

**Plant productivity, radiation interception and water balance as indicators
of tree-crop interactions in hedgerow intercropping systems:
a Jatropha - Kikuyu case study**

by

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*Hoping this makes a worthy dedication to my parents who are my epitomes of
strength and patience!*

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DECLARATION

I, Solomon Beyene Ghezehei declare that the dissertation, which I hereby submit for the degree PhD (Agronomy) at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

Signature:

Date:

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LIST OF ACRONYMS AND SYMBOLS

a	Half of tree crown width
AGDM	Above-ground (vegetative) dry matter
AGDMI	Above-ground dry matter increment
AG	Above-ground
a_H	Coefficient of stem diameter-tree height relationship
ANCOVA	Analyses of covariance
ANOVA	Analyses of variance
ap	Half the width of tree crown base after pruning
a_s	Coefficient of stem diameter-stem mass equation
b	Half of intra-row tree spacing
BBD	Basal branch diameter
BD	Basal stem diameter
BDM	Branch biomass of trees
BG	Belowground
c	Half of tree crown height
CAMASE	Concerted Action for the development and testing of quantitative Methods for research on Agricultural Systems and the Environment
Cf	correction factor
CV	Coefficient of variation
$CV_{i,j}$	Control volume (i, j)
D	Index of agreement of Willmott
DCV_i	Depth of $CV_{i,j}$
$DM_{i(R)}$	Radiation limited net primary production
$DM_{i(W)}$	Water limited net primary production
DM_i	Daily net primary production
DOY	Day of year
DR	Double-row treatment
DWR	Dry matter-water ratio
E_c	Radiation conversion efficiency
ET	Evapotranspiration
ET ₀	FAO short grass reference evapotranspiration
f_{cv}	Ratio of crown volume after pruning to its volume prior to pruning
FDM	Fruit/flower biomass of trees
f_f	Proportion of net primary production allocated to tree foliage
f_i	Parameter in tree height - vertical root growth relationship
FI_{transp}	Fractional radiation interception by the crown for photosynthesis and transpiration
f_j	Parameter in the tree height and horizontal root growth relationship
FLDD	Day degrees required to reach flowering
f_R	Fraction of net primary production apportioned to tree root
$froot_{(i,j)}^0$	Root fraction in the control volume prior to pruning/tillage
$froot_{(i,j)}$	Maximum root fraction of a control volume (assuming no pruning/tillage occurred)
G	Heat flux of the soil
GDD	Growing degree days
h	Row spacing
HI	Harvest index
HPV	Heat ratio method

i	Vertical node position
ICRAF	International Centre for Research in Agroforestry
j	Horizontal node position
JO	<i>Jatropha</i> -only treatment
Kcb	FAO basal crop coefficient.
Kc _{max}	Maximum crop coefficient
LAD	Leaf area density
LAI	Leaf area index
LANMODEL	Land-use Model
LDM	Foliage biomass
LDMagei	Age of leaf biomass increment
LDMage _{max}	Thermal time accumulated by foliage until leaf senescence
LIDD	Growing degree day requirement for leaf initiation
LL	Life span of the leaves in the crown
MAE	Mean absolute error
MBE	Mass balance error
MULBUD	Multiple Cropping Budget Model
NE	North-eastern
n _H	Exponent of tree height-stem diameter equation
n _s	Exponent of stem diameter-stem mass equation
P	Summation of p _(i,j)
p _(i,j)	Index of 'favourability' of CV _{i,j} for tree root growth
Pa	Atmospheric pressure
PAR	Photosynthetically active radiation
PART	Parameter of biomass allocation to stem and leaves
PD	Depth of pruning of tree root
PE	Potential evaporation
PET	Potential evapotranspiration
PT	Potential transpiration
q	Ratio of crown width to crown height
r	Coefficient of correlation
r ²	Coefficient of determination
RDM	Root dry matter
RDMD _(i,j)	Root biomass density in CV _{i,j}
RDM _(i,j)	Root biomass increment CV _{i,j}
RF	Rainfall
RGR	Relative growth rates
RH	Relative humidity
R _i	Vertical root extent
R _j	Horizontal root extent
RO	Run off
rpf	Reproductive partitioning fraction
RUE	Radiation use efficiency
SDM	Stem biomass
SI	Stress index
SLA	Specific leaf area
SR	Single-row treatment

SS	Standard-spacing treatment
SW	South-western
SWB	Soil Water Balance model
SWB-2D	2D energy interception and water balance model for hedgerow tree crops
SWD	Soil water deficit
T	Transpiration
T_b	Base temperature
T-C	Tree-crop
TCI	Tree-crop interface
T_{cutoff}	Temperature at which maximum plant development occurs
TD	Depth of tillage of the intercropping
TDR	Time domain reflectometer
T_f	Index of temperature effects on growth
TH	Tree height
T_{lo}	Optimum temperature for growth when radiation limits growth
TR	Triple-row treatment
TransDD	Transition period day degrees
Transl _F	Parameters of assimilate translocation for flowering initiation
Transl _L	Parameters of assimilate translocation for leaf initiation
U_2	Wind speed as measured at 2 m height
$V_{(i,j)}$	Volume of a CV _{i,j}
VDMi	Vegetative dry matter increment
V_F	Crown (foliage) volume
VPD	Vapour pressure deficit
WaNuLCAS	Water Nutrient and Light Capture in agroforestry Systems model
WDM	Woody biomass of trees
WRC	Water Research Commission
wsf	Index of the effects of water stress on leaf fall
WUE _{Econ}	Economic water use efficiency
$Z_{(i,j)}$	Depth of CV _{i,j}
Z_0	Height of crown centre from soil surface
Z_b	Height of the crown base from the soil surface
Z_o	Centre of the crown from the soil surface
$\Psi_{(i,j)}$	Soil matric potential in CV _{i,j}
α	Leaf absorptivity to direct solar radiation
γ_f	Leaf fall rate
$\rho_{F(\text{mass})}$	Foliage density by mass
γ_R	Root turnover rate
Ψ_{wilt}	Soil matric potential at permanent wilting point
γ	Psychrometer constant
Δ	Slope of the saturation vapour pressure curve
ΔSW	Change in soil water
ΔX	Width of control volumes
ΔY	Breadth of the control volume
ΔZ	Thickness of control volumes
λ	Latent heat of vaporization

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by

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ABSTRACT

The potential of agroforestry to alleviate problems related to scarcities of arable land, water, food and fuel wood is subject to understanding system functioning and implementing and managing an efficiently designed system. The objectives of this study were to understand interactions and productivity of a hedgerow intercropping system with reference to water and radiation use, and analyse system design and management scenarios in order to enhance returns. Field trials monitoring soil water, solar radiation and plant productivity were conducted during 2006-2008 at Ukulinga Research Farm (KwaZulu Natal, South Africa) using a *Jatropha*-Kikuyu (*Pennisetum clandestinum*) hedgerow intercropping system as case study. In order to extrapolate results, a process-based hedgerow intercropping model was developed by building intercropping and tree growth into the SWB-2D model. Data collected from the field trials were used to parameterise and evaluate the model, which was used to analyse hedgerow orientation and spacing to determine income scenarios of virtual system and to help develop design criteria.

Allometric relationships of *Jatropha* using basal stem diameter and crown width as predictor variables were found to be very reliable. Stem diameter was linearly related with wood and branch proportions and inversely proportional to foliage. Neither below-ground (BG) interspecies competition nor tree spacing had any significant effects on allometry. Allometric equations were proven valid for accurate, non-destructive and rapid predictions of tree growth under various growing and non-destructive canopy management conditions.

When interspecies competition was present, none of the tree spacing/arrangement options tested resulted in consistently highest tree relative growth rates (RGR). Treatments had no effect on tree RGR when high water availability and kikuyu dormancy coincided. The single-row treatment (SR) produced the shortest trees, but generally had the highest stem RGR during low rainfall periods. The standard-spacing treatment (SS) had the highest RGR during the spring and summer seasons. *Jatropha*-only treatment (JO) trees were the tallest and biggest. Treatments affected post-pruning tree height increase, even when rainfall was high. Length of tree-crop interface (TCI) generally decreased tree yield, especially as trees matured toward their maximum-yield age (4-5 years). SR trees showed slow response to pruning due to a high TCI. They, however, exhibited compensatory growth during May to August, when competition for water with grass was low. BG competition reduced tree nut yield more than tree biomass. Tree spacing/arrangements had no effect on tree harvest index.

Soil water varied among treatments and was asymmetrically distributed across tree hedgerows. System ET was generally the highest in SR and lowest in the double-row treatment (DR). Differences were mainly due to transpiration. Treatments affected tree root distribution, which was inferred using correlations between tree RGR and soil water deficit (SWD). In JO and SR, fine tree roots were asymmetrically distributed. Their distribution in DR was essentially symmetrical. Strong vegetative RGR-SWD correlations during the 2007/08 season indicated that tree growth was mainly water-limited. Though DR and SR had comparable tree RGRs, DR produced less grass than SR. This implied DR had more intensive BG competition than SR. Interspecific

competition was severe due to a lack of temporal complementarity between *Jatropha* and kikuyu and a shallow soil profile (0.6 m). Tree water uptake predominantly came from the 0.2 – 0.6 depth, which had about 8.6% of the total root biomass in the profile. There was no clear relationship between intercrop growth and root distribution. Radiation use efficiency of kikuyu decreased towards tree hedgerows possibly due to preceding interaction of the irradiance with tree canopy reducing photosynthetically active radiation. The effect of radiation distribution on tree-crop (T-C) interactions was mainly to magnify effects of water. Finally, tree spacing/arrangement could be manipulated to optimise radiation and soil water distribution and intercrop growth.

Predictions of solar radiation distribution, profile water content and tree water use were quite accurate. In general, intercrop productivity simulations were acceptable. Intercrop growth was overestimated when rainfall was high and underestimated when rainfall was low. During model *calibration*, tree woody biomass, leaf area index, crown width and nut yield were predicted adequately, while leaf dry mass was overestimated. During model *validation*, woody biomass and crown width were simulated reasonably well. However, foliage biomass, leaf area index and nut yield were overestimated. Overall, adequacy of the model for simulating tree productivity was established. Using scenario modelling, model capabilities to facilitate design/planning and management of hedgerow intercropping systems and interpretation of model outputs were demonstrated. The model can be used to determine the T-C trade-off that yields maximum income. By selecting best-case row orientation and spacing scenarios using the model, and keeping in mind values of tree and intercrop yields, system returns can be maximised. Tree crown growth can also be predicted in order to decide on the extent and timing of pruning.

The present model is applicable to any potential tree-intercrop combination. It should be linked to a nutrient simulator of SWB, its component, and appraised further by considering shade-intolerant and shade-loving crop species, along with evergreen and deciduous tree species. This provides model users with numerous T-C combinations to choose from. Various tree spacing/arrangement options can also be explored using the model in order to realise the full potential and implications of the experimental findings of this study and others.

CHAPTER 1

GENERAL INTRODUCTION

1.1 RATIONALE

Production of food crops and pastures faces ever increasing scarcities of arable land and water resources. The problem with the land is deterioration, whereas water problems are due to limited available sources and erratic and relatively low rainfall. Yields and food security are compromised by poor agricultural production technologies/practices and low inputs (Everson *et al.*, 2012).

In South Africa, wood consumption is 9 to 11 million tons per year, more than 60% of which is from natural woodland. Approximately 40% of the population lives in poverty and rural areas and are heavily dependent on fuel wood (DWAF, 1996). The above critical limitations necessitate consideration of more resource efficient production systems that enable sustainable production and land rehabilitation.

Productivity of marginal lands can be greatly enhanced by incorporating trees into crop and animal production systems (Cooper *et al.*, 2004; Rethman, 1999), a practice known as agroforestry. Agroforestry is a practice of integrating woody and non-woody plants and/or animals within a land management unit simultaneously or sequentially, bringing about significant ecological and economical interactions (www.icraf.cgiar.org). It offers multiple productivities and/or services (Huxley, 1999). Tree hedgerow intercropping systems cover roughly 60% of the land under agroforestry (700 million ha), occupying mainly humid and sub-humid tropical and temperate (North America, Canada Europe) regions (Zomer *et al.*, 2009; Nair, 2012). It can take other forms, including silvopastoral, silvoarable, agrosilvopastoral (crops/timber/livestock), multi-level plantations (fruit/timber/crops) and agrisilvicultural (crops/timber) (Swaminathan, 1987). An additional 450 million ha of land is estimated to be used for silvopastoral systems, especially in the semi-arid and sub-humid regions of Africa, India and USA (Nair, 2012).

Agroforestry has the potential to solve problems of land marginality (Brenner, 1996; Kang, 1997) and firewood (Cameron *et al.*, 1991; Fenn, 1995), provide benefits of fodder (Swaminathan, 1987), soil conservation and live fencing, and reduce runoff, evaporation (Oteng'I *et al.*, 2000) and deep percolation

(Ong *et al.*, 1996; Lott *et al.*, 2003). Trees also help in enhancing soil fertility and organic matter levels (Nair, 1993; Sanchez, 1995) and minimising nutrient and organic matter losses (Young, 1989). Conversely, tree-crop (T-C) competition for resources, which is a function of resource availability and extractability (van Noordwijk and Purnomasidhi, 1995) and space and increased evaporative losses due to high rain interception by trees may occur (Ong *et al.*, 2000). Hence, in order to ascertain sustainability of agroforestry systems, obtaining insights of the various interactions taking part is crucial (Berlyn and Cho, 2000; Ong *et al.*, 2000).

In agroforestry, T-C interfaces can be controlled effectively (Huxley, 1999) and interspecies competition minimised by employing the best-case tree density, row orientation and spacing/arrangement, which represents T-C trade-offs and possibly involves more than one tree row (Garrett and McGraw, 2000). Systems can have higher efficiency and lower interspecific competition via tree crown (Huxley, 1999) and root management (Jose *et al.*, 1995) and selecting compatible species (Ong, 1996; Ong *et al.*, 2002) and right planting dates (Smith, 2000).

Worldwide applications of agroforestry are growing (Cubbage *et al.*, 2012). Nevertheless, farmers are hesitant about agroforestry due to lack of know-how and confidence over system relevance and practicality (Doyle and Waterhouse, 2008). Adoption of agroforestry in South Africa since its first introduction in 1887 (Hailey, 1957 cited in Nair, 1993) has been very limited. Focus has rather been on separate agricultural and forestry production. At institution level, this is due to the fact that, until 2009, the Departments of Agriculture and Forestry were separate. At farmer level, there is lack of exposure to agroforestry systems and their benefits, limited production resources and technologies and the misconception of trees being high water consumers and their inclusion in farmlands being seen as a waste of land. Lack of documentation has also been another limiting factor.

Implementation of this technology in South Africa can be improved by familiarising potential users with this technology, selecting compatible plant mixtures, adding to the existing knowledge and experience of agroforestry interactions and system functioning and developing means of making its future design and management more efficient. In addition to the incentive of the value of the trees (Stirzaker and Lefroy, 1997), farmers should be informed of unique economic benefits of agroforestry, namely: maximising land

use efficiency, securing periodic earnings and reduced investment risks attributed to the mixture of highly market-sensitive shorter-term revenues from crops and more stable longer-term revenues from trees (Kurtz, 2000).

Identifying conditions under which overall system output/income from agroforestry systems is higher than mono-cropping or animal production systems is challenging (Doyle and Waterhouse, 2008). In addition, agroforestry research findings tend to be practice-specific (Kurtz, 2000). These challenges present modelling, with a key role of filling-in knowledge gaps via analyses of system scenarios and extrapolation of research findings. The information obtained from modelling also helps in lowering cost of agroforestry practice and research and enables better decision-making (Kurtz, 2000). The current study was part of a project (K5/1480/1/12) funded by the Water Research Commission (WRC) of South Africa entitled 'Agroforestry systems for improved productivity through the efficient use of water', with core objectives of undertaking knowledge synthesis, experiments and modelling on selected agroforestry systems and technology transfer.

1.2 INTERACTIONS IN AGROFORESTRY

1.2.1 Tree - crop interactions

Tree – crop (T-C) interactions refer to the effects of tree and crop components of an agroforestry system on each other and the system (Nair, 1993). Factor that affect T-C interactions can be grouped into biological, environmental and management factors. The biological factors include genotype, phenotype, phenology and forms of the plants (Huxley, 1996, Ong *et al.*, 2000). Environmental affects T-C interactions via temperature, nutrients, water, radiation, (Huxley, 1996; Huxley, 1999), slope of the land (Garrity, 1996) and their interrelations. Main management factors include tree canopy and root pruning (Schroth, 1995; Ong *et al.*, 2000), planting time and density, fertilizer application, irrigation (Huxley, 1996) and selection of component species (Ashton and Ducey, 1999).

Three possible interactions exist in agroforestry systems, namely: complementary, competitive and supplementary. Complementary interactions (Figure 1.1a) result in positive relationships between outputs of component species. Trees provide benefits of water and soil conservation (Nair, 1993) and reduced

crop-weed competition by blocking radiation from reaching shade-sensitive weeds and suppressing their growth (Nair, 1993; Ong, 1996). Microclimate may be improved because of tree shading effects resulting in more favourable air temperature, humidity, air movement and soil temperature and moisture (Nair, 1993).

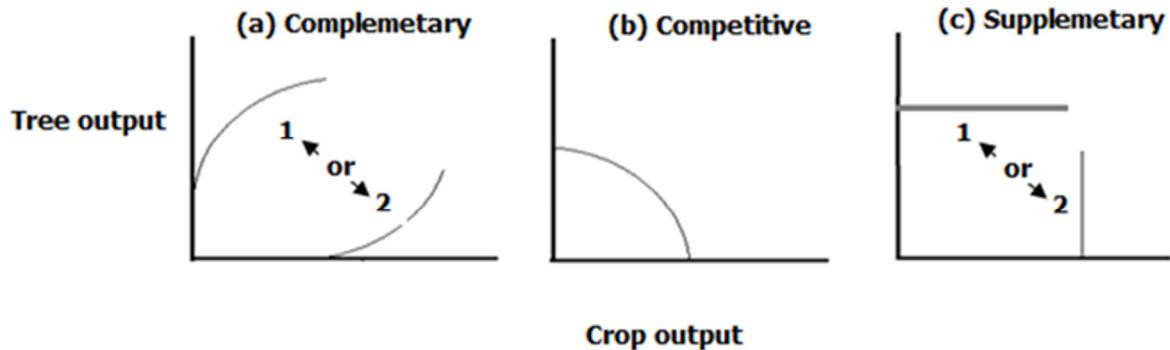


Figure 1.1 Possible interactions and products in agroforestry systems with two component species (T-C) (Nair, 1993; Kurtz, 2000), where 1 and 2 in Figures 1.1a and 1.1c represent output possibilities of the respective interactions

Competitive interactions (Figure 1.1b) are characterised by inverse relationships between outputs of the component species. Initially slower tree growth and reduced crop growth is common in agroforestry systems (compared to monoculture systems) due to T-C competition (Ong *et al.*, 2000) taking place directly and indirectly (Huxley, 1999). Species can compete for radiation, water (Nair, 1993, Ong *et al.*, 2002) nutrients and space or via allelopathy (Nair, 1993). In supplementary interactions or independent relationships (Figure 1.1c), outputs of component species do not affect each other. This may take place when component species use resources at different times. One example is the relationships for light and water between *Acacia albida* and intercrops, where *Acacia* trees are leafless during crop planting at the beginning of the rainy season (National Academy of Sciences 1979, cited in Filius, 1982).

1.2.2 Plant - environment interactions

Plant growth and development is affected by solar radiation, temperature, water and nutrients. There are interrelationships among these factors and the perennial presence of trees in agroforestry affects the magnitude of these interrelations (Huxley, 1999). Tree root growth is dictated by soil water content and

hence varies seasonally. By extracting water and nutrients from deeper horizons and nutrient pumping, trees reduce leaching losses and enrich the soil nutrient pool in the upper horizons (Schroth, 1995).

Plant-environment interactions in agroforestry can benefit the environment in several ways. They improve nutrient recycling, resource use efficiency, soil fertility and organic matter (Nair, 1993; Sanchez, 1995; Schroth, 1995; Kang, 1997; Schroth and Sinclair, 2003). They help in reducing land and environmental degradation by providing wind-breaking (Oteng'I *et al.*, 2000) and biological soil conservation (Swaminathan, 1987; Young 1989; Nair, 1993); reducing forest clearing and artificially enhancing biodiversity; reducing land degradation (Brenner, 1996), soil acidity, alkalinity and salinity (Kang, 1997); reducing organic matter and nutrient losses (Young 1989); minimising microclimatic extremes, such as wind, temperature and solar radiation (Kang, 1997); and sequestering carbon.

On the other hand, plant-environment interactions can negatively impact the environment in a number of ways. To mention some: release of growth-deterring chemicals by some components of the system; nutrient losses due to tree harvesting (Huxley, 1999); plants reducing groundwater recharge by intercepting rainwater (10-25% of the total rainfall); plants reducing groundwater recharge by using soil water available in the unsaturated zone (Schofield, 1990).

1.2.3 Economic implications of interactions

A major economic goal of agroforestry systems is to maximise total income/profit from farmland over time (Kurtz, 2000). Numerous studies have reported profitability of agroforestry (Etherington and Matthews, 1983; Kurtz *et al.*, 1984; Dangerfield and Harwell, 1990; Kurtz *et al.*, 1991; Clason, 1995; Cubbage *et al.*, 2012), which depends on trees and their effects on crops, land and present values of future costs and earnings (Doyle and Waterhouse, 2008). The best-case T-C combination should be identified and productivities of the individual species further regulated via management (Kurtz, 2000; Doyle and Waterhouse, 2008).

In order to reflect effects of values of tree and crop products on optimum T-C combination, a production possibility curve (PPC) and an iso-revenue line are required (Kurtz, 2000). PPC shows possible product combinations that can be produced with the same fixed input level (labour, land, capital, management so

on). Iso-revenue lines depict possible T-C product combinations generating the same total income. At a particular input level, the highest total net value is obtained at the point (T, in Figure 1.2b) where the iso-revenue line is tangent to the PPC (Kurtz, 2000). At point T, values of marginal tree and crop products are equal (Filius, 1982) and a shift from T causes a bigger income loss due to the reduction of one output than the value added by an increase in the other (Kurtz, 2000).

When a PPC is concave (Figure 1.2b, solid) to the origin, marginal tree product and the decline in crop product increase and agroforestry can be efficient. However, if the iso-revenue line is steep or flat, agroforestry can only be justified in the presence of strong complementarity or supplementarity. For convex PPCs (Figure 1.2b, dotted), marginal crop product is associated with a shrinking decline of tree product and vice versa and forestry or crop production is preferred to agroforestry (Filius, 1982).

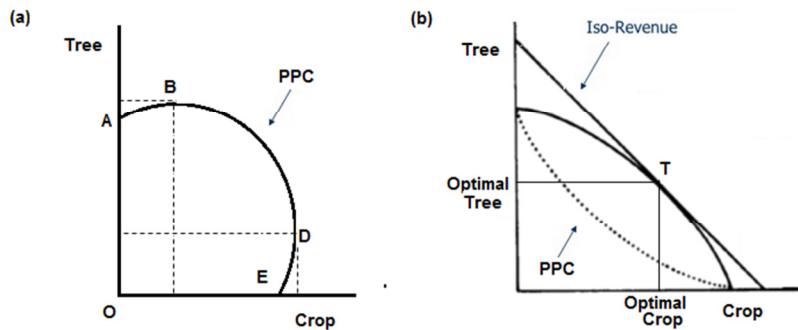


Figure 1.2 (a) Production possibility curve (PPC) showing various complementary (AB and ED), supplementary (B and D) and competitive (BD) T-C interactions and (b) optimum T-C combination point (at T) and convex (dotted) and concave (solid) PPCs (Filius, 1982; Kurtz, 2000)

1.3 RESOURCE AVAILABILITY AND USE IN AGROFORESTRY: RADIATION AND WATER

1.3.1 Radiation distribution and use

Radiation not utilised for photosynthesis immediately cannot be stored and is, therefore, lost (Kropff, 1993a). The quantity and quality of solar radiation that plants intercept is dictated by a number of factors, such as altitude, canopy structure, clouds, latitude, time of year, time of day and topography (Ong *et. al.*, 1996; Berlyn and Cho, 2000). Plant utilise radiation based on their internal and external structures and

water and chlorophyll contents of their leaves (Kropff, 1993b; Berlyn and Cho, 2000). Radiation, then, takes part in photosynthesis, stomatal aperture, crown and leaf characteristics, photoperiodism, enzyme activation, radiation driven reactions and cold hardiness (Berlyn and Cho, 2000). Indirectly, radiation affects plant use of other growth resources (Huxley, 1999).

In agroforestry, interspecies competition for radiation (Nair, 1993; Ong *et al.*, 1996), heterogeneity and constant variation in crown architecture makes radiation distribution complex. Shading of field crops is a function of closeness to trees (Ong *et al.*, 1996), tree height (Reifsnyder 1989), nature and structure of tree canopy, tree foliage density, position of the sun, latitude and altitude (Ong *et al.*, 1996; Berlyn and Cho, 2000). Management also plays an important role in radiation distribution of agroforestry. The spatial distribution of transmitted radiation to an agroforestry floor is dependent on tree canopy management (Ong *et al.*, 2000), planting geometry of component species, tree spacing and row orientation, (Ong *et al.*, 1996; Berlyn and Cho, 2000). Radiation distribution can be optimisation using appropriate design of tree spacing and row orientation and management of tree canopies especially during establishment phases of understory crops (Ong *et al.*, 1996; Garrett and McGraw, 2000).

1.3.2 Water balance

Interspecies competition for water takes place directly or indirectly. When water is limited, the component with the better developed root system dominates. When water is not limited, potential growth of component species dictates potential competition for water at later stages (Kropff, 1993b). In agroforestry, trees affect water availability to crops by enhancing soil physical properties, decreasing (runoff and evaporation) losses and intercepting rain and competing for water in the crop-root zone (Wallace, 1996). Even when water is not limited, trees affect crop transpiration by affecting other growth limiting resources (Kho, 2000). According to van Noordwijk *et al.* (1996), hydraulic lift, which is the redistribution of soil water from deeper soil horizons to drier upper horizons via plant root systems (Richards and Caldwell, 1987), plays a role in soil water recycling in agroforestry.

Agroforestry can have higher rainwater use efficiency than mono-cropping (Ong *et al.*, 1996; Wallace, 1996). Reduction in evaporation is due to mulching and perennial tree presence shielding the soil from

radiation and wind (Wallace, 1996). Trees can utilise post-harvest residual water in the crop root zone (Leyton, 1983) and rainfall between crop growing seasons. According to Lott *et al.* (2003), tree water use between crop growing seasons could be as much as 25% of annual tree water use and 16% of annual rainfall. While a fraction of canopy-intercepted rain is evaporated, the rest falls through plant canopies depending on rainfall intensity and atmospheric demand (Ong *et al.*, 1996; Wallace, 1996). Runoff is reduced and infiltration is higher due to modification of kinetic energy of raindrops, reduced soil crusting, improved soil hydraulic conductivity, mulching and increases in soil faunal and floral communities that modify soil structure and permeability (Wallace, 1996).

1.4 MODELLING IN AGROFORESTRY

1.4.1 Overview

In agroforestry, modelling was first practised in 1983 when the "Multiple Cropping Budget Model (MULBUD)" and the "Land-use Model (LANMODEL)" were developed. Before this, however, a concept of "Modelling organic-matter flows and nutrient cycles in agroforestry systems" was established by 1981 (Young, 1997).

There are two conventional ways of developing agroforestry models. A model is developed and its predictions are compared with independent field data to decide its acceptance or need for modification. An alternative way involves modifying agricultural, forestry, soil or economic models (Young, 1997). Modular approach agroforestry model programming offers benefits of ease of model design, modification, structural configuration and possibility of exploring subroutines independently (Muetzelfeldt, 1995).

Agroforestry comprises several unique features. These include multiplicity of system components and outputs, perennial presence of trees and their effects and complex aboveground (AG) and belowground (BG) T-C interactions and structures (Young, 1997). Computerized agroforestry models provide possibilities of analysing these interactions and plant selection scenarios (Huxley, 1999). They can be used as system designing/planning, management/decision-making and research/education tools (Lawson *et al.*, 1995) by helping users to understand system functioning (Kurtz, 2000), predict and evaluate long-run system

trends, benefits, uncertainties and limitations (Lott *et al.*, 2000), interpret experimental results and design future systems (Muettzelfeldt, 1995; Young, 1997).

One of the most important simulations in hedgerow intercropping systems is tree interference with irradiance of intercrops (Reid and Ferguson, 1992). Overestimation of radiation interception by a species leads to overestimations of growth and resource use at the expense of other components (Mobbs *et al.*, 1999). The spatio-temporal variability of irradiance of intercrops is a function of tree crown growth and management and solar path. The approaches of the radiation-driven models developed for pure-stands (Smart, 1973; Jackson and Palmer, 1979; Cohen and Fuchs, 1987, Berliner, 1988; Nilson and Kuusk, 1989) and mixed cropping systems (McMurtrie and Wolf, 1983; Spitters and Aerts, 1983; Rimmington, 1985; Graf *et al.*, 1990; Ryel *et al.*, 1990; Sinoquet *et al.*, 1990; Sinoquet and Bonhomme, 1992) are not ideally suited for hedgerow intercropping applications. Their applicability is limited by over-simplification of foliage distribution, and lack of consideration of various solar positions and irradiance variations with distance from trees.

Another important simulation to make in hedgerow intercropping systems is BG T-C interactions (Van Noordwijk and Lusiana, 2000). Matthews *et al.*, (2004) summarised models of BG interactions in agroforestry systems. These interactions are functions of root distribution, possibly preferential tree root turn-over and regrowth after root pruning or tillage. These are affected by factors such as soil water and oxygen distribution. For water modelling, water demands of components need to be characterised fully. Canopy growth of component species also determines their water use and affects system water balance. According to Van Noordwijk *et al.* (1996), water uptake modelling in agroforestry can be based on one of the following approaches: implicit roots, uptake efficiencies, curve fitting to root growth, functional equilibrium between root growth and nutrient and water status of plant and root growth response as affected by availability of nutrients, water, oxygen and mechanical impedance.

A number of models have been used to for predicting various aspects in agroforestry systems. Table 1.1 presents a list of such models and their brief descriptions. WaNuLCAS and HyPAR are the most comprehensive process-based agroforestry models and can simulate a wide range of agroforestry systems (Cannell, *et al.*, 1998; Mobbs *et al.*, 1999; Walker, *et al.*, 2007).

Table 1.1 List of models integrating simultaneous agroforestry interactions

Model name (Reference)	Key characteristics
Always (Bergez <i>et al.</i> , 1999)	Processes linking tree, sward, animals, microclimate & soil in tree-sward systems
Tree-Grass (Simioni, <i>et al.</i> , 2000)	Light, water & carbon fluxes of plants in tree-grass systems
SWAT (Garg <i>et al.</i> , 2011)	Spatio-temporal hydrological processes, water flow, soil (sediment) & nutrient loss and plant growth in complex watersheds (tested for tree plantation in grazing land); daily to annual day-step
SCUAF (Young <i>et al.</i> , 1998)	Nutrient cycling, soil erosion, organic matter, T-C competition for nutrients; Simple & easy to use
HyPAR (Mobbs <i>et al.</i> , 1999)	T-C interactions, growth and resources capture under a range of soil, climate & management
WaNuLCAS (Van Noordwijk & Lusiana, 2000)	T-C-soil interactions in various simultaneous & sequential agroforestry systems
HyCAS (Matthews & Lawson, 1997)	Light, water, N & P competition of tree-cassava system
COMP8 (Smethurst & Comerford, 1993)	Nutrient uptake by competing root systems
SSAND (Comerford <i>et al.</i> , 1993)	Modified COMP8 and includes variable root growth and soil water and mineralization
WIMISA (Mayus <i>et al.</i> , 1998)	Crop growth as affected by tree windbreaks; 2D soil water balance; competition for water
APSIM (McCown <i>et al.</i> , 1996)	Modular T-C interactions for light & soil resources
CropSys (Caldwell & Hansen, 1993)	Crop system performance across genotype, soil, weather & management; long-term water & N balances; light, water, NO_3^- & NH_4^+ competition
ALAMANAC (Kiniry <i>et al.</i> , 1992)	Plant growth, water & nutrient balances for competing species
GAPS (Rossiter & Riha, 1999)	Intercrop light & water competition between species

Despite the existence of many models, by far the most comprehensive agroforestry models are WaNuLCAS and HyPAR. WaNuLCAS (Van Noordwijk and Lusiana, 2000), is a process-based model of resource use (radiation, water, N and P) and plant growth in sequential and simultaneous agroforestry systems, including hedgerow intercropping on sloping lands. Its soil system has 16 user-specified cells (four layers by four zones). Trees occupy the first zone while influencing crop-occupied zones via their roots and foliage. Plant water uptake and competition for water, N and P are determined by root length density and demands. Plant growth is a function of potential growth rate and the most limiting resource. Crop roots can grow exponentially to a specified maximum, or can grow preferentially based on resource availability. Assimilate allocation follows shoot-to-root functional equilibrium. Tree root distribution is either user-specified or a decreasing (elliptical) function with depth and distance from the tree component, or dictated by functional equilibrium and preferential growth. Radiation interception is a function of tree and crop LAI

per canopy layer and relative plant heights. Tree management, fertiliser application and litter-fall are also simulated. WaNuLCAS is useful as a null-hypothesis of principal interactions of agroforestry system while allowing users to add more interactions (van Noordwijk *et al.*, 2004).

HyPAR (Mobbs *et al.*, 1999) is a process-based plant growth and resource (radiation, water and nutrient) capture model developed by merging a forest (Hybrid) and a crop (PARCH) models. Tree net primary production is a function of net photosynthesis, water balance, stomatal conductance and respiration. Carbon allocation follows stem diameter-stem carbon allometry, foliage-sapwood area proportionality and canopy to fine-root carbon ratio. Laterally uniform (1D) or disaggregate (3D) option can be selected for the tree canopy and roots (in 3D, roots decrease exponentially away from tree). Trees can be pruned, coppiced or thinned. Crop growth is dictated by the most limiting of radiation, water, nutrients and possibly temperature. Stress (temperature, water or nutrient) modifies crop growth and development. Resource uptake is a function of root length density and demand and is modified by competition if resource availability is less than the demand. The soil profile is assumed to be free-draining and non-sloping, and has 15 layers, only nine of which are accessible to crops. Soil water is modelled in one-dimension using a tipping bucket, a Brooks-Corey, a van Genuchten or a Campbell-Darcy hydrologic model, which obtains parameters from one of Campbell, Rawls, Mishara and Tomasella or Hodnett pedo-transfer functions (Mobbs *et al.*, 1999).

1.4.2 Potential source models for developing a mechanistic hedgerow intercropping model

Accurate modelling of agroforestry systems necessitates focus on plant-resource and plant-plant interactions, which vary across T-C interfaces. Key elements that need accurate characterizations include root and canopy growth, resource demand and use, positions of plant, growth and productivity of component species and the nature of interspecific interactions (Mobbs *et al.*, 1999). Some models are capable of characterising aspects of agroforestry systems due to their robustness, which makes them viable candidates as agroforestry model components. The Soil Water Balance (SWB) model and two dimensional energy interception and water balance model for hedgerow tree crops (SWB-2D), are two such models (Annandale *et al.*, 1999; Annandale *et al.*, 2002; Annandale *et al.*, 2003; Annandale *et al.*, 2004).

SWB is a mechanistic, real-time, generic, crop growth and soil water balance model, developed by Annandale *et al.* (1999) as an irrigation management tool. Using soil, weather and crop inputs, it simulates crop growth as limited by radiation or water and water balance using cascading or finite difference approaches. The model has been widely tested for several crop and sites and has proven to be reliable. SWB-2D was developed as an extension of SWB. It has a radiation distribution and interception predictor, a soil evaporation predictor, a tree transpiration predictor and a 2D soil water redistribution predictor. These components were evaluated independently and altogether and have shown that the model and its components are quite accurate if properly parameterised (Annandale *et al.*, 2002; Annandale *et al.*, 2003; Annandale *et al.*, 2004). SWB and SWB-2D are discussed in greater detail in sections 5.2 and 5.3.

1.5 OBJECTIVES AND HYPOTHESES

Objective 1: To understand interactions and productivity of a hedgerow intercropping system with reference to water and radiation use by conducting applicable measurements related to soil, water and plant productivity

Objective 2: To analyse various scenarios so as to maximise system returns. Scenarios include:

- Tree and crop yield trade-off by manipulating design of tree row spacing and orientation, and
- Deriving information on timing and extent of tree row management (pruning) to aid intercrops

To address the first objective, field experiments involving *Jatropha curcas L.* and kikuyu (*Pennisetum clandestinum*) were conducted. *Jatropha* was selected as a multi-purpose, high-value (due to its bio-diesel rich nuts) and drought tolerant tree that can grow on low fertility soils. Since *Jatropha* is not consumed by browsing animals (Heller, 1996), when incorporated into silvopastoral systems, its growth and yield is not compromised by animals. Kikuyu, on the other hand, was selected due to its high capacity as a grazing pasture even under dryland. The *Jatropha*-Kikuyu system could potentially improve livelihood of small-scale farmers as a source of pasture (kikuyu) and income (through the sale of *Jatropha* nuts). Hence, feasibility of such a system and suitability of *Jatropha* for agroforestry, especially dryland, were investigated.

The following hypotheses were tested:

- Aboveground (AG) allometry of *Jatropha* using stem diameter and crown depth as predictor variables is reliable regardless of
 - The presence/absence of BG interspecies competition
 - Tree spacing/arrangement.
- BG interactions between a non-nitrogen fixing deciduous tree and a perennial grass in semi-arid areas are largely competitive, resulting in productivity reductions of trees.
- In a well-fertilized hedgerow intercropping system,
 - Pasture production can be linearly proportional to radiation transmission, especially if other resources are not limiting growth and
 - Water availability is more limiting than solar radiation under semi-arid conditions.
- At a given tree density in hedgerow intercropping, tree arrangement can be manipulated to
 - Minimise BG competition and productivity reduction of trees
 - Optimise radiation and water distribution and crop growth across the T-C interface.

The second objective was carried out using modelling. The reason behind this approach is the practice-specific nature of agroforestry systems that makes the need for extrapolating lessons learned from existing systems essential. In addition, investigating different design and management options through research is very expensive and time consuming, if not totally impractical. To overcome these limitations, model robustness to address component interactions and various possible scenarios of yield optimization, design and management is key. System productivity and returns are determined as the total value of outputs/products of component species, emphasising the need for accurate and robust predictions of component growth and productivity. Considering the variety of possible T-C associations taken into account when designing agroforestry systems, growth and productivity simulations should also be generic (non-specific) and mechanistic. To achieve all this, a process-based hedgerow intercropping model is required. WaNuLCAS and HyPAR are capable of meeting the above requirements and even include nutrient simulations. However, they have limitations that can potentially reduce their practicality and applicability. WaNuLCAS has an extensive parameter requirement (*e.g.* 54 for crops and 97 for trees) many of which are difficult to determine. Hence, parameterisation, parameter refinement and sensitivity analyses are

potentially complex (Dupraz, 2002). It has been suggested that some default parameters in the model can be applied to new simulation set-ups (van Noordwijk *et al.*, 2004). However, since the model is a prototype, users may need to add interactions and this could hinder applicability of the default values. Since hedgerow shadows on crops and interference of neighbouring hedgerow are not considered, radiation capture in WaNuLCAS may not hold at low solar angles or high altitudes. Tree assimilate allocation employed in WaNuLCAS is not suitable for a tree species with a strict phenology (Dupraz, 2002).

HyPAR also requires a large number of parameters (*e.g.* 50 crop and 43 tree species-specific parameters). It is not easy to determine many of the species-specific tree parameters experimentally. The complexity levels of this model's components are also very different. Currently, HyPAR crop modelling is equipped to predict two crop species only (four cultivars in total) (Mobbs *et al.*, 1999) and modelling other crops requires cultivar-specific parameterisation. Its crop modelling is not suitable for temperate conditions (Dupraz, 2002). Finally, HyPAR is no longer available in the public domain, which has significant implications for its future adoption.

The decision to incorporate a hedgerow intercropping model into SWB (instead of using existing agroforestry models) to address productivity trade-offs, enhance efficiency of design and management and develop design criteria emanated from the following reasons:

- Model accessibility for programming and future applications by farmers, consultants and researchers
- Its relative accuracy, simplicity and user-friendliness as a host model and source of powerful, mechanistic and robust components of modelling crop growth, water balance, radiation distribution and various elements of hedgerow intercropping systems
- It boasts vast crop databases, making numerous crops available for T-C combinations scenarios. SWB and SWB-2D offer powerful components of a hedgerow intercropping model upon appropriate setup modifications to meet requirements of hedgerow intercropping systems
- Its general reception by farmers, consultants and researchers for various production purposes in South Africa, a bonus when considering future adoption of the hedgerow intercropping model developed in this study.

Development of the current hedgerow intercropping model involved spatial integration of SWB crop growth simulator into the framework of SWB-2D. The motivation behind the framework selection was the accuracy of SWB-2D in simulating solar radiation interception and soil water balances of fruit tree hedgerows, which has the same structure as hedgerow intercropping systems. The two-dimensional modelling approach represents the fundamental interfaces of hedgerow intercropping interactions, across T-C intersects and vertically along these intersects (including along plant height and soil depths).

The crop growth routine of SWB was selected for predicting growth of intercrops due to its accuracy and robust, generic and mechanistic nature. These strengths also provided the growth simulator the potential of characterising tree growth. In the current study, advantage was taken of this while also adding new routines of tree growth characterisation and growth of crown and roots. The newly developed model was evaluated following the CAMASE modelling guidelines (1995), including checking dimensional, software and qualitative aspects of the model, comparison of its simulations with actual measurements (calibration and validation) and checking model responses to input changes.

