WATER USE EFFICIENCY OF MULTI-CROP AGROFORESTRY SYSTEMS, WITH PARTICULAR REFERENCE TO SMALL SCALE FARMERS IN SEMI-ARID AREAS

Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

WATER USE EFFICIENCY OF MULTICROP AGROFORESTRY SYSTEMS, WITH PARTICULAR REFERENCE TO SMALL-SCALE FARMERS IN SEMI-ARID AREAS

This project commenced in 1999. It was conducted in several phases, namely:

(a) "On-station" on the Hatfield Experimental Farm of the University of Pretoria in which pure stands of sorghum, cowpeas, sweet potatoes and *Leucaena leucocephala* were compared with intercropping of Leucaena hedgerows with the same crops in the alleys for three seasons.

(b) "On-station" at the University of Pretoria, in which pure stands of sorghum, maize and Leucaena were compared with intercropping of Leucaena hedgerows with the same crops in the alleys for the two seasons.

(c) "On-farm" sylvopastoral system in Venda to produce forage and fodder for a small scale communal dairy project.

(d) "On-farm" alley cropping systems (with maize and Leucaena), at Sekakane and Chuene Maja, compared with mono-culture maize.

(e) Community development in the Sekakane and Chuene Maja areas.

As this project developed it became evident that this effort to expand the use of alley cropping / agroforestry away from the humid and sub-humid tropics, where it has yielded excellent results, to the semi-arid regions, and in particular with reference to small scale farmers, was faced with specific problems. While the "on-station" work was conducted in Pretoria, which internationally would be classified as semi-arid, in South African terms this area receives a relatively good rainfall and the site was characterised by good physical and chemical soil conditions.

As a result, the extrapolation of results to "drier" conditions, because of rainfall, temperature, evaporation and soil conditions, is open to question. In the context of relative aridity, if Hatfield was classified as semi-arid, then the "on-farm" sites could be classified as arid with certain seasons qualifying as semi-arid, and certain seasons as hyper-arid. The implications for crop selection are very important in this project, especially in the context of sustainability. Of the species used, Leucaena, although at its best in humid to sub-humid tropical conditions, can survive fairly dry conditions. Cold might place limitations on the growing season, the availability of leaf in winter, and the incidence of top kill and consequent coppicing. Sweet potatoes were a poor choice as intercrop as it does better in warmer and wetter environments and in rotations rather than in a mono-culture.

Cowpeas were probably a good choice in terms of being indigenous and hardy, but in terms of community preference this crop would not be preferred. Moreover the advantages of being leguminous would be negated to some extent by combining it with a leguminous tree crop. It would also probably perform better in a rotation where considerations of fertility, weed control and pest control would be better managed. Cereal or grain crops would, therefore, be the preferred intercrops with Leucaena.

Maize is an exotic species which dominates the diet preferences of many rural communities in Africa. In semi-arid conditions, good management practices can ensure sustainable maize production. Where, however, the rainfall and soil conditions are unfavourable, and maize is not a sustainable option, more drought-tolerant (sorghums and millets) grain crops should be considered, despite the priorities of the farming communities.

Sorghum in the above-mentioned conditions would be a viable alternative crop. Where, however, growing conditions are better maize would remain the first choice grain crop. The grain millets should also be considered in future work even though there is a stated

preference for maize. The farming community needs to be made aware of the relative risk of different grain crops in areas where the rainfall indicates greater aridity.

The need is for mixed farming systems, which meet the diverse needs of the community. As a "needs-driven" project the emphasis on the system would concentrate on one or more needs, for grain, bulk roughage, high protein fodder and/or fuel wood.

It is in the context of needs (and hence relative value of the different products from multi-crop systems) that the production data from both "on-station" and 'on-farm" trials should be interpreted. Assuming a need for a diversity of products for both man and beast, the decision which needs to be made is – do we recommend an alley cropping system or do we recommend separate blocks of the different crops?

Under marginal climatic and soil conditions, and the latter may be affected by financial ability of small scale farmers to ameliorate (rip, deep plough, drain, lime, fertilize) the soil, the results from this project would appear to indicate the avoidance of competition between different crops in alley systems and the optimization of mono-culture agronomic practices would be the route to go. With better growing conditions the choice between alley systems and monocultures, would depend on the needs for different components and the relative values allocated to these products. For example, a small scale farmer producing maize grain for use within the community, would probably attach a value comparable to what that community would have to pay the local trading store, while a producer marketing to millers would have a value determined by national supply and demand and the global market. Similarly fuel wood prices/values would be determined by the availability and prices of alternative sources of energy, and this would vary tremendously from area to area. The demand for (and value of) livestock feed would also vary from area to area, depending on such factors as the availability and quality of veld and the nutritive needs of different classes of stock. Feeding for survival or for production, for beef or mutton or milk are all very different scenarios, each of which can justify certain inputs into feed. Under good climatic and soil conditions (prime land capability with minimal erosion hazard) the choice of land use system would be governed by economic considerations, although certain land users may persist with less profitable enterprises because of personal preferences, irrespective of which was the most profitable enterprise. Under South African conditions, which are so often typified by high variability (even in high potential areas), there is probably a valid argument in favour of diversification, mixed farming or spreading the risk. Where this is practiced, annual crops, perennial crops and fodder trees could be combined in a range of alternative land use scenarios. Apart from mono-cultures, crop rotations, intercropping, etc., this might include different forms of agro-forestry.

Monitoring of competition for light and water in this project has indicated that:

(a) row orientation of trees in alley cropping (this changes constantly in conditions where most plantings are on the contour) at these latitudes do not have a major effect on light interception during the summer months, but might have negative impacts on the southern side of rows in the winter months, or depending on the pruning/hedge row policy for the trees. The effect will also vary tremendously depending on the intercrop. Temperate species generally have lower threshold values than tropical species at which they can still photosynthesize effectively, but even within each of these groups there is considerable variation in shade tolerance. Hence, complementary work, conducted at Hatfield, has demonstrated that while virtually all the intercrop annual row crops did extremely poorly in the rows adjacent to the trees, *Panicum maximum* (a tropical C4 perennial grass species) was at its best virtually under the canopy of Leucaena coppice. This observation might be confounded by the high fertility under the canopy of the leguminous tree crop. However, the annual row crops did not benefit from this situation.

(b) While the favourable soil conditions and better rainfall conditions at Hatfield would hypothetically reduce negative competition for water because of the deeper rooting habit of the trees, in practice competition for water in the upper soil layers was very strong in the rows closest to the trees (probably because under the experimental conditions there was little or no recharge of subsoil moisture and trees competed in the shallower horizons for moisture). On the "on-farm" site at Sekakane, which was the only co-operative site to yield production data, it appeared that in the poorest season maize survival and productivity was severely impaired up to 5 m from the trees, while in the best season (with ±360 mm of rain this was by no means a good season) maize rows 3 m from the trees had the best yielding plants. Such results should be interpreted in the context of two factors:

1. In other work conducted on Leucaena by the University of Pretoria, it was found that the lateral spread of tree roots was much greater where unfavorable sub-soil conditions impeded root penetration;

2. Simulations of the water balance (using the SWB model) in a range of soils under a range of rainfall conditions indicate that under unfavourable rainfall conditions there is no water recharge of the deeper soil layers in 6 of the 9 scenarios examined. As a result there would be strong competition for water between different plant species in the upper soil layers as opposed to complementarity under better growing conditions.

Finally, considerable inputs into the functionality of different agro-forestry models and their uses, has demonstrated that some of these could find application in developing systems or "what if-scenarios" incorporating trees, which could improve crop productivity and sustainability. At the same time, however, it must be emphasized that considerable research must still be conducted to provide a sound basis for predicting crop and tree productivity.

With respect to community development, it must be recognized that while the technology of implementing alley cropping systems in harsh environments is still in its infancy, it will be difficult to gain acceptance by land-users who operate under difficult socio-economic pressures. Agro-forestry/alley cropping should clearly be an integral part of extension programmes designed to provide alternatives for land users to improve the productivity of their land (whether for crops or livestock). It should not be seen as an objective in itself but rather as one of numerous means to the realization of objections.

In future, such projects should therefore be years in the planning, based on comprehensive surveys of natural, human and financial resources and not months as is currently often the case. In this project the human factor often proved to be the biggest limitation. On the other hand, the progress that was made was ascribed to the inputs of staff, students, government officers and, most importantly, members of the communities.

ACKNOWLEDGEMENTS

A special word of appreciation to the Water Research Commission for financial support since 1999, which enabled the University to build on two masters studies which had been conducted on the Hatfield site over the five year period preceding the commencement of field work for this project. Also for their flexibility and encouragement when proposals for the "on-station" research and "on-farm" developmental work required modification. In this respect the members of the steering committee always provided guidance and support. Over the years the steering committee has included:

As chair and vice-chair from WRC:	Dr GR Backeberg Dr SS Mkhize Dr AJ Sanewe Mr H Maaren
As regular members:	Prof ATP Bennie Dr T Everson Dr AJ Kruger Mr BD Mappeldoorn Mr MW Sefara Mr T Mudau Mr OA van der Westhuysen

with eight other nominated members having attended only one or no meetings.

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LIST OF SYMBOLS AND ABBREVIATIONS

BECVOL	Biomass Estimate from Canopy VOLume model
D	Drainage (mm)
DM	Dry Matter ($kg.ha^{-1}$)
DOY	Julian Day Of Year, from 1 for 1 January
E	Evaporation
FC	Field Capacity
HyPAR	Integrated model for semi-arid areas based on the Hybrid and PARCH models
LER	Land Equivalent Ratio
NEWSWB	NEW Soil Water Balance model
PAR	Photosynthetically Active Radiation ($\mu mol.m^{-2}.s^{-1}$)
PAW	Plant Available Water
PWP	Permanent Wilting Point
T	Transpiration (mm)
TDR	Time Domain Reflectometer
T_f	Fractional transmission
VWC	Volumetric Water Content ($m^3.m^{-3}$)
VWC_{FC}	Volumetric Water Content at Field Capacity ($m^3.m^{-3}$)
VWC_{PWP}	Volumetric Water Content at Permanent Wilting Point ($m^3.m^{-3}$)
WaNuLCas	Water, Nutrient and Light Capture model
Y	Yield ($kg.ha^{-1}$)
ψ_{50}	Matric potential at 50% Plant Available Water between Field Capacity and Permanent Wilting Point.
Ψ_{FC}	Matric potential at Field Capacity.
Ψ_{PWP}	Matric potential at Permanent Wilting Point

INTRODUCTION AND LITERATURE REVIEW

Agroforestry, the name given around two decades ago to the science of cultivating trees in association with crops, remains, to proponents, a solution to agricultural problems, particularly in developing countries, while it is often dismissed as an environmental fashion by others (Torquebiau, 2000).

Agroforestry began several thousand years ago with the development of slash-and-burn agriculture. In clearing areas and leaving them fallow for a few cropping cycles, it became practice to allow and, even encourage, the co-existence of trees and crops on the same land. Since the beginning of the last century, slash-and-burn agriculture has been largely replaced by monoculture as the predominant agricultural practice in developed countries, but slash-and-burn and other agroforestry systems remain commonplace in developing countries (Torquebiau, 2000). Examples of large-scale use of agroforestry in Asia and Africa include the following:

- The famous parklands systems of Africa, still considered the largest agricultural land use system in Sub-Saharan Africa;
- Agroforestry systems employing shading of coffee and cocoa under trees (Beer et al., 1998);
- Tropical agroforestry home gardens (Torquebiau, 1992);
- Stratified agroforestry (layered plant canopies) of south-east Asia (Aumeeruddy and Sansonnens, 1994 ; Gouyon et al., 1993) and
- The “Taungya” systems, where foresters allow landless farmers to establish crops under plantation canopies, provided that they tend the tree saplings as well (Kruger, 1999).

Combe (1982) classified agroforestry systems into three broad groups, namely agrosilvicultural (mixing trees and crops), silvopastoralism (mixing trees, pastures and animals) and agrosilvopastoralism (mixing trees with crops and animals). These groups can further be subdivided as either simultaneous (where trees and crops are grown simultaneously), or sequential (where trees and crops are grown separately, temporally, over a number of seasons, as with improved fallows).

Alleycropping, or hedgerow intercropping, the system used in this investigation, can be classified as simultaneous agrosilvicultural. Alleycropping usually involves the simultaneous cultivation of two species, with one species (usually a leguminous, taller tree species) grown as a hedgerow, and the second species (often an annual agronomic grain crop) grown in the alley between the hedgerow species. Proposed benefits of this form of agroforestry would include the following:

1. Improved water use efficiency due to interspecific complementarity of root systems.
2. Decreased evaporation of water from the soil surface due to shading.
3. Availing of nutrients to shallow-rooting crops through deep recycling by tree roots and nitrogen fixation (if leguminous species are used).
4. Reduction of soil erosion and improved soil fertility while providing diversified production options in forms of fuel, food and fodder.
5. Decreased risk through product diversification.

This study will concentrate on points 1, 2 and 5.

1.1 Improved water use efficiency due to interspecific complementarity of root systems

In semi-arid environments water becomes the most limiting resource, and thus the resource most susceptible to interspecific competition between trees and crops. In environments where water is less limiting, interspecific competition for nutrients and light are more likely to be responsible for diminished advantage, or even disadvantage of intercropping.

Deeper-rooting species theoretically utilize water at soil depths beyond the rooting depths of the shallower-rooting companion crops. Deeper-rooting species have also been shown to be able to lift water hydraulically, and sometimes make this water available to companion crops through a "sprinkler-like" distribution (Sekiya and Yono, 2004). In semi-arid regions, alleycropping has been recommended to improve water use efficiency and soil nutrient status. Improvement of water use through alleycropping in semi-arid areas is based on assumed root complementarity between tree and cash crops. The central hypothesis of agroforestry is that "trees must acquire resources that the crop would not otherwise use". Crop complementarity requires that annual and perennial crops should have roots that utilise different soil zones, usually with annual crops dominating the shallow rooting depths, and perennial crops dominating the deeper zones. Crop complementarity is seldom dependant only on the correct combination of species. Rather, an integrated, flexible approach of management manipulation and crop combination to suit the prevailing conditions is required.

Realising this desired complementary benefit often proves difficult in practice. That intercropped trees and crops can have complementary root distributions, with tree roots dominating subsoil and crop roots dominating topsoil, has been proven. Lehmann *et al.*(1998), in studies using natural C-13 discrimination between C3 and C4 plants (in arid northern Kenya with flood irrigation - annual precipitation 318 mm), observed that the proportion of tree roots in the subsoil increased during drier periods. Lehmann *et al.*(1998) concluded that root length density decreased more with depth in wet seasons than in dry seasons, suggesting that hedgerow trees tend to penetrate deeper during dry periods to find soil water. In Lehmann's study, intercropping resulted in the spatial separation of the root systems of trees and crops between the hedgerows, with more crop roots in the topsoil and tree roots in the subsoil than was the case in monocultures. Soil water depletion was higher for alleycropped soils than for monocultures, and higher under the tree row than in the alley. In the study by Lehmann *et al.*(1998), the agroforestry system used the water between the hedgerows more efficiently than the sole-cropped trees or crops.

Deeper-rooting hedgerow species have been proven to not only lift water hydraulically for their own use, but to also transfer lifted water to surrounding plants. This was observed by Corak *et al.*(1987) between alfalfa and maize, and by Dawson (1993) in a study of water hydraulically lifted by sugar maples for use by neighbouring grasses. These observations were further strengthened by the observations of Sekiya and Yono (2004) who, using deuterium isotopes to observe hydraulic lift by leguminous companion crops (in this case, pigeon peas and Sesbania) in a study in semi-arid Zambia, observed that, through hydraulic lift, water was made available not only to the legume, but also to the accompanying intercrop (maize). Sekiya and Yono (2004) also noted that the "sprinkler" effect of distribution to accompanying crops occurred only with pigeon peas, and not with Sesbania.

The degree to which hydraulically-lifted soil water is distributed to shallower-rooting companion crops was ascribed to the degree of intertwinedness of roots between the two intercrops, with the pigeon pea and maize roots in this case overlapping the most. This observation was corroborated by Hansen and Dickson (1979), cited in Sekiya and Yono (2004), who noted that translocation of water and nutrients between plants can be facilitated by closely-associated, intertwined root systems. The actual "sprinkling action" seems to be a function of stomatal closure (Caldwell et al., 1998) in response to light intensity, so that shading of the deeper-rooting species induces distribution of water from that species to the accompanying crop. It has been suggested that a method of facilitating the sprinkler action could be to prune deeper-rooting species, allowing the accompanying crop to shade the now-shorter pruned species, stimulating distribution of hydraulically-lifted water to the companion crop (Sekiya and Yono, 2004). This again raises the question about the relevance of root complementarity as a means of improving water use efficiency in semi-arid environments. The same closely-associated, intertwined nature of roots that allows translocation of hydraulically-lifted water between species, obviates the benefit of root complementarity based on the assumption that roots operate in different soil zones.

