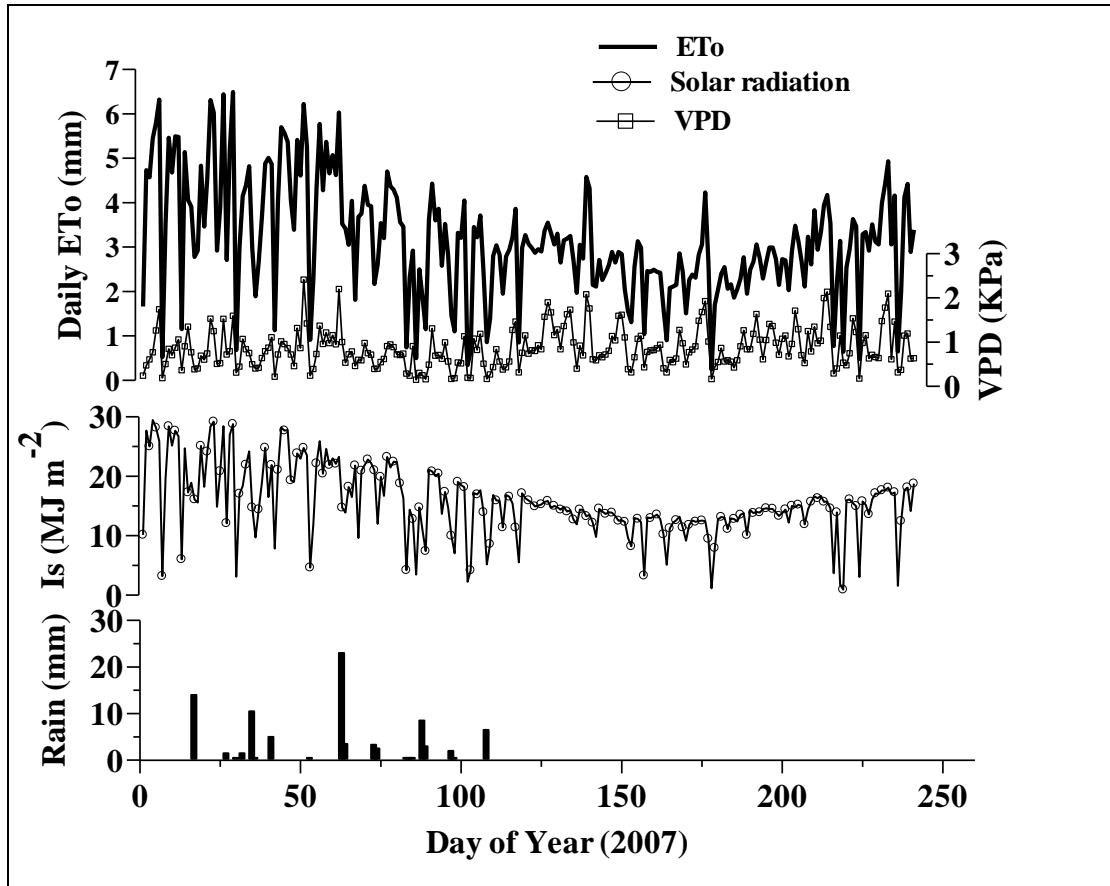


Fig. 9. Graphical summary of Penman-Monteith grass reference evapo-transpiration (ET_o), rainfall, solar radiation (I_s) and vapour pressure deficit (VPD) for the months January to August 2007 from the AWS station at Ukulinga.