1.6 THESIS OUTLINE

This PhD study has field experiment and modelling components, which are outlined in chapters as follows: Chapter 2 addresses reliability of allometry of *Jatropha* and effects of interspecies competitions and tree spacing on these relationships. Chapter 3 examines interspecies interactions in the hedgerow intercropping system by studying their effects on tree growth and yield and the possibility of alleviating competitive negative tree – crop interactions by manipulating spacing/arrangements of trees but without changing tree density. In Chapter 4, the focus is on investigating tree - crop interactions in the system from the viewpoints of radiation, soil water and total root biomass distributions and intercrop growth. Also, the possibility of optimising radiation and water distribution and intercrop profile by adjusting tree spacing/arrangement without changing tree density is examined. Chapters 5 and 6 are dedicated to the development and evaluation of a hedgerow intercropping model, which is used in Chapter 7 to demonstrate scenario modelling of selected system design elements to maximise economic returns. Finally, general conclusions and recommendations are presented in Chapter 8.

CHAPTER 2

SHOOT ALLOMETRY OF *JATROPHA CURCAS L.*

2.1 INTRODUCTION

Jatropha curcas L., also known as Physic nut, is a small (up to 6 m tall), deciduous, poisonous, fast and growing tree belonging to the family Euphorbiaceae. It originated from Mexico and Central America and is widely distributed in the tropical and sub-tropical Africa and Asia (Jongschaap et al., 2007). It grows well within altitude and temperature ranges of 0 to 1800 m (prefers below 500 m) and 11.0 to 28 °C respectively (Foidl et al., 1996; Sirisomboon et al., 2007). Under favourable conditions, *Jatropha* matures to full productivity as early as 3 to 4 years after planting (Jongschaap et al., 2007). It is highly adaptable to arid and semi-arid conditions (Heller, 1996), requiring rainfall of at least 250 mm per annum. It can grow on heavy to well-drained soils and soils with poor fertility. It tolerates mild frosts (PIER, 2004) but is not affected by day-length (Heller, 1996).

Jatropha is a multi-purpose tree. Most prominently, it is a source of bio-diesel rich nuts (Foidl et al., 1996; Achten et al., 2008), containing high concentration of highly extractible oil (Winkler et al., 1997). The oil produces minimal smoke and engine wear and has better efficiency than diesel (Foidl et al., 1996; Gübitz et al., 1999) in its pure, mixed and biodiesel forms (Heller, 1996; Sirisomboon et al., 2007; Achten et al., 2008). Other applications of *Jatropha* or its parts include for erosion control, live-fencing against browsing animals (Jongschaap et al., 2007), poles and fence posts (Openshaw, 2000); making soaps, pesticides and insecticides (Sirisomboon et al., 2007) and for medicinal applications (Gübitz et al., 1999).

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 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; Xia and Ceulemans, 2004). On the contrary, Cole and Ewel (2006) warn about challenges of allometry in dicotyledonous trees, a group that *Jatropha* 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 paper addresses questions regarding reliability (strength) of allometric relationships in *Jatropha*; 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 AG allometry of *Jatropha* using basal diameter and crown depth as predictor variables; effects of BG interspecies interactions and tree spacing on allometry; and validity of these relationships with independent data.

2.2 MATERIALS AND METHODS

2.2.1 Definition

Allometric equations are usually defined as:

$$Y = a D_{\text{stem}}^b \quad 2.1$$

Where Y is tree biomass (g), D_{stem} 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 dependent variable (Y) may also represent 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_{stem} ". The linear form of equation (2.1) is:

$$\log Y = b \log D_{\text{stem}} + \log a \quad 2.2$$

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):

$$cf = \text{antilog} \left[0.5 \left(\frac{\sum (\log Y - \log Y_{\text{Predicted}})^2}{n - 2} \right) \right] \quad 2.3$$

Where Y is the value of a sampled dependent variable, $Y_{\text{Predicted}}$ 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 *Jatropha* hardly grows as high as the DBH before it forms branches.

2.2.2 Treatments

Data were collected from the Ukulinga Research Farm of the University of KwaZulu Natal, Pietermaritzburg Campus, South Africa ($30^{\circ}24'S$, $29^{\circ}24'E$). Ukulinga has mean annual rainfall of 680 mm and an altitude of

781 m above sea level. Summers are warm to hot and winters mild with frosts rarely occurring. Mean annual temperature is 18.4 °C (Camp, 1997). The soil type at the site 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) with mean bulk density of 1580 kg m⁻³ (*cv* = 4.74%) and organic matter content of 1.28% (*cv* = 69.8%).

The study site was divided into a number of plots to accommodate various trials involving *Jatropha* (*Jatropha curcas L.*) and kikuyu (*Pennisetum clandestinum*). The plots were 50 m by 25 m. They had a planting density of 1100 trees ha⁻¹. The trials (based on tree spacing) were *Jatropha*-only (JO, 3 m x 3 m), standard-spacing (SS, 3 m x 3 m), single-row (SR, 5 m x 2 m), double-row (DR, 6 m alley width, 2 m between adjacent trees within a row and 2.5 m spacing between tree rows on either side of the alleys), and triple-row (TR, 7 m wide alley, 2 m spacing between adjacent trees within a row and 3 m between adjacent tree rows on either side on the grassed alleys). Figure 2.1 illustrates the setup of the double-row and triple-row trials. All trials but the *Jatropha*-only had kikuyu planted in their alleys (the widest spacing).

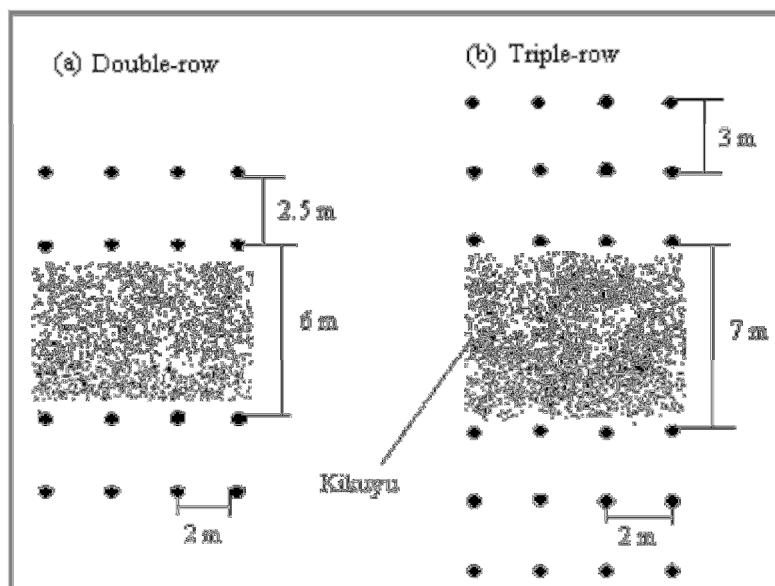


Figure 2.1 Illustration of the experimental setup in the (a) double-row and (b) triple-row trials

2.2.3 Sampling

2.2.3.1 Allometry between basal diameter and AG variables of *Jatropha*

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.

2.2.3.2 Allometry between crown depth and AG variables of *Jatropha*

The destructive sampling used in the study of allometry between basal diameter and AG biomass and dimensions of *Jatropha* was used.

2.2.3.3 Effects of interspecies competition and tree spacing on allometry

Effects of BG interspecies competition on allometry was investigated in a standard-spacing trial, containing 15 month-old *Jatropha* trees with kikuyu planted between the rows. The interactions between these species were for water and nutrients (BG) only, as the grass was too short to have any AG effects on the trees. Effects of the interspecies competition on the AG allometry of *Jatropha* 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 *Jatropha* during winter.

Jatropha-only, standard-spacing, single-row, double-row and triple-row trials were used in the study of tree spacing effects on allometry. 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.

2.2.3.4 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.

2.2.4 Data analyses

2.2.4.1 Allometry between basal diameter and AG variables of Jatropha

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

$$V_F = \frac{4}{3} \pi \frac{CH(\overline{CW})^2}{8} \quad 2.4$$

Where V_F (m³) is crown (foliage) volume, CH (m) is depth and \overline{CW} (m) is mean width (m) of the crown respectively.

Data set of basal diameter (BD) was paired with data sets of total AG dry mass, woody AG 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 log₁₀-log₁₀ 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 (equation 2).

2.2.4.2 Allometry between crown depth and AG variables of Jatropha

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

2.2.4.3 Effects of interspecies competition and tree spacing on allometry

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

2.2.4.4 Validation of the allometric relationships using independent data

Basal diameters were used in the height-diameter equation developed by destructive sampling. Predicted vs. measured tree heights were plotted against each other and their relationship examined.

2.3 RESULTS

2.3.1 Allometry between basal diameter and AG variables

At tree level, the allometric regressions were highly significant ($p < 0.0001$), with high and positive correlation coefficients. Results of the regression analyses, correction factors and corrected allometric equations are presented in Table 2.1. All correction factors were very low (close to one). Hence, basal stem diameter has a highly significant relationship with the AG variables. The relationship between total AG dry mass and basal stem diameter (before log-transformation) is presented in Figure 2.2 (a).

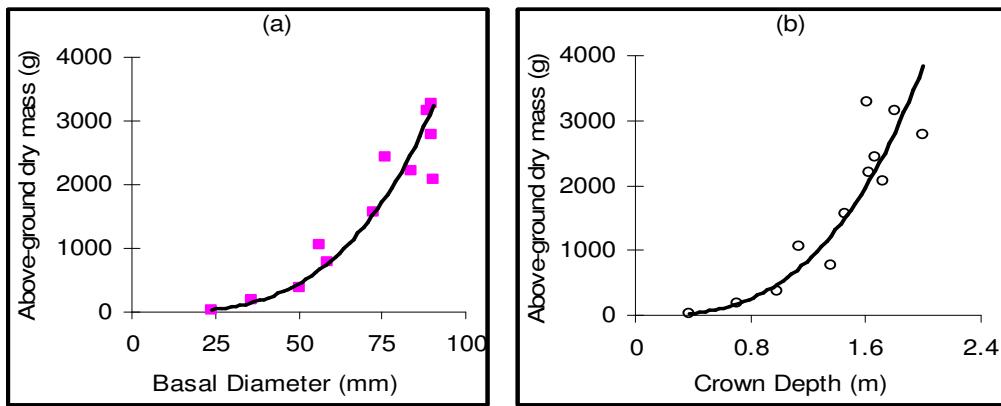


Figure 2.2 Relationship of AG dry mass with (a) basal stem diameter and (b) crown depth before log-transformation

Table 2.1 Results of regression analyses of the linearized allometric relationship of basal diameter with AG variables of *Jatropha* and corrected allometric equations ($Y = a BD^b$)

Tree parameter	b	log a	r	cf	Corrected $Y = a BD^b$
Tree height (m)	1.044	-1.714	0.98	1.002	$Y = 0.0193 BD^{1.044}$
Crown volume (m^3)	3.243	-5.798	0.97	1.013	$Y = 0.000002 BD^{3.243}$
Crown depth (m)	1.114	-1.907	0.98	1.017	$Y = 0.0126 BD^{1.114}$
Mean crown width (m)	1.065	-1.805	0.95	1.005	$Y = 0.0157 BD^{1.065}$
Leaf area (m^2)	2.734	-4.463	0.97	1.004	$Y = 0.000035 BD^{2.734}$
Foliage dry mass (g)	3.017	-2.921	0.97	1.021	$Y = 0.00126 BD^{3.017}$
Stem dry mass (g)	2.469	-2.273	0.99	1.015	$Y = 0.00541 BD^{2.469}$
Branch dry mass (g)	3.391	-3.386	0.97	1.029	$Y = 0.000423 BD^{3.391}$
AG dry mass (g)	3.354	-3.053	0.98	1.025	$Y = 0.000907 BD^{3.354}$
Woody AG dry mass (g)	3.529	-3.549	0.99	1.002	$Y = 0.000283 BD^{3.529}$

n = 12; Unit of BD is mm.

Partitioning of AG biomass of *Jatropha* into wood and foliage showed strong linear relationships ($r = 0.91$) with stem diameter without log-transformation of the data (Table 2.2). Percentage of branch exhibited a highly significant linear relationship ($p < 0.0001$) with basal diameter ($r > 0.95$). With increasing stem diameter, the proportion of woody biomass increased at the expense of leaf biomass (Figure 2.3 (a)). This increase is due to increased biomass allocation to branches, which was from 39.4% to 59.7%.

Table 2.2 Results of regression analyses of the linear relationships between basal stem diameter and percentages of AG wood and leaf biomasses of *Jatropha*

Percentage	Slope	Intercept	<i>r</i>
Wood	0.223	50.998	0.91
Leaf	-0.223	49.002	0.91
Branch ^a	0.322	29.898	0.95

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

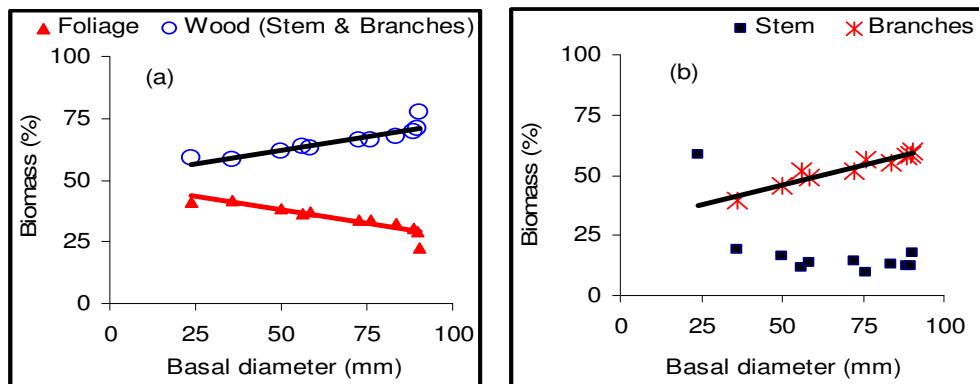


Figure 2.3 Partitioning of AG components of *Jatropha*, expressed as a percentage of total AG biomass

Results of regression analyses on branch level allometry are summarised in Table 2.3. Basal branch diameter was of highly significant ($p < 0.0001$) value in explaining variations in the branch level variables of *Jatropha*. The systematic biases resulting from log-transformation were very low (Table 2.3).

Table 2.3 Results of regression analyses of the linearized allometric relationship ($\log Y = b \log BBD + \log a$) of branch diameter with branch-level variables of *Jatropha* and resulting corrected allometric equations ($Y = a BBD^b$)

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

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

2.3.2. Allometry between crown depth and AG variables

The allometric relationships using crown depth as a predictor were highly significant ($p < 0.0001$). The correlation coefficients were very high and the correction factors very low, as shown in Table 2.4. Figure 2.2 (b) shows the relationship between AG dry mass and crown depth before log-transformation.

Table 2.4 Results of analyses on linearized shoot allometry ($\log Y = b \log CD + \log a$) of *Jatropha* using crown depth and corrected allometric equations ($Y = a CD^b$)

Tree parameter	b	$\log a$	r	P > F	cf	(Corrected 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 AG dry mass (g)	2.955	2.694	0.98	0.0001	1.018	$Y = 503.312 CD^{2.955}$
Woody AG 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.

2.3.3 Effects of BG interspecies competition and tree spacing on allometry

Slopes and intercepts of the regressions between stem diameter and tree height developed for the competition treatments were homogeneous, as was the case for tree spacing treatments. Table 2.5 shows results of the statistical analyses proving that the height-diameter equations were equivalent regardless of BG competition or tree spacing (equations not presented). Hence, neither BG interspecies competition nor tree spacing had any effects on allometry.

Table 2.5 ANCOVA results of the effects of interspecies competitions and tree spacing on diameter-height allometry of *Jatropha* ($\log Y = b \log BD + \log a$)

Treatment	Contrast	Mean Square	F Value	P > F
BG Competition	Slopes (b)	0.00068165	0.58	0.4507
	Intercepts ($\log a$)	0.00058344	0.50	0.4851
Tree spacing	Slopes (b)	0.00422389	0.11	0.7462
	Intercepts ($\log a$)	0.00553091	0.14	0.7112

2.3.4. Validation of the allometric relationships using independent data

The relationship between predicted and measured values of tree height was linear (Figure 2.4). 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.

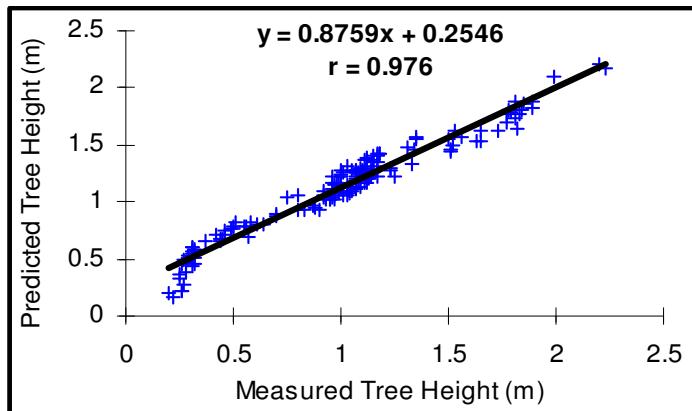


Figure 2.4 Relationships between predicted and measured tree height of *Jatropha*

2.4 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; Xia and Ceulemans, 2004). The outcomes of the current study are in agreement with these results. AG allometry is

justified, as the growing AG 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 AG 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 *Jatropha* 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 *Jatropha* 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 *Jatropha*, 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 2.3 (b)) signals such dynamics of allocation in *Jatropha*.

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 BG competition and spacing of trees had no effect on allometry of *Jatropha*. 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 AG dry matter; and estimating of AG interactions when trees are used for agroforestry purposes. While the inclusion of data from additional sites may make the equations developed here more generalised, the fact that widely differing tree spacing management and growing conditions had no significant effect on allometry, indicates that these equations show a potential relevance to other sites.

2.5 CONCLUSIONS

The results of this study reveal that tree level and branch level allometric relationships of *Jatropha* 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 BG 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 *Jatropha*. They are also valuable for comparative evaluation of suitability of sites for growing *Jatropha*, which is relevant because the species has attracted global attention for its high potential as a source of biodiesel.

CHAPTER 3

EFFECTS OF TREE-PERENNIAL GRASS INTERACTIONS ON TREE PRODUCTIVITY

3.1 INTRODUCTION

South Africa is facing scarcities of arable land (only 15%) and water. In most regions, rainfall is erratic and generally low. Consequently, immediate implementations of more resource-efficient approaches of food production are necessitated. Agroforestry could be a possible solution.

Agroforestry is a practice of incorporating trees and crops in the same land management using spatial or temporal arrangements. Such an approach not only provides a multiplicity of products but also aids in rehabilitation of the environment and improvement of resource use efficiencies (Kang, 1997; Oteng'I *et al.*, 2000). An important disadvantage is the interspecific competition for resources and space (Ong *et al.*, 2000), resulting in reduced yields. A sustainable agroforestry system entails more benefits than disadvantages for an extended period. To achieve sustainability, compatible species should be selected, tree spacing and density designed carefully (Ong, 1996; Ong *et al.*, 2002) and applicable management practices implemented.

In agroforestry systems, extent of interspecific interactions varies depending on tree configuration. For species with no nitrogen-fixing characteristic, BG interspecific interactions are mainly competitive. Tree growth is slower than in sole cropping. The difference, however, narrows as trees mature and tend to dominate competitions (Ong *et al.*, 2000).

Rainwater use in agroforestry is more efficient than under sole cropping (Ong *et al.*, 1996; Wallace, 1996). Trees utilise water left-over in the rooting zone of harvested understory crops. Such water can contribute up to 25% of annual water use of trees (Lott *et al.*, 2003). Competition for water takes place during limited water availability (directly) and indirectly where transpiration efficiency when water is not limited dictates potential competition when water is limited (Kropff, 1993b). Water use efficiency of agroforestry systems (ratio of total system yields to water used (Ong *et al.*, 1996)) can be maximized by implementing optimum tree density and spacing/arrangement (Ong *et al.*, 1996; Ong *et al.*, 2002).

Hedgerow intercropping systems consist of trees planted in hedgerows and alleys between the hedgerows where understory crops are grown. The understory crops may be harvested (alley-cropping systems) or grazed (silvopastoral systems). More than a single row of trees (sets of two or three rows) may be employed in order to possibly minimise reductions in tree productivities and maximise earnings (Garette and McGraw, 2000) by optimizing trade-offs between intraspecific and interspecific interactions in the system.

The objectives of this study were to examine:

- The nature (competition or complementarity) of BG interactions between non-nitrogen-fixing tree species and perennial grass in a rain-fed hedgerow intercropping system by studying their effects on vegetative and reproductive tree productivities
- The feasibility of alleviating negative effects of the T-C interactions by manipulating tree spacing/arrangements while keeping tree density constant.

In accordance with the objectives, the following hypotheses were formulated:

1. BG interactions between a non-nitrogen fixing deciduous tree species and a perennial grass in hedgerow intercropping systems in semi-arid areas are predominantly competitive, resulting in reductions of growth and yield of non-pruned and pruned trees
2. For a given tree density in hedgerow intercropping, tree spacing/arrangement can be optimised so as to reduce BG competition and minimise growth and yield reductions of non-pruned and pruned trees.

3.2 MATERIALS AND METHODS

3.2.1 Treatments

The hedgerow intercropping system where the current study took place was a rain-fed silvopastoral system at the Ukulinga Research Farm (described in Chapter 2, section 2.2.2). Planting density of 1110 trees ha⁻¹ was used. *Jatropha curcas* was selected as a high value tree component of the silvopastoral system due to its reported potential as a source of biofuel, which is contained in its nuts, and poisonous

nature to prevent ruminant browsing (Everson *et al.*, 2012). Prior to this study, little was known about effects of BG competitions between *Jatropha* and understory crops on growth and yield of *Jatropha* (Augustus *et al.*, 2002).

Five experimental treatments arranged in a randomised-block design with three replicates and differentiated by presence/absence of kikuyu and spacing/arrangement of *Jatropha* trees were used. They were: *Jatropha*-only (JO, 3 m x 3 m, control), standard-spacing (SS, 3 m x 3 m), single-row (SR, 5 m x 2 m), double-row (DR, 6 m x 2 m x 2.5 m) and triple-row (TR, 7 m x 2 m x 3 m). Details of set up of the treatments are presented in Figure 3.1 and Table 3.1. During each growing season, recommended amounts of Nitrogen (200 kg ha⁻¹), Phosphorous (20 kg ha⁻¹) and Potassium (100 kg ha⁻¹) were applied to the treatments (based on soil analyses).

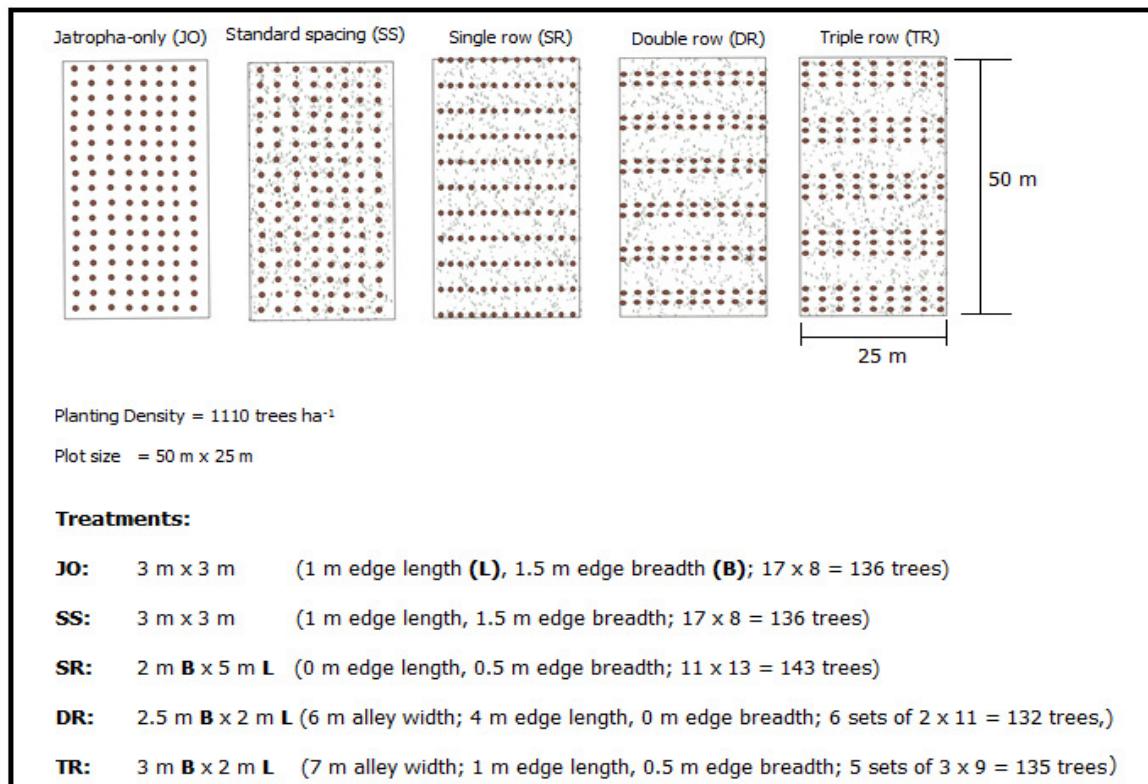


Figure 3.1 Plot details *Jatropha*-only (JO), standard-spacing (SS), single-row (SR), double-row (DR) and triple-row (TR) treatments at Ukulinga research farm

Table 3.1 Characteristics of tree-grass (T-G) interface and area occupied by trees only in the treatments of the hedgerow intercropping system at Ukulinga research farm

Treatments	T-G interface per tree (m)	System area (m ²)	T – area System area (%)	T – G interface T – area (m m ⁻²)	T – G interface System area (m m ⁻²)
			(%)		
JO	0	9	100	0	0
SS	4	9	11.11	4	0.44
SR	4	10	20	2	0.40
DR	2.5	20	18.75	0.67	0.25
TR	Outer row	3 m	13.64	0.67	0.18
	Centre row	0 m	18.18	0	0
	Weighted mean	2	15.13	0.13	0.06

Where System area refers to the area between the midway of alleys on either side of a tree set and half the intra-row spacing on either side of a tree in a row; T-area refers to the grass-cleared area around a tree (and occupied only by the tree) per unit system area; (T-G interface/T-area) and (T-G interface/system area) are implicit indicators of the intensity of BG interspecific interactions; and weighted mean of T-G interface in TR was calculated as:

$$\text{Mean length T-G interface (m)} = (33.3\% \times 3) + (66.6\% \times 0) \approx 2 \text{ m} \quad 3.1$$

Where 33.3% represents the five centre rows per plot having T-G interface length of 0 m and 66.6% the 10 outer rows in a plot, which had T-G interface length of 3 m.

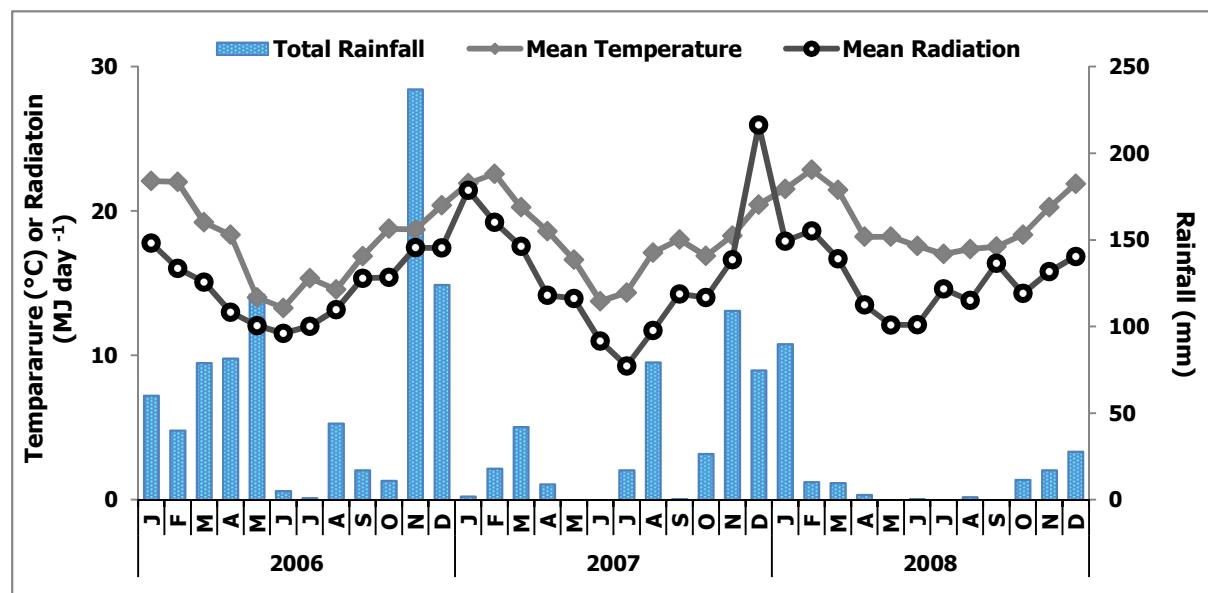


Figure 3.2 Monthly values of total rainfall, mean temperature and solar radiation at the Ukulinga study site during the study period

3.2.2 Sampling

3.2.2.1 Effects of BG interspecies competition, and tree spacing/arrangement on tree growth

Basal stem diameters of 30 trees from each of the 15 plots (5 treatments x 3 replicates) were monitored monthly between June 2006 and August 2008 to examine treatment effects on growth rate of stem diameter. The trees were 18 month-old at the beginning of the monitoring.

All trees in the 15 plots were top-pruned to a height of one metre in September 2007 in order to stimulate additional branching for increasing nut production and for maintaining the trees as hedgerows. Tree heights of 30 trees per plot were monitored monthly from October 2007 to May 2008 to examine effects of the treatments on post-pruning growth rate of tree height.

3.2.2.2 Effects of BG interspecies competition, and tree spacing/arrangement on tree yield and harvest index

Ready-to-harvest *Jatropha* seeds were picked from the 15 plots between April and August of 2007, 2008 and 2009 to study what effects treatments had on seed yield of *Jatropha* trees. These yields represented 2006/07, 2007/08 and 2008/09 growing seasons respectively.

End-of-April basal stem diameter measurements of 30 sample trees were taken from each plot for the 2006/07 and the 2007/08 growing seasons. These data were used in conjunction with yield data to investigate effects of treatments on harvest index of *Jatropha* trees.

3.2.3 Calculations and data analyses

3.2.3.1 Calculations

Treatment effects on stem growth rate

Diameter data from treatment replicates were used to calculate seasonal relative growth rates (RGR, %) of basal stem diameter using the equation:

$$RGR = 100 \times ((D_2 - D_1) / (t_2 - t_1)) / D_1 \quad 3.2$$

Where D_1 and D_2 represent stem diameters at times t_1 and t_2 respectively.

Seasonal growth rates were approximated using monthly data and grouped as:

- Winter: June, July and August
- Spring: September, October and November
- Summer: December, January and February
- Autumn: March, April and May.

Seasonal RGR values of all treatment replicates were determined for winter 2006 to autumn 2008.

Treatment effects on post-pruning tree height increase

Monthly tree heights from all treatment replicates were used to calculate monthly post-pruning height RGR using equation 3.1, by replacing D_1 and D_2 with tree height H_1 (at t_1) and H_2 (at t_2) respectively.

Treatment effects on tree yield

Total dry mass of seed harvest of each treatment replicate was divided by the number of trees in the treatment (Table 3.1) to obtain yield per tree per treatment replicate.

Treatment effects on harvest index

Harvest index shows if T-C competition or tree spacing/arrangement in hedgerow intercropping affect tree yield more (or less) than tree growth. Plot average of end-of-April stem diameters were used to estimate average AG tree biomass using the equation for AG dry mass presented in Table 2.1. Yield and AG biomass per tree were used in equation 3.3 to compute harvest index (HI, %) of each plot:

$$HI = 100 \times (\text{Seed yield} / \text{AG biomass}) \quad 3.3$$

Where seed yield and AG biomass are in g tree⁻¹.

This procedure was carried out for 2006/07 and 2007/08 seasons.

3.2.3.2 Data analyses

Treatment effects on stem growth rate

Seasonal RGR values of all treatment replicates were determined for winter 2006 to autumn 2008. Analyses of variance were carried out using SAS Proc NLIN (SAS, 2002) to examine if growth rate of stem diameter was affected by presence of perennial grass, tree spacing/arrangement.

Treatment effects on post-pruning tree height increase

Monthly height RGR values treatments were statistically compared using SAS to test if post-pruning height growth was affected by BG tree-grass competition and tree spacing/arrangements.

Treatment effects on tree yield

Tree yields during 2006/07, 2007/08 and 2008/09 seasons were statistically analysed to examine if BG competition and tree spacing/arrangement reduced tree yield.

Treatment effects on harvest index (HI)

Harvest indices of treatment were statistically compared using SAS (SAS, 2002) to examine what effect BG trees-grass interactions and tree spacing/arrangement had in the ability of the trees to produce yield per unit AG biomass.

3.3 RESULTS AND DISCUSSION

3.3.1 Effects of treatments on stem growth rate

Mean diameter of all treatments for the duration of the study are presented in Figure 3.3. Stem diameter was the highest in JO. When the trees were transplanted in January 2005 (during trial establishment), they had a stem diameter of approximately 10 mm. By January 2006, stem diameter in JO had increased to 56

mm. This was 19% larger than the biggest diameters in other treatments. Such a difference was in agreement with numerous studies (Malik *et al.*, 2000; Openshaw, 2000; Malik *et al.*, 2001). In January 2007 and January 2008, the difference was 13% in favour of JO. By January 2009, stem diameters of JO trees were at least 18% bigger than stem diameters in the tree-grass competition treatments. The fluctuations in stem diameter differences between control and treatments implied that the latter had relatively higher growth rates than the control treatment at times. It also indicated that tree-tree interactions in the system had little effect on tree growth compared to the tree-grass competition. Maximum stem growth of all treatments (sharp increases of diameter in Figure 3.3) coincided with the highest rainfall period during the study period, which was in November and December 2006 (Figure 3.2). This showed water availability was the main determinant for growth performance of trees in all treatments.

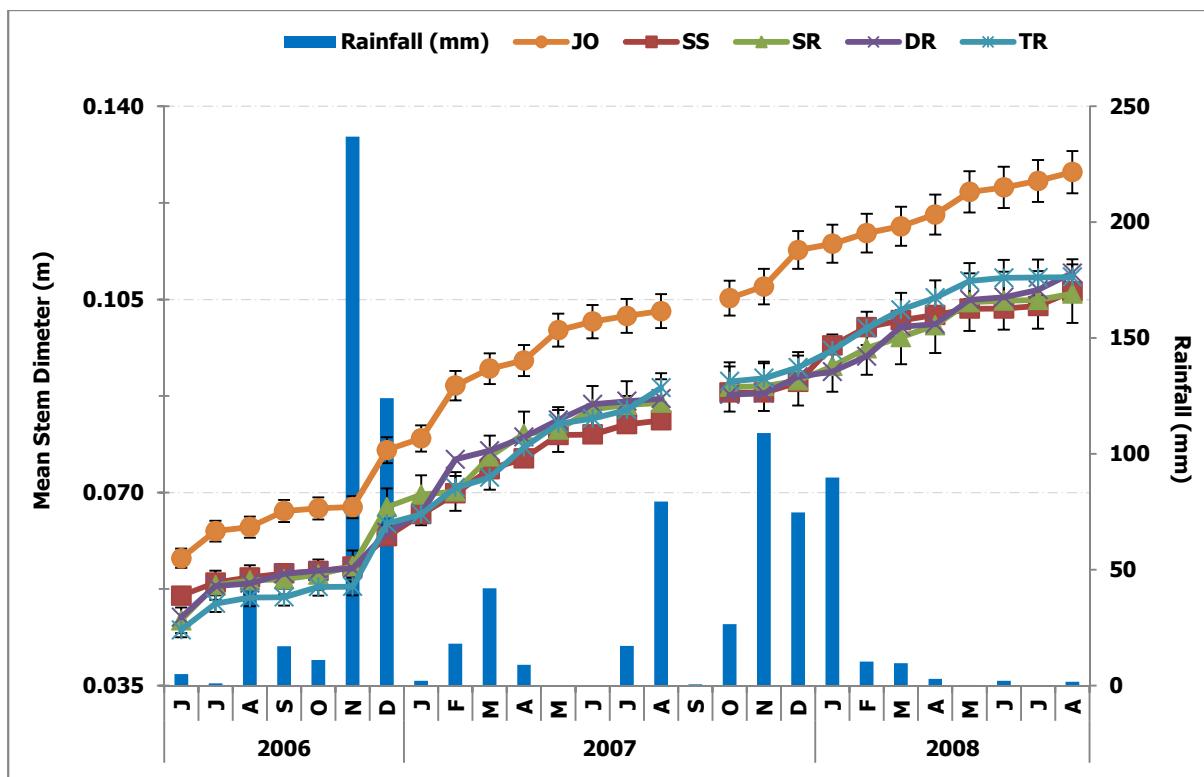


Figure 3.3 Mean stem diameter (m) of *Jatropha* trees in JO, SS, SR, DR and TR

Due to low rainfall, temperature and solar radiation, overall growth and development of *Jatropha* trees during winter was limited. One notable growth, however, was stem diameter. All treatments showed very high diameter growth rates during winter 2006 when all trees were entirely leafless, even though rainfall

during January to May 2006 was very high. This resulted from stem photosynthesis, which is especially significant when trees are leafless (Perry, 1971; Keller, 1973; Wiebe, 1975; Foote and Shaedle, 1976; Nilsen, 1995). Stem photosynthesis has considerable net-to-gross productivity ratios (Damesin, 2003) and thus has significance in the carbon balance of trees (Pfanz and Aschan, 2001). In the current study, tree height growth had slowed during winter 2006. Stem was the main assimilate sink, which was the strategy of *Jatropha* trees during poor growing conditions and minimum BG competitions (when kikuyu was dormant). Similar winter growth was not repeated in any treatment during winter 2007 and 2008 as rainfall during April and May of 2007 and 2008 was not as high as in 2006.

During winter 2006, treatments had no significant effects on tree RGR (Table 3.2). This may be due to the absence of BG interspecies competition due to kikuyu dormancy. It also implied that tree spacing/arrangement did not have any effect on diameter RGR. As kikuyu started to re-grow early in spring, differences among tree RGRs started to occur. Trees in SS showed the highest growth rates (Figure 3.4) while trees of JO and TR had the lowest rates (Table 3.2). By December, growth in the treatments that had faster spring RGRs slowed, with trees from JO, SR and TR growing at higher rates than trees of SS and DR. In autumn, the treatments showed no significant differences in stem growth rates.

Table 3.2 Results of statistical analyses on seasonal stem RGR (%) during 2006/07 and 2007/08

Treatment	2006/07				2007/08			
	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
JO	6.83 ^b	1.90 ^c	10.29 ^a	4.24	1.27 ^c	1.43 ^{ab}	1.31 ^a	0.57 ^b
SS	4.94	3.75 ^a	7.21 ^b	4.86	1.39 ^c	2.22 ^a	1.40 ^a	0.68 ^b
SR	6.57	2.72 ^b	10.09 ^a	3.81	3.85 ^a	0.87 ^b	1.13 ^{ab}	1.29 ^a
DR	6.30	3.20 ^b	7.44 ^b	3.88	1.17 ^c	0.73 ^b	0.95 ^b	1.17 ^a
TR	6.64	1.59 ^c	11.05 ^a	5.04	2.62 ^b	1.19 ^b	1.43 ^a	0.70 ^b
Significance	Ns	**	**	Ns	**	**	**	**
LSD_{0.05}	2.41	0.52	1.82	1.37	0.60	0.94	0.34	0.16
CV	13.67	6.96	10.54	11.09	10.33	25.79	9.73	6.62

^b Values followed by the same letter within a column are not significantly different

* Significant at p = 0.01; ** Significant at p = 0.05; Ns = non-significant

During winter 2007 to autumn 2008, SR had significantly and consistently higher growth rates than SS and JO. During spring and summer of 2007/08, SS had the highest growth rates. TR showed high RGR during spring but slowed down by summer.