An important aspect when considering the beneficial effects of root complementarity and hydraulic lift of water, is the ability of rainfall to replenish water absorbed from the deeper soil zones. Is the rainfall of the cropping area sufficient to supply the shallower-rooting crop with water in shallow soil zones, while still replacing water removed from the deeper horizon? Soil drainage rate (hydraulic conductivity) becomes important in assessing this, with sandy soils draining faster than soils with a higher clay content. Oluwasamire *et al.*(2002), working on a sandy soil with a rapid drainage rate (saturated hydraulic conductivity 17 $cm.h^{-1}$), measured 15%water loss through deep drainage in a lower rainfall season in Nigeria (564 mm), and estimated deep drainage at 20%in higher rainfall seasons (765 mm). By contrast, in Machakos, Kenya, McIntyre et al. (1997) observed that recharge of deeper soil water occurred only once at the start of the rainy season, and once during the long rainy season. McIntyre *et al.*(1997) also noted that water uptake deeper than 0.45 m was no greater in the alleycropping system than in monocultures. If the deeper soil zones are not replenished with water, the benefit of having deeper-rooting companion crops is negated, as the proposed advantage of root complementarity is not sustainable.

According to McIntyre *et al.*(1997), the yield of the annual crop intercropped between hedges was less than half that of the monoculture, except where severe pruning delayed canopy development and, therefore, water uptake by the hedge. McIntyre *et al.*(1997) concludes that there seems to be little opportunity to increase water uptake in hedge-intercrop systems in semi-arid environments.

1.2 Decreased evaporation of water from the soil surface due to shading

Attempts to increase agricultural productivity aim to maximize the transpiration component of the total water balance while reducing evaporation and drainage. The complete water balance is expressed as follows:

Total = P – T – E – D,

Where P – precipitation, T – transpiration, E – evaporation, D – drainage.

A basic assimilation model suggested by Tanner and Sinclair (1983), cited in Bennie *et al.*(1998), is as follows:

$A_{n,\,leaf} = kE_{leaf} / D$,

where A_n is the nett assimilation rate, k = 0.7 p_a (C_{ca}-C_{ci}), D is vapour pressure deficit of air, p_a is atmospheric pressure, C_{ca} is atmospheric CO_2 concentration, and C_{ci} is CO_2 concentration in the intercellular spaces of the leaf,

From this equation it is apparent that increased transpiration in the total water balance, or decreased vapour pressure deficit should result in improved yields and water use efficiency. Caviglia *et al.*(2004) cites decreased vapour pressure deficit, increased transpiration and increased harvest index as three of the most important means of increasing radiation capture efficiency, and therefore crop growth.

Any decrease in evaporation of water from the soil surface will increase the amount of water potentially available for transpiration and growth. A large proportion of total evaporation occurs during the early stages of monoculture growth, when seedling canopy cover is too small a fraction of the total cropping area to reduce soil evaporation by shading. Decreasing early season soil evaporation using the canopy of an already-established hedgerow or companion crop, or mulching the bare soil area, has clear potential to increase the proportion of precipitation used for transpiration.

In a study on evaporation from soils below sparse crops in contour hedgerow agroforestry in semi-arid Kenya, Kinama et al.(2005) measured reductions in soil evaporation of 9, 4 and 5%in three successive systems where hedgerow prunings were used as mulch. Walker and Ogindo (2003), in a study of water budgets in intercropping systems, comprising intercropped maize and beans, drew attention to the benefits of intercropping through reduction of soil evaporation. In that study, Walker and Ogindo (2003) measured higher shaded surface area in intercropped systems than in either of the monocultures, with a resultant higher apportioning of precipitation to transpiration in the intercropped area than in monocultures, in all four seasons observed. Besides decreasing evaporative water losses through increased canopy cover, intercropping has been documented to increase infiltration by protecting the soil from raindrop impact, thereby allowing improved availability of water for transpiration (Lal, 1974, cited by Willey, 1990).

Wallace et al.(1999) measured the soil evaporation under tree shade to be 35%less on an annual basis. Wallace and Batchelor (1997) suggested water losses to evaporation of 30-35% for millet grown in Niger, while Rockstrom (1997), cited by Walker and Ogindo (2003), reported the proportion of total precipitation lost to transpiration to be as low as 5% in West Africa. Wallace (2000) reported transpiration as a proportion of precipitation to be 15 to 30%.

Walker and Ogindo (2003) measured evaporative decreases of approximately 5% with intercropped maize and beans, resulting in increased transpiration of 5-6% above transpiration for the monocrops. Walker and Ogindo (2003) suggested that decreasing soil evaporation through intercropping goes beyond merely decreasing radiation absorbed by the soil through shading, and includes the following as additional evaporation-decreasing measures:

- Reduced atmospheric demand, due to the humidification of air and crop canopy by increased transpiration from the dense combined hedgerow and crop canopy;
- Increased water uptake from soil surface layers due to increased root density in the upper layers, thus decreasing water dissipated by evaporation.
- Particular benefit of an additional hedgerow canopy during the early season, when the alley crop canopies are small, allowing excessive evaporation.

In addition to these, a hedgerow species with a longer growing season than the intercropped companion crop/s can be used to decrease evaporation of soil water resultant from rains before and after the growing season of the alley crop.

This brings into question the possible prioritization of reduction of evaporation as the main beneficial consequence of intercropping, rather than rooting complementarity. Should intercropping systems focus on maximizing alley shading during the early growing season by allowing hedgerow shading, followed by hedgerow pruning once the alley species is established, to encourage further shading in the mid-season by the now-established alley crop canopy ?

1.3 Decreased risk through product diversification.

In his PhD thesis, Kruger (1999) stressed the global move towards monoculture as being a short-term, unsustainable answer to demands of a growing global population in need of food. He emphasized the possible long-term consequences of short-term decreased energy use efficiency and decreased production diversity due to compromised agricultural diversity.

Kruger (1999) suggested that increased biotic diversity has the following benefits:

- Increased energy use efficiency;
- Less detrimental environmental effects;
- Contribution to *in situ* conservation of genetic resource;.
- Improved use of on-farm biophysical resources and
- Improved yield stability during any particular season, as well as over a number of seasons.

After describing the 19th and 20th centuries as the industrial and technological ages, Kruger (1999) suggested that Africa, particularly, will benefit from the 21st century becoming known as the age of sustainable agricultural development. Kruger (1999) emphasised the energy-thirsty nature of modernized industrial monoculture, suggesting that the remarkable yield progress made during this revolutionary agricultural period may later compromise agricultural sustainability.

Citing Pretty (1995), Kruger used the following examples to illustrate this point:

- Doubled yields in the Phillipines during the "Green Revolution" resulted in 8-30% increases in energy consumption.
- Increased yields, in India, of 10-20% as a consequence of mechanization came at an extra energy cost of an astounding 40-260% .
- Organically-grown rice in Bangladesh, China and Latin America produces grain at an energy use efficiency 15-25 times higher than irrigated rice in the USA.

2 PROJECT OVERVIEW AND OBJECTIVES

Objectives of this project were:

- Evaluation of locally-adapted crops that may be incorporated into an agroforestry system with emphasis on water dynamics. The determination of spatial and temporal water extraction patterns from the soil profile for a given level of production for each crop. The quantification of other effects influencing the micro-climate (especially radiation) in which the accompanying crops grow.

Crops initially selected were sorghum, cowpeas and sweet potato. After the first three seasons, cowpeas and sweet potatoes were abandoned in favour of maize. Maize and sorghum are both comparatively drought-tolerant crops, which are grown successfully in areas with annual rainfall of below 500 mm, and where annual evaporation is often as much as 2000 mm. Sweet potatoes were deemed too sensitive to water stress and disease, and would probably not be productive in the climatic zones targeted by this study. Cowpeas are leguminous, and the combination of this crop with a leguminous hedgerow species (*Leucaena leucocephala*) might confound effects.

Detailed temporal and spatial water distribution patterns, as well as light interception results for various levels of productivity are discussed.

- Participatory Rural appraisal. In the “on-farm” phase of the study preliminary work to determine the availability, quality and quantity of the resources available to the target groups and the specific agricultural needs of the target groups was done. This information was to be used in the construction of applicable agroforestry systems or strategies with the aim of meeting the target groups’ needs and achieving objectives, while ensuring sustainability.

- The more detailed assessment of sustainability and ecological stability (in terms of soil parameters such as soil erosion and organic material) were to serve as criteria to determine the agronomic and economic success of the system, and as validation for the model.

Various forms and adaptations of Land Equivalent Ratios were used in an attempt to quantify the agronomic and economic values of different cropping scenarios. To further address the quantification of scenarios possible in an alleycropping system, crop and agroforestry models were considered. Validation and calibration of these models could lead to decision support systems with considerable value to this multi-faceted form of agriculture.

Crop and agroforestry models short-listed for evaluation of intercropping systems, and assisting in decision support include the following:

- SWB (Soil Water Balance) Tree model;
- WaNuLCas (Water, Nutrient and Light Capture);
- BECVOL (Biomass Estimate of Canopy Volume) and
- HyPAR

SWB is a locally-developed model based roughly on the NEWSWB model developed at Washington State University (Annandale *et al*., 2000). The ability of this model to simulate water balance and crop growth predominantly mechanistically, combined with local technical support and simple, biophysically sound inputs, made it a strong candidate for further consideration.
WaNulCas originated in Indonesia and addresses (in various degrees of complexity) numerous management and environmental factors affecting agroforestry systems. While this model is input intensive and time-consuming to run, it should not be discounted (Van Noordwijk and Lusiana, 2000).

BECVOL (Biomass Estimate from Canopy Volume) is a simplistic empirical model, which estimates tree leaf mass and volume from numerical description of canopy size and geometry. The model (described as a descriptive model – Smit, 1996) has been tested, using regression analysis, against measured biomass for six normal (single-stemmed) indigenous tree species and four coppicing species. In addition to this, it offers general models for coppicing and single-stemmed broad-leafed and microphyllous trees. In this project, measured *Leucaena leucocephala* leaf data compared fairly well to leaf and canopy estimates obtained using the general model for coppicing microphyllous trees.

HyPAR is a model based on the Hybrid and PARCH models, and was intended for simulation of agro-systems in dry areas. It has since been abandoned (Mobbs *et al.*, 1999).

3 SITE DESCRIPTIONS

Semi-arid zones are numerically classified as having aridity indices of between 0.2 and 0.5, where aridity index

$$= \frac{\text{Annual precipitation}}{\text{Annual pan evaporation}}$$

From this it is evident that "semi –arid" encompasses a wide range of environmental conditions, and, thus, includes geographic zones with a huge range of agricultural production potential. For this reason, it is necessary to consider the environmental conditions, and potential productivity, of the "on-station" (Hatfield Experimental Farm) and "on-farm" (Chuene Maja and Sekakane) trials separately.

3.1 Climatic and geographical overview of "on-station" and "on-farm" sites

Sekakane falls into a geographical zone characterized by very low rainfall (200-400 mm, Schulze *et al.*, 1997), with 400-600 mm expected in the "wettest year in 5" (Fig 3.1-3.8). This region has first frosts in June, and has a short frost-prone period of 1-30 days. Chuene-Maja cooperative site falls into a climatic zone characterised by a slightly higher annual rainfall (400-600 mm), with similar first frost dates and duration of frost period. However, site-specific conditions at Chuene (cold air drainage leading to radiation frost) differed from those associated with the region's broader climatic characteristics. Both sites have monthly evapotranspiration rates comparable to those at Pretoria (Hatfield).

Shayandima falls into a transition region between lower rainfall (400-600 mm) north-eastern Limpopo Province and higher rainfall north-central Limpopo Province (800-1200 mm). With an annual evapotranspiration similar to that of Pretoria, this area's higher rainfall makes it the least arid of all sites investigated (in both "on-farm" and "on-station trials"). It experiences little frost, and the first frost date (if any) is mid-winter (June).

Hatfield falls into a rainfall zone which stretches throughout Gauteng, and into central and southern Mpumalanga with between 600 and 800 mm of rain annually. The driest year in 5 would usually receive 400-600 mm, compared to 800-1000 mm for the wettest. In terms of aridity, this region is more arid than Shayandima, but less arid than Chuene Maja or Sekakane.

Makopane and Bela Bela (both used for water balance simulations in semi-arid areas in this chapter) could be seen as intermediate between Hatfield and Chuene Maja and Sekakane. Nelspruit experiences weather conditions more akin to those of Shayandima and Hatfield. Although Makopane, Bela Bela and Nelspruit were not included in "on-farm" and "on-station" trials, they are indicated on figures 3.1 to 3.8, since simulation of conditions in these areas has provided valuable insight into water balances in semi-arid regions.