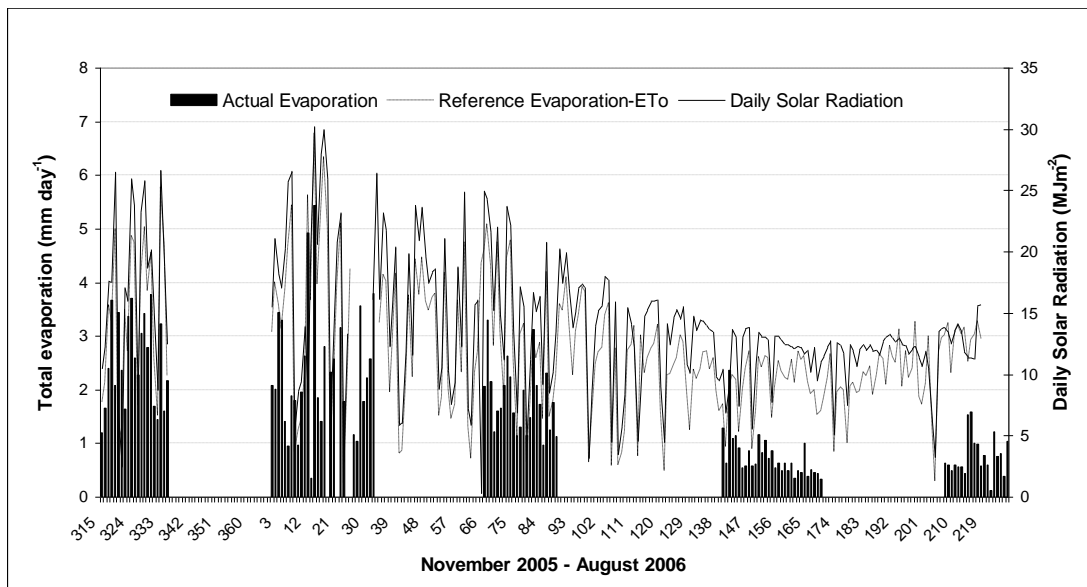


Fig. 10. Daily total EC evaporation (mm) together with the reference ET_0 (mm) and total daily solar radiation ($MJ\ m^{-2}\ day^{-1}$).

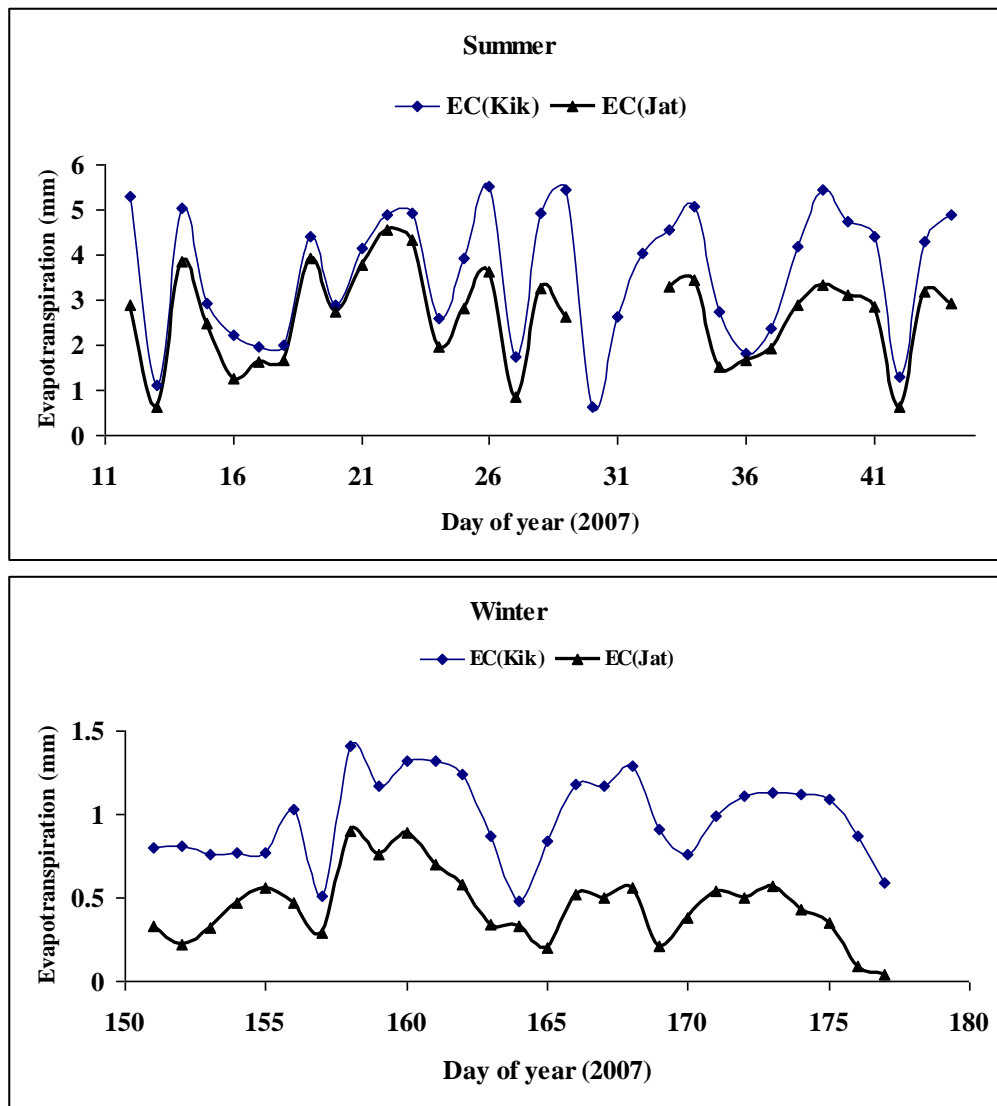


Fig. 11. Daily total EC evaporation (mm) measured in the *Jatropha* only and Kikuyu treatments in the summer (top graph) and winter (bottom graph) of 2007.

Table 1. 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