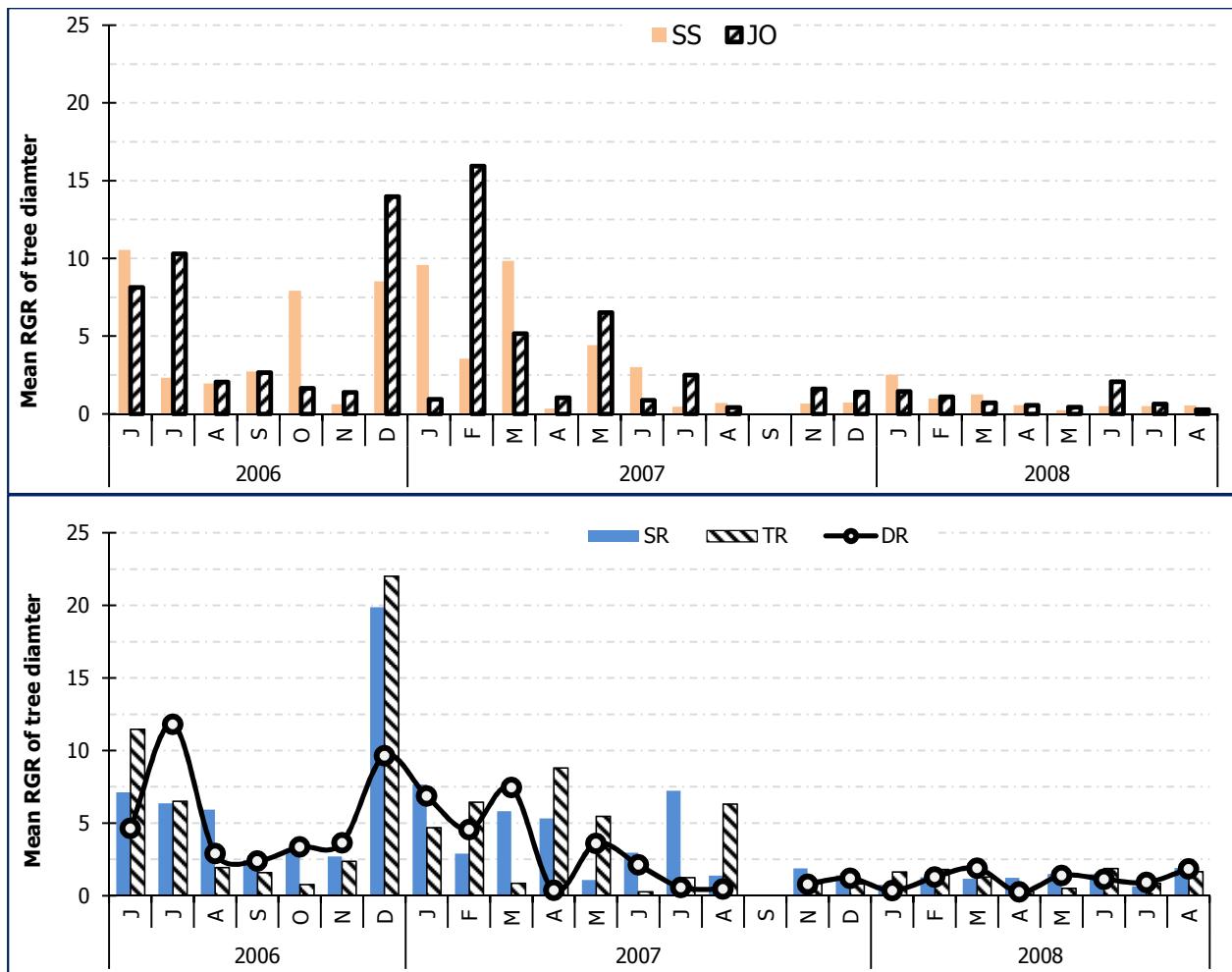


Figure 3.4 Mean stem diameter RGR of *Jatropha* in JO, SS, SR, DR and TR

When rainfall was sufficiently available, winter and autumn seasons were characterised by RGRs that were not affected by treatments. During limited rainfall, on the other hand, treatments had differing RGRs based on their efficiencies of competition for water. SR was the most efficient while JO and SS were the least efficient. During spring 2007 and summer 2007/08, SS and JO had consistently the highest diameter RGR. The same result was observed for SS, during spring 2006. This treatment had the longest tree-grass (T-G) interface and the highest T-G interface per tree area (Table 3.1), which showed that trees in SS faced the strongest competition from kikuyu for resources especially water. When rainfall was sufficient, trees of this treatment had the highest growth rates, possibly to make up for the lag. A similar T-G interface length and T-G interface to tree area ratio in SR trees resulted in increased RGRs during limited interspecific competition periods (due to kikuyu dormancy and high rainfall). Despite achieving the highest

stem diameter during the entire study period, trees in JO did not always have the highest consistent growth rate.

3.3.2 Treatment effects on post-pruning growth rate of trees

The absence of understory kikuyu and optimum tree spacing/arrangement in JO plots meant that there was no interspecific competition and minimum intraspecific competition. As a result, trees in the treatment acquired the highest tree height in just two months after pruning. Figure 3.5 shows that tree heights in all treatments increased towards the end of October, as soon as the leaves started to emerge. This, together with relatively high rainfall during November resulted in a sharp increase in the tree heights in all treatments. By March, tree heights of all treatments started to level off due to low rainfall, late development stage and low temperature.

Across treatments, temporal increases in tree height following pruning were rapid. During the first two months, trees in all treatments were leafless. Starting from the third month after pruning (December 2007) and throughout the study period (till October 2008) trees of JO were the tallest, while SR had the shortest trees. Temporal patterns of height growth rates of all treatments were similar (Figure 3.6), with JO having maximum growth rate during November 2007 to March 2008. By October 2008, JO trees grew to a height of 2.4 m, which was 20% more than the maximum tree height in the *Jatropha*-kikuyu treatments.

In high rainfall areas, *Jatropha* trees can reach a height of four metres within two to three years (Augustus *et al.*, 2002). In the current study, prior to September 2007, maximum tree height observed in JO two years and seven months after establishment was 2.98 m. In the *Jatropha*-kikuyu treatments, peak tree height during that time was 2.03 m. These findings imply that even though there were high rainfall incidents during this period rainfall was not consistently high enough for maximum height growth of *Jatropha* trees to occur. Even when rainfall was high, height RGR was affected by BG interspecific competition.

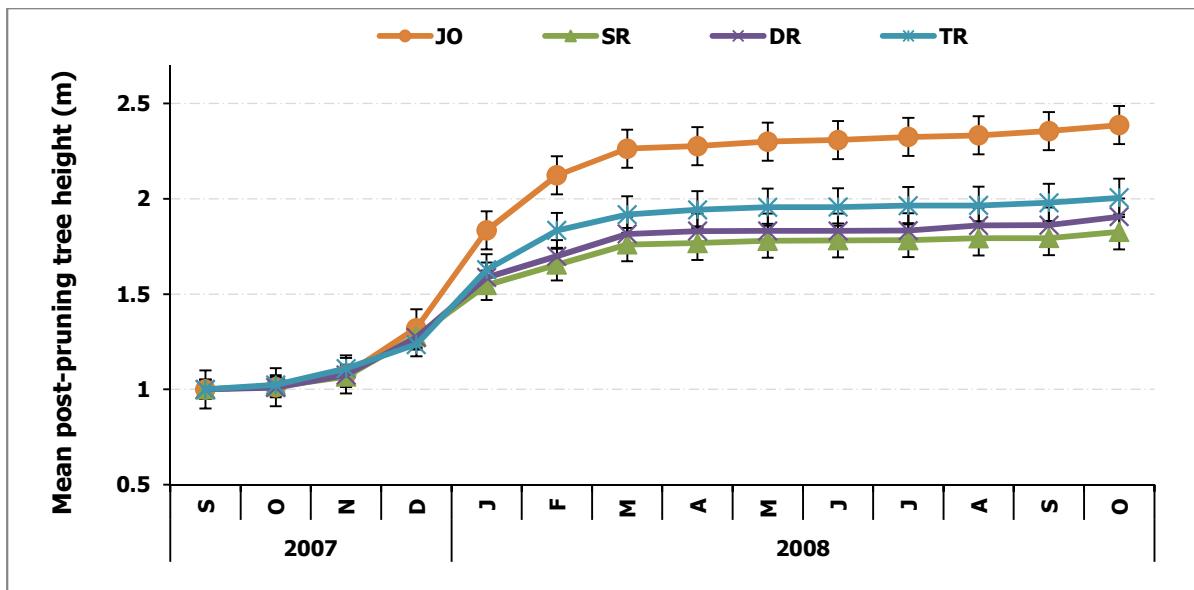


Figure 3.5 Tree height growth in JO, SR, DR and TRs after trees were pruned to one metre height in September 2007

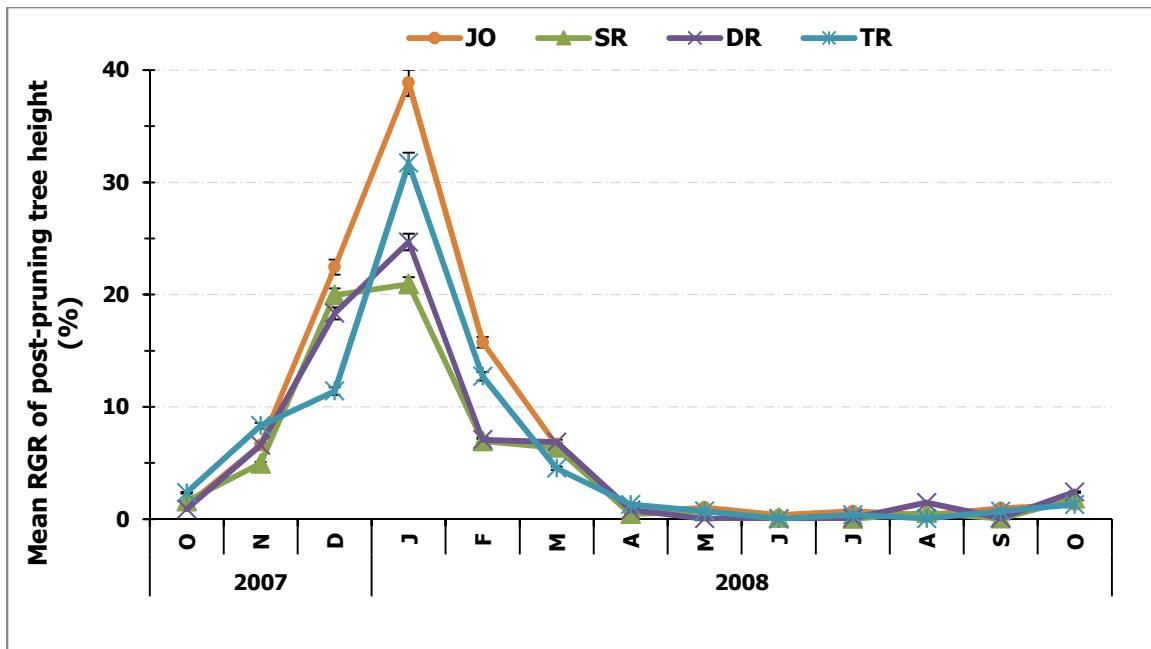


Figure 3.6 Relative growth rates (%) of tree height in JO, SR, DR and TR plots following pruning

Treatment ranking of height RGRs (Table 3.3) generally resembled the ranking of T-G interface to system area ratio (Table 3.1), which was JO > TR > DR > SR, especially during active growth months (October

2006 to April 2007). Trees of SR had the highest RGRs during kikuyu dormancy and lower rainfall and periods (Table 3.3). These lead to the following important findings:

- (a) Treatment responses to pruning were generally inversely related to the ratio of T-G interface to tree area. That is, the higher the ratio, the quicker the response and the better the performance during high rainfall period.
- (b) Trees under high interspecific competition tended to make up for their slower response to pruning during reduced interspecific competition (May to July 2008) even when rainfall availability was low.

Table 3.3 Results of statistical analyses on tree height RGRs following top-pruning of the trees to one metre height in September 2007

Treatment	Nov/Dec 2007	Jan/Feb 2008	Mar/Apr 2008	May/Jun 2008	Jul/Aug 2008	Sep/Oct 2008
JO	26.21a ^b	15.86a	1.53	1.27a	2.56a	2.20
SR	18.33c	12.13b	1.85	1.08ab	1.76ab	1.53
DR	19.65c	13.93b	1.26	0.49c	1.12b	1.65
TR	21.00b	17.83ab	1.34	0.77bc	0.80b	1.25
Significance	**	*	Ns	**	**	Ns
LSD_{0.05}	1.05	5.18	0.80	0.35	0.67	1.35
CV	2.48	15.48	26.60	19.41	22.01	36.72

^b Values followed by the same letter within a column are not significantly different

* Significant at p = 0.01; ** Significant at p = 0.05; Ns = non-significant

3.3.3 Effects of treatments on seed yield

Jatropha trees can be expected to bear seeds in a year provided water availability is high (Becker and Makkar, 2000) as confirmed in a one-year old irrigated *Jatropha* plantation (2 m-by-2 m layout) at a biofuel park in New Delhi that produced up to 0.43 kg of nuts per tree (Singh and Joshi, 2006). The first seed yield of the current study was due for harvest in March 2007; two years and three months after the trees were transplanted to the experimental site, signifying lack of consistently high rainfall.

Trees in JO produced the highest yield in all years (Figure 3.7). In 2007, the average seed yield was 95.2 g tree⁻¹, which was equivalent to 103.5 kg ha⁻¹. The yield in the *Jatropha*-kikuyu treatments ranged between 5.1 and 29% of the control (JO) treatment. In 2008, the control trees yielded an average of 135.8 g tree⁻¹ (146.6 kg ha⁻¹), while trees in the combination treatments managed to produce only 5.1 - 17% of that (7.4 - 25 kg ha⁻¹). Maximum yield (in JO) during 2009 increased to 351 g tree⁻¹ (381 kg ha⁻¹) as the trees were

older than four years and supposedly reaching the age of maximum yield. Trees of the *Jatropha*-kikuyu treatments showed more drastic yield increases (6 - 11 times) than JO trees (2.5 times). This showed that yield productivity in the mixed treatments was slower to peak.

Only in 2009 (third year of yield) did SR, DR, TR and SS show significant yield differences among themselves (Table 3.4). T-G interface length affected yield (Tables 3.1 and 3.4). JO trees had the shortest T-G interfaces and the highest yield. Trees of TR had the second highest yield because their (weighted) average length of the T-G interface (2 m) was shorter than those of SR, DR and SS. The differences in the lengths of T-G interface among SR, DR and SS did not lead to significant yield differences.

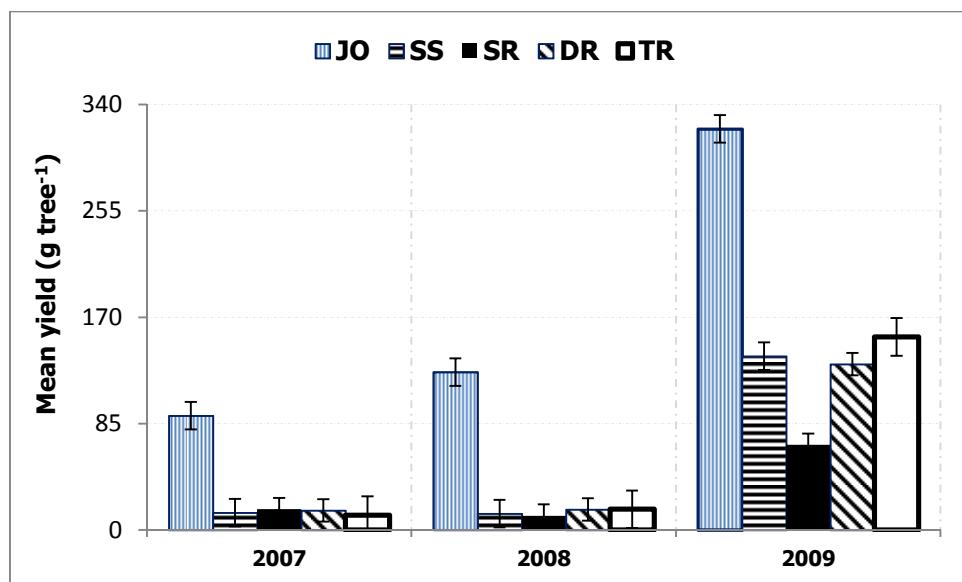


Figure 3.7 Mean seed yields (g tree^{-1}) of trees from JO, SS, SR, DR and TR plots

Table 3.4 Statistical results of yield (g tree^{-1}) of the treatments during 2007 to 2009 seasons

Treatment	2007	2008	2009
JO	91.31 a ^b	126.20a	320.57a
SS	13.88 b	12.99b	139.00bc
SR	16.58 b	11.347b	67.99c
DR	15.56 b	16.27b	132.53bc
TR	11.81 b	16.51b	154.28b
Significance	**	**	**
LSD_{0.05}	10.59	9.15	72.02
CV	18.86	13.25	23.48

^b Values followed by the same letter within a column are not significantly different

* Significant at $p = 0.01$; ** Significant at $p = 0.05$; Ns = non-significant

Compared to reports of yields of up to 2 - 3 t ha⁻¹ in semi-arid areas (Heller, 1996; Becker and Makkar, 2000; Ranga, 2006), the current yields were extremely low. High values reported were most likely extrapolations of yields from single and mature trees with high yields (Jongschaap et al 2007). On the other hand, during a 17-year period at Nashik in India mean nut yield of *Jatropha* was lower than 1.25 t ha⁻¹ (Swamy and Singh, 2006). Yields of 0.2 – 2 kg per tree per year have been reported (Franci *et al*, 2005) with yield variability of up to 0.85 kg per tree observed within the same plantation (Henning, 2008). A five-year old rain-fed plantation on good soil produced 1.2 kg nuts per tree per year, which was 40% of yield under irrigation (Prajapati and Prajapati, 2005). Hence, *Jatropha* trees can survive under stress but cannot be expected to have high yields (Kureel, 2006). Its productivity is high under sub-tropical conditions, while according to Köppen climate classification Ukulinga is temperate and warm with summer and winter rainfall. *Jatropha* is affected by even short-term water-logging (Achten, 2008), which occurred at the site intermittently.

3.3.4 Effects of treatments on harvest index

Harvest index of trees was determined to check if BG interspecific competition and tree spacing/arrangement in hedgerow intercropping affected vegetative tree growth more (or less) than tree yield. Figure 3.8 presents tree harvest index and outcomes of statistical comparisons among the treatments during 2007 and 2008. BG T-G competition reduced tree harvest index, i.e. tree yield more than tree biomass. However, tree spacing/arrangement had no effect on harvest index implying that the treatments had proportional effects on tree yield and biomass. In contrast, Behera *et al.*, (2010) recommended wider spacing in semi-arid regions as narrower layouts lead to sooner canopy closure and lower yield to biomass ratio in mature plantations.

In 2007 and 2008, SR, DR, TR and SS did not have significant differences in yield or stem diameter. This resulted in linear and positive correlation, with high coefficient of determination (0.89 in 2007 and 0.88 in 2008), between stem diameter and yield (Figure 3.9). Similar correlations between basal stem diameter and seed biomass have been found in other species (Hendrix, 1984). It should be borne in mind, however, that there is no linear relationship between diameter of a tree and its yields across years. The reason is

that young *Jatropha* trees increase in stem diameter from year to year while their yields may fluctuate between an increase and a decrease in successive years.

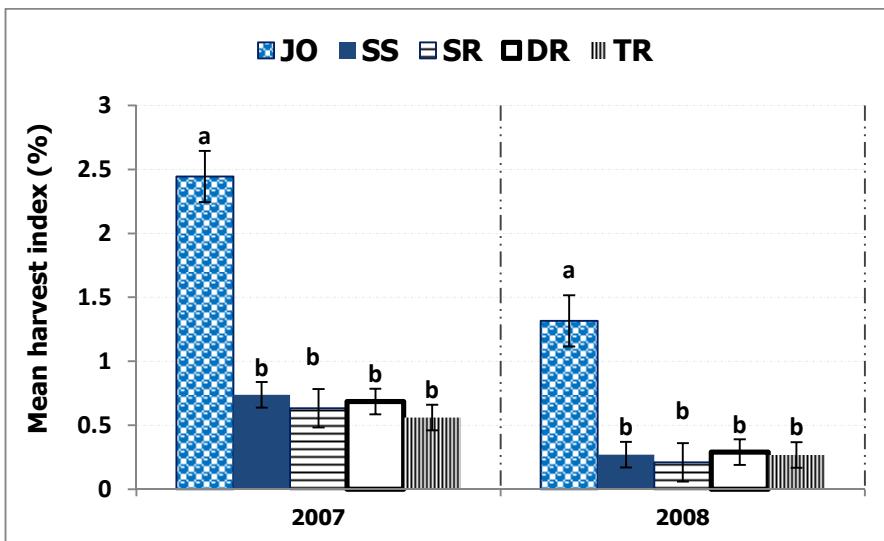


Figure 3.8 Analysis results on *Jatropha* harvest index of the treatments in 2007 and 2008

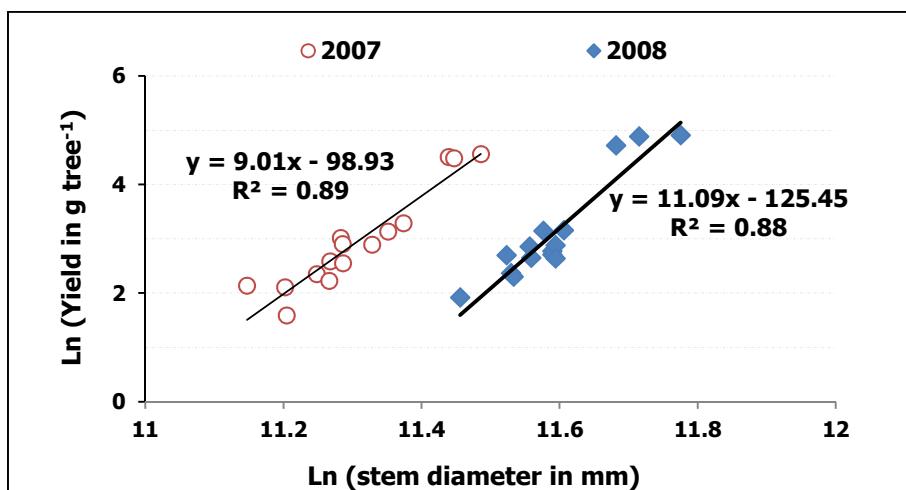


Figure 3.9 Yield per tree vs. mean stem diameter using pooled data for 2007 and 2008 seasons

3.4 CONCLUSIONS

The objectives of this study were to examine nature of BG interspecific interactions in a rain-fed hedgerow intercropping system by studying effects of tree spacing/arrangement on tree productivity. Two

hypotheses were formulated: (a) the interspecific interactions were competitive and (b) without changing tree density, varying tree spacing/arrangement results in differences in tree productivity.

Stem diameter was the biggest in JO. No significant growth differences of *Jatropha* are expected compared to narrower (e.g. 2 m-by-2 m) tree spacing (Behera *et al.*, 2010). None of the *Jatropha*-kikuyu treatments had growth rates that were consistently the highest. When high water availability and kikuyu dormancy coincided, treatment RGRs were high and not significantly different from one another. SR had the most frequent maximum stem diameter RGR and was the most efficient during limited water availability. SS had the highest RGRs during spring and summer seasons. Trees of the control treatment were the tallest, while those in SR had minimum heights. The pruning method used in this study was in accordance with several *Jatropha*-related studies (Gour, 2006; Jongschaap *et al.*, 2007; Singh *et al.*, 2007). Even when rainfall was high, post-pruning height RGR was affected by BG interspecific competition and tree spacing/arrangement. Trees under high interspecific competition tended to make up for their slower response to pruning during reduced interspecific competition periods, even when water availability was low. Generally, length of tree-grass (T-G) interfaces of treatments affected yield inversely especially as the trees matured toward their maximum-yield age. BG interspecific competition reduced tree yield more than biomass, while tree spacing/arrangement did not affect harvest index.

It was clear that BG interspecific interactions in the *Jatropha*-kikuyu treatments reduced growth and yield of *Jatropha* (Andersson, 2012). As a result the first hypothesis was accepted. The fact that none of the treatments of tree spacing/arrangement had significantly and consistently higher yield and growth led to the rejection of the second hypothesis. Water availability dictated treatment productivities in terms of temporal patterns and extent of reduction. Temporal complementarity between *Jatropha* and other species can enhance feasibility of *Jatropha* for agroforestry. For instance, with limited irrigation, groundnut intercropped between 3 m-spaced and pruned *Jatropha* rows during a dry period resulted in improved *Jatropha* growth by reducing weed competition (Singh *et al.*, 2007). Moreover, grass clearance from tree base of 0.6 m (Andersson, 2012), spatial separation of resource use (George *et al.*, 1996) and less competitive understory crops (Malik *et al.*, 2000; Lehmann *et al.*, 1998) should also be employed in order to achieve feasible use of *Jatropha* in hedgerow intercropping.

CHAPTER 4

RADIATION, WATER DISTRIBUTION AND PLANT GROWTH

IN HEDGEROW INTERCROPPING SYSTEMS

4.1 INTRODUCTION

T-C interactions refer to ways component species in agroforestry systems affect performance of each other and the system as a whole (Nair, 1993). They are affected by plant form, planting density, resource availability and timing of planting crops, tree root/canopy pruning (Huxley, 1996; Huxley, 1999) and species composition (Ashton and Ducey, 1999).

Ideally, T-C interactions should be complementary and beneficial. In reality, however, there is interspecies competition for growth resources. A successful and sustainable agroforestry system requires that complementary interactions are maximised and competition minimised. Designing optimum tree spacing/arrangement (intra-row and inter-row) and density, row orientation (Huxley, 1999; Garrett and McGraw, 2000) and selecting compatible species (Ong, 1996; Ong *et al.*, 2002) have important implications in regulating T-C interfaces. After system establishment, T-C competition can be decreased by managing distance between crops and trees across their interface (Huxley, 1999).

Competitions for water and radiation in agroforestry systems have potentially the most limiting effect on plant growth (Nair, 1993, Ong *et al.*, 2002). Their crucial difference is that un-utilised water may still remain in the system for later use whereas radiation is utilised or wasted instantly (Kropff, 1993a; Kropff, 1993b). Fine tree roots access water from any volume they can reach (Leyton, 1983). Differential soil water distribution results from tree and crop root distribution, (Kropff, 1993b) and differential runoff and infiltration beneath trees and crops (Wallace, 1996; Huxley, 1999). Shading of crops by trees is a function of closeness to trees, canopy structure (Ong *et al.*, 1996, Ong *et al.*, 2000), planting geometry (Berlyn and Cho, 2000), tree height, time of year (Smith *et al.*, 1997), solar angle, latitude and altitude (Ong *et al.*, 1996; Berlyn and Cho, 2000).

The objectives of this study were to understand the extent of T-C interactions in a hedgerow intercropping

system of non-nitrogen-fixing tree species and perennial grass by investigating:

- Spatio-temporal solar radiation, soil water and root biomass distribution, and intercrop growth
- Possibility of manipulating radiation and water distribution and intercrop growth by optimising tree spacing/arrangement without changing tree density.

The following hypotheses were formulated:

- In hedgerow intercropping systems, pasture production can be linearly proportional to radiation transmission, especially if other resources are not limiting growth
- In a well-fertilized and rain-fed hedgerow intercropping system, water availability is more limiting than solar radiation in semi-arid regions.
- Without changing tree density, tree spacing/arrangement can be manipulated to obtain optimum radiation and soil water distribution and intercrop growth.

4.2 MATERIALS AND METHODS

An automatic weather station was used to monitor solar radiation (using LI 200x pyranometer), rainfall (with Rimco R/TBR tipping bucket), relative humidity and air temperature (using HMP 35C), wind speed (with R. M. Young cup anemometer) and vapour pressure deficit at hourly and daily time intervals. CR 10x data logger (Campbell Scientific Inc.) was used to monitor and record the measurements. Monthly total rainfall, mean temperature and solar radiation at the Ukulinga site are presented in Figure 4.4.

4.2.1 Sampling

A full description of treatments used for this study is given in Chapter 3, section 3.2.1. The experimental treatments used were *Jatropha*-only (JO, 3 m x 3 m), standard-spacing (SS, 3 m x 3 m), single-row (SR, 5 m x 2 m) and double-row (DR, 6 m x 2 m x 2.5 m). In all treatments, tree row orientation was N17°W – S17°E.

4.2.1.1 Radiation distribution

Calibrated Delta-T tube solarimeters (Delta-T Devices Ltd, Cambridge, England) were used to measure hourly radiation distribution across tree hedgerows extending between centres of adjacent alleys in JO, SR and DR plots. They were placed at the soil surface in JO plot and below tree crowns and above grass in SR and DR plots (Figure 4.1).



Figure 4.1 Radiation sensor placement in JO (left) and SR (right) plots at Ukulinga

The distances selected were:

- JO: 0 m (below tree hedgerow), 0.75 m and 1.5 m (centre of alley) on the south-western (SW) and north-eastern (NE)
- SR: 0 m (below tree hedgerow), 0.83 m, 1.63 m and 2.5 m (centre of alley) on SW and NEs
- DR: 0 m (between tree rows), 1 m (below tree rows), 2 m, 3 m and 4 m on SW and NEs of the 0 m distance.

4.2.1.2 Water balance and dynamics

The study site was flat with a 0.6 m deep profile underlain by bedrock. Physical properties of the soil at the site were determined using soil core samples from selected depth increments, namely: 0 - 0.05 m, 0.10 - 0.15 m, 0.20 - 0.25 m, 0.30 - 0.35 m, 0.40 - 0.45 m, 0.50 - 0.55 m and 0.55 - 0.60 m. The soil type was a loam (21 % clay, 37 % silt and 42 % sand) to clay loam (30 % clay, 35 % silt and 35 % sand). Its average bulk density was 1.58 g cm^{-3} ($cv = 4.74\%$). Hydraulic conductivity was the highest (Figure 4.2a) where

percentage of sand was the highest and clay the lowest (Figure 4.2c-e). Clay content generally increased with depth.

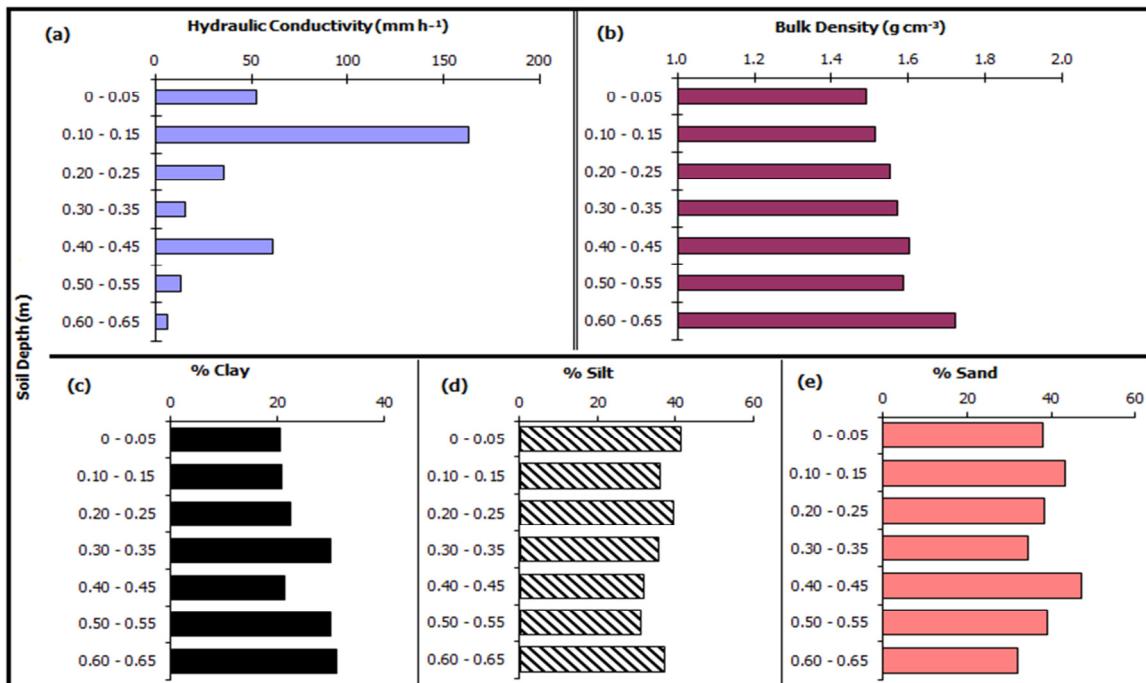


Figure 4.2 Hydraulic conductivity, bulk density and textural composition of the soil profile at Ukulinga

In order to monitor soil water dynamics, locally made three-rod CS605 TDR probes (Campbell Scientific Inc.) were carefully installed at an orientation of S73°W-N73°E, soil depths of 0.05 m, 0.15 m, 0.25 m, 0.40 m and 0.60 m and the same distances as in the radiation monitoring trial. Figure 4.3 shows the TDR probes installed in JO and SR.



Figure 4.3 TDR probe placement in JO (left) and SR (right) at Ukulinga farm

Backfilling into the bottom 0.3 m of the profile was performed by laying a 0.1 m thick layer at a time followed by manual ramming. The profile was then topped-up with kikuyu transplant together with its undisturbed soil from other parts of the field.

4.2.1.3 Grass growth

Grass biomass above a stubble height of 50 mm was monitored periodically using a 0.5 x 0.5 m quadrant at distances of

- SR: 0.83 m, 1.67 m and 2.5 m on NE and SW of tree row
- DR: 2 m, 3 m and 4 m on NE and SW of the mid-point between tree row-sets.

4.2.1.4 Root distribution

Lateral and vertical distribution of total (tree and grass) root biomass density was examined in SR since no distinction between fine roots from trees or crops was possible. Time constraints limited the scope of root investigation; hence similar studies could not be performed in DR and JO. Core samples were taken from trenches dug transversely to a tree line and extending between centres of adjacent alleys. Samples were collected at depth increments of 0 - 0.2 m, 0.2 - 0.4 m and 0.4 - 0.6 m and distances of 0 m (below tree), 1.25 m and 2.5 m on SW and NEs of a selected tree row.

Due to woody roots in some samples, the volume of the (irregular-shaped) samples could not be represented by the core sampler volume. Hence, volume of all core samples was determined by the displacement method. That is, the volume of a sample was equal to the volume of displaced water in which the sample was immersed. To isolate roots, samples were dispersed in water and sieved through 0.5 mm wire mesh. Root samples were oven-dried until constant mass was obtained. Root biomass was then divided by sample volume to obtain root biomass density.

4.2.1.5 Tree growth

Basal stem diameter of trees at the centre of soil water measurement systems of JO, SR and DR was monitored monthly during November 2007 and July 2007.

4.2.2 Data Analysis

4.2.2.1 Radiation distribution

Incident solar radiation measured at the automatic weather station was used to calculate radiation transmission at various positions in the treatments.

4.2.2.2 Soil water balance and dynamics

Runoff was assumed to occur when profile water content exceeded field capacity and calculated as the difference between the two water contents. Drainage was assumed negligible. Hence, to determine total evapotranspiration ET (mm), the equation:

$$ET = RF - Drainage - Runoff - \Delta SW \quad 4.1$$

Was simplified to:

$$ET = RF - \Delta SW - Runoff \quad 4.2$$

Where RF (mm) and ΔSW (mm) represent rainfall and change in soil water respectively.

Soil water deficit (SWD) was calculated as the difference of water content at field capacity and actual soil water content.

4.2.2.3 Grass growth

Analyses of variance (ANOVA) were carried out on grass harvests per growth cycle to determine if positions with respect to tree hedgerow affected kikuyu productivity.

4.2.2.4 Relative growth rate (RGR) of stem diameter

Monthly relative growth rates (RGR, %) of basal stem diameter were calculated using the equation:

$$RGR = 100 \times ((D_2 - D_1) / (t_2 - t_1)) / D_1 \quad 4.3$$

Where D_1 and D_2 represent stem diameters at times t_1 and t_2 respectively.

4.2.2.5 Correlation between tree RGR and SWD

Distribution of tree root density can be used as an indicator of competition potential of trees (Jonsson *et al.*, 1988). Since it was not possible to separate fine tree roots and fine crop roots, correlations between tree RGR and SWD were used to infer fine tree root distribution in the soil and contribution of sections of the profile to tree water uptake and to isolate the role of trees in competition for water. A similar approach of RGR and SWD was employed by Balandier *et al.* (2008)

4.3 RESULTS AND DISCUSSION

During the study years (2006-08), annual rainfall range was 171 mm (2008) to 818 mm (2006) up to 30.3% (2007) of which was in winter. Mean annual temperature ranged between 17.8 °C (2006) and 19.4 °C (2008), with mean summer and winter temperatures of 21.5 and 14.9 °C, respectively.

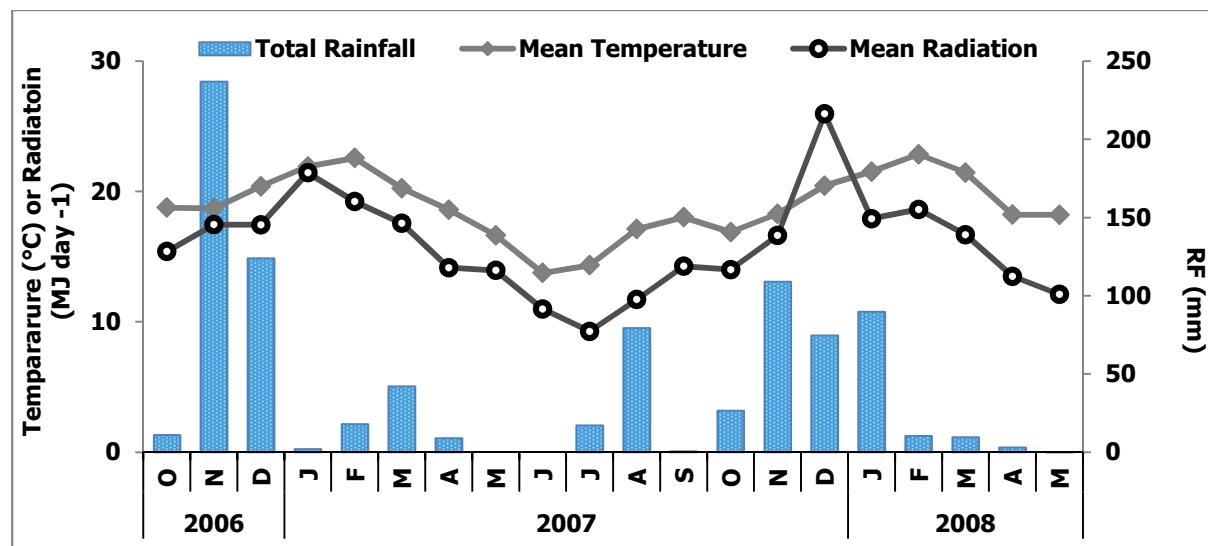


Figure 4.4 Monthly rainfall, mean temperature and radiation at Ukulinga during the study period

4.3.1 Radiation distribution

4.3.1.1 *Jatropha*-only (JO)

Diurnal irradiance at the centre of the alleys on the SW and NE of the selected tree row was similar in trend and amount (Figure 4.5). Closer to trees (0.75 m), there was a difference in the pattern between SW

and NE due to different times of unobstructed irradiance. SW had less solar radiation than NE closer to tree. Solar radiation at the base of trees was the lowest.

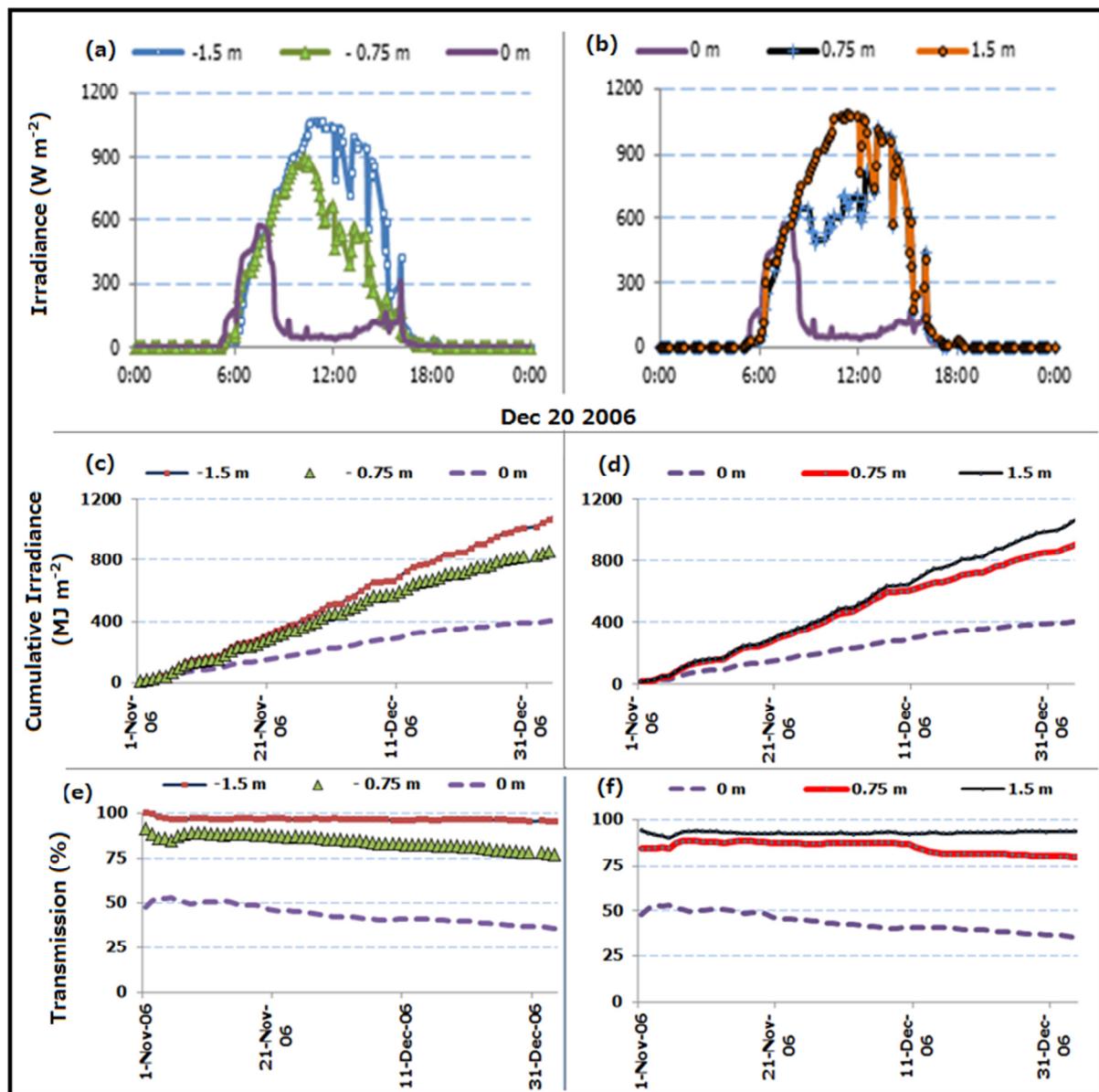


Figure 4.5 Diurnal irradiance trends (a-b), cumulative irradiance (c-d) and radiation transmission (e-f) in SW (-1.5 m, -0.75 m), below hedgerow (0 m) and NE (0.75 m, 1.5 m) of JO

Though the diurnal irradiance trends at 0.75 m SW and 0.75 m NE were different (Figure 4.5a-b), cumulative radiation at these positions was comparable. Transmission at 1.5 m distances (> 95%) was higher than at 0.75 m distances (> 82%) and at the tree base (>50%) (Figure 4.5e-f). The growing

difference in cumulative irradiance between the 0.75 and 1.5 m distances (Figure 4.5c-d) was associated with increasing tree LAI (Figure 4.9).