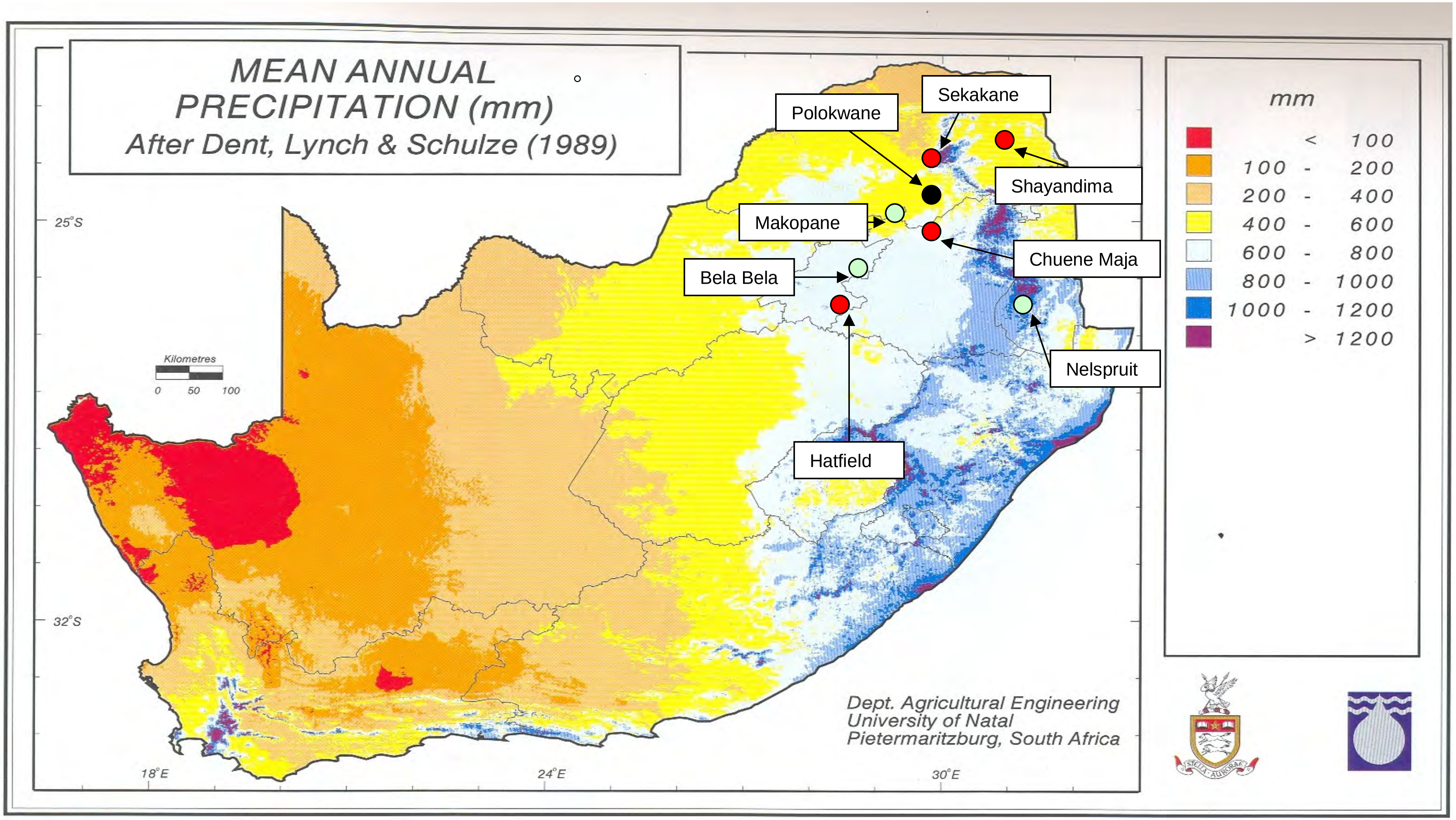

Figure 3.1 Mean annual precipitation for South African climate zones

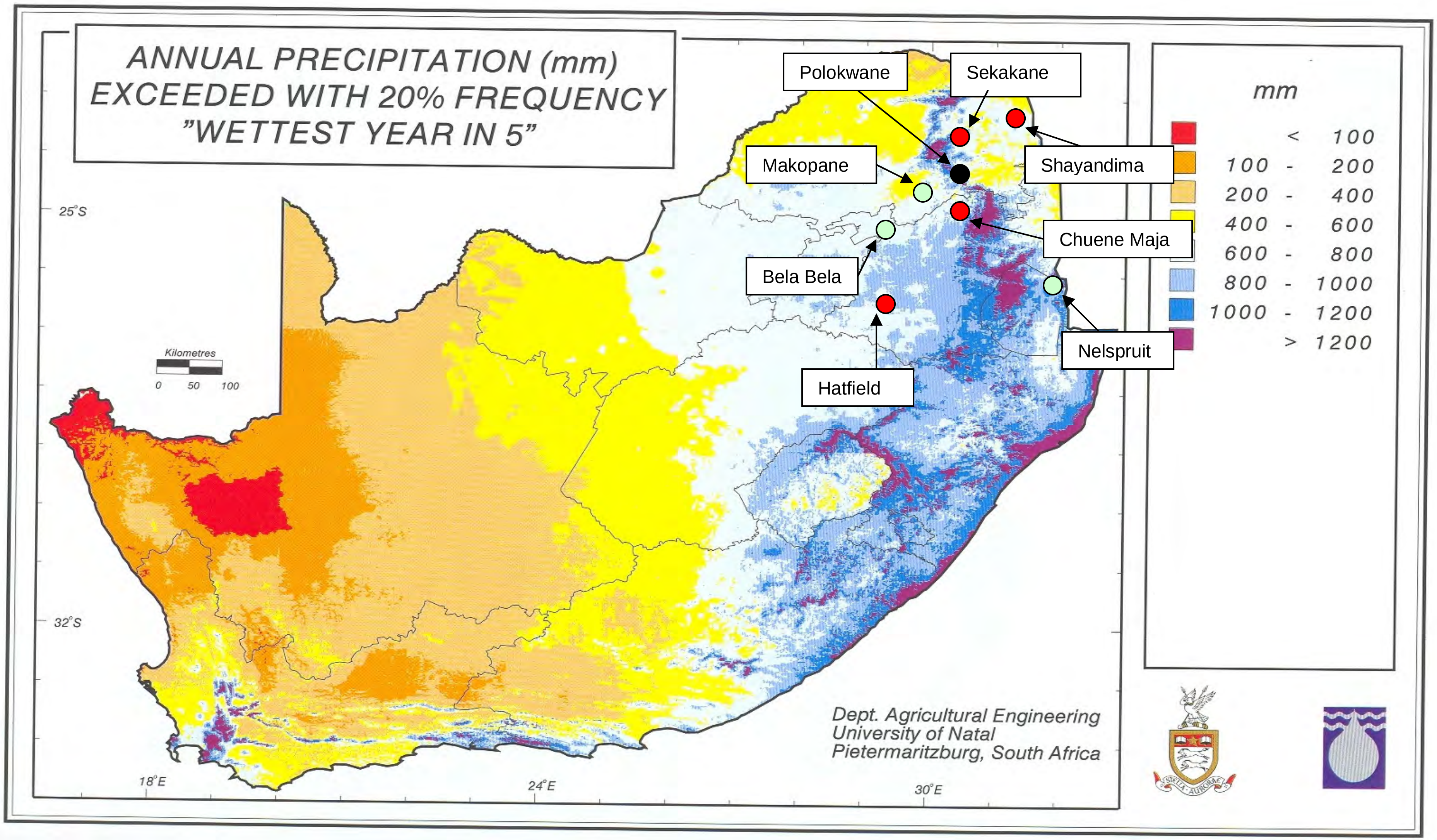

Figure 3.2 Wettest year in five for South African climate zones

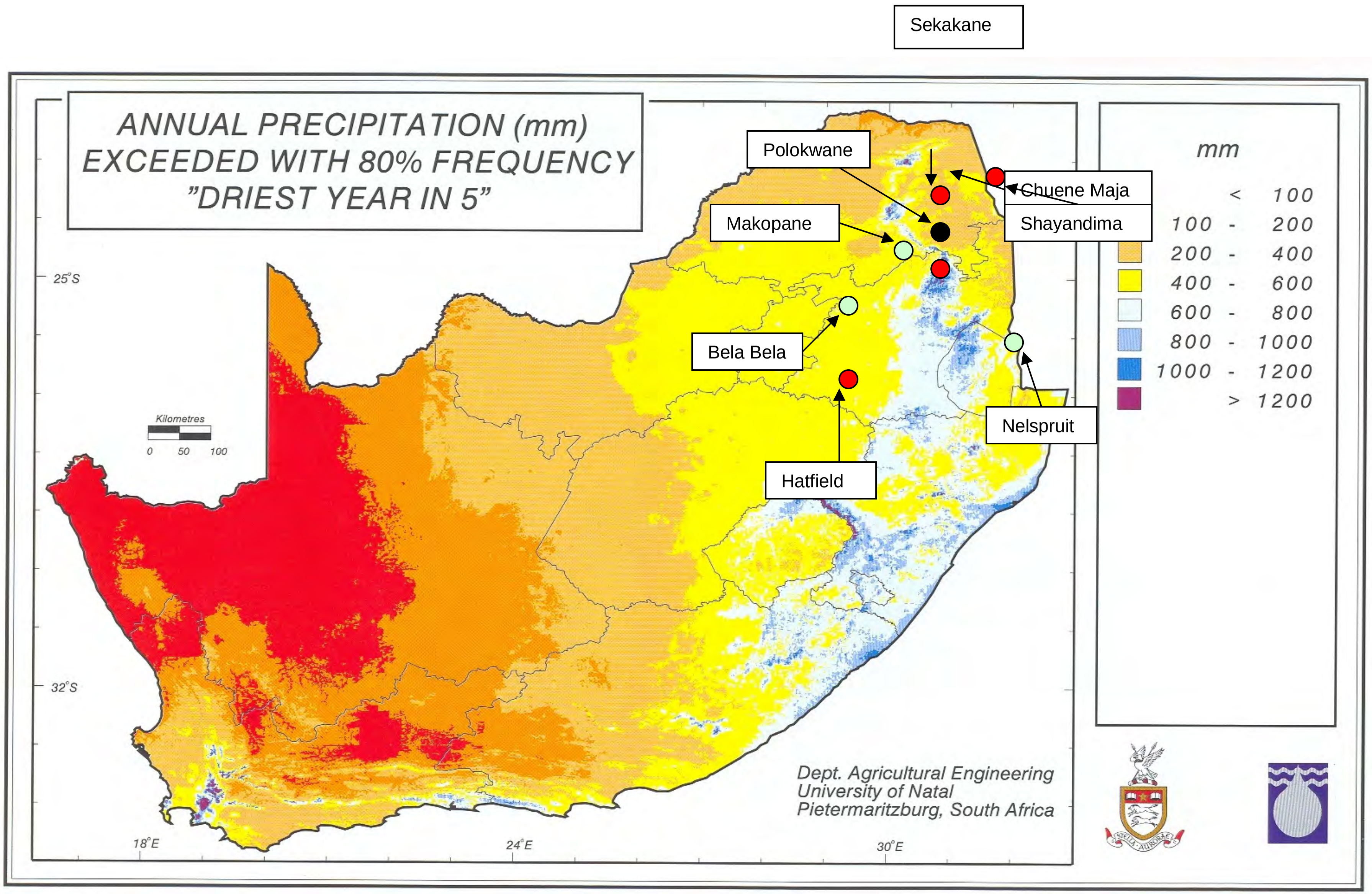

Figure 3.3 Driest year in five for South African climate zones

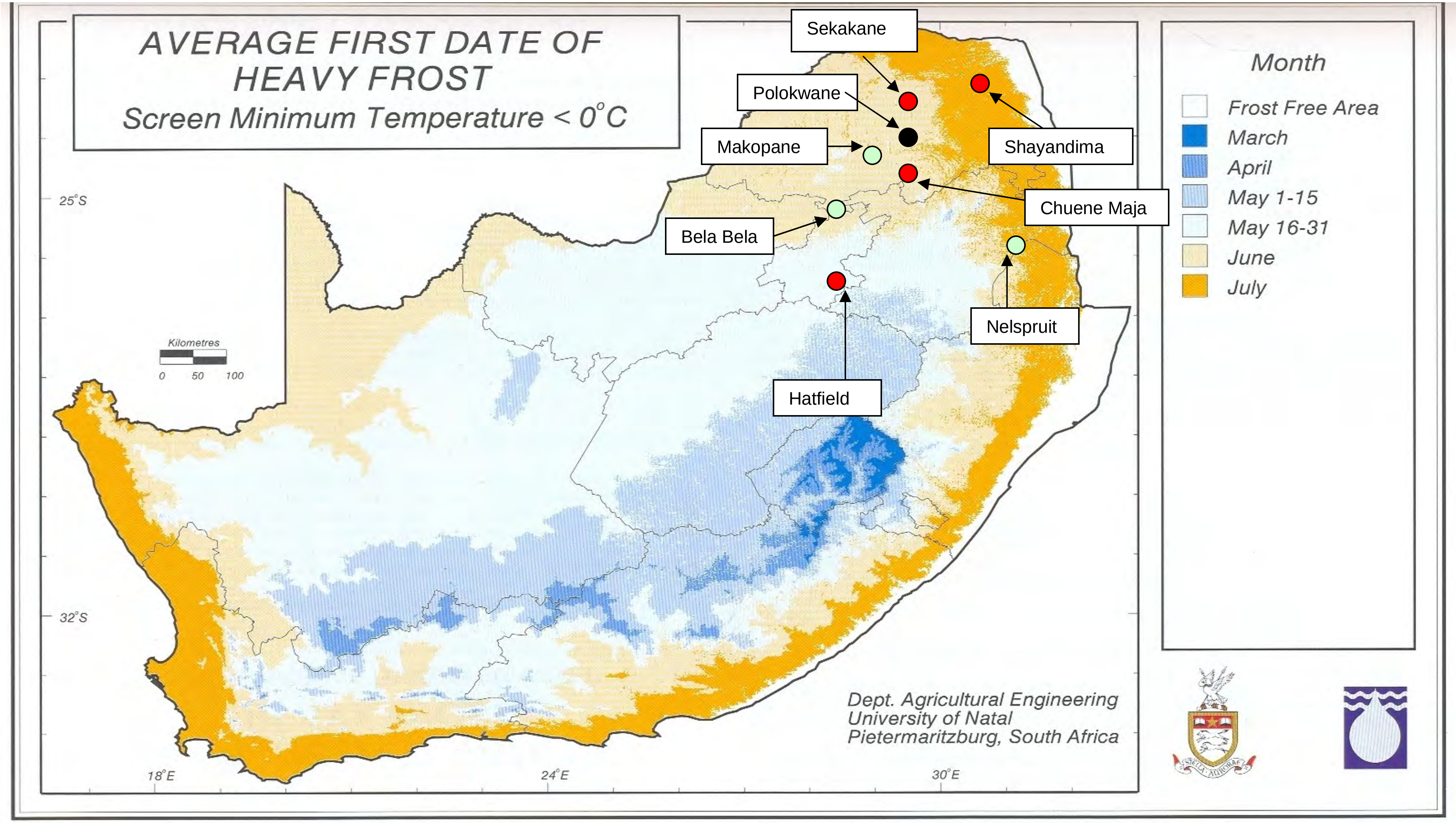

Figure 3.4 Average date of first frost for South African climate zones

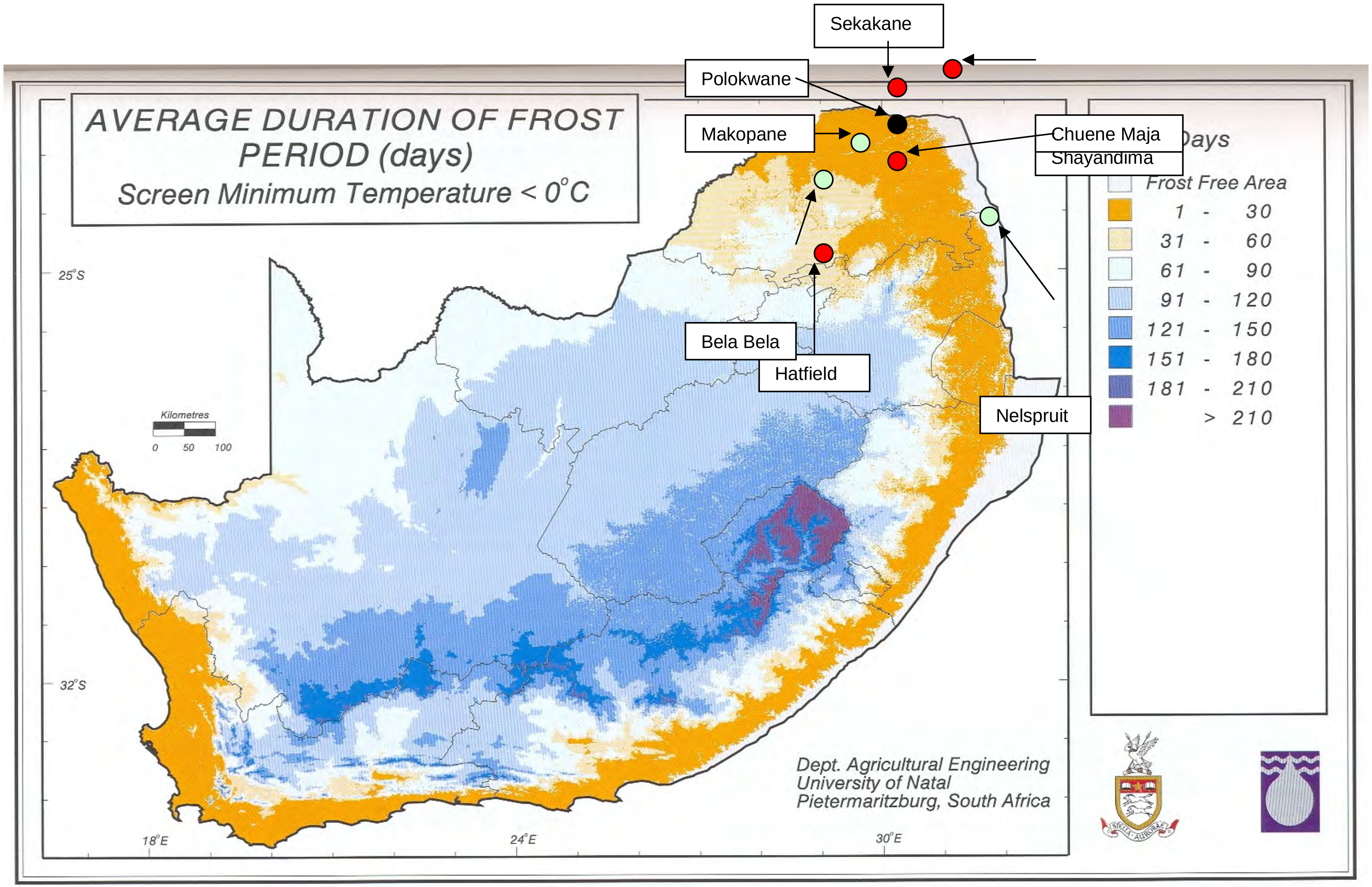

Figure 3.5 Average duration of frost for South African climate zones

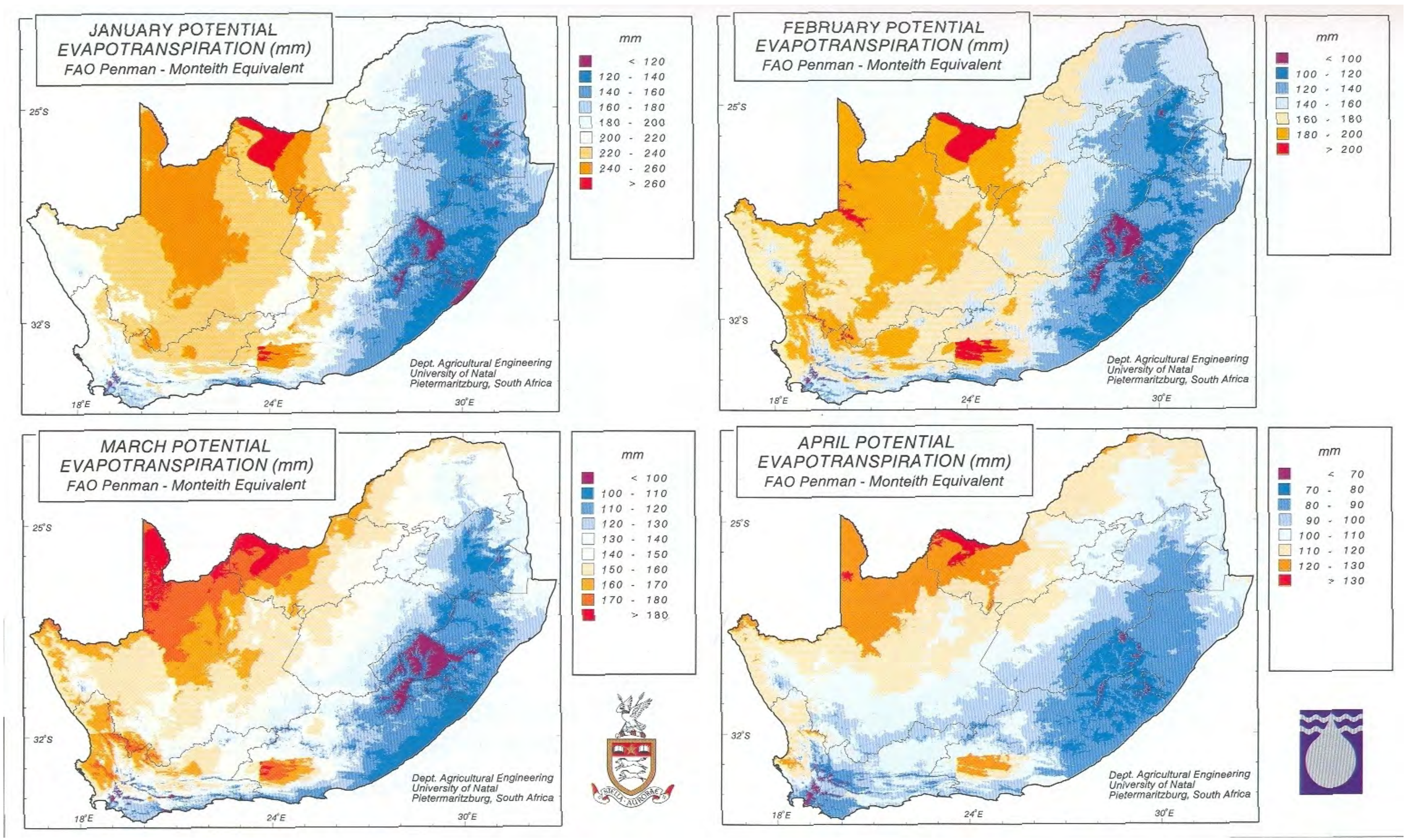

Figure 3.6 Monthly evapotranspiration (January to April) for South African climate zones