4.3.1.2 Single-row (SR)

Diurnal irradiance at 2.5 m SW and 2.5 m NE was similar; as was the case between 0.83 m SW and 0.83 m NE. Radiation at 1.67 m SW was higher than 1.67 m NE. The difference between 2.5 m and 1.67 distances was less in SW than NE (Figure 4.6a-b). SW had higher irradiance than NE at 1.67 m and 2.5 m distances (Figure 4.7a-b). Irradiance/transmission at 0.83 m SW was the lowest (Figure 4.7). Variations in transmitted radiation among distances were less steep in SR than JO due to higher LAI (Figure 4.9) and bigger tree canopy in the latter.

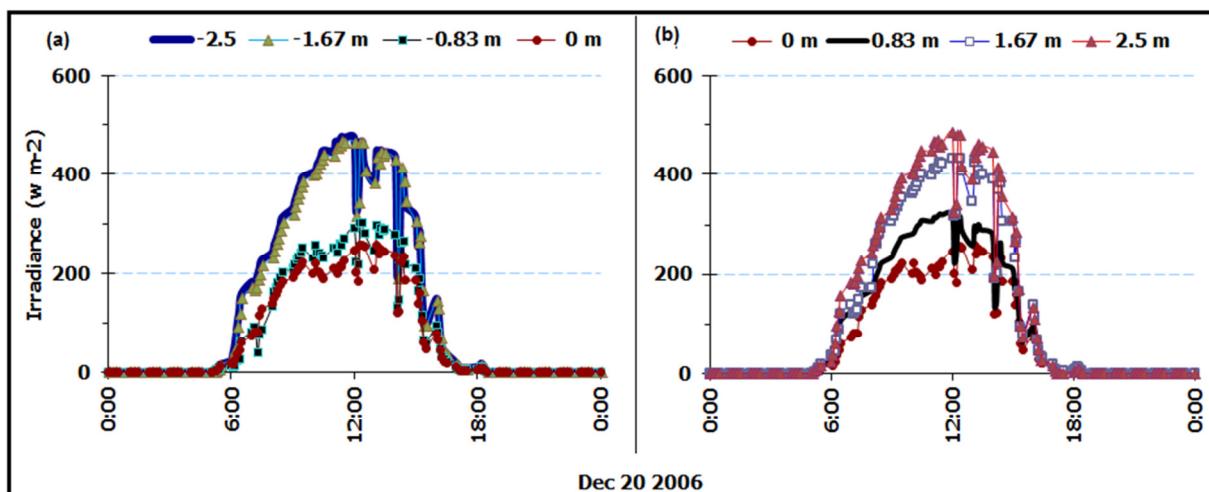


Figure 4.6 Diurnal irradiance in SW (-2.5 m, -1.67 m, -0.83 m), below hedgerow (0 m) and NE (0.83 m, 1.67 m, 2.5 m) of SR

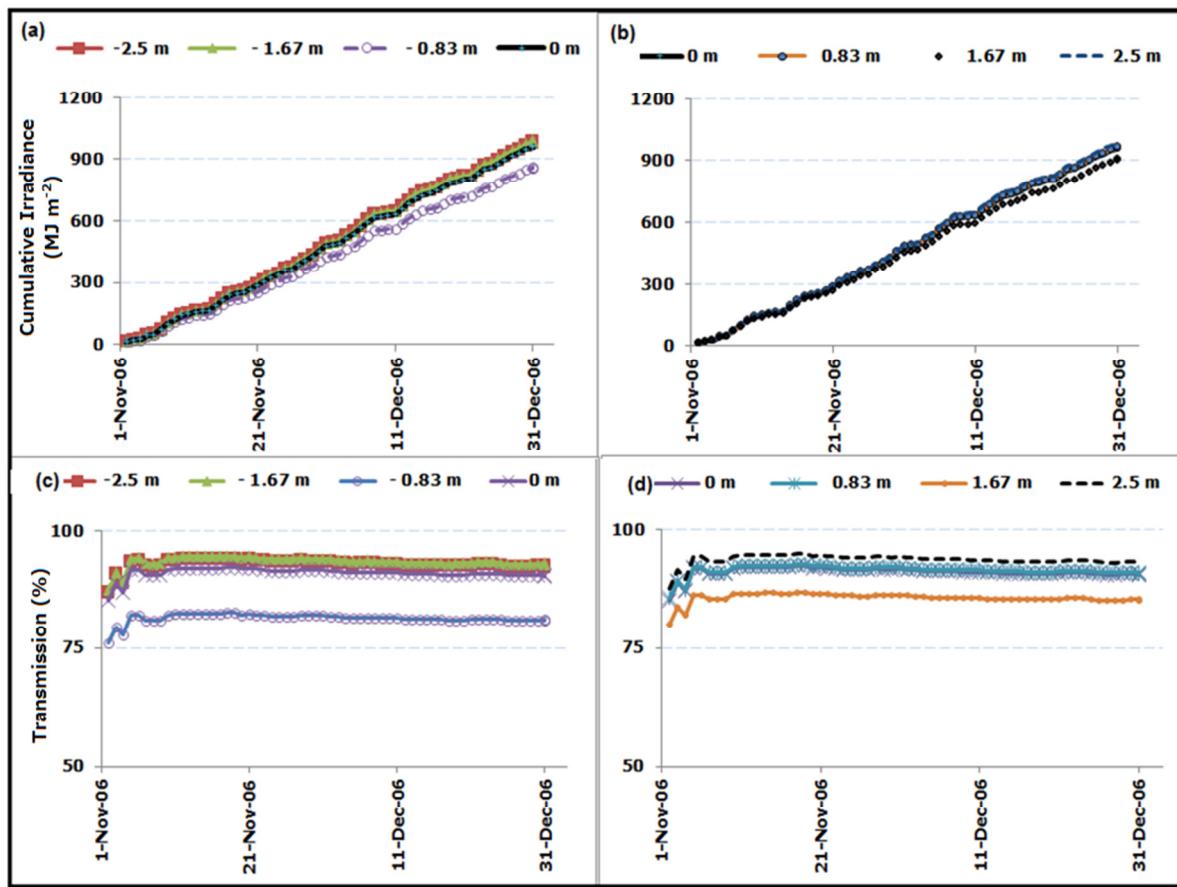


Figure 4.7 Cumulative irradiance (a, b) and radiation transmission (c, d) in SR

4.3.1.3 Double-row (DR)

Diurnal irradiance at various distances was similar (Figure 4.8a-c). Irradiance was less on NE than SW. The highest irradiance was below at the base of trees (Figure 4.8d-g). The reason for the lowest irradiance at 2 m NE was that the duration of shade at 2 m was the longest due to neighbouring double-row sets. The 3 m NE aspect was affected similarly, though to a lesser extent. These cases can be confirmed by similar yet higher transmission to 0 m.

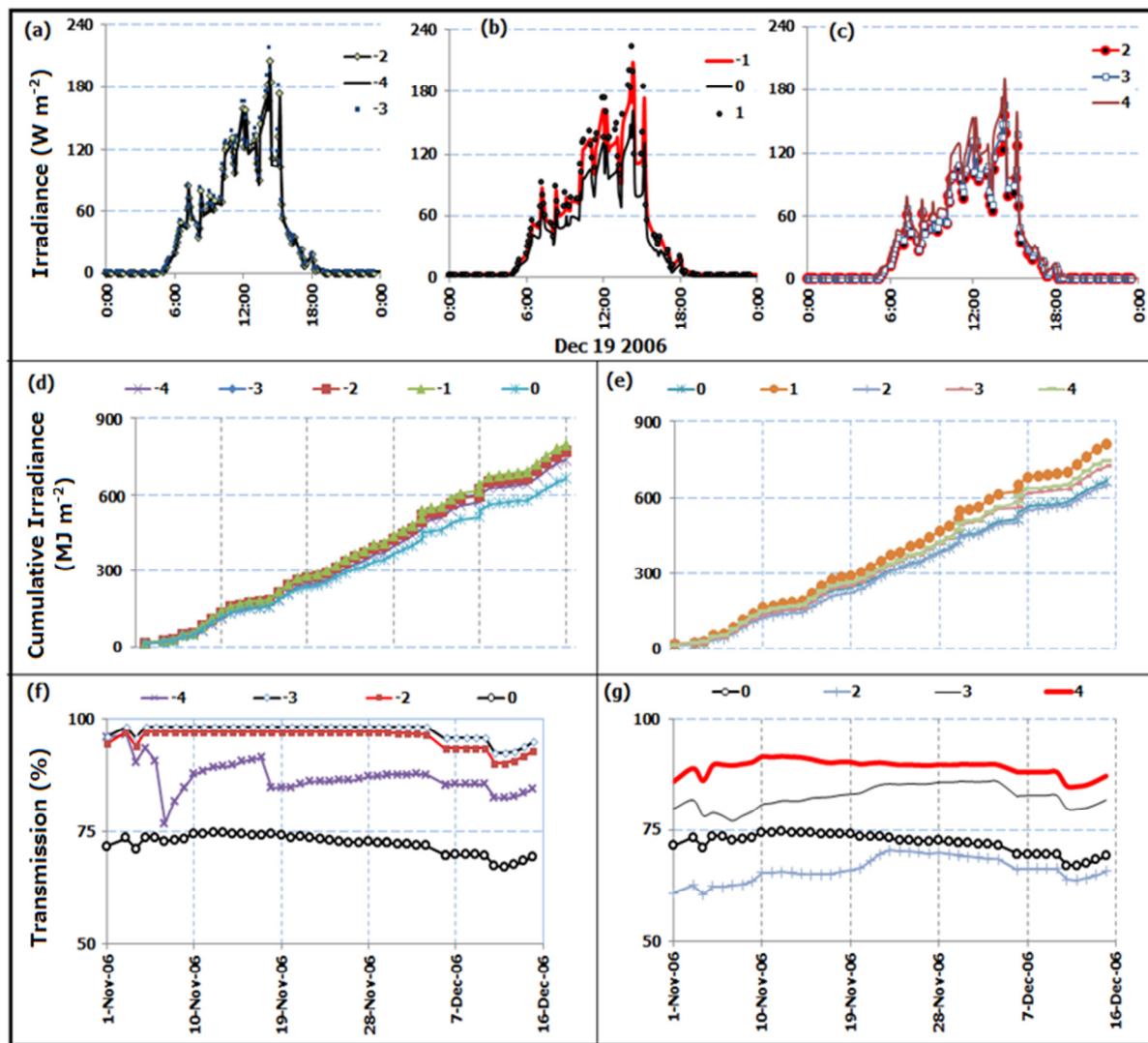


Figure 4.8 Diurnal irradiance (a-c), cumulative irradiance (d-e) and radiation transmission (f-g) in SW (-4 m, -3 m, -2 m), below hedgerows (-1 m, 1 m), between hedgerows (0 m) and NE (2 m, 3 m, 4 m) of DR

4.3.1.4 Comparison of radiation partitioning among treatments

Using solar radiation data from November 01 2006 to December 16 2006, it was observed that solar radiation partitioning was different among treatments. JO had the highest tree interception of radiation per unit system area due to its higher LAI (Figure 4.9). Tree interception was 223 MJ m^{-2} , which was 27.1% of the incident radiation (823 MJ). The averaged radiation transmission to the soil surface was 600 MJ (72.9%).

During the same period, SR trees intercepted 92 MJ (11.2%) of the incident radiation. An average radiation of 731 MJ transmitted through tree canopy. Despite comparable LAI to SR trees, trees of DR intercept the lowest amount of radiation during the same period. Only 8% (66 MJ) of the incident radiation was tree-intercepted, which amounts to 72% of radiation interception by the SR tree, an average radiation of 757 MJ reached the system floor.

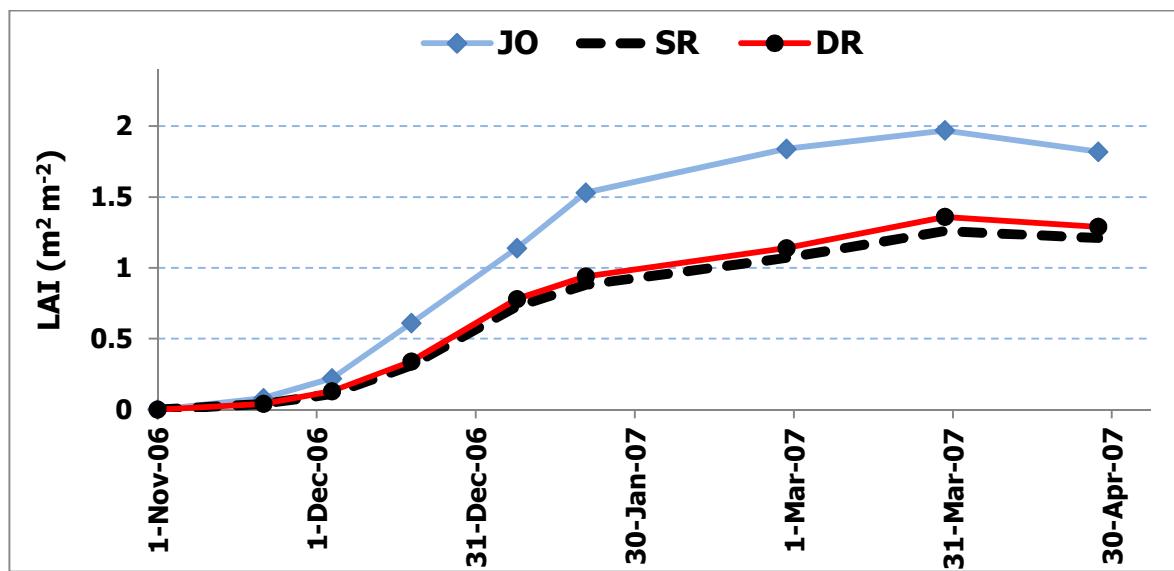


Figure 4.9 LAI ($\text{m}^2 \text{ m}^{-2}$) of *Jatropha* in JO, SR and DR during 2006-07 season

4.3.2 Water balance and dynamics

4.3.2.1 JO

Soil water generally increased with depth (Figure 4.12a-e). The reasons were increasing clay content (Figure 4.2c) and reduced evaporation with soil depth. Soil water at 0.05 m depth was lower at 1.5 m NE and 0.75 m SW. This was despite similar irradiance to 1.5 m NE and SW as well as 0.75 m NE and SW (Figure 4.5). Wet-period soil water content (Figure 4.10) below trees was the highest due to stem flow and reduced soil evaporation (increased shading). SW had lower soil water than NE and the difference increased with distance from the trees. During drier periods, on the other hand, SW had more soil water close to tree than NE counterpart. The highest drop in water content (159 mm) between wet and dry

periods (Figure 4.10) was at 1.5 m SW (the rest were between 116 to 121 mm). This was due to the fact that the highest radiation (based on 2006-07) was at 1.5 m SW.

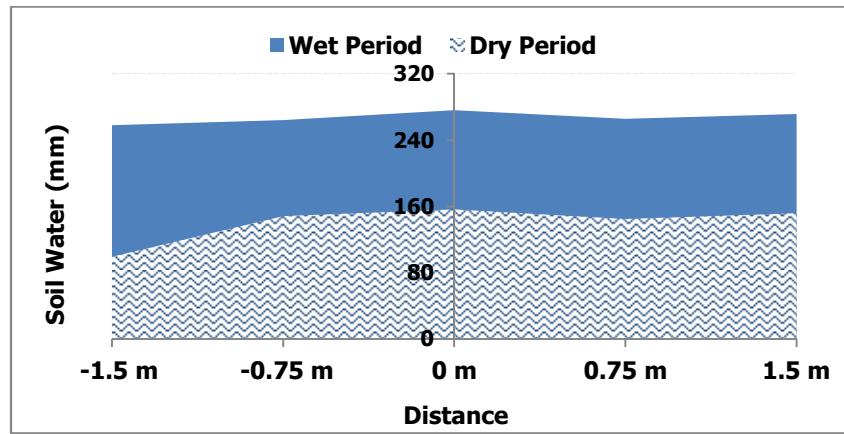


Figure 4.10 Profile water distribution during wet and dry periods in JO

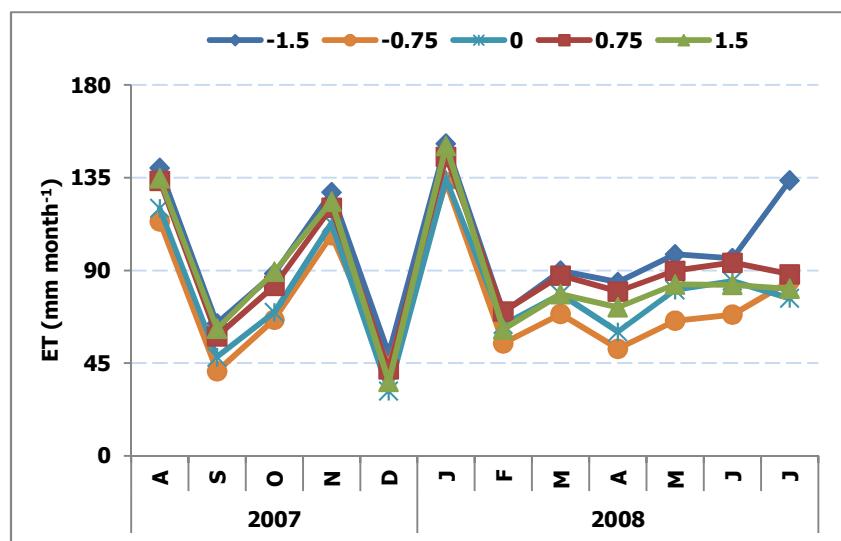


Figure 4.11 Monthly ET at the selected positions in JO

Evapotranspiration (ET) was the lowest at 0.75 m SW for most of the study period (Figure 4.11). ET differences between 0.75 m NE and the other distances were higher during dry periods (Oct/Nov 2007 and after Feb 2008), primarily contributing to the lowest water content at the 0.75m during dry period.

Tree RGR-SWD correlations in JO are presented in Figures 4.12 and 4.13. Profile level correlation was high ($R^2 \approx 0.91$). Tree RGR-SWD correlations improved towards tree rows and were higher on NE than SW. The

weakest correlation ($R^2 = 0.47$) was at 1.5 m SW and the highest ($R^2 = 0.96$) at 0.75 m NE. These outcomes suggested that fine tree roots were highly concentrated near the tree and on NE. This explains why soil water content on SW was higher than NE (Figure 4.10). The 1.5 m SW had the weakest correlation ($R^2 = 0.47$), lowest water contents at 0.05 m and 0.15 m depths (Figure 4.13) and maintained the highest ET (Figure 4.11). This indicated high soil evaporation and low transpiration proportions at 1.5 SW. The highest $R^2 (> 0.96)$ at 0.75 m NE indicated the highest fine root concentration and explains why dry-period water content at 0.75 m NE was low.

SWD in the top 0.2 m of soil had a weak correlation with tree RGR (Figure 4.12a). The implied concentration of fine roots was the highest within the 0.2 – 0.4 m depth. The 0.4 – 0.6 m increment had a significant fine root concentration (Figure 4.12d). Tree RGR-SWD correlations at the various distances and soil layers suggested that tree root distribution in JO was skewed. High fine root concentrations occurred within the 0.2 - 0.6 m depth of 0 m, 0.75 m SW and NE and 1.5 m NE. The lowest fine root concentration was within the top 0.2 m depth of 1.5 SW. The rest of the profile had significant fine root concentrations and thus had an important contribution to tree water uptake.

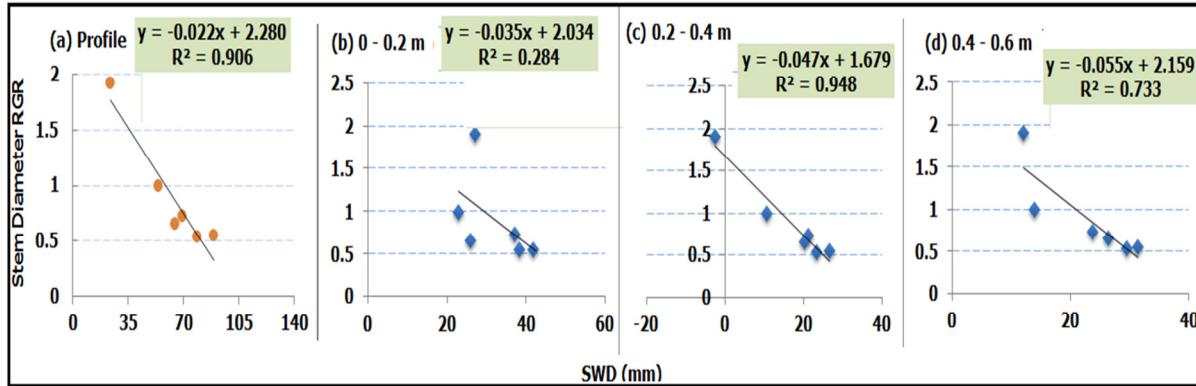


Figure 4.12 Tree RGR vs. SWD of soil profile (a) and soil layers (b, c, and d) in JO

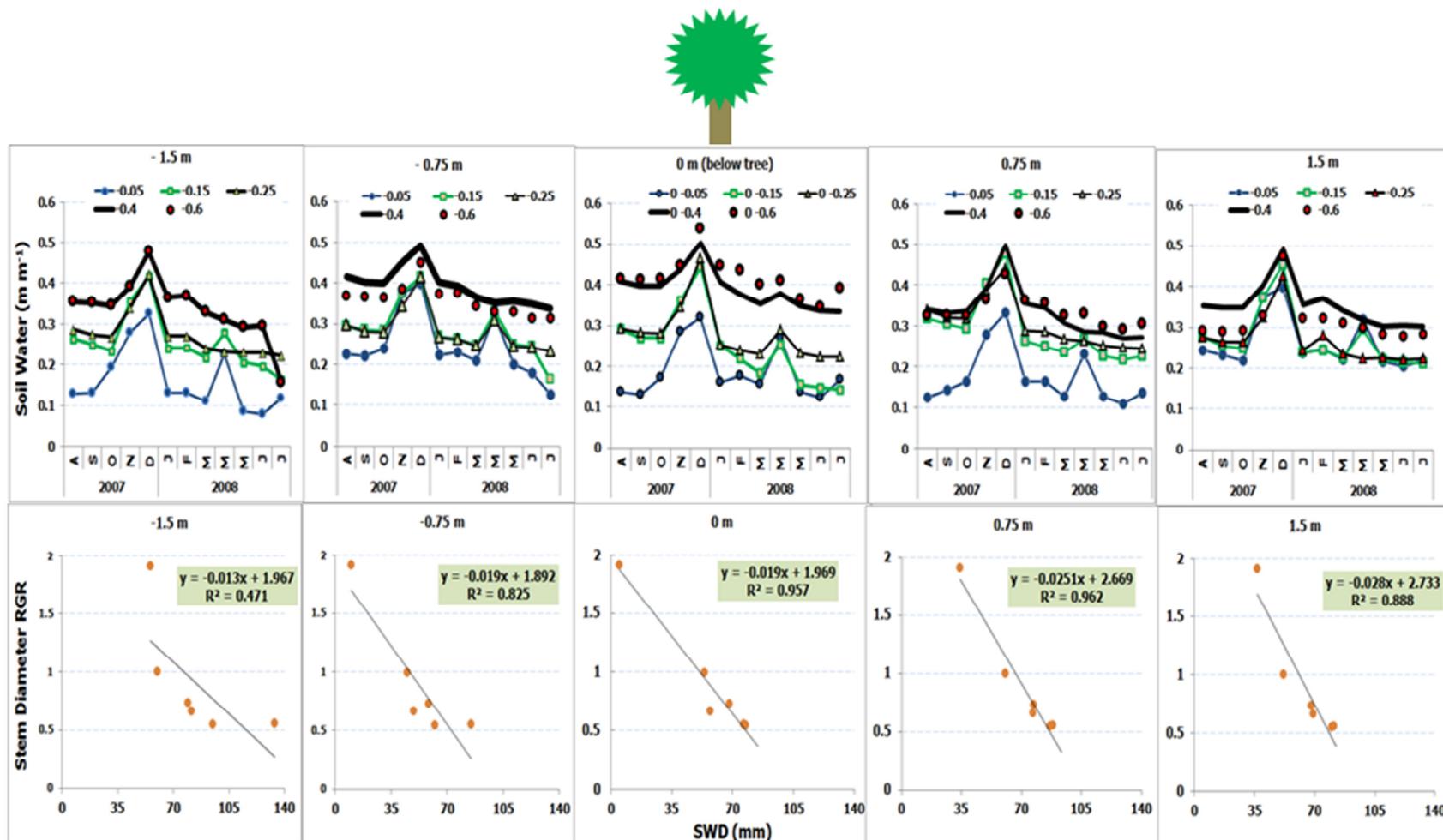


Figure 4.13 Soil water fluctuations with depth (top) and tree RGR-SWD correlation (bottom) at selected positions in JO

4.3.2.2 SR

Soil water content generally increased with depth. During wet periods, soil water was generally higher on NE than SW. The lowest soil water content was under the tree (0 m). During dry periods, soil water generally decreased with distance from tree. The decrease was steeper on NE. The 0.83 SW and 1.67 m NE maintained high soil water contents as irradiance at these distances was lower than other distances. The 2.5 m NE had the highest drop in profile water content between wet and dry periods (175 mm) compared to other distances (127 – 151 mm). This was due to high radiation transmission (Figures 4.6 and 4.7) resulting in the highest ET during dry periods (Figure 4.15).

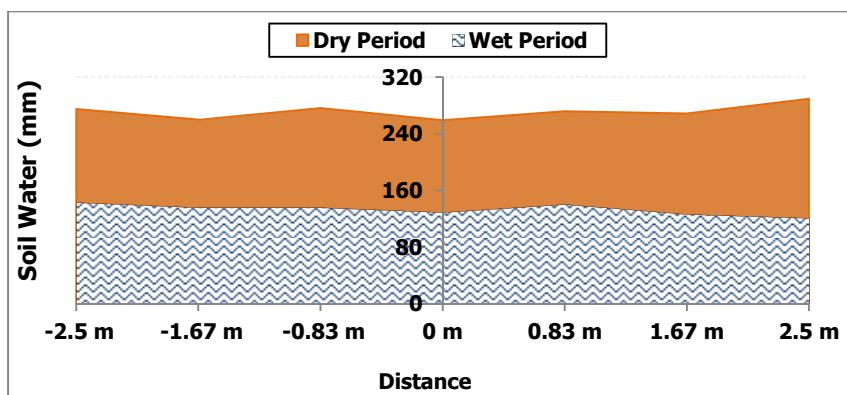


Figure 4.14 Soil water distributions in SR during wet and dry periods

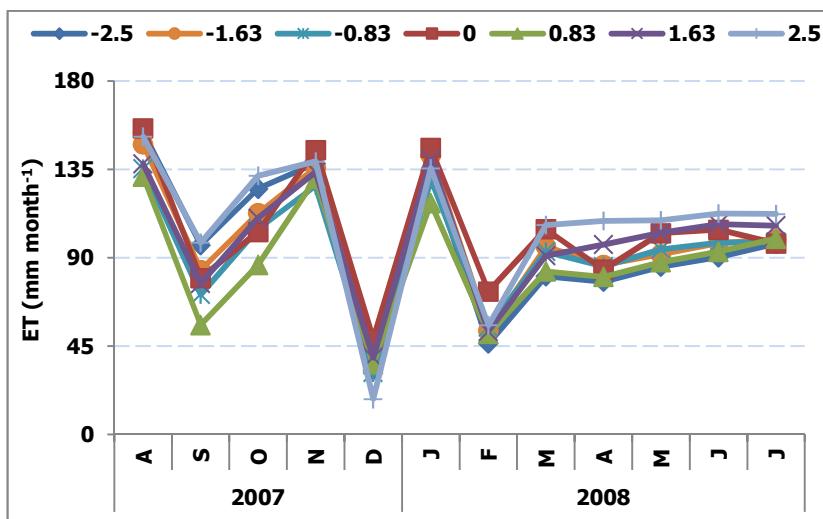


Figure 4.15 Monthly ET across the selected tree row in SR

Correlation between tree RGR and profile SWD was strong ($R^2 = 0.78$). The highest R^2 values (> 0.9) between spatial SWD and tree RGR were at 0.83 m SW and 0.83 m NE. The 0.83 m distances had the lowest grass cover/growth (Figure 4.24) suggesting that soil evaporation and grass water use were low and tree water use was dominant ET component. The highest grass growth at 2.5 m NE (7.03 t ha^{-1}) indicated contributions of tree and crop transpiration (as opposed to soil evaporation) to ET were dominant. At 2.5 m NE, the drop in soil water content between wet and dry periods (Figure 4.14) was the highest (159.8 mm). The poorest tree RGR-SWD correlations ($R^2 < 0.57$) were at 1.67 m SW and 0 m (Figure 4.17). The poor correlation at 1.67 m SW resulted in the lowest water content variations between wet and dry periods (124 mm). Below tree, absence of grass cover brought about consistently high soil evaporation at 0.05 m depth (Figure 4.17) and high ET during wet periods (Figure 4.15). As a result, tree water uptake was compromised. Variations in RGR-SWD correlations with depth in SR were similar to those in JO. The former, however, had higher R^2 (≈ 0.58) at the top layer (0 - 0.2 m) than JO ($R^2 \approx 0.28$). This could be due to T-C competition in SR forcing tree roots to explore the 0 - 0.2 m layer better than in JO.

Generally, NE had higher contribution to tree water uptake than SW. Neither distance (Figure 4.16) nor depth (Figure 4.16) consistently increased or decreased strength of RGR-SWD correlations. It can be inferred that high fine root concentrations existed at 2.5 m SW, 0.83 m SW, 0.83 m NE, 1.6 m NE and 2.5 m NE within of 0.2 – 0.6 m of the soil. The 1.67 m SW and 0 m had the lowest tree root concentrations, especially within the 0 - 0.2 m layer.

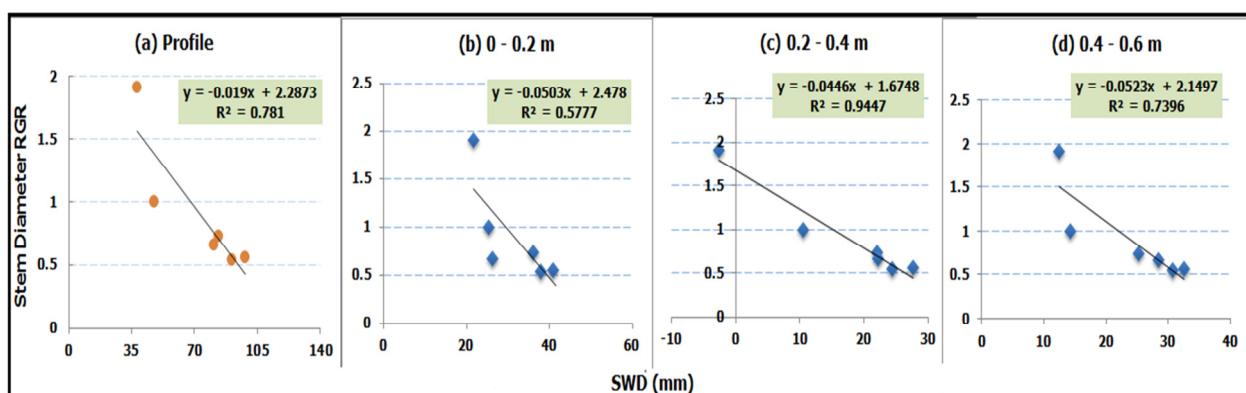


Figure 4.16 Stem diameter RGR vs. SWD of soil profile (a) and soil layers (b to d) in SR

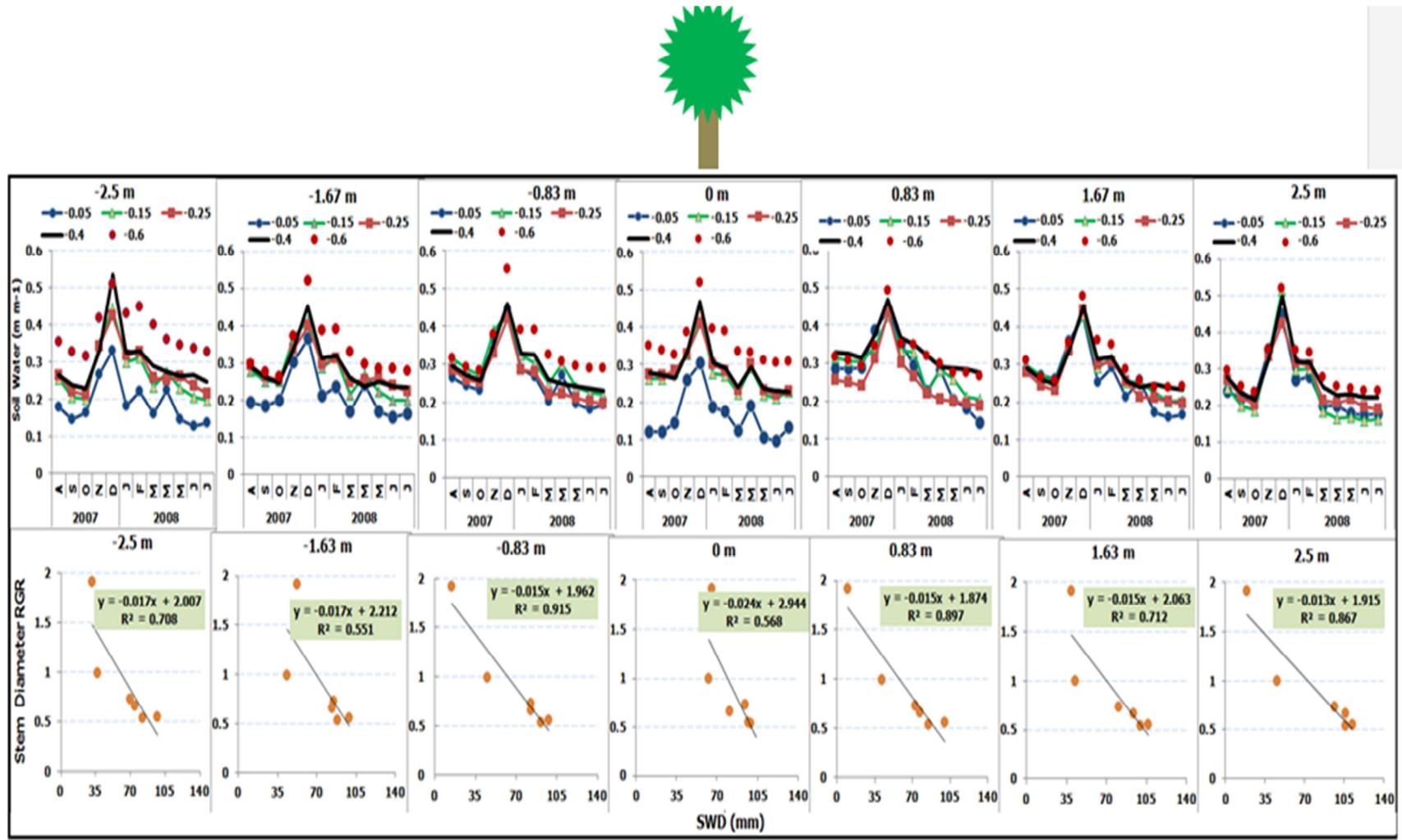


Figure 4.17 (a) Fluctuations of soil water with depth and (b) tree RGR vs. SWD at various distances in SR

4.3.2.3 DR

Soil water content generally increased with depth (Figure 4.20). The only exceptions were at 3 m SW, 3 m NE and 4 m NE. The smallest difference between wet-period and dry-period water contents was at 2 m SW (125.2 mm) and 1 m NE (130.6 mm). At 4 m SW, 1 m SW, 0 m, 1 m NE and 2 m NE, soil water consistently increased with depth during wet and dry periods (Figure 4.20). The 2 m SW had the same pattern but smaller variations. During wet periods, SWD was the highest at 4 m NE, 4 m SW and 3 m SW (Figure 4.18). The lowest was at 3 m NE. Wet-period soil water content decreased with distance from the tree rows. Soil water below SW tree row was higher than NE tree row. During dry periods, NE tree row and 2 m NE had lower water contents than their SW counterparts. ET was generally higher in NE than SW during extended dry periods (Figure 4.19).

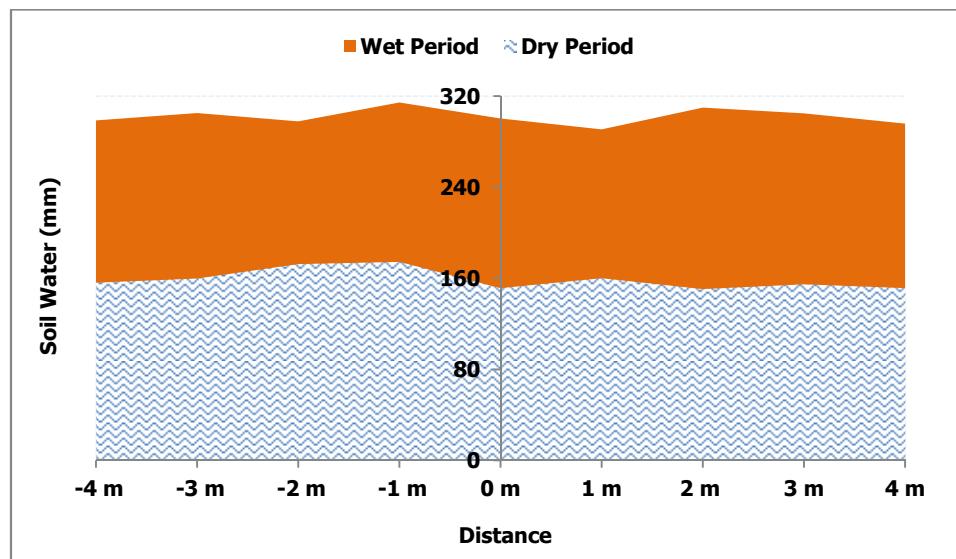


Figure 4.18 Soil water distributions in DR during wet and dry periods

Strong ($R^2 > 0.91$) RGR-SWD correlations resulted at profile level (Figure 4.21a), distances and soil depth increments (Figures 4.21b-d). It is inferred that in DR, distribution of fine tree roots in the profile was essentially symmetrical.

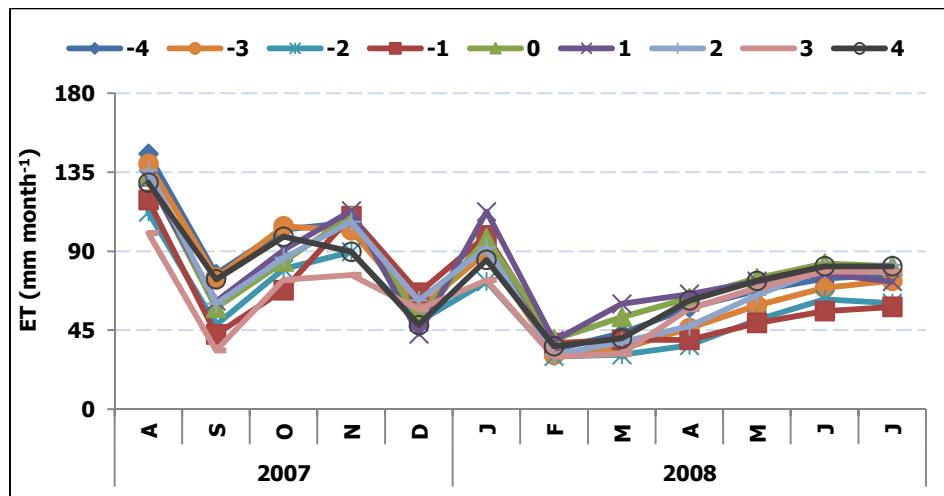


Figure 4.19 Monthly ET at the selected positions in DR

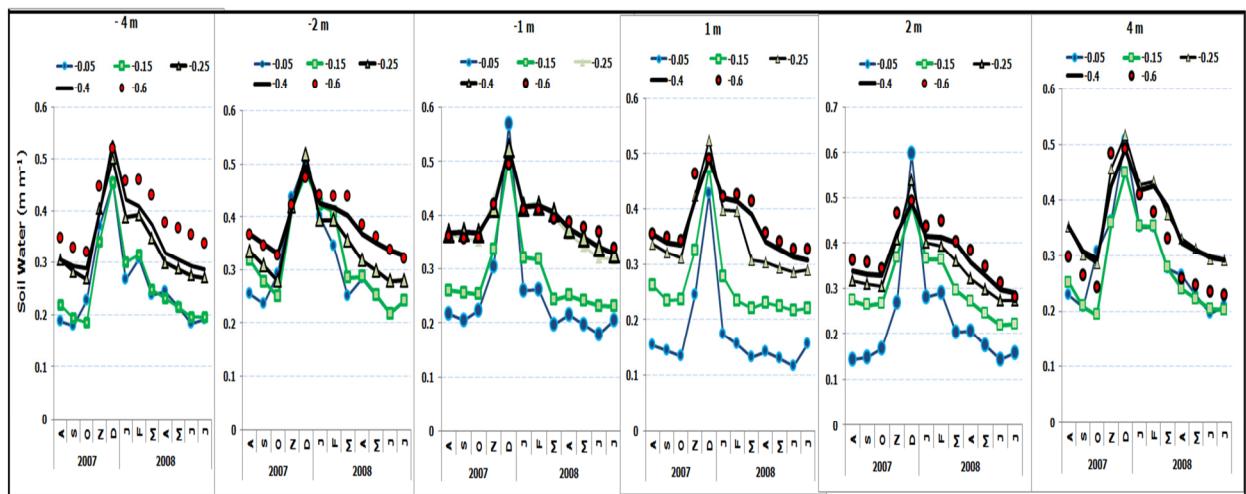


Figure 4.20 Soil water changes at selected (depth and distance) positions in DR

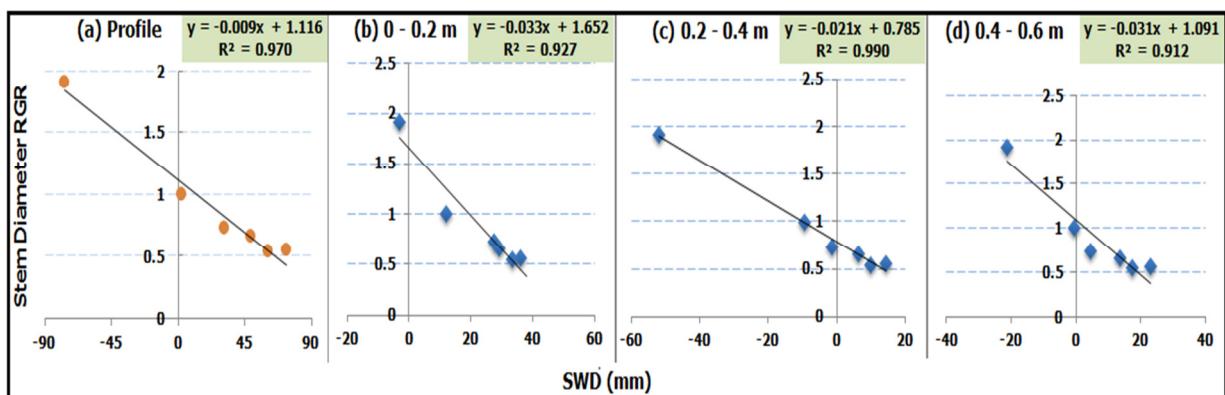


Figure 4.21 Tree RGR vs. SWD of soil layers (a to c) and profile (d) in DR

4.3.2.3 Comparison of ET among treatments

Figures 4.22 and 4.23 present comparisons of ET among treatments. Generally, there were significant ET differences among treatments ($p < 0.05$). SR had mostly the highest ET during the study period. DR, on the other hand, had generally the lowest ET. In August 2007, ET was higher in SR than JO and DR by 23%. During September and October, SR had higher ET than DR by 13-25% and JO by 16-37%. In November, ET was higher in SR by 35% and 65% than JO and DR respectively. December ET in DR was lower than in JO and SR by 47%. During January and February 2008, JO had more ET than SR and DR by 6% and 56% respectively. ET in SR during March to July 2008 was higher by 9-15% than JO and 25-57% than in DR.

The ET gap among treatments narrowed after extended dry periods (June and July 2007 and May 2008 onwards). During winter and extended dry periods, both kikuyu and *Jatropha* were largely dormant and soil evaporation remained similar across treatments. Between November and May, tree and grass growth varied among treatments accompanied by increasing ET differences (among treatments). Plant growth differences among treatments also brought about differences in ET via shading differences.

JO and SR differed in their ratios of tree water use to ET. For instance, tree water use in SR was 24.7 mm (18.3% of ET) in January and 25.1 mm (44.9% of ET) in February. For JO, trees used 52.1 mm (37% of ET) of water in January and 47.1 mm (84.2% of ET) in February.

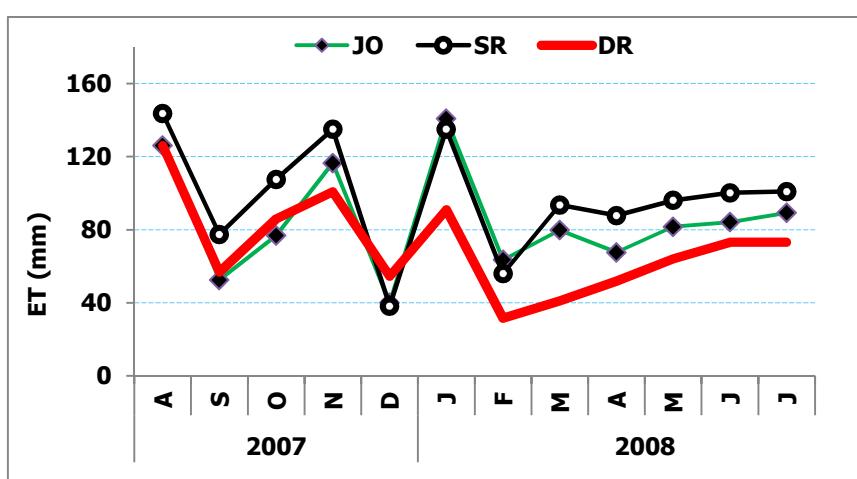


Figure 4.22 Monthly ET in JO, SR and DR during August 2007 to July 2008

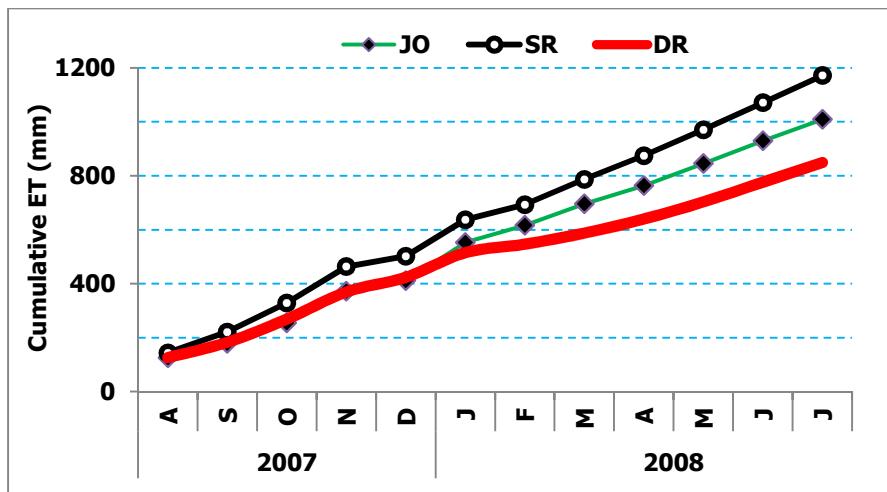


Figure 4.23 Cumulative ET in JO, SR and DR from August 2007 to July 2008

4.3.3 Plant growth

4.3.3.1 Grass productivity in SR

During 2006-07 and 2007-08, grass growth in SR consistently increased with distance from the tree (Figures 4.24 and 4.25). On NE, there were significant increases in grass growth from 0.83 m to 1.67 m and 1.67 m to 2.5 m. SW had a similar pattern, but the increases were non-significant. At 0.83 m and 1.67 m distances, grass growth on NE and SW was comparable. The 2.5 m NE had significantly higher growth than 2.5 m SW. The fact that 2.5 m NE had the highest grass growth and consistently high ET suggests that grass water use was the major ET component.

Grass productivities at 0.83 m NE (2.61 t ha^{-1}) and 0.83 m SW (3.03 t ha^{-1}) were the lowest (Figures 4.24 & 4.26) and not significantly different from each other. This was despite irradiance differences at these positions. González-Hernández and Rozados-Lorenzo, (2008) also found significantly lower pasture productivity close to the tree than without the influence of nearby trees. From a radiation distribution point of view (Figure 4.24), the lowest growth would be at 0.83 m SW and the highest at 2.5 m SW, 1.67 m SW and 0.83 m NE. Grass growth at 2.5 m NE was the highest (7.03 t ha^{-1}) despite radiation transmission suggesting higher yield would be expected at 2.5 m SW (5.75 t ha^{-1}) and 1.6 m SW (4.12 t ha^{-1}). At 2.5 m NE, the highest grass productivity was accompanied by the lowest soil water during dry periods (Figure

4.14), the highest water content difference between wet and dry periods ($\approx 170\text{ mm}$), relatively small soil water variations with depths (Figure 4.17) and the highest ET (Figure 4.15). At 0.83 m NE and 0.83 SW (Figure 4.17), the strongest tree RGR-SWD correlations (the highest contribution to tree water uptake) were indicative of the intensive interspecies competition for water kikuyu experienced. Hence, these positions had generally low ET (Figure 4.15). At 2.5 m NE, the highest grass productivity (7.03 t ha^{-1}) and high distribution of fine tree roots (R^2 of RGR-SWD of 0.87) resulted in the biggest change in soil water content between wet and dry periods (170 mm).

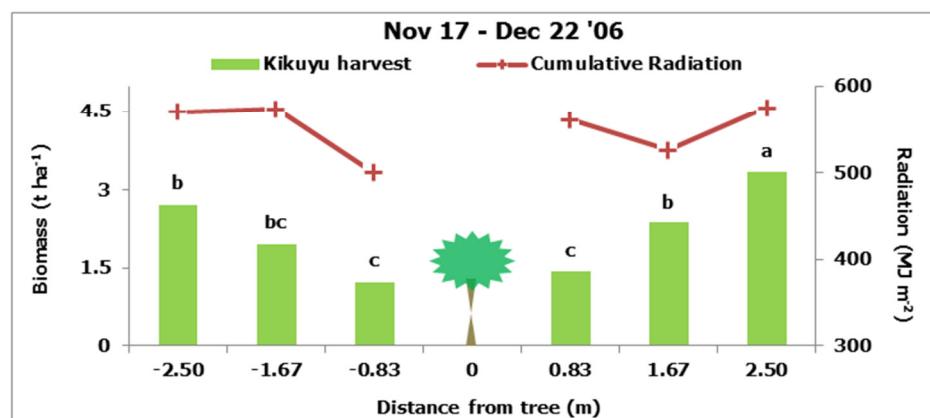


Figure 4.24 ANOVA results of kikuyu harvests (t ha^{-1}) and cumulative irradiance at selected positions in SR from Nov 17 to Dec 22 2006

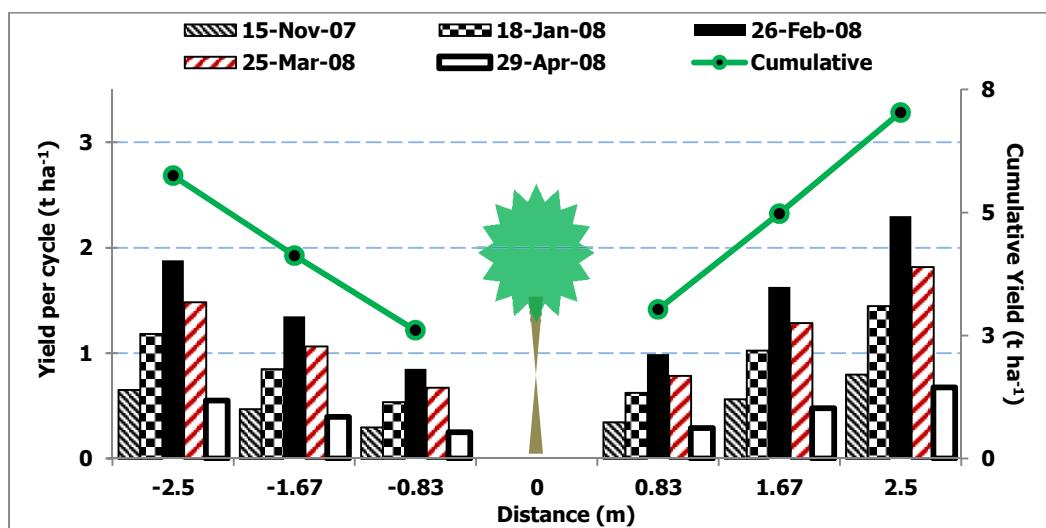


Figure 4.25 Kikuyu harvests (t ha^{-1}) at selected positions in SR during 2007-08

4.3.3.2 Grass productivity in DR

During 2006-07 and 2007-08 seasons, grass growth in DR increased with distance from tree rows (Figures 4.27 and 4.29). The increases from 2 m SW to 3 m SW ($\approx 85\%$) and 3 m SW to 4 m SW ($\approx 53\%$) were significant. NE, on the other hand, had non-significant increases from 2 m to 3 m ($\approx 47\%$) and 3 m to 4 m ($\approx 44\%$). Grass yields at the same distance on NE and SW were not significantly different. During 2006-07 season, grass productivity was higher on SW than NE, which was the same as cumulative irradiance (Figures 4.9c-d, 4.7 and 4.28). The high productivity periods (January 18 to February 26 2008 and February 27 to March 25 2008) coincided with high rainfall. The wet-period soil water distribution with distance was generally the inverse of kikuyu growth.

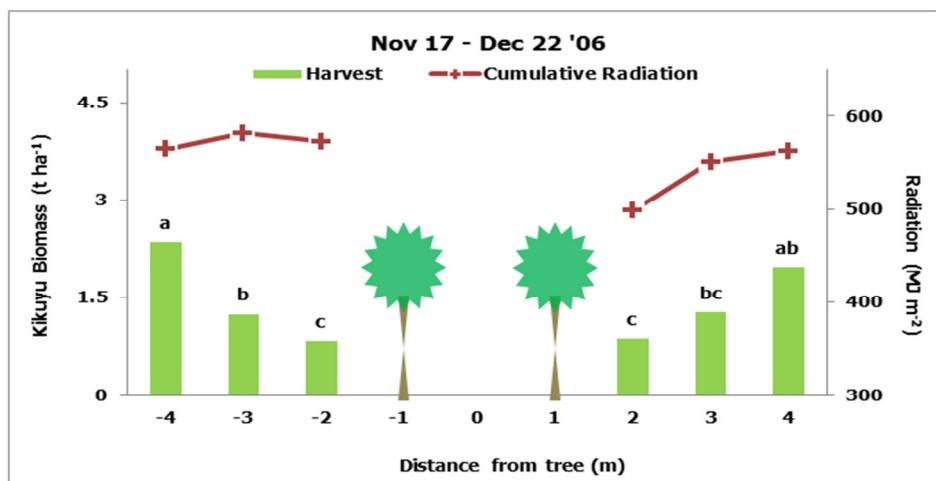


Figure 4.26 ANOVA results of kikuyu harvests ($t ha^{-1}$) and cumulative irradiance at selected positions in DR from Nov 17 to Dec 22 2006

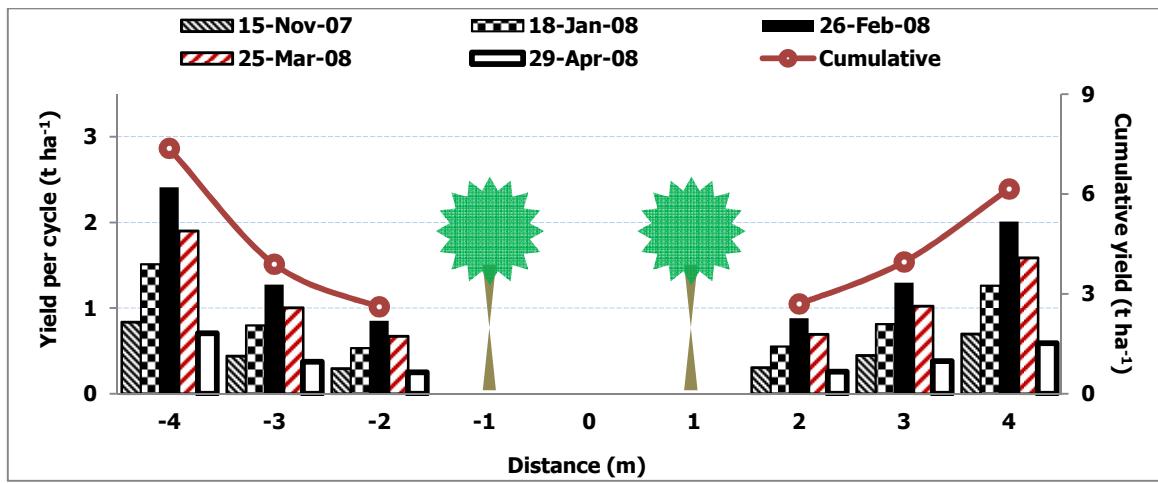


Figure 4.27 Kikuyu harvests ($t\text{ ha}^{-1}$) at selected positions in DR during 2007-08

4.3.3.3 Comparison of grass productivity between treatments

In SR and DR, cumulative grass yields during 2006-07 were higher than for 2007-08. Cumulative harvests in DR (8 t ha^{-1} in 2006-07 and 4 t ha^{-1} in 2007-08) were less than in SR (8.7 t ha^{-1} in 2006-07 and 4.3 t ha^{-1} in 2007-08). The reason for this was that tree roots were better developed and more competitive in DR than SR. Correlation between SWD and grass biomass in SR was poorer ($R^2 = 0.16$ to 0.38) than for DR ($R^2 = 0.61$).

Table 4.1 Total productivity and ET of SR and DR from Oct 01 2006 to Apr 27 2007

Treatment	Tree yield (kg ha^{-1})	Tree AG dry mass (t ha^{-1})	Grass yield (t ha^{-1})	Seasonal ET (mm)
JO	99.3	3.7	-	1019
SR	18	2.2	8.7	1171
DR	16.9	2.3	8	849

Table 4.2 Radiation use efficiency (g MJ^{-1}) of kikuyu in SR and DR

Treatment	Kikuyu radiation use efficiency (kg MJ^{-1})						
	SW			NE			
SR	2.5 m 0.32	1.67 m 0.23	0.83 m 0.17	0.83 m 0.17	1.67 m 0.30	2.5 m 0.39	0.27
DR	4 m 0.44	3 m 0.21	2 m 0.14	2 m 0.17	3 m 0.23	4 m 0.34	0.25

Correlations between kikuyu biomass and irradiance were poor (SR, $R^2 = 0.32$; DR $R^2 < 0.1$). This was contrary to strong linear correlations ($R^2 = 0.9$) reported previously (Sibbald and Sinclair, 1990; Knowles *et al.*

al., 1999; González-Hernández and Rozados-Lorenzo, 2008). Radiation use efficiency (RUE) of kikuyu in SR and DR increased with distance from tree rows. This indicated that the photosynthetically active radiation range of the transmitted radiation was reduced due to interactions between irradiance and tree canopy that preceded radiation transmission to the intercropping zone (Ong *et al.*, 1996).

4.3.3.4 Root distribution in SR

Distribution of total root density in SR was skewed towards SW (Figure 4.28a-d). Within 0.2 - 0.6 m, root density was higher on NE than SW. The highest percentage of root biomass (91.4%) was within the 0 - 0.2 m depth and below the tree, where SWD-RGR correlations were the lowest (Figure 4.16), confirming dominance of woody tree roots. The 0.2 - 0.4 m and 0.4 - 0.6 m depth increments were dominant contributors to tree water uptake. Yet, these depth increments accounted for less than 8.6% of total root biomass in the profile.

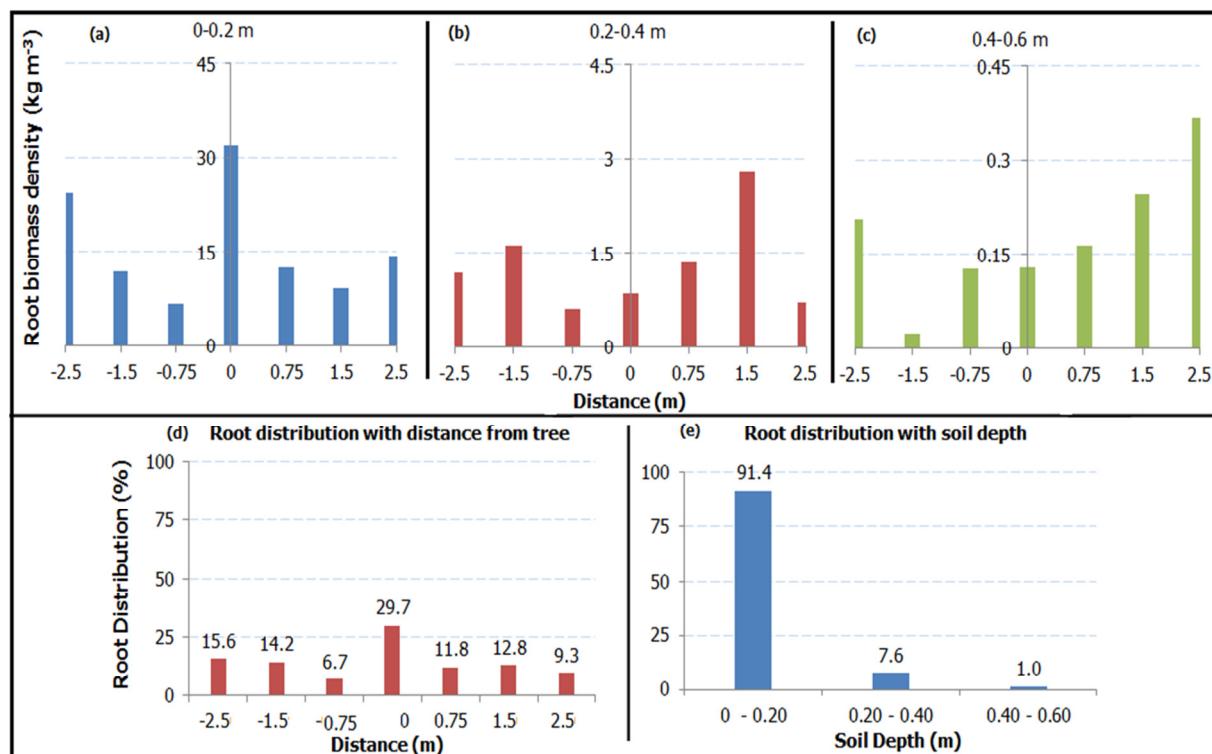


Figure 4.28 Total root distribution in SR (Note that different Y-axis scales are used)

Neither of the combination treatments showed a clear relationship between grass growth and root distribution. This implied that total root biomass is not an indicator of roots responsible for water uptake, just the combined woody and fine roots of kikuyu and *Jatropha*. The decrease in total root density with distance from trees (Figure 4.28d) was in agreement with previous studies (Van Noordwijk *et al.*, 1996, Livesley *et al.*, 2000)

4.4 CONCLUSIONS

In all treatments, radiation distribution was generally asymmetrical. JO had the steepest inter-distance differences in transmission due to the highest tree LAI. Grass biomass vs. irradiance correlations were poor in SR ($R^2 = 0.32$) and DR ($R^2 < 0.1$) despite the treatments not being nutrient-limited and rainfall during the study period being high. Possible reasons were that high interspecific competition for water and photosynthetically active radiation of the transmitted radiation was reduced as evidenced by the reduction in radiation use efficiency (RUE) as one nears the tree rows. RUE of kikuyu increased asymmetrically with distances from tree lines. Kikuyu was confirmed to be non-tolerant to drought. The hypothesis of the linear correlation between radiation and plant growth was rejected.

Soil water was asymmetrically distributed, varying with rainfall and depth and among treatments. Unlike in previously studied similar systems, which showed reduced soil water content close to trees (Malik and Sharma, 1990; Onyewotu *et al.*, 1995; Livesley *et al.*, 2000; Odhiambo *et al.*, 2001), the current treatments did not exhibit consistent soil water increase/decreases towards the trees. The differences between ET in SR (the highest) and DR (the lowest) narrowed after extended dry periods. The extent of *Jatropha* root distribution in search for soil water varied among treatments. In JO and SR, strength of tree RGR-SWD correlations varied with distance and depth implying asymmetrical fine tree root distribution. RGR-SWD correlations of DR implied that the entire profile was contributing to tree water use significantly and that fine tree roots were symmetrically distributed in the profile. The strength of the correlations was due to tree dominance of radiation capture and mainly water-limited tree growth. Absence of interspecific competition not only ensured that tree RGR in JO remained the highest but also that trees did not have to make use of the entire profile. SR and DR trees had comparable RGRs. Yet, tree water uptake was more preferential and less extensive in SR, which also had better cumulative grass growth. These suggest that

SR trees faced weaker interspecific competition for water than DR trees. In DR, tree roots explored the profile more comprehensively, only to achieve similar tree RGR and less cumulative grass growth. This suggested more intensive interspecific and possibly intraspecific competition than in SR. Hence, the hypothesis that water availability would be more limiting to T-C interactions than radiation distribution in semi-arid climate was accepted. It was also confirmed that radiation mainly magnified the effects of soil water.

High grass growth coincided with high rainfall periods. Grass growth in the treatments consistently increased with distance from the tree lines. NE of SR had higher grass productivity (7.03 t ha^{-1}) than SW (5.75 t ha^{-1}). In DR, SW had higher productivity (7.36 t ha^{-1}) than NE (6.15 t ha^{-1}). In the combination treatments, tree and grass roots overlapped greatly due to shallow rootedness of the trees and the limited soil profile depth (0.6 m). High fine root concentration within crop rooting depth has been observed in numerous fast growing trees (Jonsson *et al.*, 1988; Daniel *et al.*, 1991; Van Noordwijk *et al.*, 1996). *Jatropha* and kikuyu are perennial plants and are dormant during extended dry periods and active during the rest of the year leaving no room for temporal complementarity between them. This resulted in severe competition for water. Distribution of total roots in SR was skewed towards SW. Tree water uptake predominantly came from the 0.2 – 0.6 depth, which had less than 8.6% of the total root biomass in the profile. There was no clear relationship between grass and root distribution.

Finally, the hypothesis of being able to manipulate tree spacing/arrangement to optimise radiation and water distribution and crop growth in hedgerow intercropping was accepted. More options should be explored in order to ascertain the full potential and implications of the above findings.

CHAPTER 5

DEVELOPMENT OF A HEDGEROW INTERCROPPING MODEL

5.1 INTRODUCTION

Agroforestry systems have unique features including multiplicity of components and outputs, perennial presence of some components and complexities of T-C and plant–resource interactions (Young, 1997). Robust modelling approach is, therefore, vital in order to achieve full characterisation of resource demand and use, plant positions, growth and productivity of component species and nature and extent of component interactions (Mobbs *et al.*, 1999).

One way of developing agroforestry models is by modifying specialised (agricultural, forestry etc.) models (Young, 1997). Since various T-C associations may be considered when designing/planning agroforestry systems, viable candidate models for such a purpose should be robust, generic and mechanistic. System productivity and returns are determined from products of component species. Relevant modelling should necessarily include simulators of productivity of all component species. Accordingly, in the current study, a mechanistic and process-based hedgerow intercropping model that meets these fundamental requirements was required. A hedgerow intercropping model was developed by integrating two models, which met requirements of a ‘candidate’ model. These models were Soil Water Balance model (SWB) (Annandale *et al.*, 1999) and a two dimensional energy interception and water balance model for hedgerow tree crops (SWB-2D) (Annandale *et al.*, 2002). Overviews of these models are provided in sections 5.2 and 5.3.

The developed model adopted the framework of SWB-2D. This is due to the accuracy of SWB-2D to predict solar radiation interception and soil water balance in tree hedgerow systems, which have the same structure as hedgerow intercropping systems. The two-dimensional modelling approach represents the fundamental interfaces of hedgerow intercropping interactions, across T-C intersects and vertically along these intersects (including along plant height and soil depths). For predicting growth of intercrops, the crop growth routine of SWB, which makes use of the cascading soil water balance approach, was selected due to its accurate, robust, generic and mechanistic nature. These strengths also provided the growth model with the potential of characterising and predicting tree growth generically and mechanistically. To this, new

routines of tree crown and root growth were incorporated. The newly developed hedgerow intercropping model was verified, calibrated and validated using the CAMASE modelling guidelines (1995), and used for scenario analyses.

5.2 OVERVIEW OF THE SOIL WATER BALANCE (SWB) MODEL

SWB model is a real-time, mechanistic, generic and user-friendly model of crop growth, soil water balance and irrigation scheduling (Annandale *et al.*, 1999) developed based on the NEWSWB model (Campbell and Diaz, 1988). It employs two simulation approaches of crop growth, namely: an FAO-based model and a mechanistic simulation model of crop growth. According to the FAO-based model, water use and crop growth/canopy cover are determined from a relatively simple and empirical crop coefficients set for various growth stages (Jovanovic and Annandale, 1999). In contrast, the mechanistic crop growth simulator is more robust, flexible and capable of taking various effects, such as water stress on growth mechanistically (Jovanovic and Annandale, 2000). It, however, requires more inputs and parameters.

Crop growth and water balance simulations of SWB are based on weather, soil and crop units. Its weather unit calculates daily Penman-Monteith reference evapotranspiration (ET₀) using the FAO-56 recommendations (Allen *et al.*, 1998). SWB employs two soil water redistribution approaches, one a cascading approach and the other a finite difference approach. The mechanistic crop model calculates a daily increment of dry matter as the lesser of radiation-limited production, which is based on the simple model of Monteith (1977), or water-limited production based on the simple gas exchange model of Tanner and Sinclair (1983). Using soil water content and environmental conditions, it determines crop phenological development, growth and yield starting from emergence to maturity. Crop transpiration is determined as a function of soil water potential, leaf water potential at maximum transpiration and root conductance. Development stages of crops are determined mechanistically, as the accumulation of the required thermal time of the various stages, as declared through crop-specific parameters. Hence, the length and onset of the development stages of the same crop may vary from place to place and depend on planting dates (Oliver and Annandale, 1998). Water-limited dry mass production is affected by a crop stress index and leaf water potential (Annandale *et al.*, 2000). The model also accommodates various irrigation management strategies (Annandale *et al.*, 1999).

Comprehensive evaluations of SWB under a wide range of crops and growing conditions (Jovanovic *et al.*, 1999; Annandale *et al.*, 2000; Beletse *et al.*, 2008; Singles *et al.*, 2010) have confirmed accuracy and robustness of the model. It also has parameter-rich databases available for a vast range of crops (Annandale *et al.*, 1999).

5.3 OVERVIEW OF TWO-DIMENSIONAL RADIATION INTERCEPTION AND WATER BALANCE MODELLING (SWB-2D)

SWB-2D was developed as an extension of SWB to address spatial and temporal non-uniformity of energy distribution (as opposed to uniform energy distribution in mono-cropping) and improvement of managing and use efficiencies of irrigation and rain under micro-irrigation (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 tree crown. It also takes into consideration interferences of neighbouring rows on radiation interception by a particular row. It has four main components, namely: a tree crown radiation interception predictor, a soil water evaporation predictor, a tree transpiration predictor and a predictor of water redistribution in the soil.

In the model, Beer's law is used to determine radiation transmittance through an ellipsoidal tree crown from the path length of rays through the crown and leaf area density. The path length of the ray through crown of a tree row whose foliage density is assumed constant is a function of solar zenith and azimuth angles, spacing and orientation of the rows, crown size, shape and leaf area density of trees. Leaf area density of an ellipsoidal crown with a spherical leaf distribution is a parameter that indicates the total one-sided area leaves in a unit volume of a crown. The model also recognises differences in plant canopy interactions with direct and diffuse solar radiation components (Annandale *et al.*, 2002, Annandale *et al.*, 2004) arising from differences in use efficiencies (Weiss and Norman, 1985) and angles of incidence (Annandale *et al.*, 2002, Annandale *et al.*, 2004). It 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).

SWB-2D was developed to be user-friendly. Its components were evaluated independently and altogether in several trials and have shown that SWB-2D is quite accurate if properly parameterised (Annandale *et al.*, 2002; Annandale *et al.*, 2003; Annandale *et al.*, 2004). Due to the mechanistic approaches followed, these models form powerful components to an integrated two-dimensional agroforestry system model.

5.4 TREE GROWTH MODELLING

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

- Use of stem translocation of assimilates approach to initiate leaf growth in deciduous trees after dormancy, similar to flower start in SWB (Annandale *et al.*, 1999)
- Priority of biomass allocation to plant parts depending on which resource (solar radiation or water) is more limiting.

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

- Fraction of assimilates allocated to tree roots
- Litter-fall for evergreen and deciduous trees
- Growth of tree height and stem diameter
- Tree root growth and distribution
- Tree crown growth

Figure 5.1 illustrates inputs of tree model. The tree growth model requires initial inputs of crown width (2a) and height (2c), height of crown centre from soil surface (Z_0), root biomass, lateral and vertical rooting extent, soil fertility rating, tree row spacing and orientation (from North), stem diameter, daily weather data, latitude, standard meridian and longitude. Depth of root pruning or tillage in case of root/soil management and width of crown base (2ap), height of pruned part of crown (cp) and crown base from the soil surface (Z_b) after base-pruning of crown are also required. Species-specific tree parameters required to run the model (along with values for a sample tree -*Jatropha curcas*) are presented in Table 6.2.

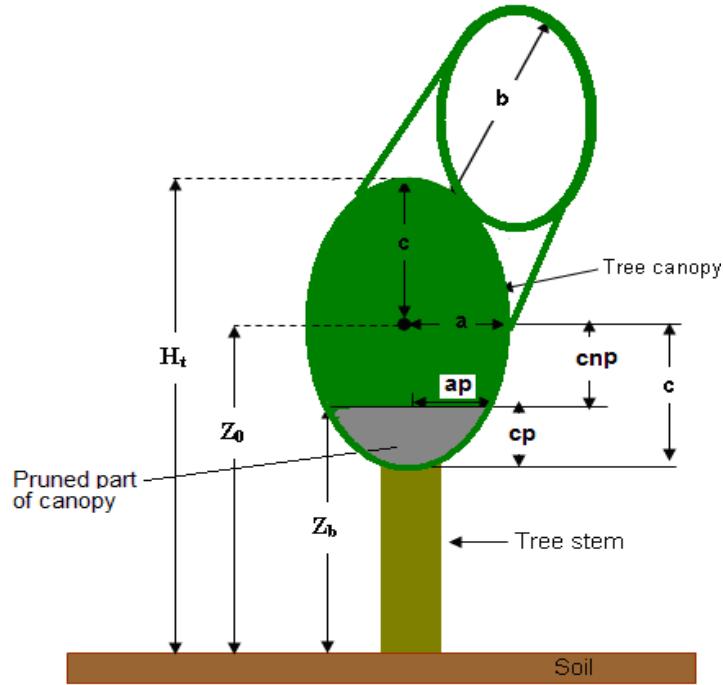


Figure 5.1 A diagrammatic representation of tree dimensions. a is half-crown width, b is half-crown depth, c is half-crown height, ap is half the width of the crown base after pruning, cp is the reduction in tree crown height due to pruning, cnp is the remaining part of the lower half-crown, TH is tree height, Z_0 and Z_b the heights from the soil surface to the crown centre and the crown base respectively.

5.4.1 Biomass production and allocation

On the first day of simulation or first day after pruning, leaf dry mass (LDM, in kg m^{-2}) is determined as:

$$\text{LDM} = \rho_{F(\text{mass})} V_F / \text{ground area} \quad 5.1$$

Where $\rho_{F(\text{mass})}$ is tree foliage density by mass (kg m^{-3}), which is a tree species model parameter, V_F is crown volume (m^3) and ground area (m^2) refers to the area occupied by a tree and is calculated as the product of intra-row spacing and inter-row spacing, both in metres.

The volume of an ellipsoidal crown is calculated as:

$$V_F = \pi a b c \quad 5.2$$

Where a , b and c in metres are half-crown width, half-crown depth (assumed to be equal to half of intra-row tree spacing) and half-crown crown height respectively (Figure 5.1).

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

$$\text{LAI} = \text{LDM SLA}$$

5.3

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

A flow chart of the tree growth model showing major processes of biomass production and allocation is presented in Figure 5.2.

Branch biomass of trees is calculated using the allometric relationship developed by Ghezehei *et al.* (2009) for *Jatropha*:

$$\text{BDM} = a_b (D_{\text{stem}})^{n_b} \quad 5.4$$

Where D_{stem} is stem diameter (m), a_b and n_b are empirical parameters.

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

$$\text{BDM}_{\text{new}} = f_{cv} \text{ BDM}_{\text{old}} \quad 5.5$$

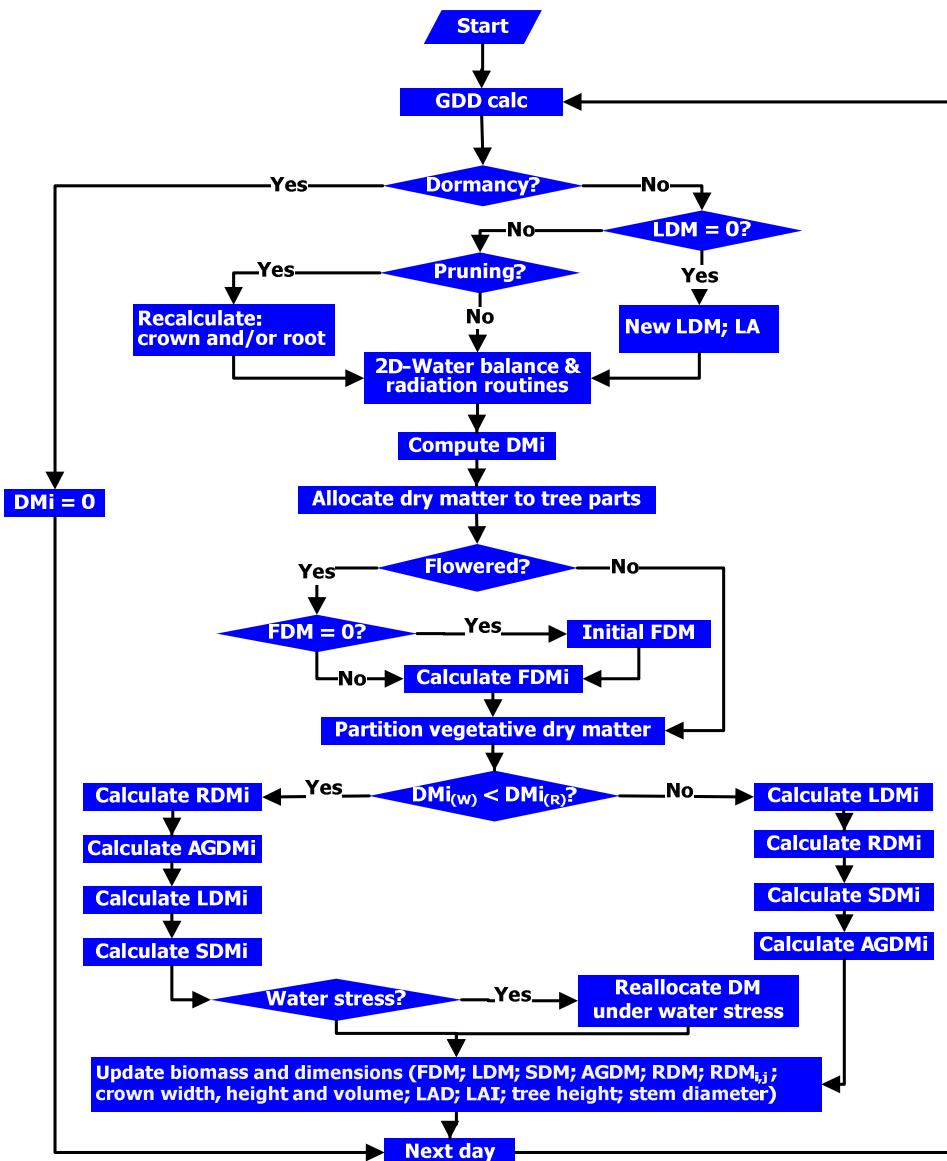


Figure 5.2 Flow chart of the tree growth model. AG stands for aboveground, DM for dry matter, i for increment, F for flower/fruit, L for leaf, R for root, subscript (R) for radiation limited, S for stem, subscript (W) for water limited, LAI is leaf area index, LAD is leaf area density and GDD denotes cumulative growing degree days.

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

- When water limits growth, net primary production is (Tanner and Sinclair, 1983):

$$DM_{i(W)} = DWR \cdot (T / VPD) \quad 5.6$$

Where $DM_{i(W)}$ is water limited net primary production (kg m^{-2}), DWR is dry matter-water ratio (Pa), VPD is vapour pressure deficit (Pa) and T is tree transpiration (mm)

- When solar radiation limits growth, net primary production ($DM_{i(R)}$) is calculated by (Monteith, 1977):

$$DM_{i(R)} = E_c T_f FI_{transp} R_s \quad 5.7$$

Where E_c denotes radiation conversion efficiency (kg MJ^{-1}), FI_{transp} is fractional solar radiation interception by crown for photosynthesis and transpiration and R_s is solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$), T_f is an index ($0 \leq T_f \leq 1$) taking the effect of temperature on radiation-limited plant growth, and is given by:

$$T_f = (T_{ave} - T_b) / (T_{lo} - T_b) \quad 5.8$$

Where T_{ave} is average air temperature ($^{\circ}\text{C}$), T_b is base temperature ($^{\circ}\text{C}$), and T_{lo} is optimum temperature for growth ($^{\circ}\text{C}$) when radiation limits growth.

Daily net primary production (DM_i) is equal to the lesser of water-limited ($DM_{i(W)}$) and radiation-limited ($DM_{i(R)}$) net primary production, which also decides whether water-limited mode or radiation-limited mode of assimilate partitioning is followed (Table 5.1). For instance, if $DM_{i(W)}$ is less than $DM_{i(R)}$, then DM_i is equal to $DM_{i(W)}$ and water-limited mode of assimilate partitioning is executed.