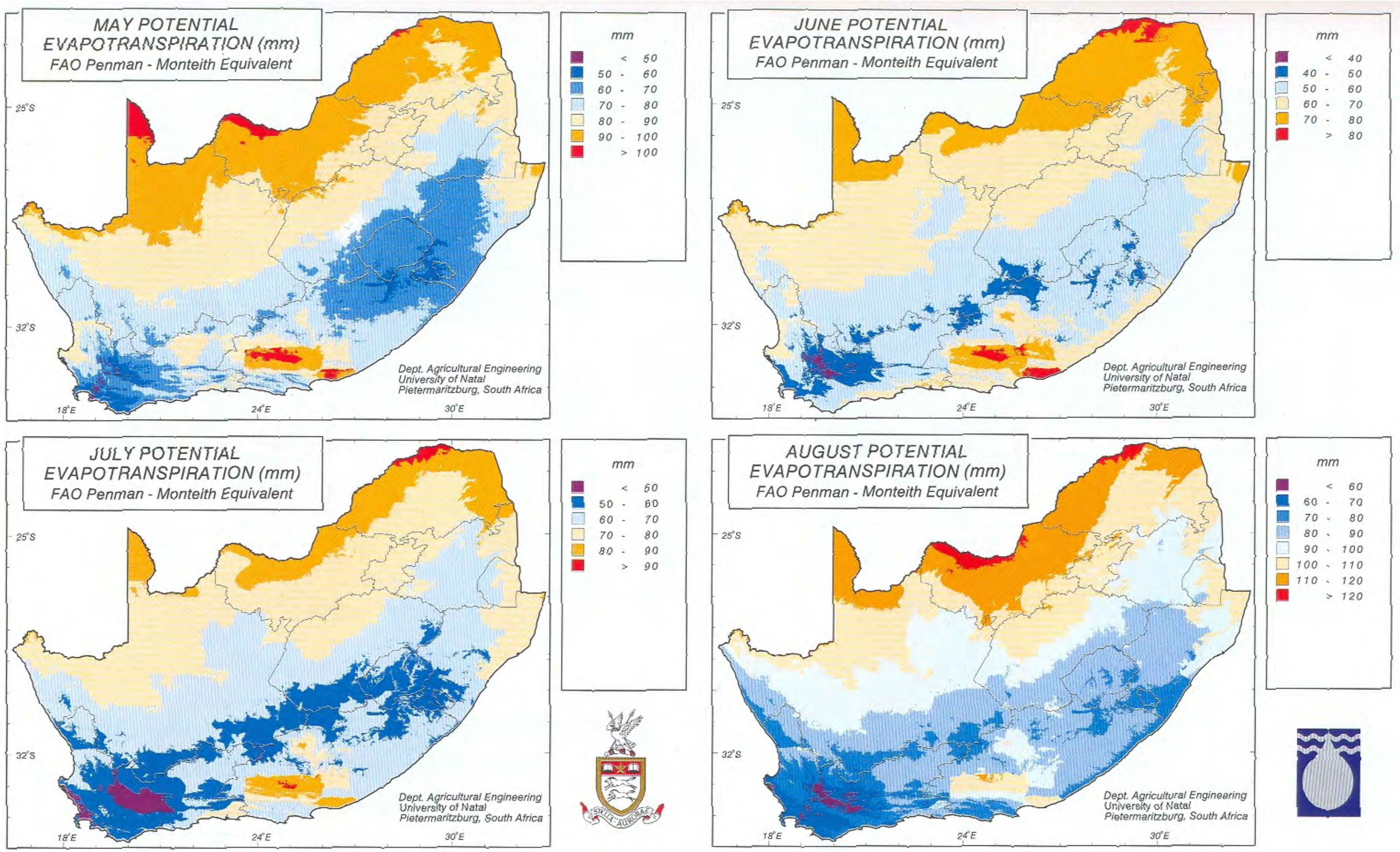

Figure 3.7 Monthly evapotranspiration (May to August) for South African climate zones

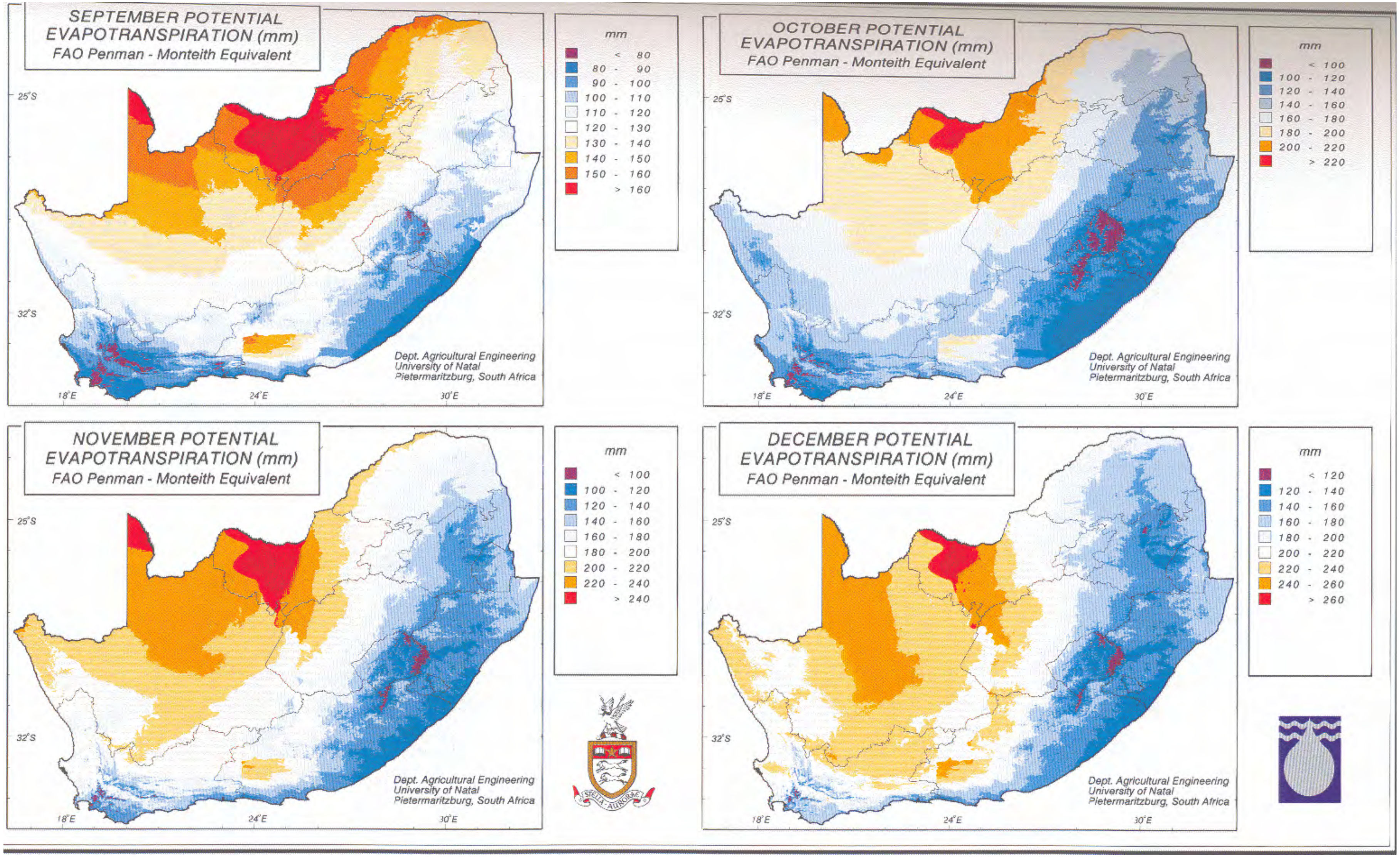

Figure 3.8 Monthly evapotranspiration (May to August) for South African climate zones

3.2 Hatfield

3.2.1 Hatfield site description

The Hatfield Experimental Farm is situated in Pretoria, South Africa (25.75º N, 28.25 º E) at an altitude of 1342 m. The long term annual rainfall for Pretoria is 674 mm. Rainfall is concentrated mostly in summer, with over 80% falling from October to March. The average annual pan evaporation is approximately 2000 mm, giving the site an aridity index of 0.3-0.35.

3.2.2 Hatfield soil descriptions

The soil on the Hatfield trial site is a Hutton (Soil Classification Working Group, 1991) or Ferrosol (FAO, 1998) ranging in texture from sand-clay-loam in the topsoil to sand-clay in the subsoil. It has a fairly high cation exchange capacity, and is well-drained, and contains a gravel layer at a depth of approximately one metre. Soil physical and chemical analyses are presented in Table 3.1.

Table 3.1 Physical and chemical characteristics of the Hutton soil found on the Hatfield trial site

Depth (cm)	Sand (%)	Silt (%)	Clay (%)
0-30	50.1	15.3	36.1
0-60	33.4	16.6	49.9

Depth (cm)	P ($mg.kg^{-1}$)	Ca ($mg.kg^{-1}$)	Ca ($meq.100g^{-1}$)	K ($mg.kg^{-1}$)	K ($meq.100g^{-1}$)	Mg ($mg.kg^{-1}$)	Mg ($meq.100g^{-1}$)
0-30	19.5	750	3.75	254	0.65	209	1.74
0-60	2.3	784	3.92	126	0.32	173	1.44

Depth (cm)	Na ($mg.kg^{-1}$)	Na ($meq.100g^{-1}$)	CEC ($meq.100g^{-1}$)	Ca+K+Mg ($meq.100g^{-1}$)	base sat	pH
0-30	1	0.0043	9.99	6.15	61.5	6.5
0-60	4	0.0174	10.78	5.70	52.9	6.5

This soil, despite being well-aerated and well-drained, contains sufficient clay to ensure good water holding capacity, with pressure plate analyses suggesting plant available water between permanent wilting point and field capacity of above 0.13 $m^3.m^{-3}$ at most soil depths (Table 3.2) Figures 3.9 to 3.13 graphically illustrate the relationship between volumetric water content ($m^3.m^{-3}$) and matric potential (kPa) for soil samples taken at the five different depths 0.2, 0.4, 0.6, 0.8 and 1 m).

Table 3.2 Results of pressure plate analysis on the Hutton soil on the Hatfield trial site

Soil depth (cm)	VWC ($m^3.m^{-3}$) at 10 kPa	VWC ($m^3.m^{-3}$) at 30 kPa	VWC ($m^3.m^{-3}$) at 100 kPa	VWC ($m^3.m^{-3}$) at 1000 kPa	VWC ($m^3.m^{-3}$) at 1400 kPa	PAW ($m^3.m^{-3}$)
0-20	0.248	0.186	0.15	0.117	0.109	0.139
20-40	0.288	0.233	0.19	0.156	0.153	0.135
40-60	0.339	0.259	0.214	0.215	0.17	0.169
60-80	0.317	0.252	0.209	0.168	0.163	0.154
80-100	0.287	0.231	0.195	0.159	0.153	0.134

Where: VWC – Volumetric Water Content.
PAW – Plant available water between Field Capacity and Permanent Wilting Point.