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

$$FDM = Transl_F SDM \quad 5.9$$

Where FDM is in kg m^{-2} , $Transl_F$ is a dimensionless parameter for stored assimilate relocation from tree stem for fruit production, SDM is tree stem biomass (kg m^{-2}).

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

$$FDM_i = rpf \text{ DM}_i \quad 5.10$$

rpf is the reproductive partitioning fraction, which is the fraction of daily biomass increment allocated to flower/fruit production, with $0 < rpf \leq 1$. It is calculated as:

$$rpf = (\text{GDD} - \text{FLDD}) / \text{TransDD} \quad 5.11$$

Where GDD is total growing degree days ($\text{d } ^\circ\text{C}$), FLDD is GDD for flowering initiation, and TransDD is tree GDD required to transition from the vegetative stage to flowering.

Growing degree days are incremented and summed using the following equations:

$$\text{GDD}_i = (T_{ave} - T_b) \quad 5.12$$

$$\text{GDD}_i = 0 \quad \text{if} \quad T_{ave} < T_b \quad 5.13$$

$$\text{GDD}_i = (T_{cutoff} - T_b) \quad \text{if} \quad T_{ave} > T_{cutoff} \quad 5.14$$

$$\text{GDD}_t = \text{GDD}_{t-1} + \text{GDD}_i \quad 5.15$$

Where GDD is in $\text{d } ^\circ\text{C}$, T_{cutoff} ($^\circ\text{C}$) is the temperature at which maximum plant development occurs and subscripts "i" and "t" denote increment and current day respectively.

Daily vegetative dry matter increment (VDM_i), which is biomass left after fruit biomass increment is apportioned, is available for tree root, crown (foliage) and stem and is calculated as:

$$VDM_i = \text{DM}_i - FDM_i \quad 5.16$$

Trees use carbohydrate (assimilate) reserves for new leaf growth during spring (Dickson, 1991). For deciduous trees, leaf initiation after winter is modelled when cumulative GDD since the end of the previous fruit stage is equal to the GDD requirement for leaf initiation (LIDD). While all perennial tree parts can store and supply assimilates (Loescher *et al.*, 1990), an initial biomass for leaf production is assigned from assimilates stored in the stem (due to its proximity as a source of assimilates) using the equation:

$$LDM = \text{Transl}_L \text{ SDM} \quad 5.17$$

Where LDM is leaf dry matter in kg m^{-2} and Transl_L is a parameter for relocating assimilates stored in the stem for leaf production.

Priority of allocating daily increment of vegetative biomass (VDMi) to root and foliage is decided based on whether growth is limited 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 explore soil more widely and deeply. Under water stress conditions, would be allocated to 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 5.2 and 5.3 summarize the alternative procedures.

Table 5.1 Assimilate reallocation to tree foliage, root and stem based on whether growth is limited by radiation or water. V stands for vegetative, AG for aboveground, DM for dry matter, i for daily increment, L for leaf, R for root, subscript (R) for radiation limited, S for stem, subscript (W) for water limited and f_f and f_R for proportions of net primary production partitioned to tree foliage and roots respectively.

(1)	Order of assimilate reallocation when $DMi = DMi_{(R)}$	Equation
Step 1	$LDMi = f_f VDMi$	(Based on Sands, 2004) 5.19
Step 2	$RDMi = f_R (VDMi - LDMi) = f_R VDMi - f_f f_R VDMi$	(Based on Sands, 2004) 5.20
Step 3	$SDMi = VDMi - LDMi - RDMi = VDMi - f_f VDMi - f_R VDMi + f_f f_R VDMi$	5.21
Step 4	$AGDMI = LDMi + SDMi = (f_f VDMi) + (VDMi - f_f VDMi - f_R VDMi + f_f f_R VDMi)$	5.22
(2)	Order of assimilate reallocation when $DMi = DMi_{(W)}$	Equation
Step 1	$RDMi = f_R VDMi$	5.23
Step 2	$AGDMI = VDMi - RDMi = (1 - f_R) VDMi$	5.24
Step 3	$LDMi = f_f AGDMI = f_f (1 - f_R) VDMi$	5.25
Step 4	$SDMi = AGDMI - LDMi = (1 - f_f) AGDMI$	5.26
Mass balance error (MBE) = $VDMi - LDMi - RDMi - SDMi$		5.27

The fraction of net primary production apportioned to tree root (f_R) is calculated based on the approach of Landsberg and Waring (1997):

$$f_R = 0.8 / (1 + (2.5 m T_f)) \quad 5.18$$

Where T_f is an index of temperature effects on growth, m is a factor representing effects of soil fertility on biomass allocation to root, with a value of 0 indicates infertile soil and $m = 1$ implying highly fertile soil.

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

$$f_f = 1 / (1 + \text{PART AGDM})^2 \quad 5.28$$

Where PART is a parameter of biomass allocation to stem and leaves and AGDM is total aerial (vegetative) dry matter and is computed as:

$$\text{AGDM} = \text{AGDM}_{t-1} + \text{AGDMI} \quad 5.29$$

Where t-1 indicates yesterday

There is no leaf growth for water-stressed trees (when their threshold stress index is higher than calculated stress index, SI). Hence, daily leaf biomass increment calculated for no stress (equation 5.25) is equally re-partitioned between roots and stem. Daily water stress index (SI) is calculated as (Annandale *et al.*, 1999):

$$SI = T / PT \quad 5.30$$

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

$$PET = ETo Kc_{max} \quad 5.31$$

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

ETo is calculated by:

$$ETo = [0.408 \Delta (R_n - G) + \gamma 900 / (T_{avg} + 273) U_2 VPD] / [\Delta + \gamma (1 + 0.34 U_2)] \quad 5.32$$

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

$$\Delta = 4098 e_s / (T_a + 237.3)^2 \quad 5.33$$

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

$$G = 0.38 [T_{avg}(t) - T_{avg}(t-1)] \quad (\text{Wright and Jensen, 1972}) \quad 5.34$$

T_{avg} - Mean daily ambient temperature ($^\circ\text{C}$) given by:

$$T_{avg} = (T_{max} + T_{min}) / 2 \quad 5.35$$

γ - Psychrometer constant ($\text{kPa } ^\circ\text{C}^{-1}$) calculated as

$$\gamma = 0.00163 P_a / \lambda \quad 5.36$$

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

$$\lambda = 2.501 - 2.361 \times 10^{-3} T_{\text{avg}} \quad 5.37$$

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):

$$Kc_{\max} = \text{Max} \{Kc_{\max(1)}, Kc_{\max(2)}\} \leq 1.45 \quad 5.38$$

$$\text{Where } Kc_{\max(1)} = 1.2 + [0.04(U_2 - 2) - 0.004(RH_{\min} - 45)](TH / 3)^{0.3} \quad 5.39$$

$$Kc_{\max(2)} = Kcb + 0.05 \quad 5.40$$

Where TH is height of the tree (m), Kcb is the FAO basal crop coefficient.

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

$$SDM = a_s (D_{\text{stem}})^{n_s} \quad 5.41$$

Where D_{stem} is stem diameter (m), a_s and n_s are parameters.

Total tree stem biomass is updated by adding daily stem increment to initial stem biomass. Stem diameter and height are updated from allometric relationships, as:

$$D_{\text{stem}} = (SDM / a_s)^{\frac{1}{n_s}} \quad 5.42$$

$$TH = a_H D_{\text{stem}}^{n_H} \quad 5.43$$

Where TH (m) is 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 parameters of the stem diameter-stem biomass and stem diameter-tree height relationships respectively.

5.4.2 Tree root growth and distribution

In hedgerow intercropping, there are continuous BG interactions among component species for nutrients and water uptake. Growth and distribution of tree and crop roots define nature and intensity of these interactions. Trees, as perennial components of two-dimensional agroforestry systems, have well-established root systems. Their roots are more developed than alley-crop roots. Tree roots also re-grow after root pruning or alley-zone tillage between cropping seasons. Vertically and horizontally root growth differs as a result of variations in soil profile characteristics, soil water and soil oxygen.

The tree root modelling approach presented here estimates root growth and distribution with soil depth and across T-C interface. It also allows tree roots to re-grow following root pruning and alley-zone.

Root biomass is updated daily using the equation:

$$RDM_t = RDM_i + (1 - \gamma_R) RDM_{t-1} \quad 5.44$$

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 5.4.3.

The soil profile across the hedgerow is divided into a grid of nodes (Figure 5.4). The soil volume around a node representing a unit of water balance and water re-distribution (laterally and vertically) is referred to as a control volume (i, j), where i and j denote its vertical and horizontal nodal positions (Annandale, 2003). Tree root biomass is allocated to the 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 ($RDM_{(i,j)}$) by:

$$RDM_{(i,j)} = RDM_i (p_{(i,j)} / P) \quad 5.45$$

Where $RDM_{(i,j)}$ denotes increment of root biomass in 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 control volume (i, j) for tree root growth and P is summation of $p_{(i,j)}$, calculated to enable allocation of root biomass according to the proportional '*favourability*' of control volumes.

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

$$p_{(i,j)} = (1 - (\psi_{(i,j)} / \psi_{wilt})) (1 - (DCV_i / R_i)) froot_{(i,j)(t-1)} \quad 5.46$$

$$P = \sum p_{(i,j)} \quad 5.47$$

Where $\psi_{(i,j)}$ is sum of matric and gravitational potential in control volume (i, j) ($J \text{ kg}^{-1}$), ψ_{wilt} is soil matric potential at permanent wilting point ($J \text{ kg}^{-1}$), DCV_i is depth of control volume (i, j) (m), R_i is vertical rooting extent (m), $froot_{(i,j)(t-1)}$ is fraction of total root biomass in control volume (i, j) at previous time step and is calculated as:

$$froot_{(i,j)(t-1)} = RDM_{(i,j)(t-1)} / RDM_{(t-1)} \quad 5.48$$

Where $RDM_{(i,j)(t-1)}$ is tree root biomass in control volume (i, j) (kg m^{-2}) at the previous time step, and $RDM_{(t-1)}$ represents total tree root biomass at previous time step (kg m^{-2}).

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

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

$$R_j = f_j TH \quad 5.49$$

$$R_i = f_i TH \quad 5.50$$

Where R_j is horizontal root extent (m), f_j is a parameter in the tree height and horizontal root growth relationship, R_i is vertical root extent (m), f_i is a parameter in the tree height - vertical root growth relationship, and TH is tree height (m).

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

reached, root biomass is allocated to control volumes for replacing dead roots and increasing root density.

Root biomass increment of each control volume ($RDM_{(i,j)}$) is converted to root biomass density ($RDMD_{(i,j)}$) using:

$$RDMD_{(i,j)} = RDM_{(i,j)} / V_{(i,j)} \quad 5.51$$

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

$$V_{(i,j)} = \frac{1}{4} [(\Delta X_{j-1} \Delta Z_{j-1}) + (\Delta X_{j-1} \Delta Z_j) + (\Delta X_j \Delta Z_j) + (\Delta X_j \Delta Z_{j-1})] \Delta Y \quad 5.52$$

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

Root pruning is a tree management practice involving lateral cutting of roots using disc or blade root pruners or digging trenches on selected or all sides of the tree. Tillage is a soil management practice. Nevertheless, in agroforestry, both are intended to make a favourable growing medium available for the understory crops and compromise tree root systems. No root pruning or tillage is allowed in the control volumes beneath the tree ($j=6$). The model user selects depth of tillage/root pruning. In other words, roots do not have to be pruned all the way to the bottom of the soil profile. The first day after tillage/root pruning, root biomass densities are set to zero in the control volumes in which tree roots are affected directly (by pruning/tillage). That is,

$$RDMD_{(i,j)} = 0 \text{ for } \left\{ \begin{array}{l} j \neq 6 \\ DCV_i \leq PD \\ \text{or} \\ DCV_i \leq TD \end{array} \right. \quad 5.53$$

Where PD is root pruning depth (m) and TD is tillage depth (m).

When determining biomass allocation for root re-growth into control volumes following pruning or tillage, the model uses $p_{(i,j)}$ calculated by replacing equation 5.48 with:

$$froot_{(i,i)} = \text{Max} (froot_{(i,i)}^o; froot_{(i,i)(t-1)}) \quad 5.54$$

Where $froot_{(i,j)}$ is maximum root fraction of the control volume (assuming no pruning/tillage occurred), $froot_{(i,j)}^0$ is the highest root fraction in the control volume prior to pruning/tillage and is updated during every root pruning/tillage event.

Finally, root biomass densities of control volumes in which root pruning or tillage takes place are updated using equations 5.51 and 5.52.

5.4.3 Tree crown growth

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

$$LDM_t = LDM_i + (1 - \gamma_f) LDM_{t-1} \quad 5.55$$

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

Daily leaf fall rate of evergreen trees is calculated as:

$$\gamma_f = 1 / (365 LL) \quad 5.56$$

Where LL (years) is leaf life span in the crown and 365 is used to convert years into days (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 $LDMage_i$ (in $\text{d}^{-1} \text{C}^{-1}$). Once maximum age ($LDMage_{max}$) of a 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).

Leaf-fall facilitation due to stress is reflected as follows:

$$LDMage_i = (1 / SI) GDD_i \quad 5.57$$

Where GDD_i is daily increment of growing degree days, and $1/SI$ denotes effect of water stress on leaf fall, with values between 1 and 2.

Using updated foliage biomass (LDM_t), LAI (using equation 5.3) and crown volume (V_F) are updated using:

$$V_F = LDM_t / \rho_{F(\text{mass})} \quad 5.58$$

Where $\rho_{F(\text{mass})}$ is tree foliage density by mass (kg of foliage m^{-3} crown volume), which is a tree parameter.

Leaf area density (LAD), which is leaf area (m^2) per unit crown volume (m^{-3}) is calculated as (Annandale *et al.*, 2002):

$$\text{LAD} = \text{LAI} (2 b h / V_F) \quad 5.59$$

Where b and h (in m) are intra-row tree spacing and tree row spacing respectively.

Trees in hedgerow intercropping systems are planted in rows forming a continuous (closed) crown along tree rows. The model assumes ellipsoid crown shapes and that intra-row spacing is used in place of crown depth for calculating crown volume. If crown base is pruned, crown volume (V_F) is calculated by subtracting volume of pruned (removed) part, which is equal to bottom half of an elliptical crown with dimensions $2ap$, $2cp$ and $2b$, from volume of un-pruned crown (Figure 5.1). That is:

$$V_F = [\pi a b c] - [(1/2) \pi ap b cp] \quad 5.60$$

Where a and c represent dimensions of un-pruned crown, b is equal to half of intra-row tree spacing, ap is half of the width of crown base after pruning (m), cp denotes height (m) of pruned crown part, and $1/2$ indicates that the pruned crown part is equal to half of a crown with dimensions $2ap$ $2cp$ and $2b$.

The vertical extent (m) of the pruned part of a crown (cp) is calculated as follows:

$$cp = c - cnp \quad 5.61$$

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

$$q = a / c \quad 5.62$$

Using crown depth (equal to intra-row tree spacing) and q and by rearranging the equation of the volume of an ellipsoid (to solve for "a"), crown dimensions are updated as follows:

$$V_F = \pi a b c = \pi a b (a / q) \quad 5.63$$

$$a = [(V_F q) / (\pi b)]^{0.5} \quad 5.64$$

$$c = a / q \quad 5.65$$

Crown height increment Δc_t is equal to:

$$\Delta c_t = c - c_{t-1} \quad 5.66$$

Where c is updated height of half of the tree crown (from equation 5.67), and c_{t-1} is half of crown height at previous time step

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

$$cnp_t = cnp_{t-1} + \Delta c \quad 5.67$$

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

$$cp = c - cnp \quad 5.68$$

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

$$Z_o = TH - c \quad 5.69$$

$$Z_b = Z_o - cnp \quad 5.70$$

$$ap = q cp \quad 5.71$$

Another crown pruning option considered is pruning to a smaller size and elliptical (or maintaining original) shape. Required inputs for the pruning options are listed in Table 5.1.

5.5 BUILDING OF THE HEDGEROW INTERCROPPING MODEL

The component modules and equations presented above are based on sound biophysical principles. The development of the current hedgerow intercropping model entailed the following:

- 1 The hedgerow intercropping model takes SWB-2D as the main framework, to which routines of tree and intercrop growth and water balance and redistribution are added.
- 2 The radiation routine of SWB-2D simulates radiation interception by trees and irradiance at 11 points across a tree hedgerow, referred to as soil surface nodes. An illustration of this is shown in Figure 5.3.

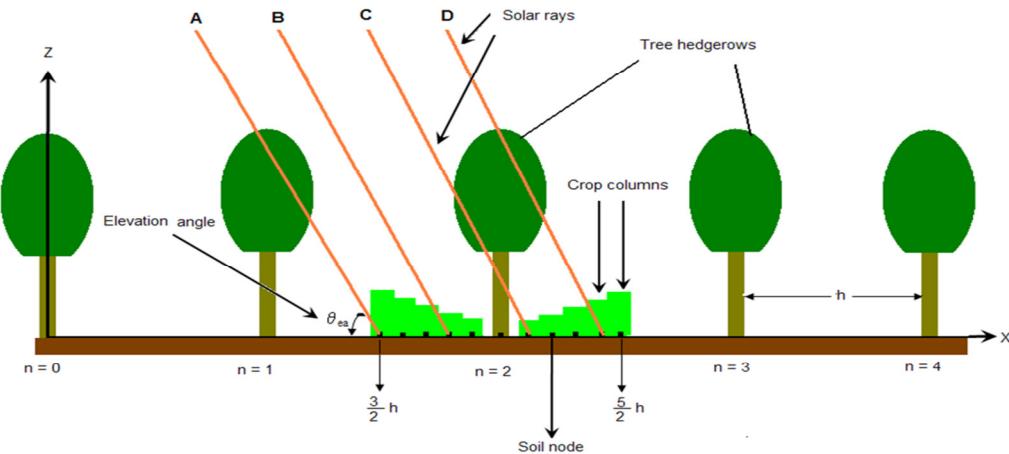


Figure 5.3 The radiation unit (within $3/2 h$ and $5/2 h$ distances from the origin at $n = 0$) in the hedgerow intercropping model, including interferences of adjacent tree rows. Cases A to D represent possible paths of solar rays towards the unit.

- 3 Each surface node bar the one beneath the tree row represents mid-point of a 'crop column' using radiation estimated at the node and soil water available in the control volumes that lie beneath the crop column. For the purpose of intercrop growth, crop growth routine of SWB was adopted (Figure 5.4).
- 4 The cascading soil water balance routine of SWB is used for modelling 'crop column' water balance. The SWB-2D water balance routine models a two-dimensional (2D) soil water balance and redistribution, taking into account tree uptake and lateral tree root expansion in intercrop zone. Figure 5.5 illustrates the two-dimensional nodal system employed and how component species of hedgerow intercropping systems are integrated into the water balance system. At the end of each time-step, soil water redistribution and updating is carried out in all control volumes using 2D soil water routine.
- 5 As comprehensively described in this chapter, the crop growth routine of SWB was adapted for tree growth modelling via developing and incorporating additional model components, namely: tree root growth and distribution, tree crown growth, radiation interception by intercrops and the soil.

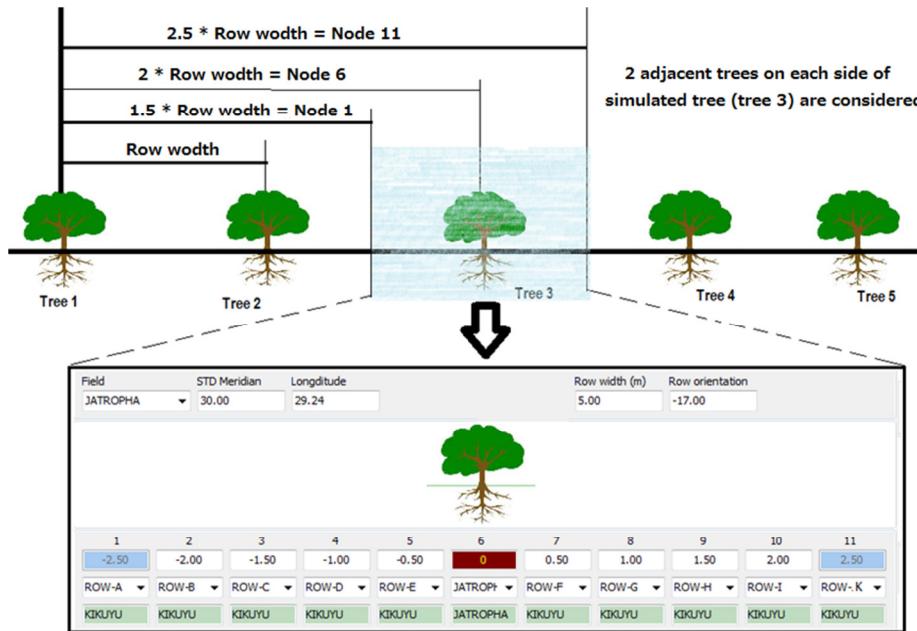


Figure 5.4 Setup of tree and intercrop rows according to the hedgerow intercropping model. Trees 1, 2, 4 and 5 represent the neighbouring trees considered for radiation modelling

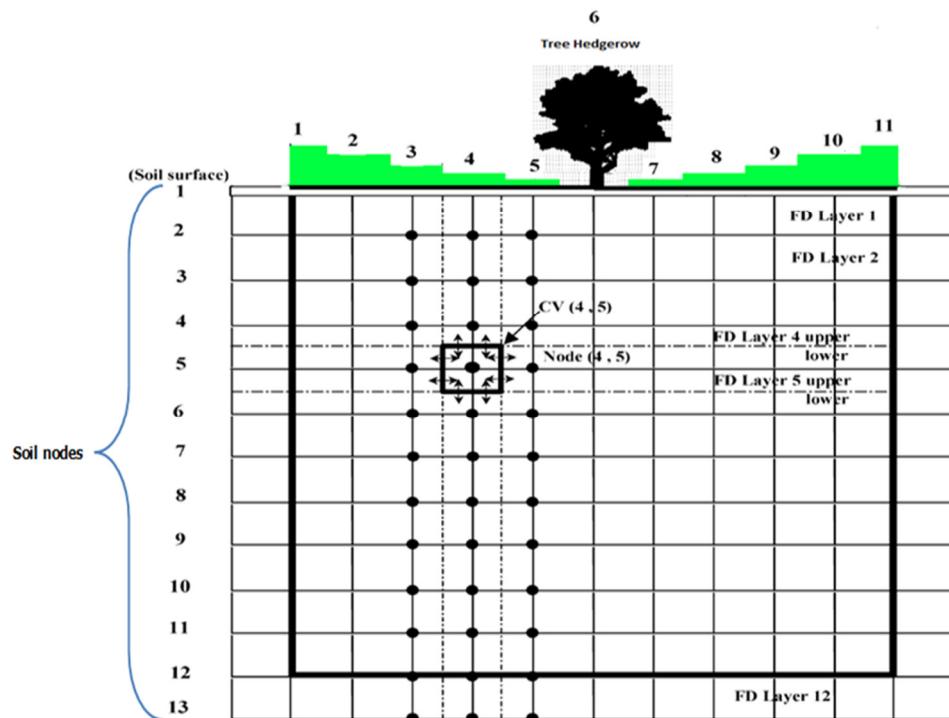


Figure 5.5 Soil nodal system and plant rows of the model (Horizontal numbers (1-11) represent plant rows and lateral nodes that make up control volumes (CV), along with the vertical nodal numbers (1-13)

CHAPTER 6

EVALUATION OF THE HEDGEROW INTERCROPPING MODEL

6.1 INTRODUCTION

Modelling guidelines developed by CAMASE (1996), a Concerted Action for the development and testing of quantitative Methods for research on Agricultural Systems and the Environment were followed in evaluating the current hedgerow intercropping model. Model evaluation is defined as the investigation of model acceptability through verification, calibration and validation (CAMASE, 1996). Its components can be defined as:

- Model verification: Assessment of model stability and reliability through dimension and unit evaluation, ascertaining of mass conservation, fixing parameter and variable errors and examination of qualitative (theoretical) implications of model applicability (CAMASE, 1996). In short, "*verification is a demonstration that the modelling formalism is correct*" (Rykiel, 1996).
- Model calibration: Estimation and refinement of model parameters by comparing measured data with model simulations (CAMASE, 1996; Rykiel, 1996).
- Model validation: Investigation and ascertaining of model applicability for desired purposes and accuracy of its simulations by comparing its simulations with measured data not used for the purposes of model development (CAMASE, 1996). According to Rykiel (1996), validation "*demonstrates that a model meets some specified performance standard under specified conditions*" and "*is a yes or no proposition in the sense that a model does or does not meet the specified validation criteria*".

A comprehensive model evaluation procedure necessitates

- Description of purposes of evaluation and the limitations of the model
- Description of the specific purpose and the specific range over which the model is valid
- Quantification of accuracy (errors) for the intended model applications. Large errors imply model's diminutive predictive value despite possibly significant instructive value

- Validating simulation outputs selectively when evaluating models developed for scenario studies and
- Using validation data representing conditions and ranges characteristic of the planned model applicability.

6.2 MATERIALS AND METHODS

6.2.1 Statistical criteria for model evaluation

The parameters used to evaluate simulation capabilities of the model were (de Jager, 1994)

- Coefficient of determination (r^2)
- Index of agreement of Willmott (1982) (D)
- Mean absolute error (MAE)

In order for model predictions to be acceptable, the coefficient of determination and the index of agreement of Willmott should be higher than 0.8 while the mean absolute error should be lower than 0.2.

6.2.2 Sampling

Data for evaluating the hedgerow intercropping model were collected from the single-row treatment (SR) at Ukulinga during the 2006/07 and 2007/08 growing seasons. An automatic weather station at the site was used to monitor incident solar radiation, rainfall, relative humidity, air temperature, wind speed and vapour pressure deficit on an hourly and daily basis. The soil type was 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), with mean bulk density of 1580 kg m^{-3} ($cv = 4.74\%$). The 50 m by 25 m plot of the treatment had 1100 trees per hectare in a 5 m by 2 m arrangement and S 17° W-N 17° E row orientation. Nitrogen, phosphorous and potassium fertilisers were applied regularly in an attempt to ensure these elements did not limit growth. Site and treatment details are provided in Chapter 2 (sections 2.2.2) whereas soil type and fertiliser applications are detailed in Chapter 3 (section 3.2.1) and Chapter 4 (section 4.2.1.4).

Biomass of kikuyu in SR and its variations with distance from a tree row was monitored periodically using a 0.5 m-by-0.5 m quadrant during the 2006/07 and 2007/08 seasons (details provided in Chapter 4, sections 4.2.1.4 and 4.3.3.1). Tree LAI (measured using a Licor LI-2000) and crown width and basal stem (trunk) diameter were also monitored periodically. Woody tree biomass was predicted using the basal stem diameter and the allometric relationship developed in Chapter 2. Foliage biomass (LDM, in kg) was determined as:

$$LDM = LAI (m^2 m^{-2}) * \text{ground area per tree (m}^2\text{)} / SLA (m}^2 \text{ kg}^{-1}\text{) } \quad 6.1$$

Ready-to-harvest *Jatropha* seeds were picked from the selected treatment between April and August of 2007 and 2008 representing the 2006/07 and 2007/08 growing seasons respectively. The seeds were oven-dried until constant masses were obtained.

Two-dimensional TDR probe arrangements were installed for monitoring of soil water distribution and dynamics. TDR probes were installed at soil depths of 0.05 m, 0.15 m, 0.25 m, 0.40 m and 0.60 m without disturbing the soil section where monitoring was carried out. At each depth of SR, the TDR probes were installed at selected distances perpendicular to the plant rows to the mid-point of SW and NE of selected T-C interfaces (i.e. probes were orientated S73⁰W-N73⁰E). Since the site had shallow soil profile (0.6 m deep) underlain by bedrock, drainage was assumed negligible. Hence, evapotranspiration (mm) was determined as rainfall (mm) minus change in profile soil water content (mm) and runoff (mm), which was assumed to be equal to the amount of water in the soil in excess of field capacity. Hourly tree water use was determined using the heat ratio method (Burgess et al. 2001), which has successfully been used on *Jatropha* in South Africa (Gush, 2008).

6.2.3 Model parameterisation

6.2.3.1 Crop specific parameters

Specific parameters used for the selected intercrop are provided in Table 6.1. All parameters with the exceptions of the canopy extinction coefficient for solar radiation, the day degrees at the end of vegetative growth and the day degrees for maturity were obtained from Annandale *et al.* (1999). The value of the

canopy extinction coefficient was refined via model calibration to obtain the best fit between simulated and measured values. The values of day degrees requirements of kikuyu to end vegetative stage and reach maturity were selected based on the fact that in practice, kikuyu is kept vegetative. A measured value of total dry matter after cut was used.

Table 6.1 Specific parameters of kikuyu used for calibrating and validating the crop growth component of the hedgerow intercropping model (Annandale *et al.*, 1999)

Parameter	Value	Unit
Canopy extinction coefficient for solar radiation	0.4	-
Dry matter water ratio (VPD-adjusted water use efficiency)	3.5	Pa
Radiation conversion efficiency	0.0015	kg MJ ⁻¹
Base temperature	10	°C
Temperature for optimum growth	20	°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	10	d °C
Day degrees for leaf senescence	700	d °C
Maximum crop height	0.4	m
Maximum root depth	1.0	m
Fraction of total dry matter translocated from to harvestable biomass	0.01	-
Leaf water potential at maximum transpiration	-1500	kPa
Maximum transpiration	9	mm d ⁻¹
Specific leaf area	10	m ² kg ⁻¹
Leaf-stem partition parameter	0.3	m ² kg ⁻¹
Fraction of total dry matter partitioned to roots	0.2	-
Root growth rate	4	m ² kg ^{-0.5}
Stress index	0.95	-
Total dry matter at emergence	0.05	kg m ²
Total dry matter after cut	1	t ha ⁻¹

6.2.3.2 Parameterisation of the tree growth model

Table 6.2 presents species-specific growth parameters of *Jatropha* developed in this study with the exceptions of base, optimum and cut-off temperatures. The procedures followed when developing/refining the tree parameters are described in this section. It should be noted that due to the highly destructive and costly nature of root investigations, parameters whose determination requires total tree biomass (radiation conversion efficiency and dry matter water ratio) were determined based on AG tree biomass alone. Model calibration was then carried out keeping in mind the effects of the resultant underestimations of these parameters (due to ignoring roots).

From December 01, 2006 to January 04, 2007 (35 days), cumulative irradiance was calculated from hourly irradiance measurements at the weather station. Area-averaged cumulative irradiance below the tree crown and above the intercrops was determined from radiation measured perpendicular to the row at distances of 0 m (below tree), 0.83 m, 1.63 m and at 2.5 m, the mid-point of adjacent alleys (solarimeters were orientated S73°W-N73°E). Radiation intercepted by trees was then calculated as the difference between the two. This measurement period was characterised by high rainfall.

For the measurement period, total AG biomass produced was determined as the sum of woody and leaf dry matter production. Woody AG dry mass was estimated using basal tree stem diameter on the first and the last days of the measurement period and allometric equations developed in Chapter 2 (Table 2.1). Foliage biomass (in kg) was determined using equation 6.1, replacing LAI with Δ LAI, which represents LAI increase during the measurement period. Radiation conversion efficiency (E_c in kg MJ⁻¹) of the trees was computed as the ratio of total AG biomass (kg) and radiation intercepted by the tree (MJ).

Total AG biomass was determined for the period December 20, 2007 to February 29, 2008 (71 days). Cumulative tree water use (mm) during this period, as measured using the heat ratio (HPV) method was also computed. Dry matter water ratio in Pascal was then determined as the ratio of the product of total AG biomass and average vapour pressure deficit (VPD) during this period to the cumulative tree water use.

Base, optimum and cut-off temperature values were obtained from literature (Buyssonali, 2003). Day degrees required for leaf initiation (LIDD) was determined as growing day degrees (GDD) accumulated between September 1 (assumed to be the first day trees start accumulating thermal time in the southern hemisphere) and the first day leaf flushes occurred during the 2007/08 growing season. Day degrees required to reach flowering (FLDD) was determined in the same manner. Transition period day degrees (TransDD), the thermal time accumulated by foliage until leaf senescence (LDM_{age^{max}}), and the parameters of assimilate translocation for leaf (Trans_L) and flowering (Trans_F) initiation were estimated via the model calibration process.

Tree root depth was assumed to be limited by soil depth. Coefficients and exponents of stem diameter versus branch and stem biomasses (destructively sampled) were determined as slope and antilog of

intercepts of the linear relationships between log-transformed values of stem diameter and the corresponding biomasses respectively (Chapter 2). Specific leaf area was determined as the ratio of area (measured using a Licor LI-3000) to dry mass of destructively sampled *Jatropha* leaves. Foliage density by mass ($\rho_{F(mass)}$) in kg m⁻³, was computed as the ratio of destructively sampled leaf dry mass to tree crown (foliage) volume (V_F in m³) calculated as:

$$V_F = \frac{4}{3} \pi \frac{CH(\bar{CW})^2}{8} \quad 6.2$$

Where CH (m) and \bar{CW} (m) denote height and geometric mean width of tree crown.

Table 6.2 Parameters for *Jatropha* used for calibrating and validating the tree growth and yield component of the hedgerow intercropping model

Parameter	Value	Unit
Solar radiation absorptivity of leaves	0.5	-
Dry matter water ratio	8.2	Pa
Radiation conversion efficiency	0.0005	kg MJ ⁻¹
Base temperature	11	°C
Temperature for optimum growth	24	°C
Cut off temperature	38	°C
Tree type	Deciduous	-
Day degrees required for leaf initiation (LIDD)	280	d °C
Day degrees required to reach flowering (FLDD)	445	d °C
Transition period day degrees (TransDD)	10	d °C
Day degrees for leaf senescence (LDMax _{max})	350	d °C
Fraction of dry matter translocated for leaf/flowering (Transl)	0.01	-
Leaf water potential at maximum transpiration	-1500	kPa
Maximum transpiration	10	mm d ⁻¹
Specific leaf area	9.05	m ² kg ⁻¹
Leaf-stem partition parameter (PART)	5.6	m ² kg ⁻¹
Stress index	0.90	-
Coefficient of stem diameter-branch biomass relationship (a _b)	6111.8	-
Coefficient of stem diameter-stem mass relationship (a _s)	135.7	-
Stem diameter-branch biomass relationship exponent (n _b)	3.4	-
Stem diameter-stem mass relationship exponent (n _s)	2.47	-
Foliage density by mass ($\rho_{F(mass)}$)	0.24	(kg m ⁻³)

Leaf-stem partition parameter (PART) for AG assimilate allocation of *Jatropha* was determined using the method described in Annandale *et al.* (1999). That is, leaf-stem partition parameter (PART) is the slope of AGDM versus (SLA AGDM)/(LAI-1), where SLA denotes specific leaf area, AGDM and LAI denote AG dry mass and leaf area index, respectively. Figure 6.1 shows PART determination for *Jatropha*.

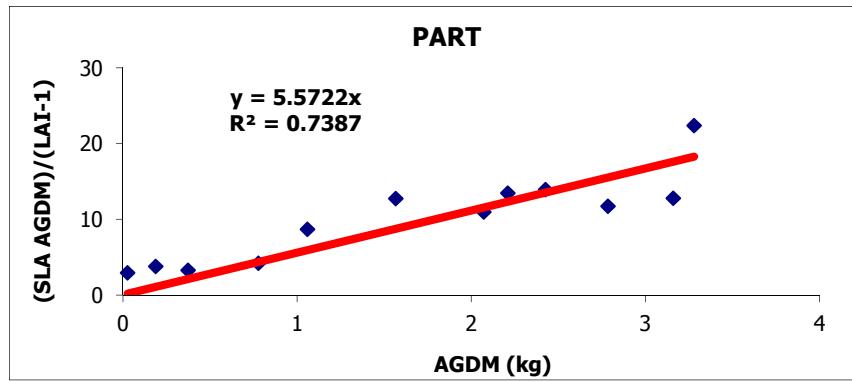


Figure 6.1 Determination of PART for *Jatropha*

6.3 RESULTS AND DISCUSSION

6.3.1 Validation of radiation distribution

The model simulated solar radiation distribution and incidence in the intercropping zone accurately, with only a slight tendency of overestimation at some distances as shown in Figure 6.2 and Table 6.3. These results are consistent with results obtained on deciduous trees by Annandale *et al.* (2004).

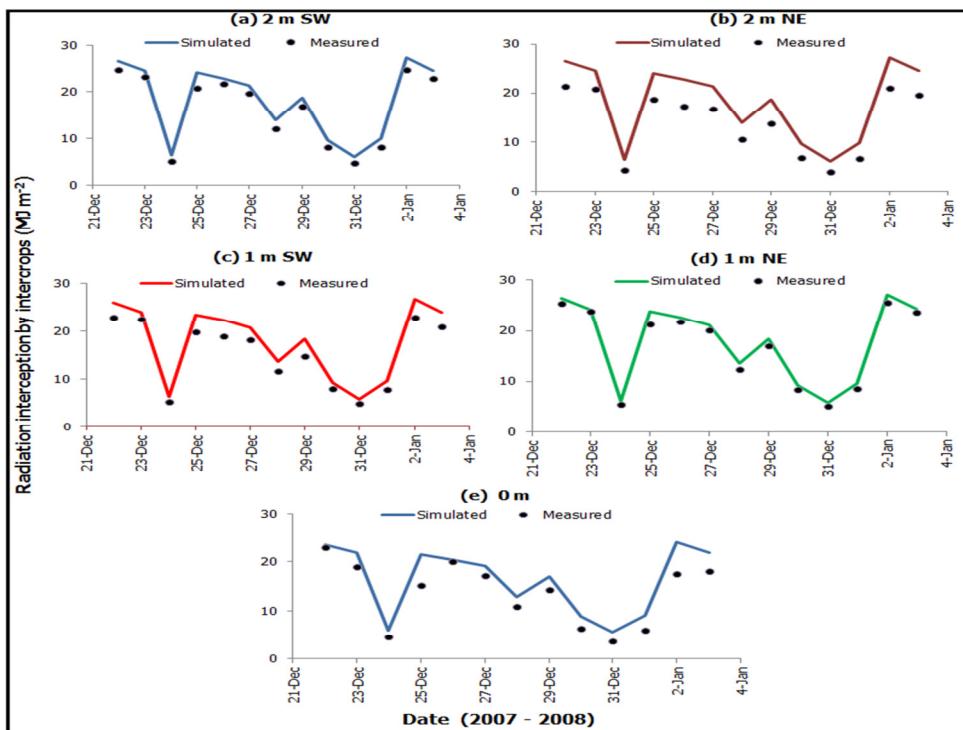


Figure 6.2 Simulated (lines) and measured (symbols) solar radiation distribution in SR

Table 6.3 Validation of modelling solar radiation distribution in SR

Evaluation Parameter	SW		Below tree (0 m)	NE	
	2 m	1 m		1 m	2 m
r ²	1.00	0.92	0.93	1.00	0.99
D	0.99	0.88	0.93	0.99	0.91
MAE	0.11	0.31	0.21	0.06	0.30

6.3.2 Validation of soil water distribution

Despite spatial variability of soils, the model simulated profile water contents below the intercrops at various distances (Figure 6.3a to 6.3d) and the tree (Figure 6.3e) accurately tracking temporal soil water fluctuations very well. The relevant validation results are presented in Table 6.4.

Model performances related to soil water predictions are bound to be affected by high soil variability and soil disturbance during installation of measurement sensors (Annandale *et al.*, 2003). In the current model, the soil water balance models used for the intercrops 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 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.

Table 6.4 Validation of modelling soil water distribution in SR

Evaluation Parameter	SW		Below tree (0 m)	NE	
	2 m	1 m		1 m	2 m
r ²	0.76	0.77	0.58	0.80	0.99
D	0.88	0.81	0.80	0.64	0.83
MAE	0.04	0.05	0.11	0.07	0.05

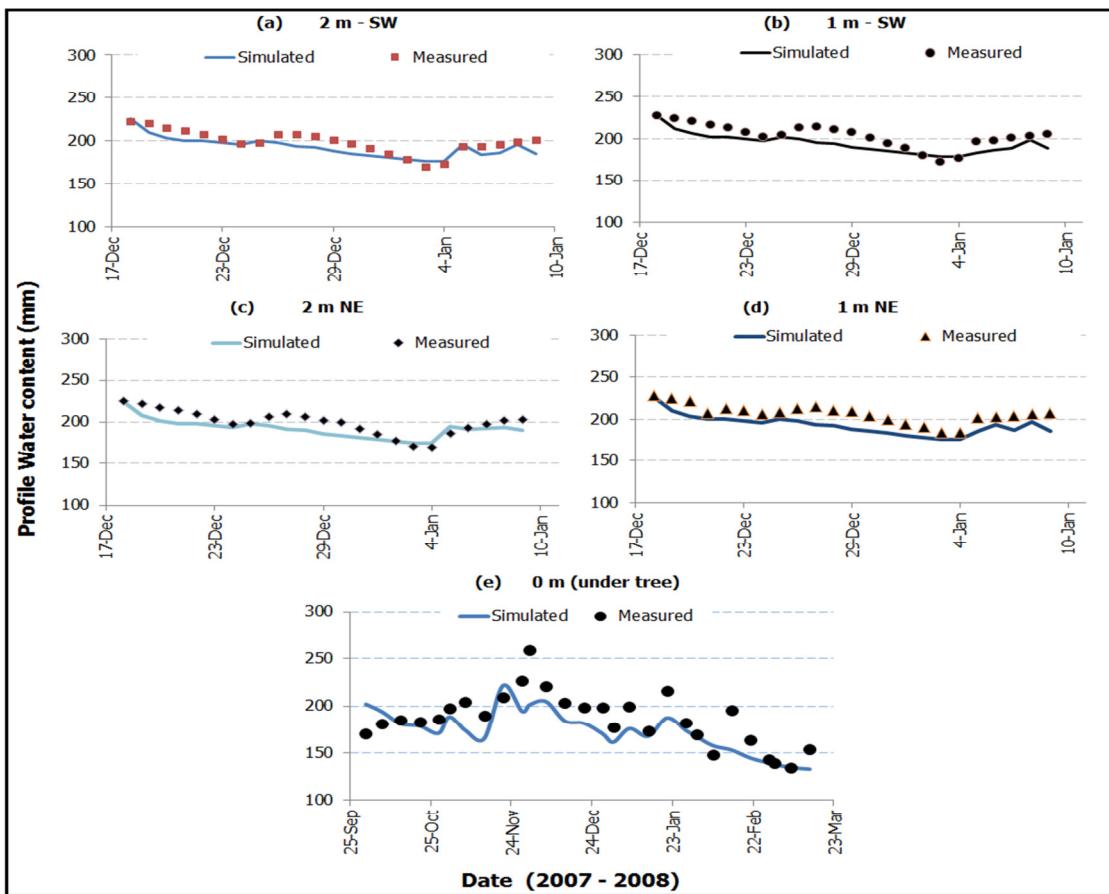


Figure 6.3 Simulated (lines) and measured (symbols) spatio-temporal fluctuations of profile water content in SR at Ukulinga

6.3.3 Validation of tree water use

The two-dimensional energy interception and water balance model (SWB-2D) was proven accurate for hedgerow applications (Annandale *et al.*, 2003; Annandale *et al.*, 2004). Therefore, tree water use is validated here in the context of hedgerow intercropping.