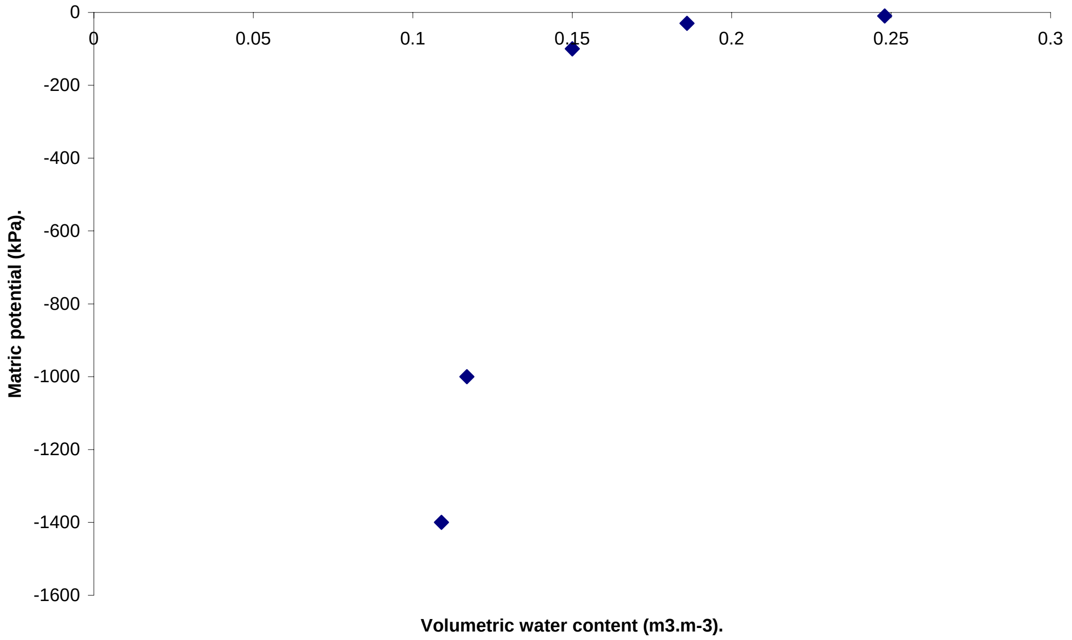

Figure 3.9 Water retention curve for soil sampled at depth 0-0.2 m

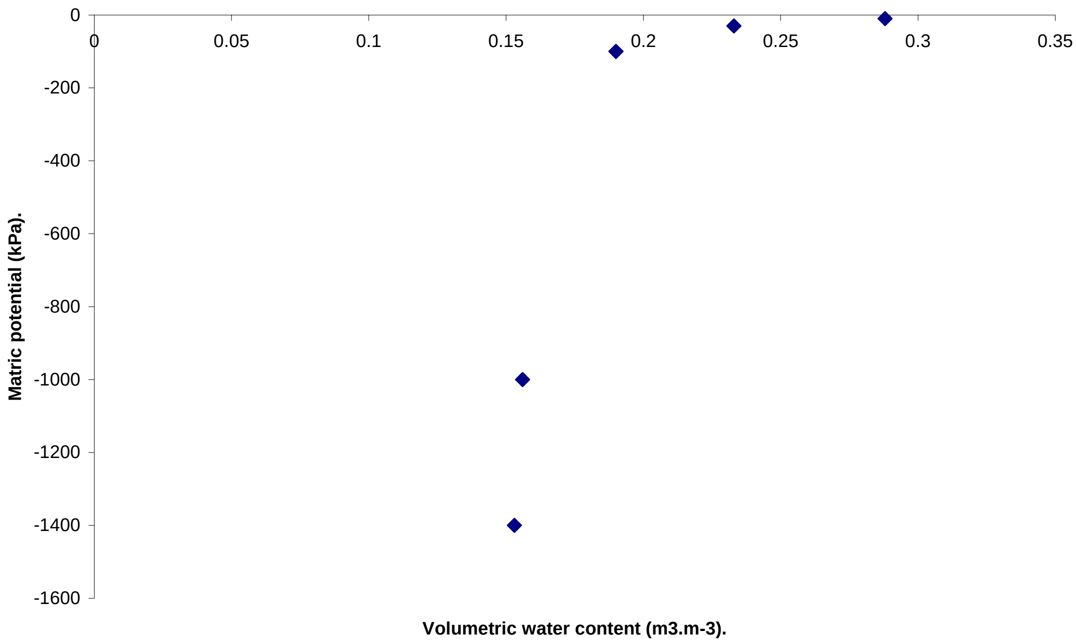

Figure 3.10 Water retention curve for soil sampled at depth 0.2-0.4 m

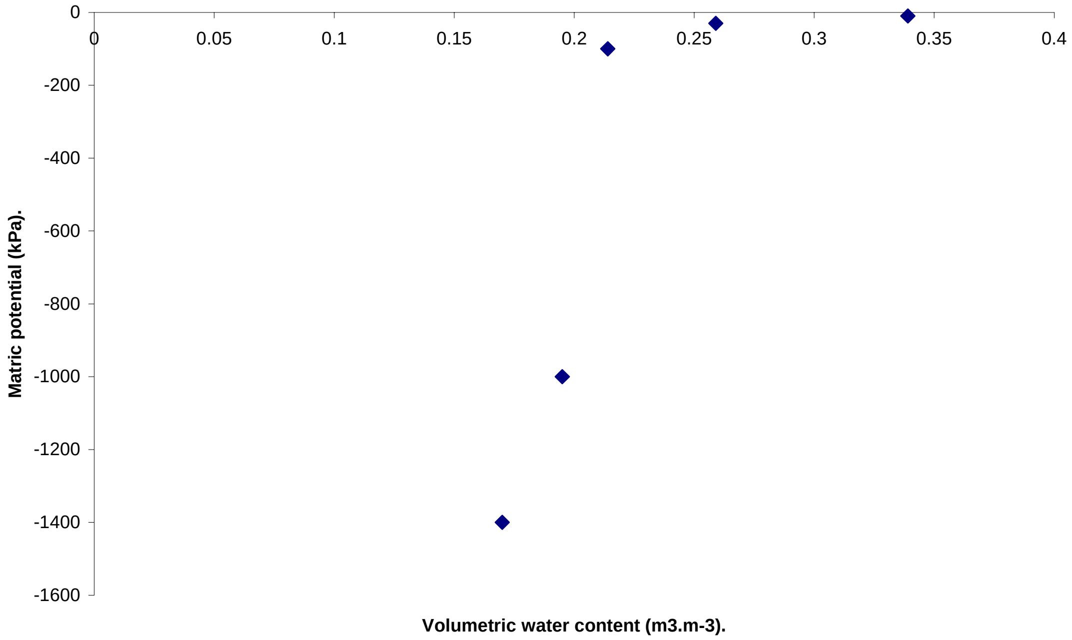

Figure 3.11 Water retention curve for soil sampled at depth 0.4-0.6 m

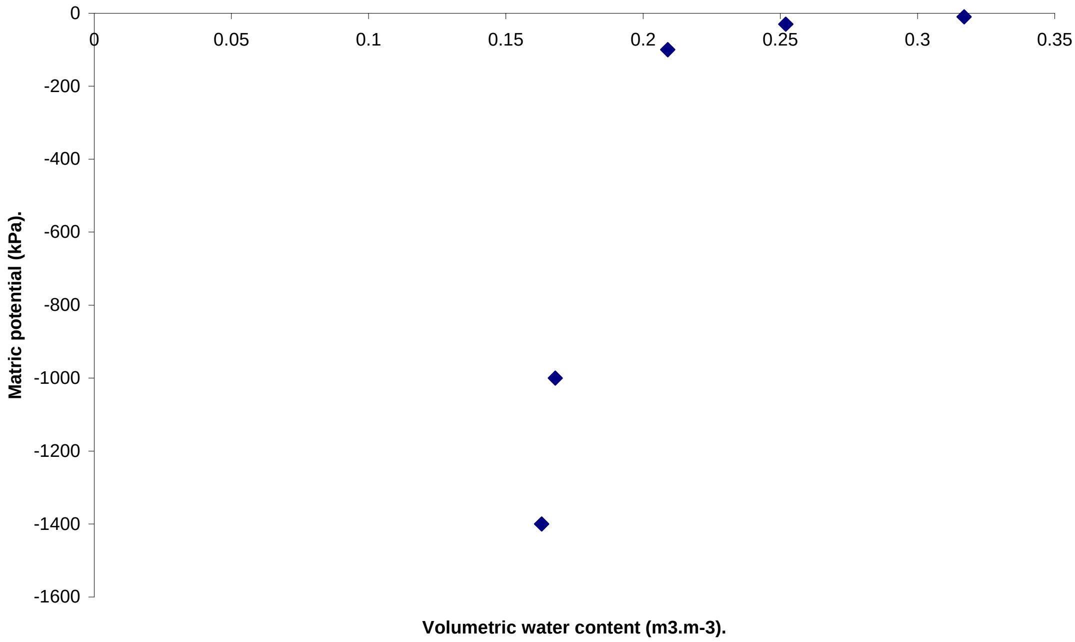

Figure 3.12 Water retention curve for soil sampled at depth 0.6-0.8 m

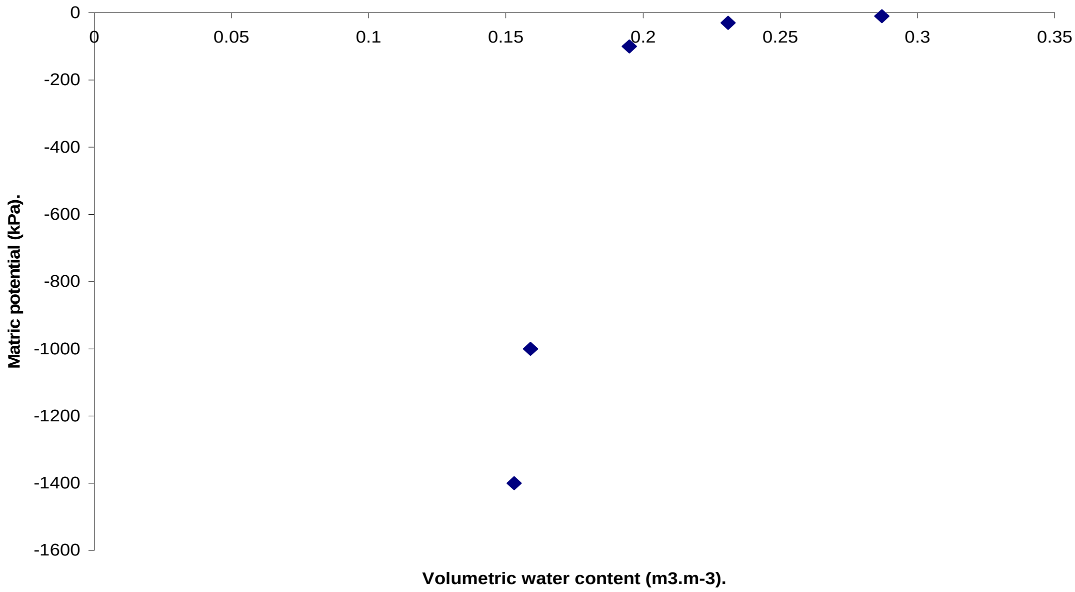

Figure 3.13 Water retention curve for soil sampled at depth 0.8-1.0 m

3.2.3 Hatfield Experimental Farm – water balance perspective from simulations

To gain perspective on the likely apportioning of rainfall and soil water into evaporation, transpiration and drainage for environmental conditions similar to Hatfield, computer simulations were run on the Soil Water Balance (SWB) crop growth model, using historical weather data sets for Pretoria. All seasons used were comparatively low rainfall seasons, with 382, 608 and 407 mm for the 1982/83, 1985/6 and 1997/98 seasons respectively. Assumptions used in the simulations included the following:

- Soil textures were loamy-sand (10% clay and 5% silt) and sand-clay-loam (30% clay and 10% silt).
- Soil depths were 0.6, 0.9 and 1.2 m. Slope was set at 0 degrees, so that no water was lost to runoff.
- Simulations were for summer cultivation of monoculture maize, with planting date set at 10 November, and season extending from 1 July (to allow filling of the soil profile prior to planting date) to 30 June the following year.
- Initial soil water content (θ_i), on 1 July was set to Field capacity (θ_{FC}), 50% Plant Available Water (θ_{50}) and Permanent Wilting Point (θ_{PWP}). For the loam-sand soil, θ_{PWP} was 0.071 and θ_{FC} 0.195. For the sand-clay-loam soil, θ_{PWP} was 0.167 and θ_{FC} 0.287.
- Average Grass Reference Evapotranspiration (FAO 56), from planting to maturity, was 4.12mm.day^{-1} for the 1982/83 season, 3.98 mm.day^{-1} for 1985/86, and 3.8 mm.day^{-1} for 1997/98. Pan evaporation would be slightly higher (probably between 20 and 40% higher) than this.

Results of these simulations are included in Tables 3.3 and 3.4.

Sandy-clay-loam soil simulation

The highest proportion of water potentially available for growth (soil water + rainfall) was during the 1985/86 season (Table 3.3). Simulations indicated that high transpiration in this season resulted in rapid plant growth, and consequential low proportional total (soil and leaf) evaporation. Simulated drainage beyond depth 1.2 m for this season occurred when θ_i was set to θ_{FC} and θ_{50}, but not at θ_{PWP}. For the 1997/98 season, simulated drainage beyond 1.2 m only occurred when θ_i was set to θ_{FC}. Simulated drainage for the 1982/83 season was 0 for all values of θ_i.

Table 3.3 Apportioning of water into components for simulations for a sandy-clay-loam soil on the Hatfield Experimental Farm

Season	`	1982/1983			1985/1986			1997/1998		
		*PWP	50% PAW	FC	PWP	50% PAW	FC	PWP	50% PAW	FC
1.2	**T	7	95	239	377	381	381	99	214	255
	E	368	341	288	230	237	244	290	258	261
	D	0	0	0	0	60	125	0	0	41
	Y	200	700	4500	10300	10600	10600	200	2000	4100
0.9	T	7	107	190	334	334	334	98	162	169
	E	368	261	306	234	241	248	289	271	277
	D	0	0	0	32	79	126	0	0	41
	Y	200	400	3000	8600	8600	8600	200	900	1200
0.6	T	7	44	128	237	237	237	98	119	119
	E	367	367	326	245	252	260	287	289	296
	D	0	0	0	104	133	162	0	12	41
	Y	200	300	1800	5100	5100	5100	200	200	200

Where * PWP-Soil volumetric water content set to permanent wilting point at the beginning of the simulation,
FC - Soil volumetric water content set to field capacity at the beginning of the simulation.
50%PAW - Soil volumetric water content set to 50% of Plant Available Water (between wilting point and field capacity) at the beginning of the simulation.
** T – Cumulative Transpiration over the growing season (mm),
E - Cumulative Total Evaporation over the growing season (mm),
D - Cumulative Drainage over the growing season (mm),
Y – Yield ($kg.ha^{-1}$)

Loamy-sand soil simulation

Simulated drainage beyond 1.2m for the coarser-textured sandy-loam soil was understandably slightly higher than for the sandy-clay-loam soil (Table 3.4). As with the sandy-clay-loam soil, simulated drainage was highest (137 mm for the growing season) in the 1985/86 season, with deep drainage expected for all levels of θ_i. In the 1997/98 season, simulated deep drainage only occurred with θ_i set to θ_{FC}. Simulated drainage was negligible (1mm over the entire growing season) irrespective of level of θ_i in the 1982/83 growing season.

In summary, for the rainfall and weather conditions appropriate to drier seasons in Pretoria, drainage beyond 0.6 m occurred in 5 of the 9 scenarios ,and drainage beyond 1.2 m in only 3 of the 9 scenarios. Furthermore, simulations suggested total evaporation was a greater depleter of water than transpiration in 7 of the 9 scenarios tested. Generally, in semi-arid environments, transpiration constitutes a smaller proportion of total water balance (Kinama et al., 2005).

Compared to transpiration and evaporation, drainage generally comprised a far smaller component of the total water balance. These simulations summarise the situation in semi-arid zones, indicating that the greatest gains in agroforestry could be obtained by manipulating management to decrease evaporation rather than by decreasing drainage. Complementarity of root distribution between crop and tree species in alleycropping systems may improve water use efficiency in regions where rainfall is higher (resulting in drainage of water to soil depths inaccessible to crop species, but accessible to hedgerow trees). In drier, semi-arid areas, it is unlikely that water absorbed from deeper soil layers will be replenished in subsequent seasons, making the sustainable maintenance of soil water in these deeper layers almost impossible, and thus negating any advantage of interspecific root complementarity.

In 6 of the 9 modelled scenarios on this soil type, total evaporation caused the greatest loss of water. It appears that the greatest benefit of intercropping in semi-arid zones could be through management practices orientated towards decreased total evaporation rather than through root complementarity.

Table 3.4 Apportioning of water into components for simulations for a Loamy-sand soil on the Hatfield Experimental Farm

Season		1982/1983			1985/1986			1997/1998		
Soil depth (m).		*PWP	50% PAW	FC	PWP	50% PAW	FC	PWP	50% PAW	FC
1.2	**T	8	102	246	384	384	384	109	242	264
	E	347	328	277	216	223	231	268	238	245
	D	0	0	1	4	70	137	0	0	46
	Y	200	800	4600	10500	10500	10500	200	3000	4600
0.9	T	8	78	201	340	340	340	110	186	188
	E	347	339	288	219	226	234	265	246	254
	D	0	0	1	41	89	138	0	0	46
	Y	200	500	3100	8700	8700	8700	200	1400	1500
0.6	T	8	131	135	255	255	255	154	162	162
	E	347	229	316	227	235	242	251	263	270
	D	0	0	1	114	144	173	0	17	47
	Y	200	300	2000	6000	6000	6000	1500	1400	1400

Where * PWP-Soil volumetric water content set to permanent wilting point at the beginning of the simulation,
FC - Soil volumetric water content set to field capacity at the beginning of the simulation.
50%PAW - Soil volumetric water content set to 50% of Plant Available Water (between wilting point and field capacity) at the beginning of the simulation.
** T – Cumulative Transpiration over the growing season (mm),
E - Cumulative Total Evaporation over the growing season (mm),
D - Cumulative Drainage over the growing season (mm),
Y – Yield (kg.ha^{-1})

3.3 Shayandima

Shayandima is situated at 30° 33' E x 23° 03' S at an altitude of 600 m.a.s.l. with an average annual rainfall of 872 mm (concentrated in the summer months).

3.4 Sekakane

3.4.1 Sekakane site description

The Sekakane Garden Vegetable Project adjoining the Sekakane Village is situated approximately 60 km north of Polokwane, on the Tropic of Capricorn The people involved are a well organized co-operative group, confronted with the problem of how to utilize their dryland cropland. A relatively small proportion of the total area available for cropping was used for vegetable production under irrigation and in the area this group identified the need for fruit trees (to generate extra income) and shade trees (to provide relief for the labour during the hot summers).

3.4.2 Sekakane soil description

The soil profile description conducted in the first season placed the soil in the Glenrosa form with 15% clay. Although it tended to crust (probably because of the lack of organic material) the chemical analysis was generally favourable with a pH (H2O) if 6.1, P content of 20 $mg.kg^{-1}$, Ca content of 582 $mg.kg^{-1}$,Mg content of 138 $mg.kg^{-1}$ and K content of 242 $mg.kg^{-1}$.

Apparently this site had been used as a demonstration plot by a seed company several years previously and had been clean fallowed since then.

3.5 Chuene-Maja

3.5.1 Chuene Maja site description

This co-operative site is situated 40km south of Polokwane (about 100 km south of the Tropic of Capricorn) on the Chuene Maja Hydroponic Project, where villagers from Ga-Chuene and Ga-Maja (north-west of Strydpoort Mountains) were primarily occupied with vegetable production under irrigation. They were interested in how to utilize their dryland croplands with crops intercropped between trees compared to mono-cultural systems. This site, although somewhat warmer than the Sekakane site, was also characterized by very poor rainfall conditions. Chuene Maja had similar rainfall conditions as those at Sekakane (low and highly variable within and between seasons) but the site appeared to be more prone to radiation frost because of cold air drainage.

3.5.2 Chuene Maja soil description

Soils at Chuene Maja are a poorly-developed, clayey Clovelly form with an A horizon containing >50% clay (very prone to crusting) above a subsoil with >60% clay. As such they could be regarded as marginal for cropping. The soil had an average pH (H_2O) of 7.0, Ca of 2500 $mg.kg^{-1}$, Mg 500 $mg.kg^{-1}$, K 255 $mg.kg^{-1}$, but a P content of only 3 $mg.kg^{-1}$.

3.6 Chuene Maja and Sekakane – water balance perspective from simulations

The “on-farm” sites are arid, with the annual rainfall in a number of growing seasons below 250 mm. Simulations for Chuene Maja and Sekakane were based on weather data obtained for Makopane (24.18º S, 29.0 º E), Nelspruit (25.43 º S, 30.98º E) and Bela Bela (24.88º S, 28.28 º E). Simulations were run (using a planting date of 15 November) on the SWB model for monoculture maize. Soil depth was set at 0.9 m, with soil water holding capacity similar to the levels obtained by pressure plate analysis for the Pretoria Hutton soils. Data for these stations were for the following seasons:

Bela Bela	1989/90, 1990/91 and 1996/97 seasons
Makopane	1986/87, 1989/90 and 1990/91 seasons
Nelspruit	1986/87, 1994/95 and 1995/96 seasons

The initial soil water content (at planting) was set at field capacity. With a well-drained profile, with high levels of plant available water (as found at Hatfield), this is highly unlikely to occur in reality. This soil scenario was chosen, however, to allow maximum possible simulation of drainage, so as not to underestimate possible deep drainage. Despite this already wet starting scenario, deep drainage below rooting depth of over 100 mm over the season was only evident in three of the nine simulations. What is more, most simulations showed a gradual drying of the deeper soil zones, with little restoration of water levels in these zones. If a central purpose of agroforestry is to improve system water use efficiency through circulation of deeper-drained water and nutrients by trees, insufficient water would likely reach the deeper soil zones in semi-arid areas. In reality, soil profiles would generally be far drier than the simulated profiles, necessitating filling beyond field capacity before onset of drainage.