Validation results of tree water use are presented in Table 6.5 and Figure 6.4. The model tracked the amount and daily fluctuations of tree water use reasonably well. Simulated water use became less than measured towards the end of the validation period. The results show that the model has good potential to simulate tree water use in hedgerow intercropping systems. Similarly, the ET validation results in Table 6.5 reveal that the model has potential for simulating monthly ET in hedgerow intercropping systems.

Table 6.5 Validation results of the model for predicting transpiration by *Jatropha* trees and ET in SR during 2007/08

Parameter	Daily T	Monthly ET	Cumulative ET
r^2	0.5	0.41	0.86
D	0.83	0.79	0.99
MAE	0.35	0.52	0.17

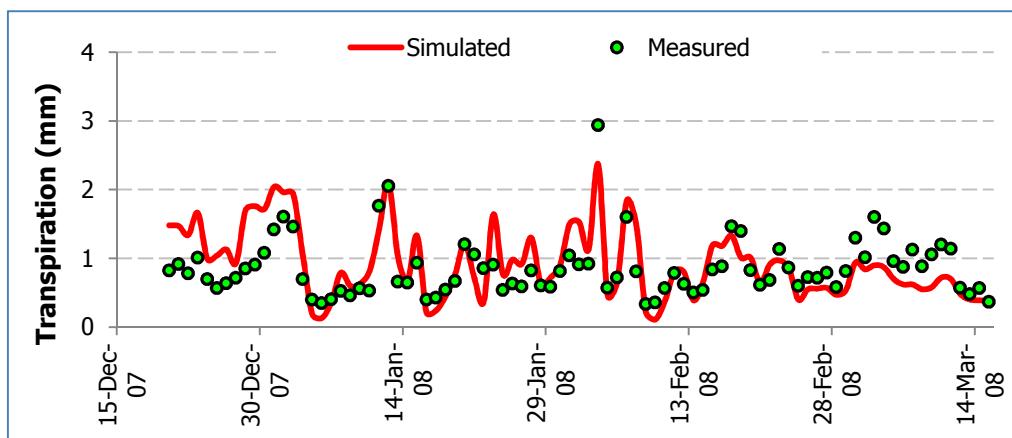


Figure 6.4 Measured (symbols) and simulated (lines) daily transpiration (T) of *Jatropha* from 20/12/2007 to 15/03/2008 in SR at Ukulinga

6.3.4 Evaluation of modelling growth and yield of intercrops and trees

6.3.4.1 Calibration of modelling intercrop growth and yield

Simulated solar irradiance increased with distance from tree rows (Figure 6.5). Closer to the tree row (at 1 m distance), seasonal total irradiance was significantly higher on the south-western (SW) side than the north-eastern (NE) side. Conversely, seasonal irradiance at 2 m distance was slightly more on NE than SW.

The intercrop modelling was calibrated by comparing measured and simulated yields from the 2006/07 season at distances of 1 m and 2 m on SW and NE of the selected tree row. The first part of the calibration was to compare predicted and measured yields of growth cycles (periodic cutting) as shown in Figure 6.7.

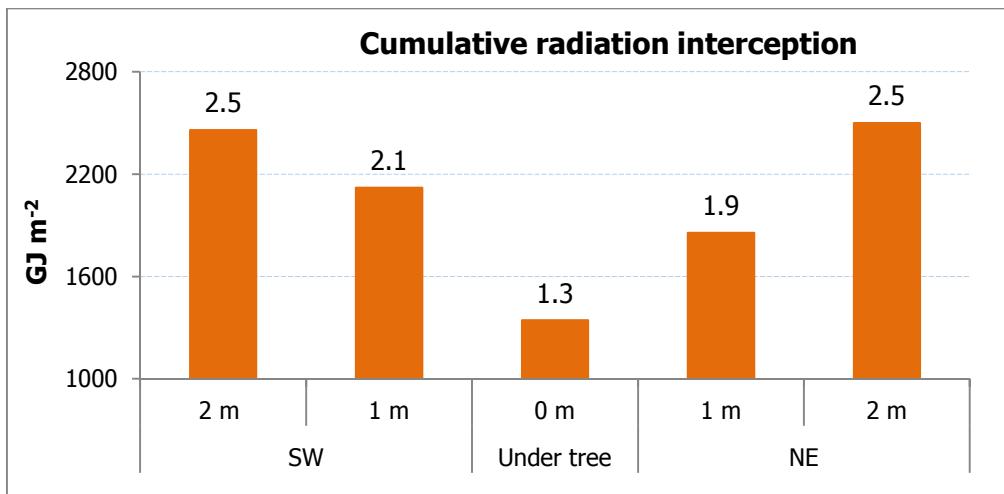


Figure 6.5 Simulated intercrop interception at different distances in SR (Oct 01 2006 to Apr 30 2007)

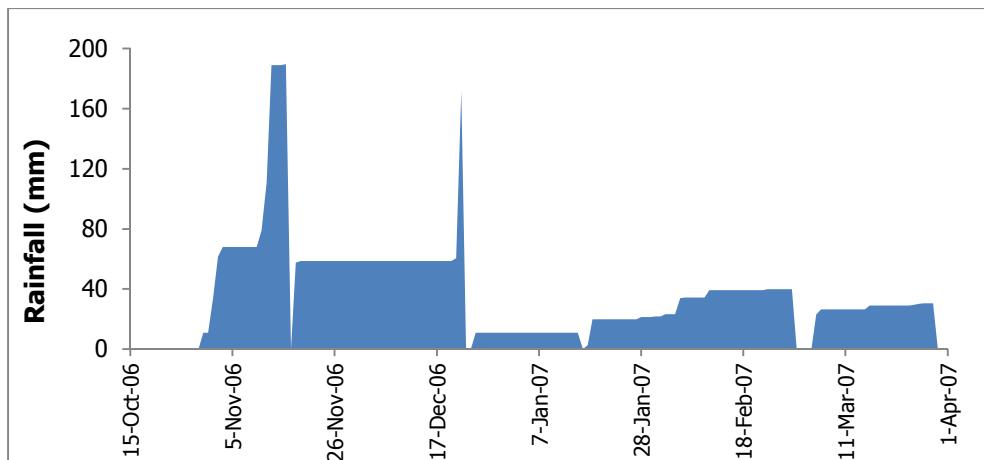


Figure 6.6 Cumulative rainfalls during each growth cycle of 2006/07 at Ukulinga

Model predictions at various distances were acceptable. Both measured and simulated yields were slightly less on SW than NE of the tree row. Kikuyu growth was also less towards the tree row. Overestimations of the periodic yields were higher at 1 m distance (than at 2 m) and on NE (than SW). From, Table 6.6, the accuracy of predicting periodic harvests can be ranked as 2 m NE > 2 m SW > 1 m SW > 1 m NE (the highest MAE), which is generally similar to the variations of soil water predictions (Table 6.4).

Table 6.6 Calibration results of modelling periodic and cumulative intercrop yields during 2006/07

Evaluation parameters	SW			NE		
	1 m	2 m	Cumulative	1 m	2 m	Cumulative
r^2	0.68	0.69	0.93	0.64	0.65	0.87
D	0.65	0.81	0.95	0.83	0.83	0.92
MAE	0.23	0.23	0.19	0.32	0.21	0.25

The model overestimated growth (Figure 6.7) when the rainfall availability (Figure 6.6) was high implying that radiation largely dictated growth simulations during the growth cycle. On the contrary, when the rainfall during a cycle was relatively low (for instance, during the cycle of December 22, 2006 to January 15, 2007), the model underestimated intercrop growth suggesting that the simulations were generally water-limited. This is based on the validation results of distribution of radiation (Table 6.3) and soil water (Table 6.4), which showed the model's tendency to slightly over-predict radiation simulation and underestimate profile water contents. The absence of growth underestimations at 1 m distance implies that growth was radiation-limited.

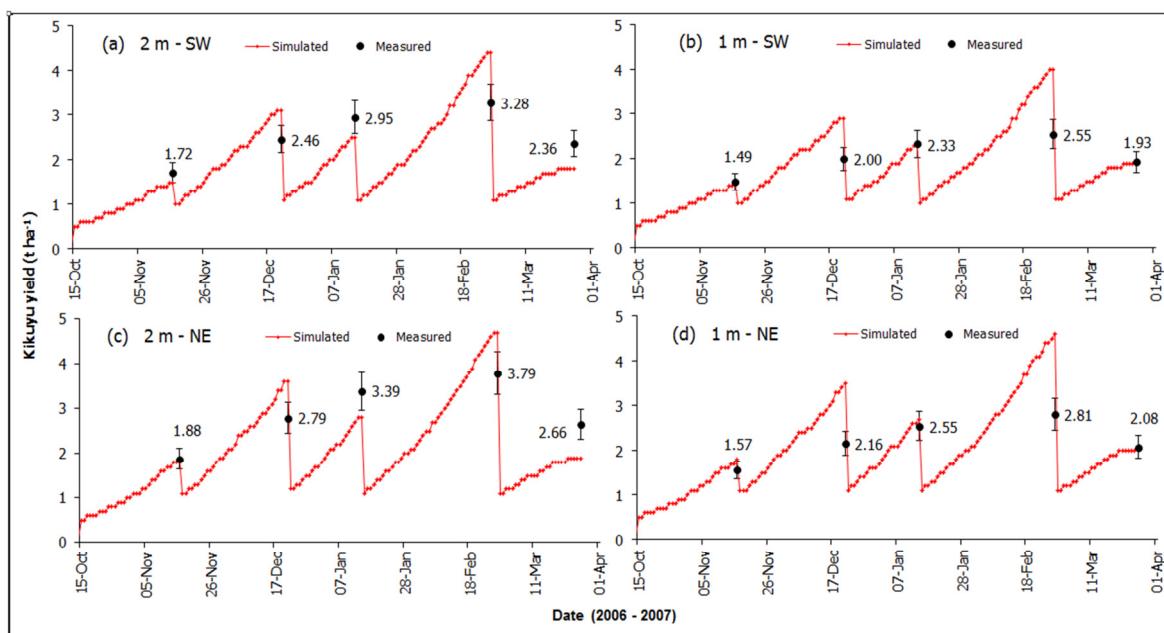


Figure 6.7 Simulated (lines) and measured (symbols) kikuyu yields at selected distances from trees in SR during growth cycles of 2006/07

Accuracy of modelling cumulative intercrop yields was acceptable (Table 6.6 and Figure 6.8). At 1 m distance, the model overestimated cumulative yields due to the fact that the errors associated with the

periodic yield predictions were overestimations only. Over the season, this leads to an increasing gap between predicted and measured cumulative yield. At 2 m distance, on the other hand, yield underestimations in some growth cycles compensated for overestimated yields in other cycles leading to a much better accuracy of predicting cumulative yields.

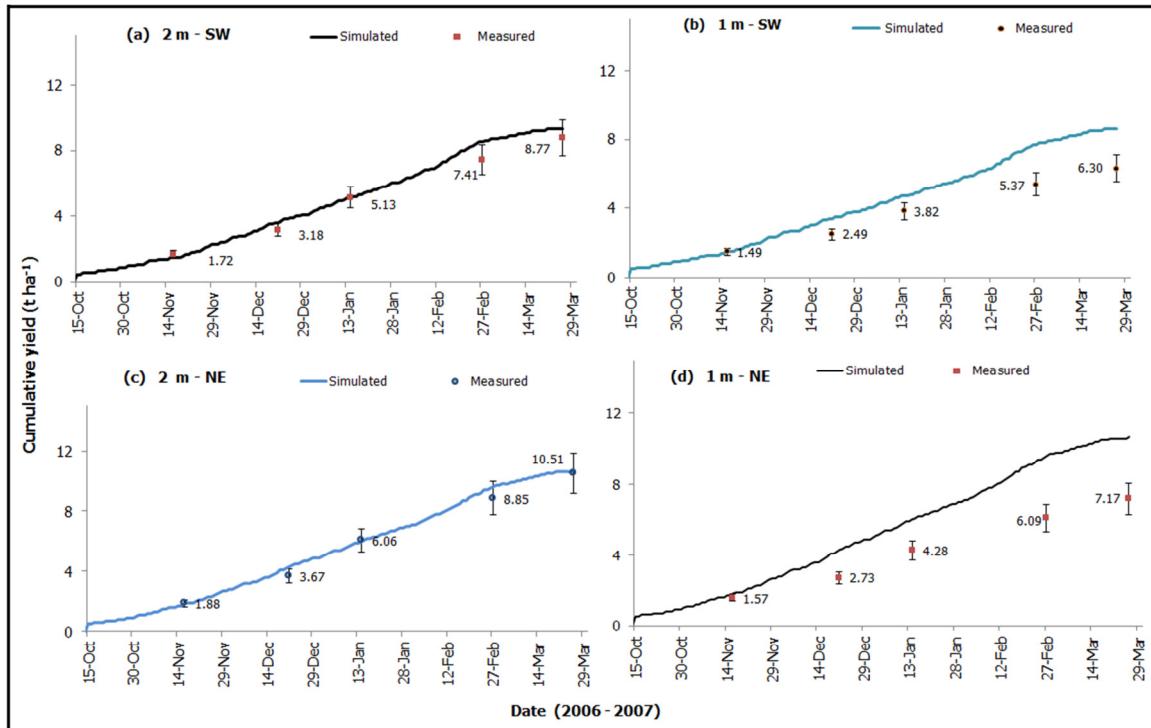


Figure 6.8 Simulated (lines) and measured (symbols) cumulative kikuyu yields in SR during 2006/07

6.3.4.2 Validation of growth and yield of intercrops

Simulated solar irradiance varied with distances and orientation with respect to the tree rows (NE or SW). Figure 6.9 shows cumulative irradiance during the growth cycles and the entire growing season of 2007/08 at the selected distances. The simulated irradiance on SW is slightly higher than NE, especially closer to the tree. On both sides, radiation intercepted by the intercrops at 1 m distance was lower than at 2 m. The yield overestimation (thus radiation-limited growth simulation) during the January 18 to February 25, 2008 growth cycle, when rainfall was relatively low, was due to high amount rain towards the end of the previous cycle (Figure 6.10).

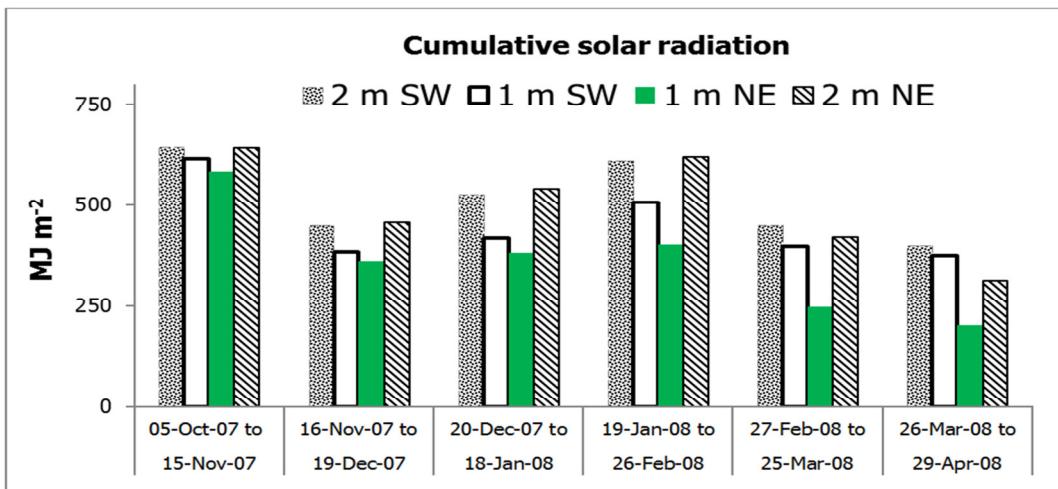


Figure 6.9 Simulated total irradiance across tree lines in SR during growth cycles of 2007/08

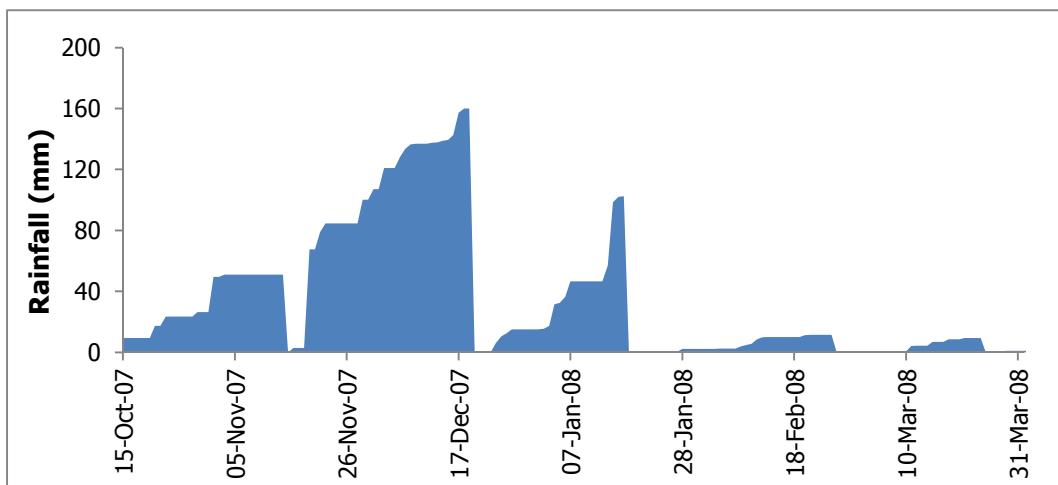


Figure 6.10 Cumulative rainfall during growth cycles of 2007/08 at Ukulinga

Table 6.7 Validation results of modelling periodic and cumulative intercrop yields during 2007/08

Evaluation parameters	SW			NE		
	1 m	2 m	Cumulative	1 m	2 m	Cumulative
r^2	0.65	0.73	0.98	0.63	0.58	0.93
D	0.74	0.68	0.85	0.66	0.64	0.79
MAE	0.31	0.34	0.39	0.47	0.38	0.57

Independent data from 2007/08 were used to validate model predictions at the distances considered in the calibration process. As far as periodic harvesting is concerned (Figure 6.11), validation results were similar to the calibration results. The difference between predicted and measured cumulative yields was, however, more pronounced during 2007/08 (Figure 6.12), resulting in lower accuracy (Table 6.7).

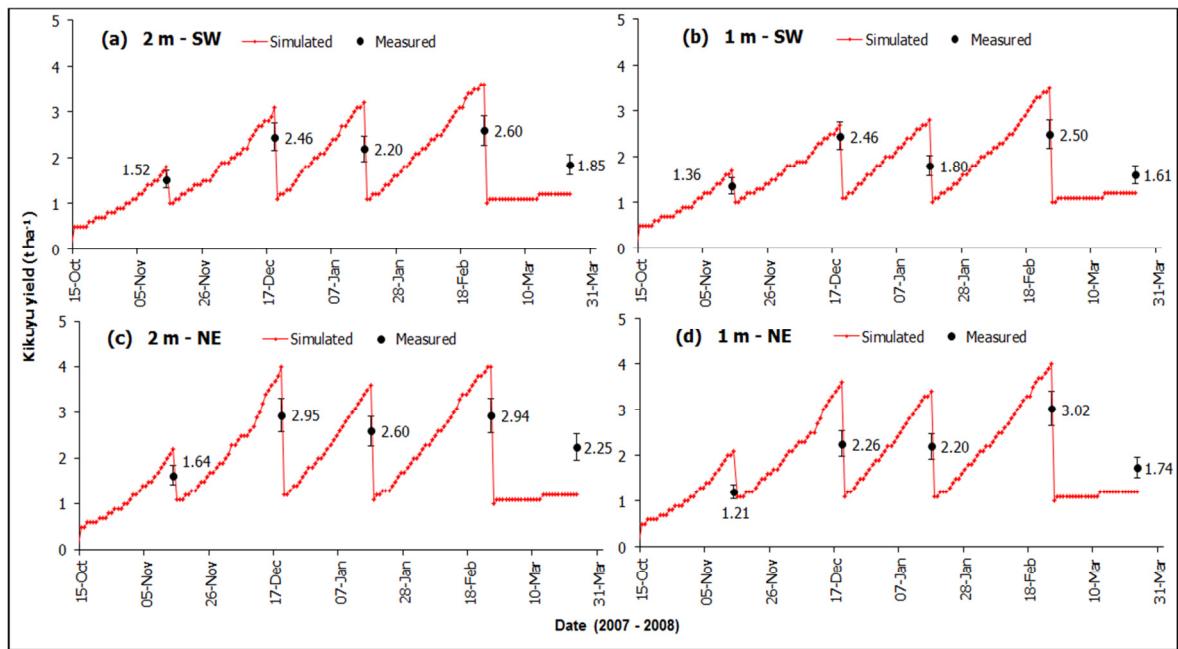


Figure 6.11 Simulated (lines) and measured (symbols) kikuyu yields at selected distances from trees in SR during growth cycles of 2007/08

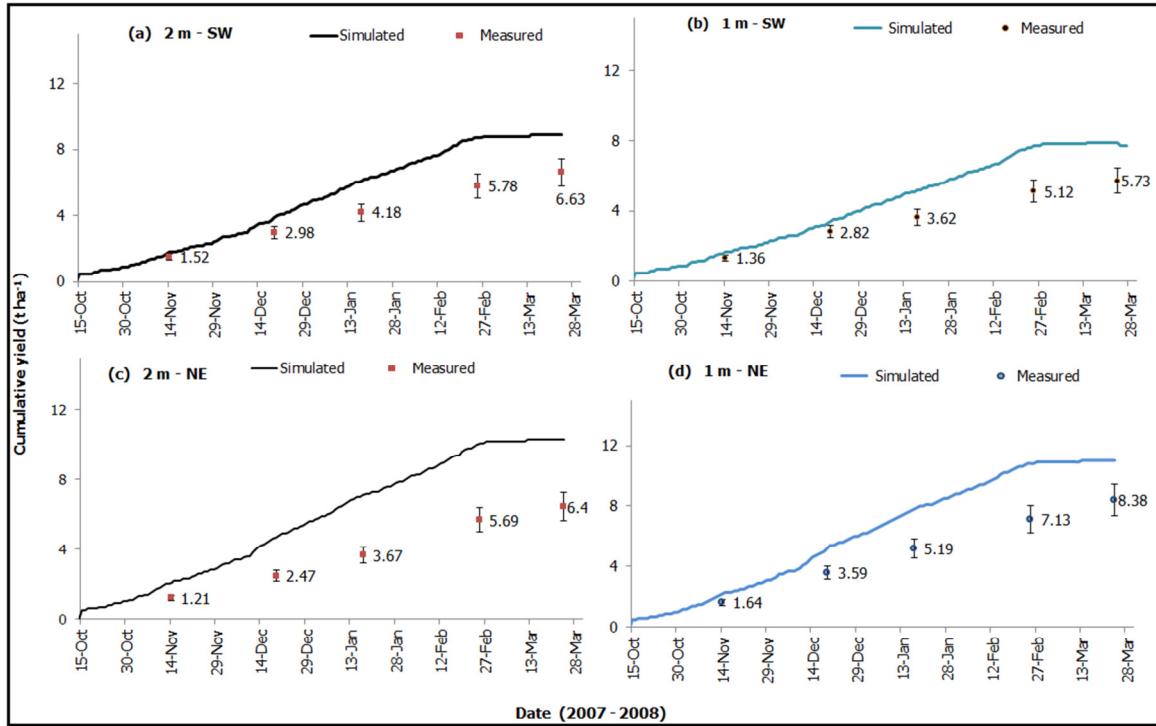


Figure 6.12 Simulated (lines) and measured (symbols) cumulative kikuyu yields in SR during 2007/08

6.3.4.3 Calibration of tree growth and yield

Calibration results of the tree growth model are presented in Table 6.8 and Figure 6.13. Good fits were achieved between measured and simulated woody biomass (WDM), LAI, leaf dry mass (LDM), crown diameter and nut yield (FDM) of *Jatropha*. The fit between measured and simulated crown diameter (Figure 6.13d) improved as more leaves were produced. The reason for the discrepancies early in the season is due to the difficulty of measuring crown width as the leaves were distributed in patches on the highly branching AG (crown) architecture of *Jatropha* trees (Figure 6.14a). After December, however, the trees attained a fuller and ellipsoidal shape making it easier to measure crown dimensions (Figure 6.14b). The calibration results (Table 6.8) were largely acceptable and implying that good fit between measurement and simulation and refinement of selected parameters was achieved.

Table 6.8 Calibration results for modelling of *Jatropha* growth in SR

Evaluation Parameter	Woody DM	Leaf DM	LAI	Crown diameter
r^2	0.97	0.98	0.97	0.91
D	0.97	0.97	0.96	0.89
MAE	0.18	0.13	0.19	0.16

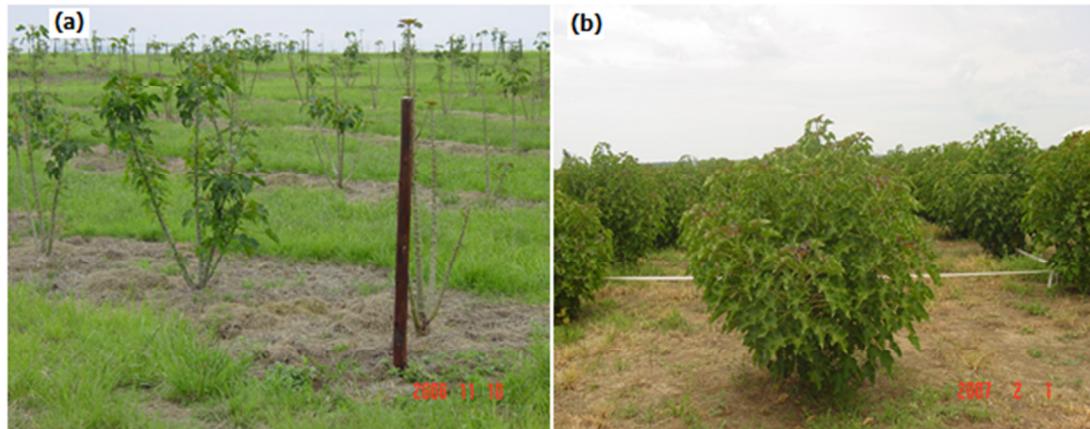


Figure 6.14 Changes in crown shape of *Jatropha* between (a) 10/11/2006 and (b) 01/02/2007

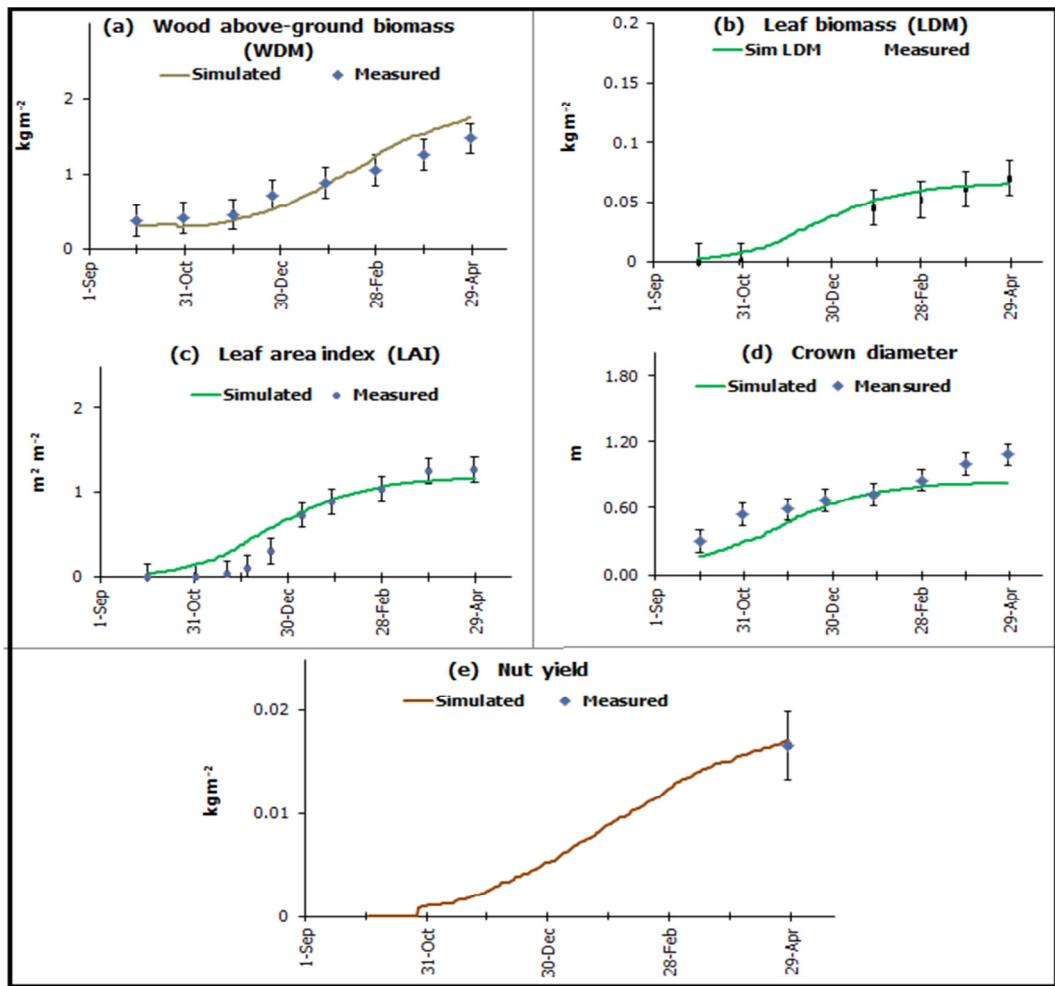


Figure 6.13 Simulated (lines) and measured (symbols) WDM, LDM, LAI, crown diameter and FDM of *Jatropha* in SR during 2006/07

6.3.4.4 Validation of tree growth and yield

The tree growth and yield model predicted temporal patterns of the selected biomass and dimension variables of *Jatropha* trees in SR very well. Simulations of woody biomass (Figure 6.15a), and crown width (Figure 6.15d) were acceptable. The model tended to over-estimate foliage biomass (Figure 6.15b), leaf area index (Figure 6.15c) and nut yield (Figure 6.15e). The statistical parameters of model performance in Table 6.9 confirm the adequacy of the model for simulating the selected tree variables.

Table 6.9 Model validation for predicting *Jatropha* growth in SR

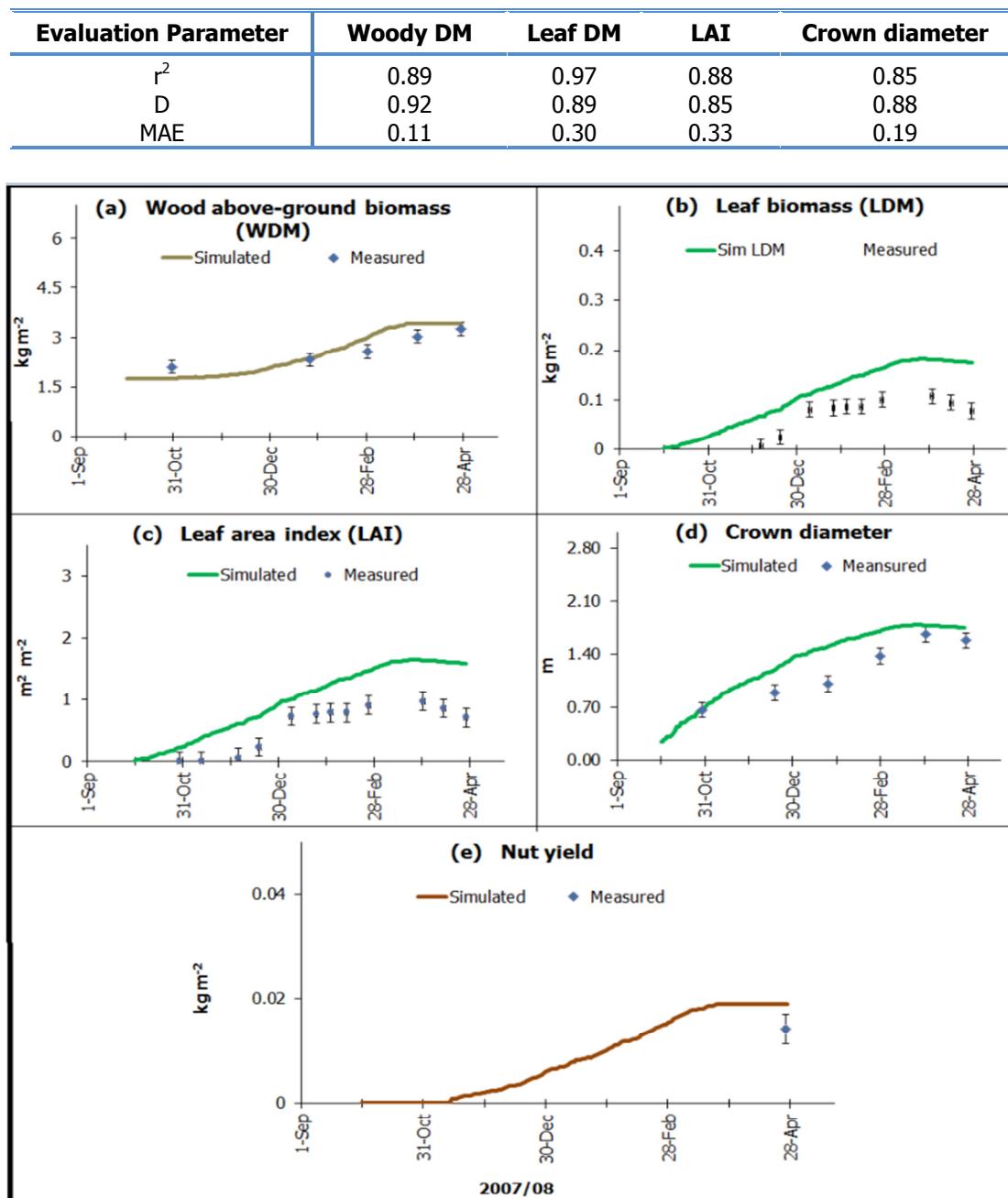


Figure 6.15 Simulated (lines) and measured (symbols) WDM, LDM, LAI, crown diameter and FDM of *Jatropha* in SR during 2007/08

6.4 CONCLUSIONS

The long-term nature of agroforestry systems necessitates the use of models to facilitate planning and optimisation of the wide range of species and tree spacing options available for implementation. The development of the current hedgerow intercropping model entailed merging well-established, mechanistic, robust and reliable component models. Calibration and validation results conducted so far have confirmed that the model offers a lot of potential for applications in silvopastoral and alley-cropping systems. The model is useful for selecting T-C mixtures, designing/planning systems, planning and analysing effects of management schemes and predicting total and component productivities. Management regimes affect simulations by affecting a number of the model parameters, including canopy and root management (pruning), soil fertility and irrigation management. As agroforestry can contribute to carbon sequestration significantly, the current model provides relevant information via its tree biomass (AG and BG) predictions under various hedgerow intercropping design/planning and management schemes.

The model is user-friendly due to its moderately low input and parameter requirements and generally easy-to-obtain and straightforward parameters. Tree leaf area density, which is the most difficult-to-obtain parameter, can be estimated using the method by Annandale *et al* (2002). A nutrient simulator currently in SWB can be used with the current model when nutrient availability is suboptimal. In order to take full advantage of its capabilities as a management and planning tool for hedgerow intercropping systems, it also needs to be evaluated for more crops and tree species (including field crops, cash crops, shade-loving crops, evergreen and deciduous trees) and management options. Although not included in this study, comparative analyses of simulations of the current model and other agroforestry models can add perspectives about complexity and practicality of agroforestry modelling.

CHAPTER 7

MODELLING DESIGN SCENARIOS IN ORDER TO MAXIMIZE INCOME FROM HEDGEROW INTERCROPPING SYSTEMS

7.1 INTRODUCTION

The development of the current hedgerow intercropping model entailed merging mechanistic, robust and reliable component models (Chapter 5). Calibration and validation results followed (Chapter 6), and showed potential for model applications in silvopastoral and alley-cropping systems. The model can, therefore, be used to simulate processes and systems for which it was validated.

Hedgerow intercropping systems comprise of a symmetrical geometry of planting trees and crops ensuring homogeneity within tree hedgerows on the one hand, and crop rows on the other (Ong, 1996). In addition to compatibility of component species and resource availability (Ong *et al.*, 2002), T-C interactions are affected by timing of crop planting and tree pruning (Huxley, 1999), tree configuration/row orientation (Garrett and McGraw, 2000) and planting density/spacing (Ong *et al.*, 1996; Ong *et al.*, 2000).

The objectives of this chapter were to model best-case system scenarios with respect to gross seasonal income (return) and economic water use efficiency (water productivity) by analysing various tree row spacing and orientation options and trading-off T-C yields and simulate hedgerow width so as to derive projected timing and extent of tree row management (pruning) to aid intercrops

7.2 MODEL SETUP

A hypothetical, rain-fed *Jatropha*-kikuyu silvopastoral system was taken into consideration for modelling tree row orientation and spacing scenarios. The virtual system was 'established' at Hatfield (27°45'S, 28°14'E) in Pretoria, South Africa. The area is 1360 m above sea level and has a mean rainfall of 670 mm per year. The soil profile is 1.2 m deep with a largely clay loam soil.

Full kikuyu cover was maintained and nutrients were assumed to be non-limiting throughout the simulation period, which was October 01, 2009 to April 30, 2010. No kikuyu was allowed to grow within 0.5 m of the

tree stem (forming a 1 m-wide stripe of soil cleared of intercrops and allocated to the tree hedgerow only). The tree crown or hedgerow can grow wider than the strip (below which intercrops can grow). Table 7.1 shows details of the selected positions across the tree hedgerow and the proportion of areas occupied by trees and crops.

7.3 SCENARIOS

The following scenarios were modelled:

1. **Row orientation:** Four scenarios were investigated in a 6 m wide hedgerow in a *Jatropha*-kikuyu silvopastoral system ($833 \text{ trees ha}^{-1}$), namely: 0° (N-S), 45° (NE-SW), 90° (E-W), 135° (NW-SE)
2. **Tree row spacing (density) scenarios:** Pure kikuyu, 3 m spacing in pure *Jatropha* (JO) stand ($1667 \text{ trees ha}^{-1}$), hedgerow intercropping spacing (density) scenarios of 3 m ($1667 \text{ trees ha}^{-1}$), 12 m ($417 \text{ trees ha}^{-1}$) and 25 m ($200 \text{ trees ha}^{-1}$)
3. **Tree crown radius:** Growth of tree crown width was also simulated in the *Jatropha*-kikuyu intercropping system using inter-row distances of 3 m, 6 m, 12 m and 25 m.

Table 7.1 Allocation of hedgerow spacing to tree and intercrop components of the hedgerow intercropping system for the hedgerow orientation and spacing scenarios

Design parameter	Hedgerow spacing (in m and (%)) covered by:		
	System (Total)	Tree (<i>Jatropha</i>)	Grass (kikuyu)
Orientation scenarios	6 m	1 (16.7)	5 (83.3)
Spacing scenarios	3 m - JO	3 m	3 (100)
	3 m	3 m	1 (33.3)
	12 m	12 m	1 (8.3)
	25 m	25 m	24 (96)

7.4 ESTIMATED ECONOMIC PARAMETERS

The motivation behind the economic interpretations of simulated tree and crop outputs (productivities) was to illustrate how these interpretations can influence decision-making with respect to land management options and design/planning hedgerow intercropping systems. As such, the economic assessment in this exercise was not exhaustive. It was based on the assumption that the land use (hedgerow intercropping, forestry and pasture) and design/planning options under consideration consumed the same total variable

cost of factors (labour, land, capital, management) although the relative costs of individual factors may vary from one land use to another. The marketable yield of the *Jatropha* was assumed to be its nuts, which are rich sources of potential biodiesel, whereas for kikuyu it was harvestable forage biomass. These yields were given hypothetical gross values of R10000.00 and R1200.00 per ton, respectively. To determine which scenario was the best, the following economic parameters were followed:

- **Economic water use efficiency (WUE_{Econ})** of each species was computed as the ratio of the economic value of the yield to evapotranspiration (ET)

Where WUE_{Econ} is in $R \text{ ha}^{-1} \text{ mm}^{-1}$, marketable yield ($t \text{ ha}^{-1}$) refers to seeds for *Jatropha* and harvestable biomass for kikuyu.