Figures A 1 to A 9 in the appendix summarise water balances at Bela Bela, Makopane and Nelspruit. Figures A 10 to A 27 (0.1-0.4 m and 0.5-0.8 m layers) show water balance summaries, as well as volumetric water content ($m^3.m^{-3}$) per 0.1 m for the three seasons at each site.

In eight of the nine simulations (Table 3.5) the soil water content below a depth of 0.6m had decreased to permanent wilting point levels by late January, without replenishment. The single exception (the 1995/96 season in Nelspruit) was an exceptional season, with nearly 1000 mm falling in the growing season alone. It is improbable that soil layers deeper than 0.6 m would be repeatedly refilled in more than 10% of all growing seasons. This makes the expectation of benefiting from complementary rooting depths associated with intercropping seem unrealistic.

Table 3.5 Summary of total precipitation, and simulated apportioning of water into transpiration, evaporation and drainage for three seasons at three representative sites in the Limpopo Province

	NELSPRUIT			MAKOPANE			BELA BELA		
Season	1986/ 1987	1994/ 1995	1995/ 1996	1986/ 1987	1989/ 1990	1990/ 1991	1989/ 1990	1990/ 1991	1996/ 1997
*P	291	240	935	450	320	497	489	367	470
T	224	235	251	270	182	393	271	262	232
E	174	136	203	232	223	188	221	170	221
D	1	11	473	62	60	32	115	6	111

Where * P - Cumulative Precipitation over the growing season (mm),
T – Cumulative Transpiration over the growing season (mm),
E - Cumulative Total Evaporation over the growing season (mm),
D - Cumulative Drainage over the growing season (mm),

4 METHODOLOGY

4.1 Experimental design and layout of "on-station" research

4.1.1 Intercropping trial

The intercropping experiment at Hatfield was constructed in a modified completely randomized design. Although the trial site was large with dimensions of the intercropping trial being 88 m x 36 m, chemical and physical analyses of soil revealed no gradients across the trial site. Alley treatments in the first three cropping seasons consisting of three crops (sweet potatoes, cowpeas and sorghum), each replicated six times, are summarised in Table 4.1.

Table 4.1 Description of intercropped row treatments in the three seasons from 1999/2000 to 2001/2002 for each alley crop

Treatment	Row number
1	1 m North of the E-W orientated hedgerows
2	2 m North of the E-W orientated hedgerows
3	3 m North of the E-W orientated hedgerows
4	4 m North of the E-W orientated hedgerows
5	5 m North of the E-W orientated hedgerows
6	6 m North of the E-W orientated hedgerows
7	7 m North of the E-W orientated hedgerows
8	8 m North of the E-W orientated hedgerows
9	9 m North of the E-W orientated hedgerows
10	10 m North of the E-W orientated hedgerows
11	11 m North of the E-W orientated hedgerows
12	12 m North of the E-W orientated hedgerows

In the 2002/03 season, when sweet potatoes, cowpeas and sorghum were replaced with sorghum and maize, row treatments were confounded by the effect of the previous crop. Treatments, replicated three times, in this season are presented in Table 4.2.

Table 4.2 Description of intercropped row treatments of test crops (sorghum and maize) in the last two seasons from 2002/2003 to 2003/2004, when they were planted following either cowpeas, sweet potatoes or sorghum (the test crops in first three seasons)

Treatment	Previous crop	Row number
1	Cowpeas	1
2	Cowpeas	2
3	Cowpeas	3
4	Cowpeas	4
5	Cowpeas	5
6	Cowpeas	6
7	Cowpeas	7
8	Cowpeas	8
9	Cowpeas	9
10	Cowpeas	10
11	Cowpeas	11
12	Cowpeas	12
13	Sweet potatoes	1
14	Sweet potatoes	2
15	Sweet potatoes	3
16	Sweet potatoes	4
17	Sweet potatoes	5
18	Sweet potatoes	6
19	Sweet potatoes	7

20	Sweet potatoes	8
21	Sweet potatoes	9
22	Sweet potatoes	10
23	Sweet potatoes	11
24	Sweet potatoes	12
25	Sorghum	1
26	Sorghum	2
27	Sorghum	3
28	Sorghum	4
29	Sorghum	5
30	Sorghum	6
31	Sorghum	7
32	Sorghum	8
33	Sorghum	9
34	Sorghum	10
35	Sorghum	11
36	Sorghum	12

4.1.2 Pure stands

In the 1999/2000, 2000/2001 and 2001/2002 seasons, the pure stands were laid out in a completely randomized design, with plots for sorghum, cowpeas and sweet potatoes, replicated six times. In the 2002/03 seasons and 2003/04 seasons plots there were nine replications, with maize and sorghum following sorghum, cowpeas or sweet potatoes planted in the first three seasons.

Statistical analyses

Differences between treatments were determined using analysis of variance (ANOVA) using MSTATC MS-DOS-based statistical software for multifactoral analysis. For single factor analysis, the NCSS statistical package was used with differences between treatments determined with the 2-sample T test. When statistical differences existed, means were separated using the Least Significant Difference (LSD) test at the 5% level of significance.

Field measurements comprised two main components, namely yield quantification, and quantification of interspecific competition for light and water. The yields of all alley crops and Leucaena hedgerows were measured. While the intercrops were harvested only at maturity, the hedgerows were harvested twice each season, in December (when the intercrops were planted) and again in early winter (after the intercrops had been harvested). Quantification of resources prone to interspecific competition included the following:

- measurement of radiation interception by Leucaena hedgerows with different orientations; and
- measurement of soil water content over time, at different points, to quantify spatial and temporal water distribution patterns of water in the intercropping system.

4.2 Experimental design and layout of “on-farm” research

4.2.1 “On-farm” and community development methodology

The objectives of the project with particular relevance to this section are:

- Using rural appraisal techniques to determine the availability, quality and quantity of resources available to the target groups. The specific agricultural needs and objectives of the target groups should also be ascertained.

- To construct applicable agro-forestry systems or strategies with the aim of meeting target groups’ needs and achieving objectives, while ensuring sustainability.

It was decided to concentrate "off-station" inputs in Limpopo Province. To this end three "on-farm" sites with communities in Shayandima, Sekakane and Chuene Maja were identified.

4.2.2 Shayandima / Dzindzi

This project was initiated in cooperation with the Tshwane University of Technology (TUT) with Prof W van Averbeke. Mr Johan van der Walt of the University of Pretoria was going to use the results for an M. Tech Degree and was assisted in the first season by two undergraduates and one post-graduate from TUT and 10 community members in the planting, fertilisation, irrigation and measurement of the fodder trees and grasses chosen for adaptation to the sub-tropical, sub-humid local climate. This was proven by the excellent growth registered in the first six months after an autumn planting. When, however, the UP participant (Mr J van der Walt) left for "greener pastures" it was decided to terminate the inputs from UP as – although a sylvo-pastoral alley cropping/agro-forestry system should do very well under such ecological conditions – these were totally different from the targeted semi-arid conditions.

4.2.3 Sekakane

4.2.3.1 Establishment and layout

Although the alley or intercrop area was not supposed to be planted in this establishment season (to minimize any competition for the young trees) the community did crop this strip and the adjacent control block with maize for their own use. This maize was, however a minimum of 1.5 m from the tree rows, so that competition between the young trees and the maize was minimal. By comparison, compared with the "on-station" trials at Hatfield, the trees were very vigorous and well established (up to 3 m tall) and intercrops were planted 0.5 to 1 m from the tree rows, with consequent strong competition.

It was on the dryland cropping area that the co-operative demonstration plot involving an alley cropping plot with two rows of Leucaena 20 m apart, interplanted with maize, was compared with a pure stand of maize. In the 2002/2003 season Leucaena saplings were planted in October. Because of the very dry season (220 mm) supplementary bucket watering of the saplings on several occasions was needed. In the winter, at the end of this establishment season, half the trees were pruned to a height of 30-35 cm to encourage coppicing. The remainder of the trees were pruned to a single stem. The original intention had been to monitor the performance of Leucaena trees, with and without water harvesting and with three pruning treatments. Practicalities, however, forced all trees to be planted with water harvesting basins (rainfall in the three experimental seasons was only 220, 260 and 120 mm respectively). Half of the trees were pruned to a single stem to a height of 1.5 m and the harvested material separated into edible and non-edible components. The former included leaves, flowers/pods and fine trimmings, while the latter was restricted to branches with a diameter of more than 5 mm. The other half of the trees were pruned to a height of 0.3-0.35 m each winter and the harvested material separated into the different components. The trees coppiced prolifically and were hence referred to as the "coppice Leucaena".

4.2.3.2 Collection of data

Observations in the 2002/2003 season were restricted to tree survival. In the 2003/2004 season the Leucaena trees were assessed in July 2004 in terms of fuel wood, leaf and pod yield from the two pruning treatments after the intercrop had been harvested in May. The maize (a short season hybrid cultivar) had only been planted in the first week of January. With 15 rows (1m between rows and 0.25m within rows) in the alley – maize was 3m from the tree rows, which minimized tree/maize competition but reduced the area planted to maize drastically. There were 30% fewer maize plants/ha on the alley crop block than on the monoculture block. With the low populations (18000-21000 per ha) the very moderate level of fertilisation (200 kg kraal manure per ha) was not a limiting factor, especially as weed control was generally very good.

4.2.4 Chuene Maja

4.2.4.1 Establishment and layout

The Leucaena saplings, also planted at this site in October 2002, were subject to similar rainfall conditions as those at Sekakane (low and highly variable within and between seasons), and were subject to the same pruning treatments and assessment as those at Sekakane.

<u>2003/2004 and 2004/2005</u>

Unfortunately neither the intercrop between the Leucaena trees nor the mono-culture row crop was planted in these seasons. There had been a change in the management group and despite repeated visits it was not possible to get our co-operators to do much more than hand weed the trees.

4.2.5 Community Development

The goal of the community orientated "on-farm" work was "to increase the viability of small scale farmers in semi-arid areas through the application of agro-forestry principles". A rural appraisal programme would be followed by an "on-farm" research and extension programme, where the farmers would be trained to apply agro-forestry techniques and conduct basic evaluations. After the evaluation phase these projects could then be developed into demonstration plots for other farmers.

The first step in the process was to identify target areas, communities, types of arable condition, etc. of potential co-operators in such a Farm Systems Research & Extension (FSR-E) programme, aimed at the optimization of alley-cropping systems in semi-arid conditions. In this context competition for water needed to be minimized while attempting to meet livestock needs using leguminous browse for protein supplementation, provision of mulch or green manure material and the supply of kindling and fuel wood. The following questionnaire helped orientate the thinking of the group (Ms CC Botha, Mr JJ Cronje and officials from the Limpopo Department of Agriculture).

1 - name and address
2 - job description
3 - community (where you live or work)
4 - dependency on agriculture
5 - land tenure
6 - livestock production
  - products
  - fodder
  - kraal at night
  - feeding in kraal
7 - crop production
  - crop choice
  - combination of crops
  - planting & harvest dates
  - seedbed preparation
  - soil limitations
  - fertilisation
8 - weed control
9 - climate
  - average rainfall
  - rainy season
  - frost occurrence
10 - soils
11 - topography
12 - energy sources

Having identified two sites, Sekakane and Chuene Maja (which with hindsight would appear to have been too dry for all but the most drought-tolerant crops and definitely too dry for maize production) the project team (Ms CC Botha, and Mr CS Keen) in consultation with the Department of Agricultural Economics, Extension and Rural Development of the University of Pretoria (Mr J Stevens) designed a simple questionnaire, based on the original questionnaire and a generic example from an agro-forestry training manual, for use at information days for the surrounding communities. These days were held in May 2003 at the end of the establishment season (trees were planted in October 2002). Before the questionnaires were completed, the concepts and basic principles of agro-forestry were explained by means of pictures and practical examples.

Parties invited to these information days, (invitation lists were compiled in consultation with the local extension officers) included villagers, neighbouring farmers, representatives of the Limpopo African Farmers Union, educators and senior learners as well as community leaders.

"AGROFORESTRY QUESTIONNAIRE"

Name
Village
Size of immediate family
Home Language
Occupation of head of family
Occupation of other family members
Land rights outside of the homestead
How long have you lived here?
Are there more/or less trees now than 25 years ago?
Does the family collect firewood in the veld? Who collects?
Does the family use other sources of fuel? What?
Is wood used for heating?
Preferred trees for fuel
Trees which are never cut for fuel
Does the family sell any wood?
Does the family or community grow trees for fuel? Woodlots.
Does the family own livestock? What sort?
Where are they fed?
What are they fed?
Do you have fruit trees?
Where are these grown?
Who owns and harvests the fruit?
Would you consider producing tree seedlings?
Would you prefer trees for fuel, fruit or fodder?

The "keystone" project planned for the community development thrust was the masters study of Tebogo Timothy Mohlasedi, a student in the Department of Agricultural Economics, Extension and Rural Development.

Working under the leadership of Mr J Stevens (M. Inst. Agrar) and Ms CC Botha (B. Inst. Agrar Hons in Rural Development and MSc in Agro-forestry) his proposed title was "The acceptability of agro-forestry technology in two rural areas in the Limpopo Province". The objectives of this study were to:

- identify the socio-economic characteristics of households which may influence adoption;
- determine the perception and attitudes of the community about the introduction of agro-forestry technology, and
- identify the constraints that can influence the adoption of agro-forestry technology.

Pre-survey interviews were conducted with extension officers and farmers to assess and refine the proposed questionnaires. The proposal was to use semi-structured interviews in groups to obtain information on community interactions, especially to those not involved/engaged in agro-forestry technology. Alternatively a small number of farmers would be surveyed to compare those involved in, or exposed to, agro-forestry with those who are unfamiliar with the concept.

4.3 Interspecific competition for resources

4.3.1 Light

Leucaena (*L. leucocephala*) trees were established in rows in November 1991, with an in-row spacing of 1 metre in North-South and East West orientations, and cut each season in summer (December) and winter (June) to a height of 0.5 m. By the time of this study (the 1999/2000 season), the trees were well established, reaching a maximum height in June of approximately 3.3 metres.

Decagon Sunfleck ceptometers were used to measure Photosynthetically Active Radiation (PAR - $\mu mol.m^{-2}.s^{-1}$). Measurements were taken at hourly intervals, at ground level, with the ceptometer held parallel to the hedgerows. For the north-south orientation, measurements were taken at 1 metre intervals, east and west of the hedgerows. For the east-west orientation, measurements were taken at 1 metre intervals, north and south of the hedgerows. All PAR measurements were taken until the nearest metre after the edge of the shade cast by the trees. The final measurements were thus taken in full sunlight.

Measured data from both sides of the two orientations were then combined to represent the situation between hedgerows at different distances (i.e. alleys of different widths). Graphs were compiled for hypothetical alleys 7, 9 and 13 metres wide. Measured PAR was processed, and converted into fractional transmission of PAR as follows:

Fractional transmission per row (T_f) = Sum of PAR recorded per row / Sum of PAR recorded in open sunlight (i.e. maximum incident PAR) per row.
For general comparison of T_f between orientations, the average T_f per orientation for a specific day was calculated as follows:

T_f (average) = sum of PAR measured in all rows / Sum of PAR recorded in open sunlight (i.e. maximum incident PAR) in all rows.

Data was collected on various days throughout the year. In certain cases, the predominance of diffuse radiation (due to cloud) prevented the use of parts of, or entire, data sets. Graphs compiled were for November, March and June – collected on 22 March (07:00 to 17:00), 12 June (09:00 to 11:00) and 9 November (10:30 to 14:30).

An Excel-generated spreadsheet was developed to generate solar declination, solar zenith angles, day length and sunrise and sunset times.

Calculations were as follows:

Solar declination = 0.39785*sin {278.97 + 0.9856*J + 1.9165 sin (356.6 + 0.9856*J)}
, where J is the calendar date, with J=1 at Jan 1. (Campbell and Norman, 1998).

Solar zenith angle = $\cos^{-1}$\{sin (latitude) * sin (declination) + cos (latitude)*cos (declination)*cos ($t-t_0$),
where t0 = 12-LC-ET,

LC is the longitude correction and ET is the equation of time

ET = (-104.7sin f + 596.2 sin2f +4.3 sin 3f – 12.7sin4f -429.3cosf -2cos2f+19.3cos3f) / 3600, where f = 279.575 + 0.9856J, in degrees.

Solar declination was used to predict sun tracking at different times and dates, so that measured results could be analysed in terms of sun positions.

4.3.2 Water

To quantify spatial and temporal water distribution patterns in the system, time domain reflectometry (TDR) technology was used. TDR probes were placed at the following positions over various periods:

In the 2000-2001 growing season, probes were positioned at depths of 0.05, 0.2, 0.6, 0.9 and 1.5 m at 2, 4 and 6 metres on either side of the EW orientated hedgerow, and under the *L. leucocephala* hedgerow. The alley crop was cowpeas. At the start of this study, the Leucaena was nearly 10 years old, and was pruned to a height of 0.5 m each winter. Each growing season, the vigorous coppice regrowth was harvested at the time that the annual alley crops were planted (usually in December) and again in the winter.

In the 2001-2002 growing season, probes were positioned at depths 0.2, 0.6, 0.9 and 1.5 m at 2 and 4 metres on either side of the hedgerow, and under the hedgerow. Deep (1.5 m) probes were positioned 6m on either side of the hedgerow. The alley crop was sorghum.

Positions of probes in the 2002-2003 season remained the same as in 2001-2002. The alley crop was maize.

Volumetric water content (VWC) was measured over the following periods:

- 2000-2001 - DOY 1-75 (representing water extraction patterns during early growing season)
- 2001-2002 – DOY 64-134 (representing water extraction patterns during mid growing season) and DOY 192-275 (representing winter water extraction patterns)
- 2002-2003 – DOY 1-64 (representing water extraction patterns during early growing season), where DOY is Julian day of year, so that DOY 1 is 1 January.

The TDR was programmed to record VWC bihourly. Daily data was used to describe general spatial and temporal water dynamics, while bihourly data was used for stem flow analysis and VWC response to rainfall events.

VWC was converted into matric potential (Ψm) using a combination of gravimetric soil sampling, pressure plate analysis and estimation of upper and lower limits of plant available water (PAW) with TDR data.

For the 0.05, 0.2 and 0.6 m probes, pressure plate analysis and gravimetric sampling revealed similar upper levels of plant available water to TDR data.

Pressure plate analyses were carried out on soils at depths 0-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8 and 0.8-1 m. Pressures applied to the soil were 10 kPa (an estimate of Matric Potential at field capacity volumetric water contents), 30 kPa, 100 kPa (an estimate of the lower level of easily available volumetric water content), 1000 kPa and 1400 kPa (an estimate of the volumetric water content at permanent wilting point (PWP)).

Pressure plate analyses of soil around the 0.9 and 1.5 m probes was not used to convert VWC into Ψm. Gravimetric sampling returned values for VWC at field capacity (VWC_{FC}) far in excess of those obtained through pressure plate analysis. Examination of the upper drained limits of TDR corroborated the gravimetrically-determined values for VWC_{FC} and volumetric water contents at permanent wilting point (VWC_{PWP}). A possible reason for the poor estimation of VWC_{FC} with pressure plate analysis was the discontinuity caused by the occurrence of a gravel layer at depths 0.80-1.0 m in the intercropping areas.

Water retention curves (curves relating VWC to Ψm) for the 150 cm probes were based on gravimetric sampling.

Results discussed in this study were based on a combination of VWC (to understand absolute water dynamics) and Ψm (to attempt to quantify levels of moisture stress in soil layers of different textural classes). Graphed matric potentials (Ψm) were expressed as soil matric suction, where matric suction is the negative equivalent of matric potential. A matric suction of 1500 kPa would be the equivalent of a matric potential of -1500 kPa. Matric potential was graphed in this manner because large variations in matric potential between different soil zones made it necessary, in certain instances, to illustrate these potentials on logarithmically-scaled graphs and it is not possible to express negatives logarithmically.

4.4 Agronomic yields of hedgerows and intercrops in "on-station" trials

In the first three seasons (1999/2000, 2000/2001 and 2001/2002), sorghum, sweet potatoes (cv. Mafuta) and cowpeas were planted in alleys between hedgerows of *L. leucocephala.* Initial planting was from 15 December. In the 2001/2002 season, plots needed to be replanted on 15 Jan, after seed predation by birds reduced plant populations. Plots were irrigated after planting with approximately 20 mm of water to ensure sufficient surface moisture content for good germination.

In the 2002/03 season, maize (cv. Phb 33A13) and forage sorghum (cv. Sugargraze) were planted in alleys, followed by maize (cv. Phb 33A13) and grain sorghum (cv. MR Buster) in the 2003/04 season.

Leucaena saplings were planted in 1991 in EW orientated hedgerows, with an inter-row spacing (alley width) of 12 m, and 1 m spacing in the rows. Alley crops were planted in 12 alley rows parallel to the Leucaena hedgerow, starting at a distance 0.5m from the hedgerow. The first (pre-planting) pruning in December comprised largely leaf material and young stems sprouting from the coppicing, multi-stemmed Leucaena, while the second harvest in June, after a longer growing period, was comprised mostly of woody material, after a longer growing period. Analysis of six years of weather data taken between 1985 and 1998 suggested that minimum temperatures usually begin to approach 0° C around mid-May, and these frost-prone conditions may continue until around mid-September (DOY250).

In order to calculate land equivalent ratios (LER), yield and/or other differences between pure and intercropped stands needed to be quantified in terms of separate yield components.

Harvested Leucaena material was sun-dried until leaves fell off the branches. Woody material was separated into soft stems suitable for animal consumption, and firewood. All plant components were then oven dried at 65° C for 48 hours.

Alley-cropped species (sorghum, maize, sweet potatoes and cowpeas) were separated into their components according to suitability for human and animal consumption, and dried at 65° C for 48 hours.

5 RESULTS AND DISCUSSION – INTERSPECIFIC COMPETITION

5.1 Light

November

In November solar declination angles vary from -14.14 ° (South) on 1 November to -21.6 °(South) on 30 November. Sunrise occurs south of East, reaching midday with a zenith angle of between 12.8° (1 November) and 6° (30 November). These high solar elevation angles (low zenith angles) should result in decreased shading on the southern side of the EW orientation. For this reason, sun tracking at this time of the year was expected to favour the EW orientation more markedly.

Measured fractional transmission supported this expectation. With the 13 metre alley, in the EW orientation (Fig 5.1.1), six of the 12 alley rows received the full radiation load. Although the northern side of the alley received more radiation than the southern side, the differences were less marked than in the March measurements.

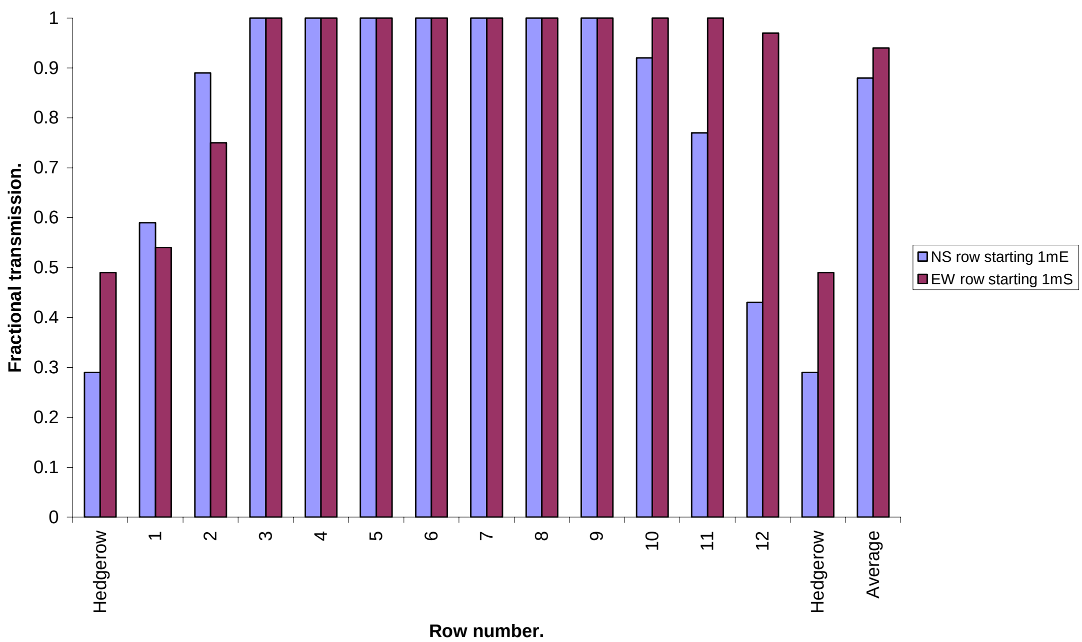

Figure 5.1.1 Fractional transmission of PAR in November in a hypothetical 13 metre alley

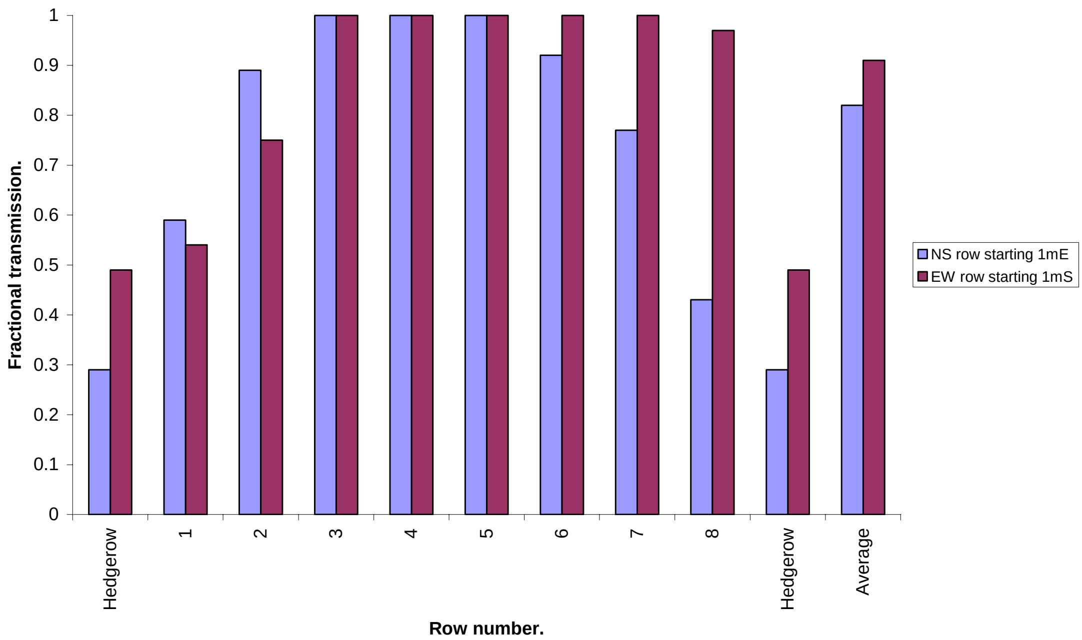

Figure 5.1.2 Fractional transmission of PAR in March in a hypothetical nine metre alley

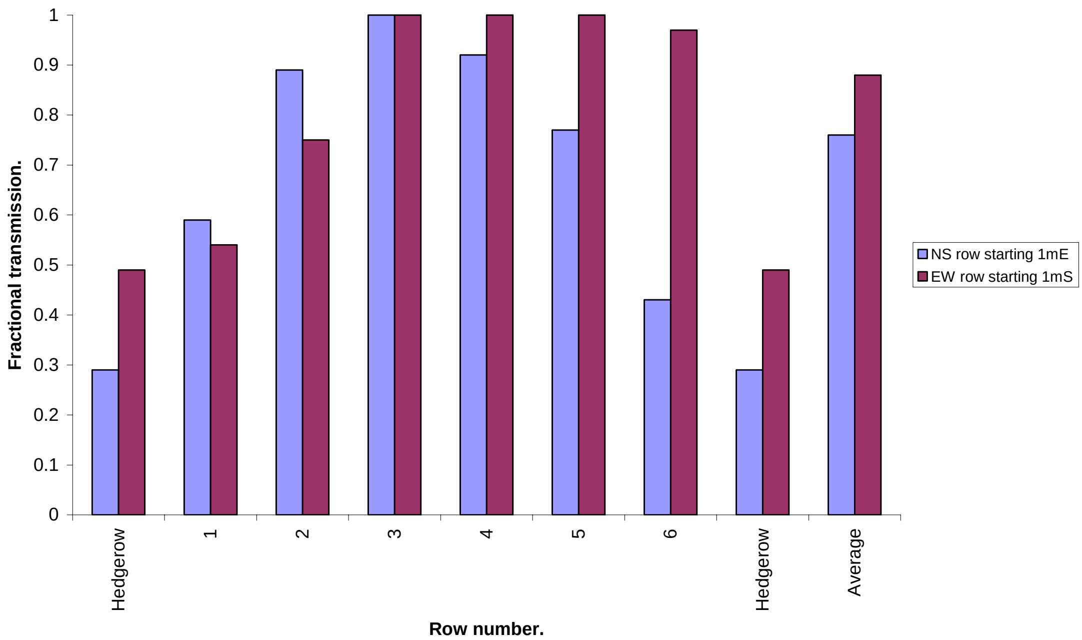

Figure 5.1.3 Fractional transmission of PAR in November in a hypothetical seven metre alley

Transmission of almost all incident radiation on the northern side of the EW orientation, coupled with a comparative increase in radiation transmission on the northern side, made this orientation more effective in transmitting radiation to the intercrop than the NS orientation. The result was a higher average transmission in the EW orientation (T_f =0.94) than the NS orientation (T_f=0.88) for the 13 metre alley.

Differences between radiation transmission for the different orientations were even greater with the nine metre alley (Fig 5.1.2). The average transmission for the EW orientation was 0.91, compared to 0.82 for the NS orientation. This tendency was further emphasised in the nine metre alley (Fig 5.1.3), where differences between average T_f for the orientations increased further (0.88 for the EW orientation, compared to 0.76 for the NS orientation).

Zenith angles in November at Hatfield become smaller around midday, so that less shading of the southern sides of alley crops occurred. This appears to be the time of year of maximum benefit for intercropping with an EW orientation at these latitudes.

March

During March (Autumn), solar declination varies from nearly -8 ° (South) on 1 March to nearly 4 ° (North) on 31 March, with an average declination of 2°. Sunrise occurs nearly due east, reaching midday with a zenith angle of between 17.8° (March 1) and 29.6° (31 March). Radiation interception is expected to occur predominantly on the southern side of an EW orientation, with an even distribution on both sides of a NS orientation.

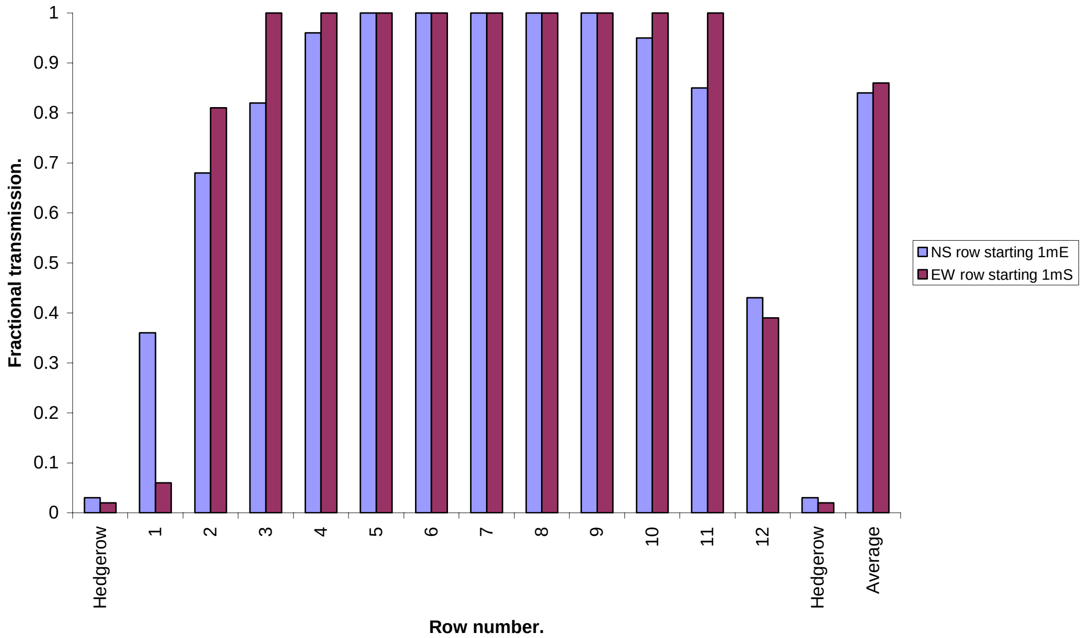

Figure 5.1.4 Fractional transmission of PAR in March in a hypothetical 13 metre alley

Measured data (Fig 5.1.4) confirmed this expectation. In the 13 metre alley, fractional transmission (T_f) for the rows closest to the hedgerows (1 and 2 metres distance) was lowest on the southern side (rows 1 and 2) of the EW orientation. T_f for the NS orientation showed a more uniform curve, with the first three rows on either side of this orientation receiving less than the full radiation load. Average T_f favoured the EW orientation marginally (0.86 for EW orientation, 0.84 for NS orientation).

T_f for the nine metre alley (Fig 5.1.5) was also slightly higher in the EW orientation (0.78) than in the NS orientation (0.76). As with the 13 metre alley, central alley rows received the full radiation load in the EW orientation (T_f was 1 for rows 3 to 7). Most central rows in the NS orientation experienced some radiation interception, but lower transmission values on the southern side of the EW orientation counteracted central alley advantages of this orientation with the nine metre alley.