- **System WUE_{Econ}** was determined as a sum of the WUE_{Econ} values of tree (*Jatropha*) and intercrops (kikuyu) in proportion to ratios of their respective areas covered to the total area (Table 7.1). The area calculations are based on unit intra-row tree spacing.
- **System gross seasonal income (return)** was computed from gross values of the component species in proportion to their respective areas. Such seasonal incomes obtained for the selected system designs were compared, in order to decide on best case scenarios for this site at the specified values of the products.

7.5 RESULTS AND DISCUSSION

7.5.1 Row orientation

Under all row orientation options considered, simulated cumulative solar irradiance in the intercropping zone during the period of simulation (October 01, 2009 to April 30, 2010) increased with distance from tree hedgerows (Figure 7.1). The 90° orientation had the highest cumulative irradiance at all distances with the exception of below the tree while the opposite is true about the 0° orientation. At all distances, there were no significant differences between cumulative irradiance distribution under row orientations of 45° and 135°. Radiation interception of trees ranged between 290.5 MJ in the 90° orientation to 342.5 MJ in the 0°

orientation, with the 45° and 135° orientations resulting in tree interception of 329.1 MJ and 326.7 MJ respectively.

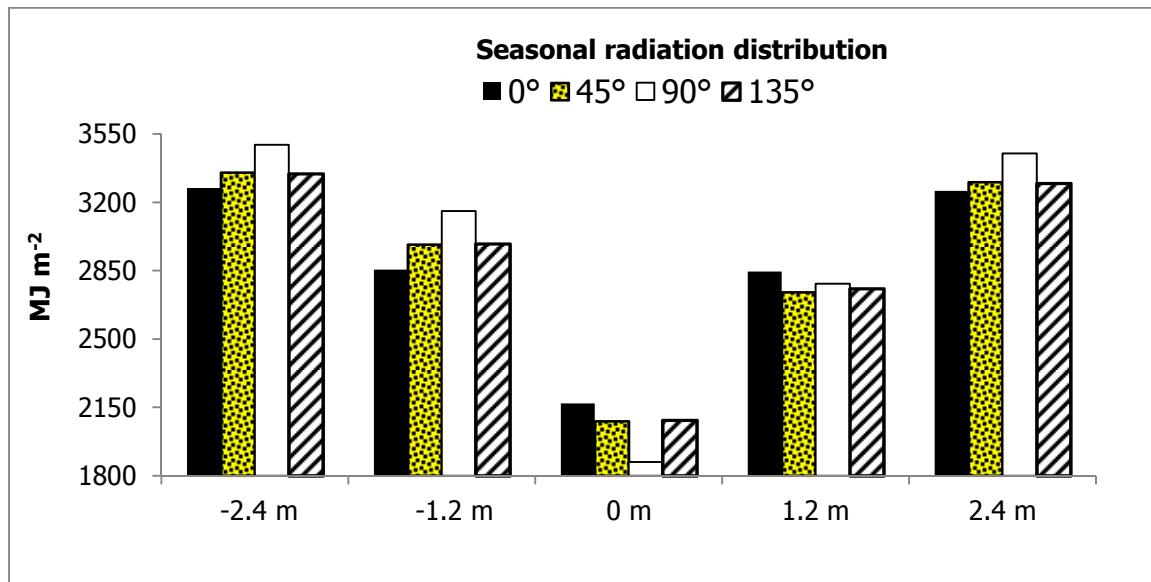


Figure 7.1 Simulated cumulative irradiance at different positions in intercrop zones as a function of orientation of the tree hedgerows (Negative distances represents W with an orientation of 0°, W with an orientation of 45°, N and SW with orientations 90° and 135° respectively)

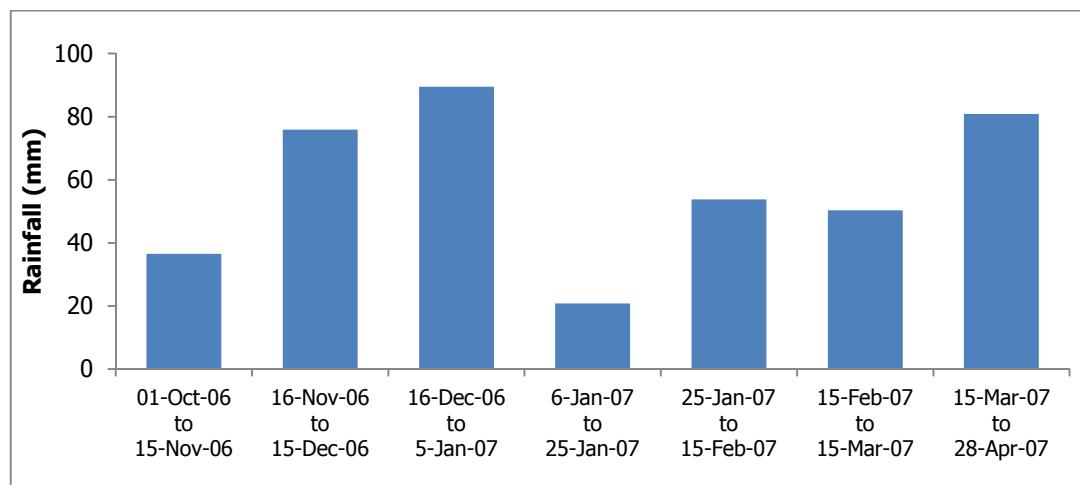


Figure 7.2 Cumulative rainfall during the growth cycles of the 2006/07 season at Hatfield

ET in the intercrop zone showed variations with distance under row orientation scenarios. However, at the selected location, ET in the intercrop zone (Figure 7.3) and tree zone (Figure 7.4) was not affected by row orientation.

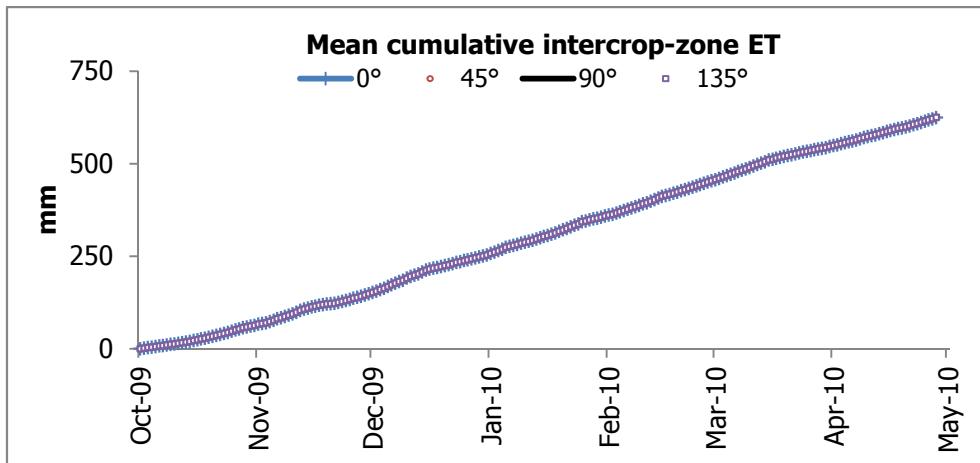


Figure 7.3 Simulated cumulative ET in the intercrop zone under the selected orientations

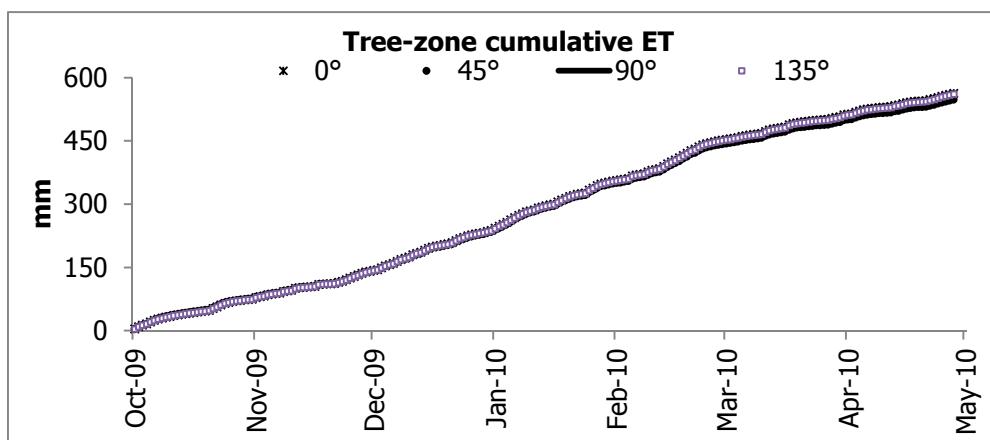


Figure 7.4 Simulated cumulative ET at in the tree-zone under the selected orientations

Under all row orientations, cumulative intercrop productivity was affected by distances from tree hedgerows (Figure 7.5a-d). Row orientation affected extent of variation of intercrop yields with distance from tree, leading to differences in cumulative intercrop productivity (Figure 7.5e and 7.5f). These variations are consistent with the variations of cumulative irradiance (Figure 7.1) suggesting that radiation largely dictated seasonal intercrop (kikuyu) productivity under the current location and orientation. This implication is supported by the fact that rainfall during the growth cycles of the selected season was

generally sufficient to high (Figure 7.2). On the contrary, tree yield was not affected by row orientation, which is due to height advantage of trees making them the dominant species as far as competition for radiation is concerned.

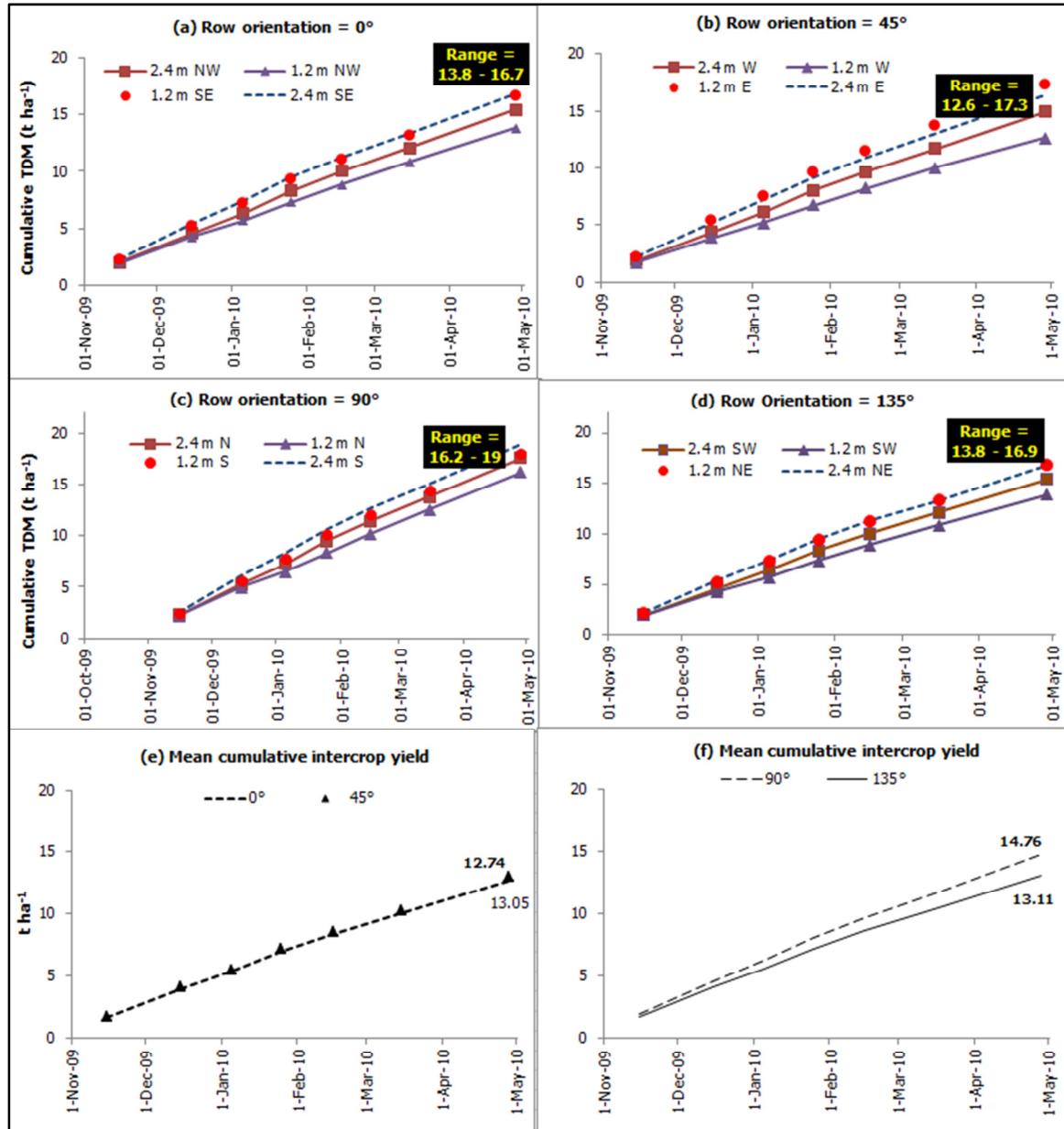


Figure 7.5 Simulated cumulative intercrop yield ($t\ ha^{-1}$) as affected by tree hedgerow orientation

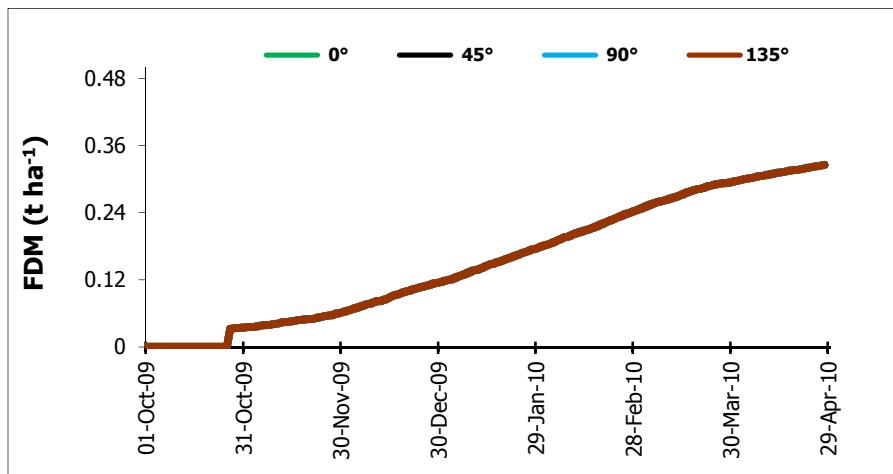


Figure 7.6 Simulated *Jatropha* yields as a function of tree row orientation

The highest income from the system at the specified location and values of the outputs can be obtained if east-west hedgerow orientation (90°) is implemented (Table 7.2). It was the most efficient scenario as far as WUE_{Econ} is concerned. The magnitudes of these advantages obviously depend on the farm area.

Table 7.2 Simulated WUE_{Econ} and seasonal gross incomes as a function of tree row orientation of a 6 m *Jatropha*-kikuyu hedgerow intercropping system in Hatfield

Variables	Row Orientation				
	0°	45°	90°	135°	
WUE _{Econ} (R ha⁻¹ mm⁻¹)	tree crop system	8.25 29.37 25.85	8.48 30.03 26.44	8.34 33.97 29.7	8.28 30.17 26.52
Seasonal gross income (R ha⁻¹)		16 066.12	16 431.05	18 488.06	16 503.41

The implication of the WUE_{Econ} is to decide on which hedgerow orientation would produce the highest return if irrigation was to be implemented. Such scenario modelling provides information about what to expect by choosing one orientation over another and without any additional costs as the scenarios were carried out maintaining all other factors and variables the same. According to Figure 7.7, the percentage of non-beneficial water loss (evaporation) from the soil under the tree hedgerows was very high and remained above 70% during the season. Hence tree WUE_{Econ} values were low. In the intercrop zone, non-beneficial water loss decreased much drastically with increasing crop cover and remained less 15% of total ET after the first month of the season. Similar results were obtained under the other row orientation

scenarios considered. Reduction in evaporation and improvement of tree WUE_{Econ} can be achieved by covering the soil below the trees (for instance mulching). Planting of shade-tolerant crops could also be considered.

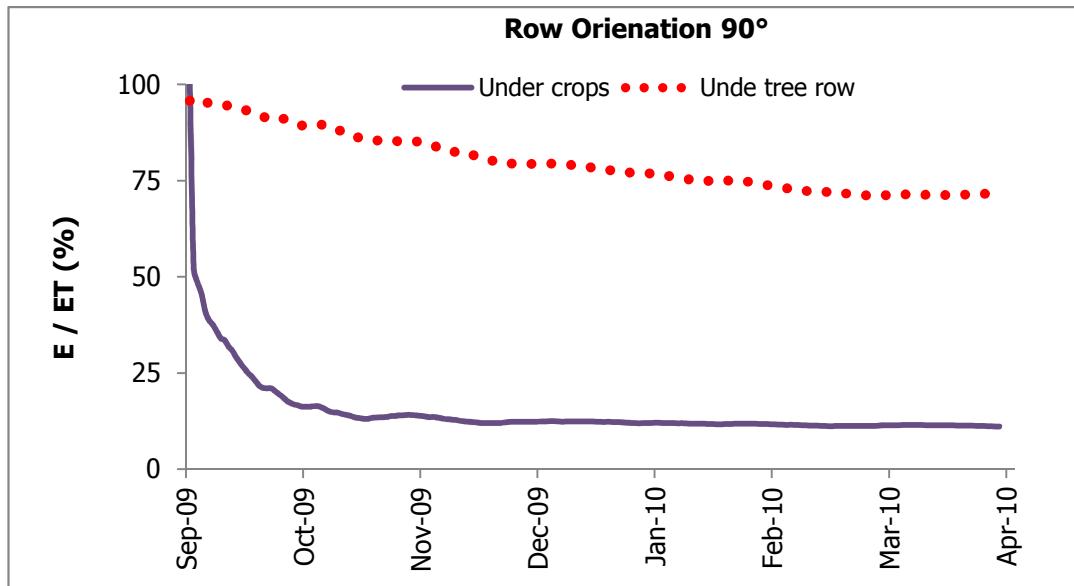


Figure 7.7 Simulated evaporation (% of ET) from the soil under trees and crops as a function of row orientation

7.5.2 Tree row spacing

As the best-case scenario, the E-W (90°) orientation was used to model row spacing scenarios. As can be expected, close spacing of tree rows produced higher tree yields than the wider spacing options (Figure 7.8). This is in part due to the significant differences in the tree occupied area proportions. Cumulative kikuyu yields were highest in the wide spacing options (Figure 7.9).

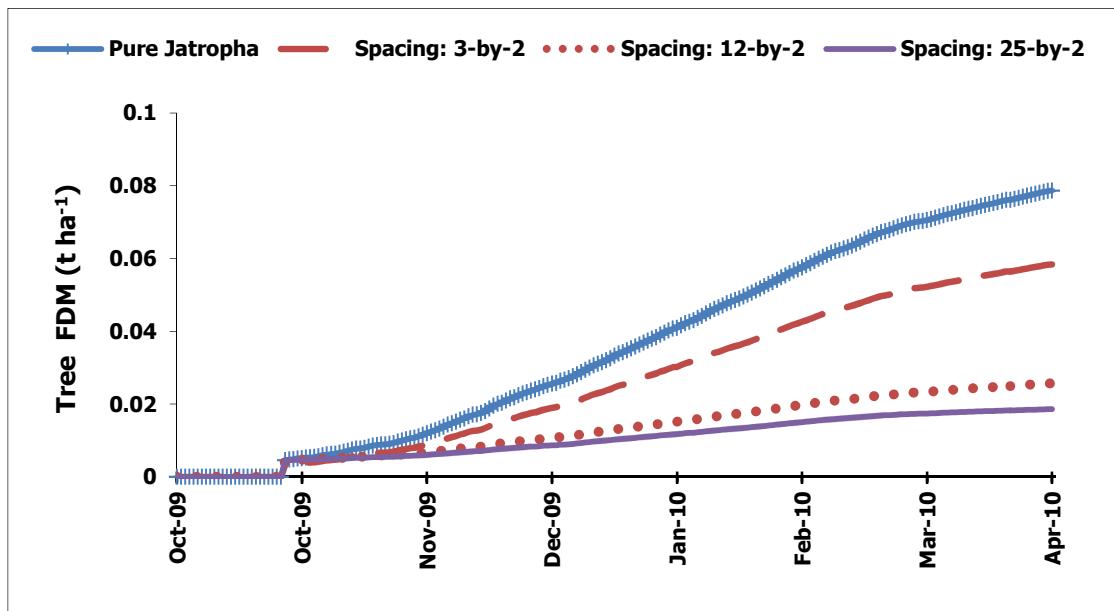


Figure 7.8 Simulated *Jatropha* yields (t ha⁻¹) as a function of the selected scenarios

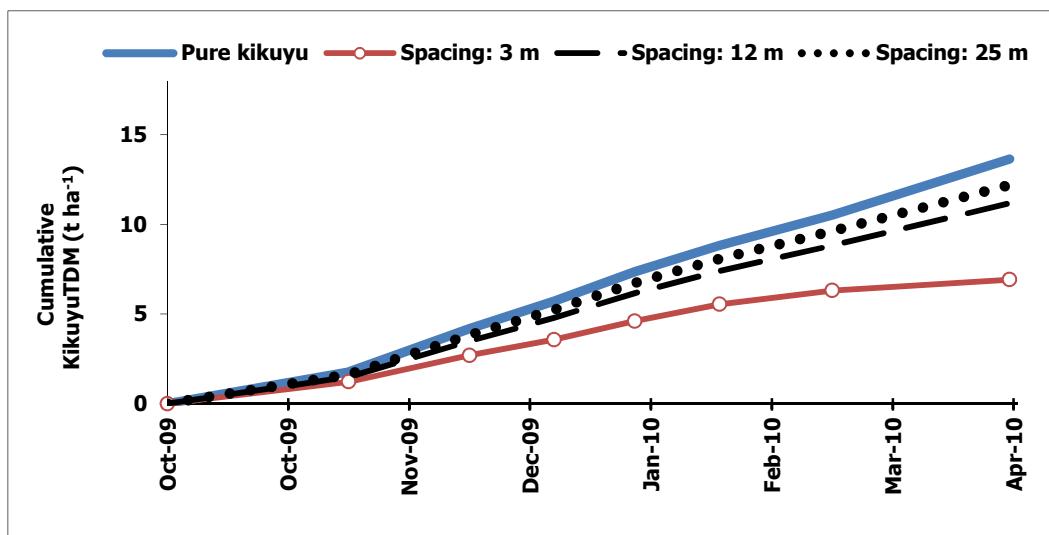


Figure 7.9 Simulated cumulative kikuyu productivities (t ha⁻¹) as affected by the selected scenarios

Despite risk reduction benefits arising from multiple output production of agroforestry systems (Kurtz, 2000), for the specified location and values of tree and crop outputs, the pure kikuyu is the best case scenario as it produces the highest return (Table 7.3). Due to very low productivity of the selected tree species (*Jatropha*) and the fact that the evaporation in the tree-zone was very high (Figure 7.7), tree WUE_{Econ} was very low. Hence, the 25 m spacing option was the best-case hedgerow intercropping scenario,

as trees were allocated the smallest proportion of the cropped area compared to narrower spacing or pure *Jatropha* options.

Table 7.3 WUE_{Econ} and seasonal gross income of the silvopastoral system as affected by tree hedgerow spacing

Variables		Pure <i>kikuyu</i>	Pure <i>Jatropha</i>	Hedgerow spacing options		
				3 m	12 m	25 m
WUE _{Econ} (R ha ⁻¹ mm ⁻¹)	tree	-	13.84	10.12	4.96	3.65
	crop	35.30	-	26.37	32.62	32.53
	system	35.30	13.84	20.95	30.32	32.45
Seasonal gross income (R ha ⁻¹)		20 970.00	7 855.06	8390.79	17 477.47	18 957.93

By enhancing productivity of the selected tree and reducing evaporation (by mulching for instance) and/or using a tree species with a higher value (than *Jatropha*), farmers can significantly improve tree WUE_{Econ} and would possibly be better off with a hedgerow intercropping system with the wide tree spacing than with narrower hedgerow spacing or mono-cropping options. Planting shade tolerant crops in the tree-zone can also increase overall system income. The outcomes of the current scenario analyses show that trees and crops had the highest WUE_{Econ} when mono-cropped. However, since their WUE_{Econ} values are most likely to differ, a hedgerow intercropping option should allocate a bigger land proportion to the more efficient species. After all, success of agroforestry is based on improving resources use efficiency and since water is the most-likely limited resource in arid and semi-arid areas, maximising system WUE is vital.

7.5.3 Crown width (growth)

The objective of this exercise was to derive information about projected timing and extent of tree canopy management (pruning) to enhance irradiance to the intercrop-zone. Tree crown width (hedgerow radius) was affected by row spacing (Figure 7.10). Since foliage of the selected tree species in the current (virtual) system is not useful as forage, the farmer need not prune its crown and would rather leave the crown un-pruned to allow trees interception sufficient radiation during the reproductive stage. This suggestion can be justified as follows:

- The tree crown under the relatively narrow hedgerow spacing scenarios (3 m and 6 m) grows past the T-C interface to a relatively limited extent during January/February when intercrops are bound to re-

grow under dominant tree canopy, while curbing competition for water via tree canopy pruning is relatively ineffective (Smith, 2000).

- For the wider spacing options (12 m and 25 m), while tree hedgerows grow into the intercropping zone to a greater extent, irradiance to the intercrops would not be detrimentally affected due to the wide hedgerow.

For evergreen trees, crown regrowth following pruning early in a growing season (to ensure better understory crop establishment) can be simulated.

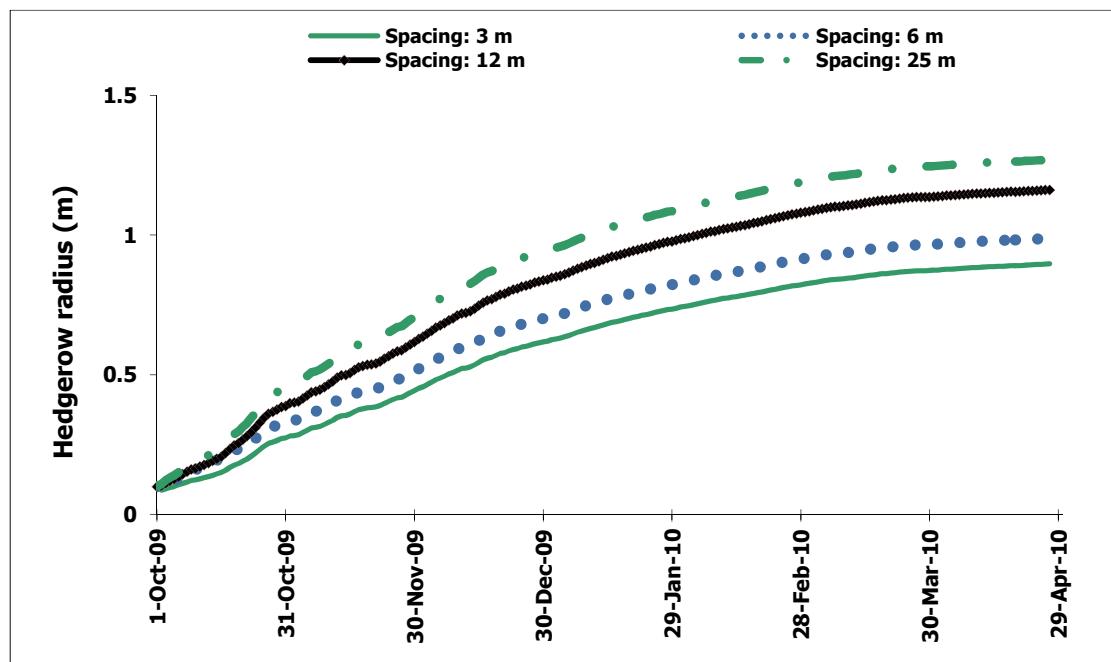


Figure 7.10 Simulated increase in crown radius of trees a function of tree row spacing

7.6 CONCLUSIONS

The objectives of the current chapter were to determine the best-case system scenarios in terms of gross income and economic water use efficiency and deriving information about tree canopy pruning. Various hedgerow orientations and spacing were analysed in a virtual hedgerow intercropping system at Hatfield in Pretoria, South Africa. Intercrop productivity was affected by distances from tree hedgerows and row

orientation, which were consistent with seasonal irradiance distribution. Tree yield was not affected by row orientation.

Tree WUE_{Econ} was low due to very high evaporation in the tree-zone. The highest system income could be obtained if east-west row orientation is implemented. Using the best-case orientation, spacing scenario modelling was carried out at specified output values of trees and crops. Kikuyu sole-cropping is the best-case scenario producing the highest return while the widest (25 m) spacing option was the best-case hedgerow intercropping scenario. By enhancing tree productivity, reducing evaporation and using a more valuable tree species, tree WUE_{Econ} could be significantly improved and a wide-hedgerow intercropping system would be better than narrower-hedgerow intercropping or mono-cropping options. Planting of shade-tolerant crops could also be considered in the tree-zone to improve system WUE_{Econ}.

Tree crown width (hedgerow radius) was affected by row spacing. It is suggested that no tree canopy pruning was necessary since no detrimental effect could be expected on the intercrops due to smaller/slower tree canopy growth in the narrower spacing options and wide spacing in the others.

The chapter demonstrated glimpses of the capabilities of the model to address vital planning, designing management aspects of hedgerow intercropping systems. However, further evaluation and refinement of the model and its parameters is highly recommended. The design and management parameters and the approaches taken to investigate them are specific to the selected system. They were simply used to illustrate how the model may be used and how its simulation results can be interpreted.

CHAPTER 8

GENERAL CONCLUSIONS AND RECOMMENDATIONS

8.1 STUDY OVERVIEW

Production of food crops and pastures face ever increasing land deterioration and water scarcity. Yields and food security are compromised by poor agricultural production technologies/practices and low inputs (Everson *et al.*, 2012). Pressure on natural woodland for fuel wood is increasing, especially in countries with larger rural poor communities. These limitations necessitate consideration of more resource efficient production systems that enable sustainable production and land rehabilitation.

The above problems can potentially be alleviated by practising agroforestry. Successful adoption of agroforestry can be achieved by understanding system functioning, selecting compatible plant mixtures, making system design/planning and management more efficient and identifying conditions under which agroforestry systems are more profitable than mono-cropping systems. The core intent of this study was to understand interactions and productivity of a hedgerow intercropping system of non-nitrogen-fixing tree and perennial grass pasture with reference to water and radiation use (Chapters 2, 3 and 4) and analyse various scenarios so as to facilitate design/planning and management and enhance returns of hedgerow intercropping systems (Chapters 5, 6 and 7). Objective one was addressed via field experimentation, while the second objective was addressed using modelling.

8.2 GENERAL CONCLUSIONS

8.2.1 Interactions and productivity of hedgerow intercropping systems

In order to understand interactions and productivity of hedgerow intercropping systems, a total of five treatments arranged in a randomised-block design with three replicates and differentiated by presence/absence of kikuyu and arrangement/spacing of *Jatropha* trees were studied. They were *Jatropha*-only (JO), standard-spacing (SS), single-row (SR), double-row (DR) and triple-row (TR) used. In all treatments, trees planting density was 1110 ha^{-1} . Nitrogen, phosphorous and potassium fertilisers were applied regularly to ensure these elements did not limit growth.

AG allometry of *Jatropha*, effects of BG interspecies interactions and tree spacing on allometry and validity of these relationships for use in a range of growing and (non-destructive) tree management conditions at a site were examined (Chapter 2). Tree level and branch level allometric relationships of *Jatropha* using basal stem diameter and crown width as predictor variables were 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 BG interspecies interactions nor tree spacing had any significant effects on allometry. Validation of allometric relationships using independent data confirmed they are valid for accurate, non-destructive and quick predictions of tree growth under various growing and (non-destructive) tree management conditions at a given site.

The nature of BG interspecific interactions in a rain-fed hedgerow intercropping system was examined by studying effects of tree spacing/arrangement on tree productivity (Chapter 3). Stem diameter was the greatest in JO. None of the *Jatropha*-kikuyu treatments had tree growth rates that were consistently the highest. When high water availability and kikuyu dormancy coincided, tree growth rates did not significantly differ across treatments. SR had the most frequent maximum stem growth rate and was the most efficient during limited water availability. SS had the highest growth rates during the spring and summer seasons. JO trees were the tallest, while trees in SR were the shortest. Even when rainfall was high, post-pruning tree height growth rate was affected by BG interspecific competition and tree spacing/arrangement. SR trees showed slow response to pruning due to a high TCI. They, however, exhibited compensatory growth during May to August, when competition for water with grass was low. Generally, length (per tree) of tree-grass interfaces affected yield inversely especially as trees matured toward their maximum-yield age (4-5 years). BG competition reduced tree yield more than tree biomass, while tree spacing/arrangement did not affect tree harvest index.

In order to understand the extent of T-C interactions in hedgerow intercropping systems, distribution of soil water, radiation and total root distribution and intercrop growth were investigated (Chapter 4). Soil water varied among treatments. It was asymmetrically distributed across tree hedgerows. ET was generally greatest in SR and the least in DR with differences being more due to transpiration than evaporation. The extent of tree root distribution in search of soil water varied among treatments. In JO and SR, the strength of correlations between tree relative growth rates (tree RGR) and soil water deficit (SWD) varied with

distance and soil depth unevenly, implying an asymmetrical distribution of fine tree roots. All tree RGR-SWD correlations in DR were strong, suggesting that the entire soil profile contributed to tree water use and that tree roots were more or less symmetrically distributed in the profile. This resulted despite SR and DR having comparable tree RGRs. Strong tree RGR-SWD correlations were due to tree dominance in terms of radiation capture and because tree growth was mainly water-limited.

Correlations between irradiance and intercrop growth were poor despite treatments being non-nutrient limited with the study conducted under high rainfall conditions. The most likely reason is the diminished proportion of photosynthetically active radiation intercepted by intercrops resulting from interactions with tree canopy (Ong et al., 1996), as evidenced by the reduction of grass radiation use efficiency close to the tree hedgerows. The effect of radiation distribution on T-C interactions was mainly to magnify effects of water as the major growth limiter and confirmed that kikuyu is not drought tolerant.

Grass growth consistently increased with distance from hedgerows. SR produced more grass than DR. This suggests that SR trees faced weaker interspecific competition for water than those in DR. In DR, tree roots explored the profile more comprehensively, and therefore cumulative grass growth was less. This suggested more intensive interspecific and possibly intraspecific competition in DR than SR. Tree and grass roots overlapped greatly due to the shallow nature of tree roots and limited soil profile depth (0.6 m). Interspecific competition was severe due to the perennial nature of *Jatropha* and kikuyu and their overlapping dormancy and active growth periods leaving no room for temporal complementarity. Total root distribution in SR was skewed towards SW. Tree water uptake predominantly came from the 0.2 – 0.6 depth, which had about 8.6% of the total root biomass in the profile. There was no clear relationship between grass growth patterns and root growth across the hedgerows.

In a nutshell, tree allometry was not affected by T-C interactions or tree spacing/arrangement and was confirmed valid under various growing and non-destructive tree management conditions. The interspecific interactions were competitive. System productivity was mainly dictated by water availability, with radiation distribution mainly magnifying effects of water on T-C interactions. Manipulation of tree arrangement/spacing without changing tree density affected resource distribution and intercrop growth but not tree productivity.

8.2.2 Maximising design/planning/management efficiency and returns of hedgerow intercropping systems

Various T-C associations may be considered when designing/planning agroforestry systems. Since system productivity and returns are determined from products of component species, relevant modelling should necessarily include productivity simulations of species involved. In the current study, a process-based hedgerow intercropping model, with tree and crop growth simulators was developed by integrating the SWB and SWB-2D (Chapter 5). SWB-2D is used as the main framework of the current model. The 1-D crop growth and the cascading water balance routines of SWB were adopted for simulating growth and water balance in the intercropping zone. The generic crop growth routine of SWB was also used for tree growth modelling after applicable modifications and additional routines of tree root growth and distribution, and tree crown growth.

The newly developed hedgerow intercropping model employs several mass balance checks and was evaluated using the CAMASE modelling guidelines (1995) (Chapter 6). Simulations were run using crop parameters from Annandale *et al.* (1999), with most tree parameters determined via measurement, and a few estimated during model calibration. The model simulated solar radiation distribution in hedgerow intercropping systems accurately, with only a slight tendency of overestimation at some positions. Despite soil spatial variability, the model simulated profile water content distribution very well. It also proved reliable in simulating tree water use in hedgerow intercropping systems.

Calibration results of modelling periodic and cumulative intercrop yields were acceptable. The model overestimated periodic growth when rainfall availability was high, implying that radiation largely dictated growth simulations. When rainfall during a cycle was relatively low, the model underestimated intercrop growth suggesting that the simulations were generally water-limited. This is based on the validation results of radiation and soil water distribution, which showed the model's tendency to slightly over-predict radiation interception and underestimate profile water content. The model overestimated cumulative yields due to the fact that over the entire season, there were more periodic yield overestimations than underestimations. Validation of modelling periodic intercrop growth yielded similar results to that of

calibration. Difference between predicted and measured cumulative yields was, however, more pronounced during validation than calibration, as can be expected.

Good fits were achieved between measured and simulated woody biomass, leaf area index, crown width and nut yield during tree growth model calibration. The model, however, somewhat overestimated leaf dry mass. All in all, the calibration results were largely acceptable, implying that refinement of selected parameters was successful. When validated using independent data, the model simulated woody biomass and crown width reasonably well. It tended to over-estimate foliage biomass, leaf area index and nut yield. Overall, model performance parameters confirmed the adequacy of the model for simulating the selected tree biomass and dimension variables.

Model evaluation results confirmed that the model offers great potential for applications in hedgerow intercropping systems. Hence, the model was used for developing design/planning and management criteria of such systems. Scenario modelling was carried out with the objectives of analysing various hedgerow orientation and spacing options in order to determine the best-case system scenarios in terms of gross income and economic water use efficiency and deriving information about timing and extent of growth and management (pruning) of tree crown width (Chapter 7).

A case study was carried out on a virtual hedgerow intercropping system at Hatfield in Pretoria (South Africa), which showed that intercrop productivity, like seasonal irradiance, was affected by distances from tree hedgerows and row orientation. Tree yield was not affected by row orientation. Tree crown width/hedgerow radius was affected by row spacing. It was suggested that no tree canopy pruning was necessary since no detrimental effect could be expected on the intercrop due to slower tree canopy growth in the narrower spacing options and wide spacing in the others. The ratio of the economic value of the yield to evapotranspiration (WUE_{Econ}) of tree was low due to very high evaporation percentage in the tree-zone. The highest system income could be obtained if an east-west row orientation was implemented. Using the best-case orientation, spacing scenario modelling was carried out at specified values (prices) of tree and crop outputs. Pure kikuyu is the best-case scenario producing the highest return while the widest (25 m) spacing option was the best-case hedgerow intercropping scenario. By enhancing tree productivity, reducing evaporation and using a more valuable tree species, tree WUE_{Econ} could be significantly improved

and a wide-hedgerow intercropping system would be better than narrower-hedgerow intercropping or mono-cropping options. Planting of shade-tolerant crops could also be considered in the tree-zone to improve system WUE_{Econ} .

The scenario modelling case study demonstrated the capabilities of the model to address vital planning, designing and management aspects of hedgerow intercropping systems. The design and management parameters and the approaches taken to investigate them are specific to the selected system. An example was simply selected to illustrate how the model may be used and how simulation results can be interpreted.

Lastly, SWB enjoys generally good reception by farmers, consultants and researchers in South Africa for various production purposes. This is expected to have positive effects on the acceptance of the current hedgerow intercropping model.

8.3 RECOMMENDATIONS

The following recommendations can be made:

- Allometric equations from this study should be developed into generalised equations for *Jatropha* using allometric equations from other sites. That way they can be more universally applicable for *Jatropha* biomass predictions and useful for comparative evaluation of site suitability for a species.
- To ensure viability of *Jatropha* for hedgerow intercropping application, grass clearance from tree base should be sufficient and *Jatropha* should be planted with crops having low competitiveness. Periodic weeding and irrigation are crucial for system performance as a whole and for *Jatropha* specifically.
- More tree spacing/arrangement options can be explored using the current hedgerow intercropping model in order to realise the full potential and implications of the experimental findings of this study, which demonstrated that resource distribution and intercrop growth can be optimised by manipulating tree spacing/arrangement without changing tree density.
- SWB has a nutrient simulator. It is recommended that the simulator be linked to the hedgerow intercropping model.

- Although *Jatropha*-kikuyu was used during evaluation of the hedgerow intercropping model and scenario modelling, it must be emphasized that the model is applicable to any potential tree-intercrop combination. While a “wealth” of parameters is available in the SWB database for many crop species, it is recommended that parameters of multipurpose trees suitable for hedgerow intercropping systems be added to the model.
- The model should be refined further through a more rigorous and thorough calibration process, taking into account shade-intolerant and shade-loving crop species, along with evergreen and deciduous tree species.
- A parameter optimization program known as PEST-ASP Model-Independent Parameter Estimation, which has been previously recommended for SWB-2D but not implemented yet, is recommended for the current model.

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