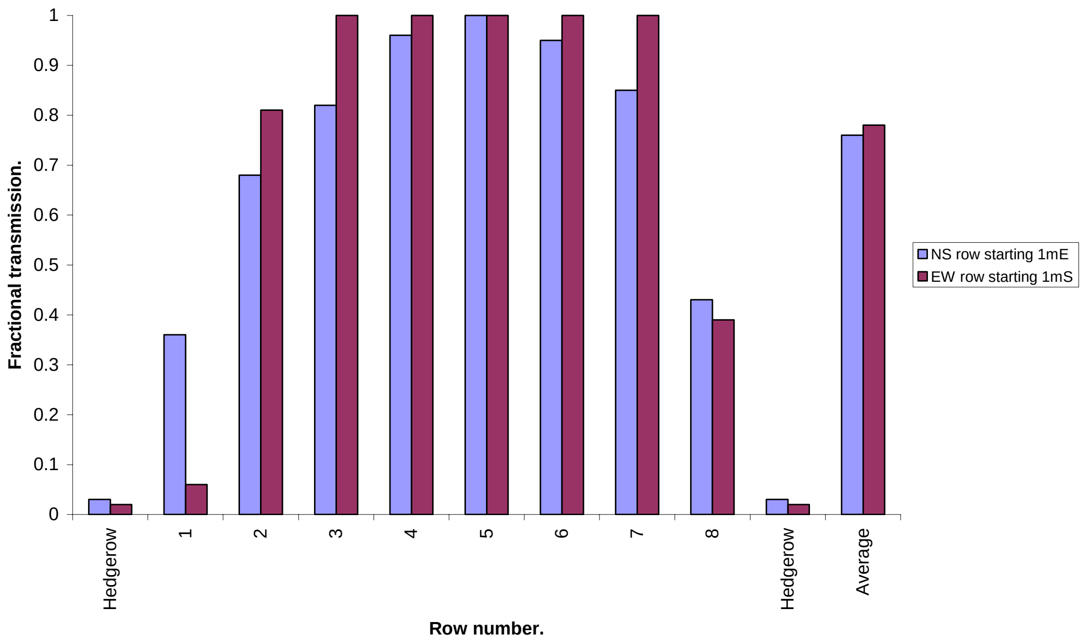

Figure 5.1.5 Fractional transmission of PAR in March in a hypothetical nine metre alley

In the seven metre alley (Fig 5.1.6), three of the central rows in the EW orientation received the full radiation load. All rows in the NS orientation experienced some level of shading. As with the nine and 13 metre alleys, transmission in the central rows of the EW orientation was insufficient to offset T_f losses on the southern side. Average T_f was similar for the orientations (0.68 for NS and 0.71 for EW).

The differences between T_f for the orientations were small enough to conclude that orientation has little impact on radiation transmission at this time of year at these latitudes.

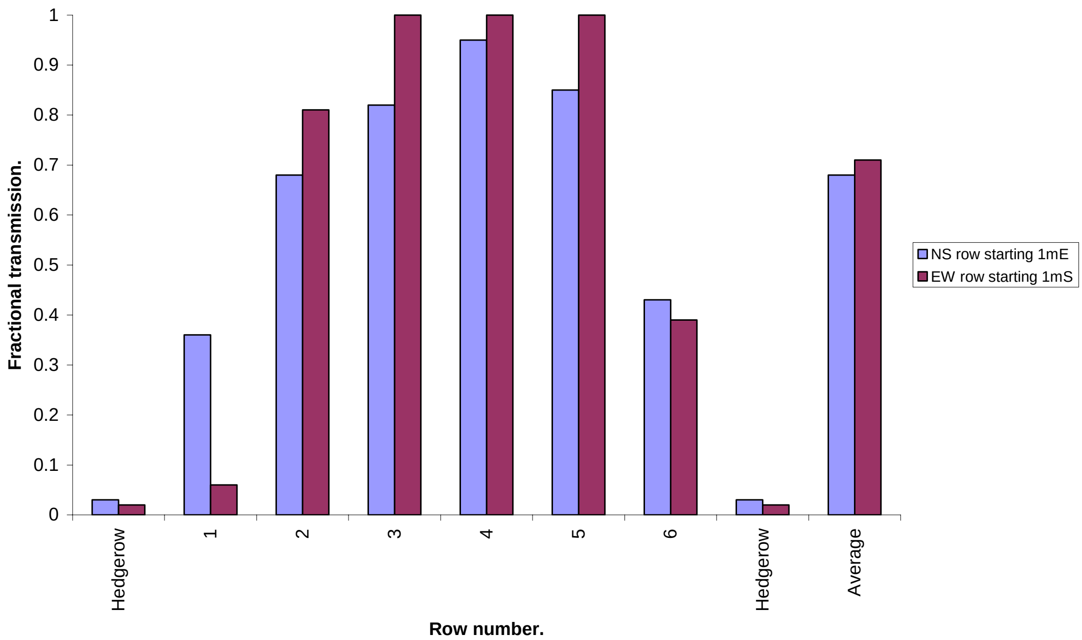

Figure 5.1.6 Fractional transmission of PAR in March in a hypothetical seven metre alley

June

In June PAR measurements were recorded at 14h30, 15h00 and 16h00 on 12 June, and 9h00, 10h00 and 11h00 on 19 June. Data was graphed for 12 June.

In June, solar declination angles range between 21.9° (1 June) and 23.2° (30 June). With the sun rising this far north of east, it was expected that shading of the southern side of the EW orientation would be more extreme.

PAR measurements (Fig 5.1.7) supported this, with four of the rows on the northern half of the 13 metre alley receiving the full radiation load, while all rows on the southern half were shaded to some degree.

The radiation transmission graph for the NS orientation was skewed to the left. The eastern side of the alley received a full radiation load in 4 of the rows on the eastern side, while the western side received a full radiation load in only 1 of the rows. This would be expected, since incident radiation would be from the eastern side before midday, and these data represent readings at 14h00-16h00 on 12 June.

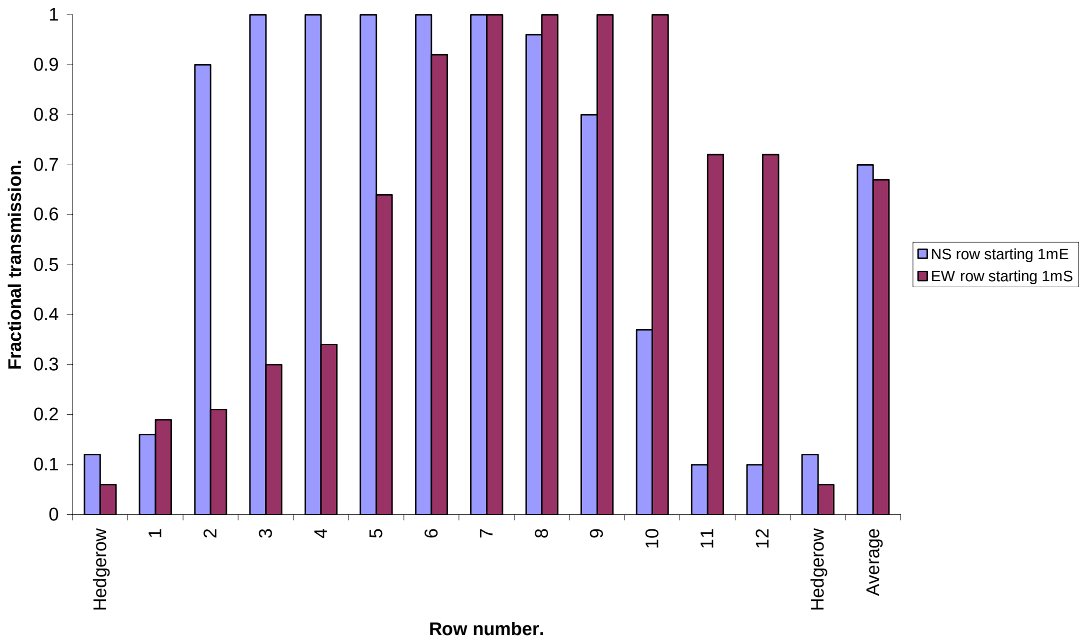

Figure 5.1.7 Fractional transmission of PAR in June in a hypothetical 13 metre alley

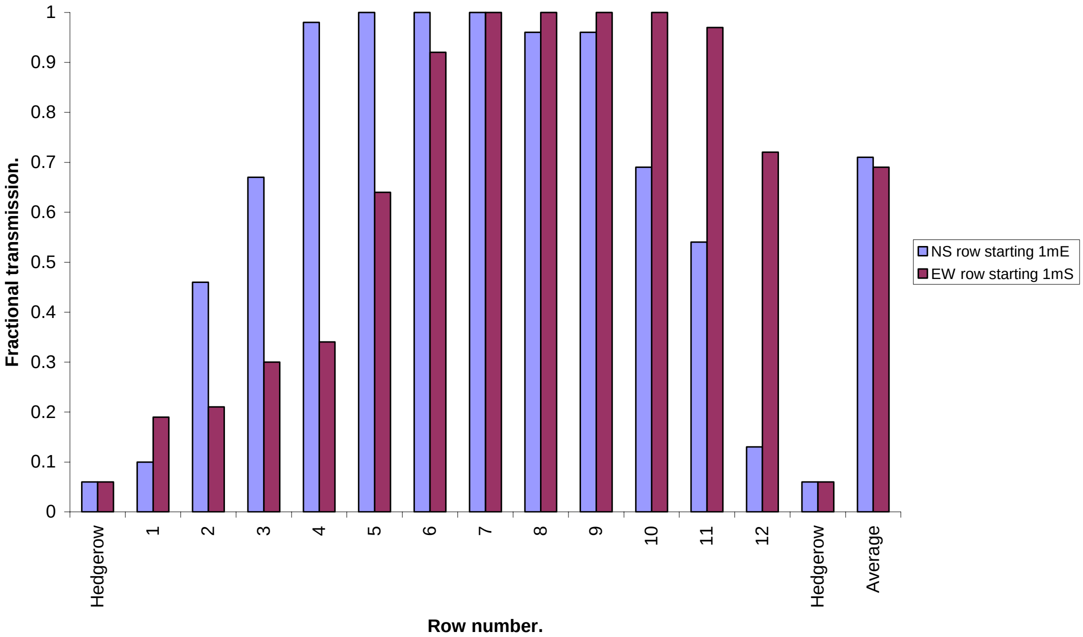

Figure 5.1.8 Reconstructed fractional transmission in June – in a hypothetical 13 metre alley

The June graph was reconstructed to include post-midday radiation. Time of solar midday was calculated as follows:

Solar midday = time of 90° sunrise + daylength/2

90° sunrise for 12 June is at 06:40 and 90° sunset is at 17:06, for a day length of 10 hours, 25 minutes.

Solar midday is at 11:53 on 12 June.

By assuming that morning radiation distribution would mirror that of the afternoon, a graph depicting shading on both sides of the NS hedgerow was created (See Fig 5.1.8).

For the first time, the June graph showed a slight overall advantage to the NS orientation. This can be ascribed to the extreme shading on the southern side of the EW orientation at this time of year.

5.2 Water

5.2.1 2000-2001 growing season

Cowpeas were planted as the alley crop in this season. Rooting depth (for cv. Saunders), according to crop parameters obtained from literature (Annandale et al., 1999) is 0.3 m.

Depth 0.05 m

Soil at the 0.05 m depth had a VWC_{FC} and a VWC_{PWP} of 0.248 and 0.109 $m^3.m^{-3}$ respectively, as determined using pressure plate analysis.

The 0.05 m probes revealed dramatic fluctuations in VWC (Fig 5.2.1). This was to be expected, since this layer was sandier than underlying soil, and was shallow enough to be strongly influenced by evaporation from the soil surface.

VWC was lowest for the probes 6 m on either side of the hedgerow, and highest for probes positioned closer to the hedgerow. This may be ascribed to shading of adjacent alley rows (especially those within 2 m of the hedgerows) by the Leucaena hedgerows. Although hedgerows were pruned prior to planting of the intercrop, the regrowth by 1 Jan 2001 appeared to be sufficient to influence radiation distribution and evaporation in the alley crop area.

Dramatic daily fluctuations in moisture were also illustrated by the Ψm values (Fig. 5.2.2). Ψm for the 6 m South alley dropped below -1500 kPa on numerous occasions, reaching nearly -6000 kPa (well below VWC for permanent wilting point). The 6 m N alley also experienced extreme Ψm values, reaching a minimum Ψm of below -3000 kPa on DOY 69. Intercrop rows 4 m from the hedgerow never experienced Ψm values associated with wilting point, but remained dryer than the 2 m probes for much of the observation period.

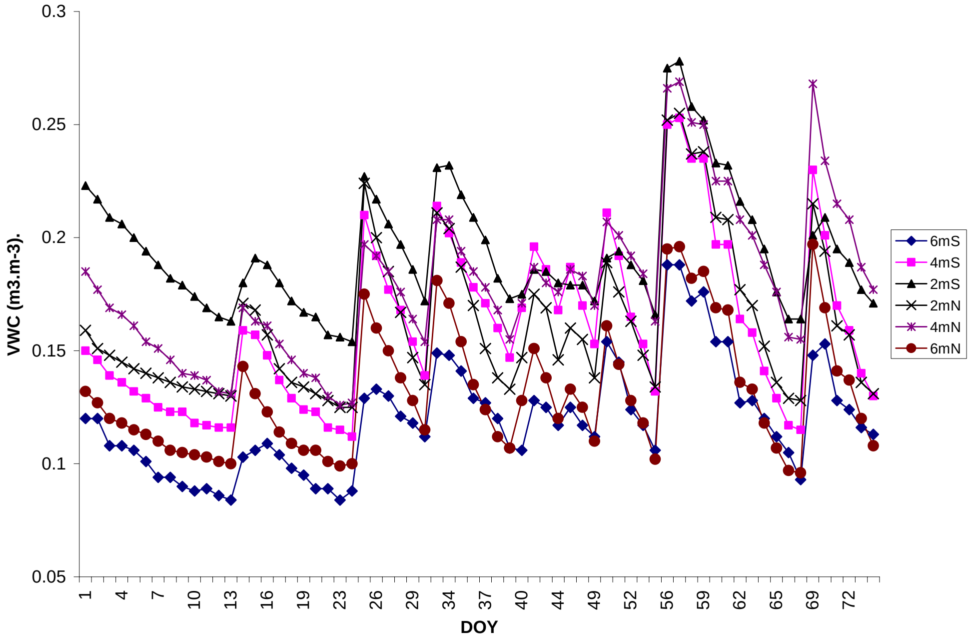

Figure 5.2.1 Daily volumetric water content of probes at depth 0.05 m (2000/01), (where matric suction is equivalent to the negative matric potential (Ψm). That is matric suction of 1500 kPa on the figures would be equivalent to matric potential (Ψm) of -1500 kPa)

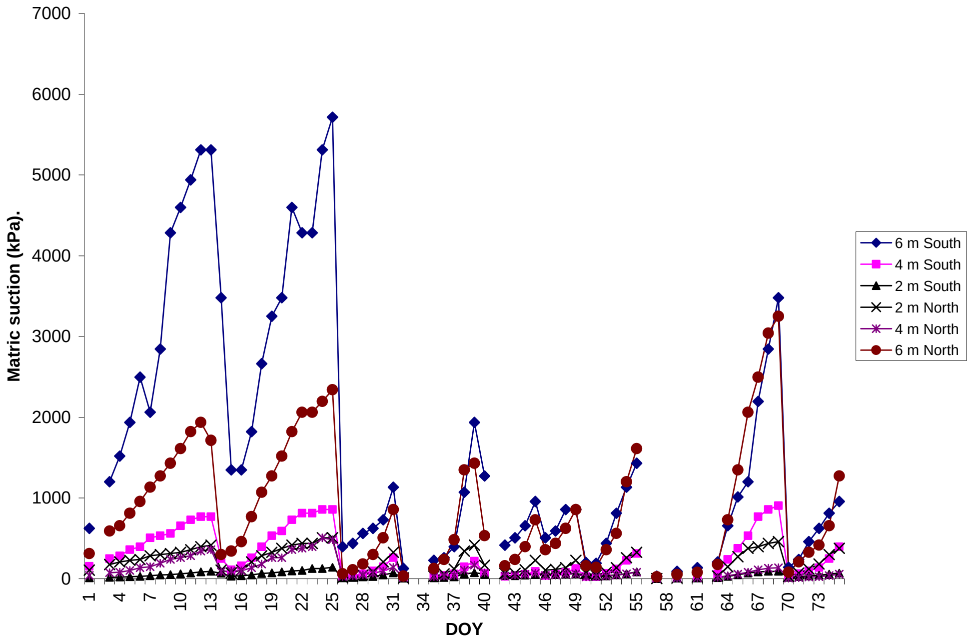

Figure 5.2.2 Daily Matric suction (kPa) at depth 0.05 m (2000/01)

Depth 0.2 m

The pressure plate analysis of the soil at a depth of 0.2 m estimated VWC_{FC} of 0.27 ($m^3.m^{-3}$), compared to 0.26 obtained using gravimetric sampling.

VWC was highest in soils 4 m S and N of the hedgerow (Fig 5.2.3). TDR VWC data suggested that soils in these alley rows remained at around field capacity for most of the observation period, with the 4 m S row the wettest. The 4 m S row showed less response to rainfall than the other rows, probably due to the already high water content in this row.

The 6 m S alley row was consistently wetter than the 6 m N row. VWC was lowest in rows adjacent to the hedgerows (2 m S and N), suggesting interspecific competition for water in this soil zone.

Matric potential analysis (Fig 5.2.4) emphasized the comparatively water-stressed conditions in the adjacent alleys, with Ψm in the 2 m N alley dropping below (dryer than) -350 kPa. If -100 kPa is considered a good estimate of onset of water stress, soils 2 m N of the hedgerow experienced water stress on 49 of the days observed, followed by 2 m S with 34 days and 6 m N with 2 days.

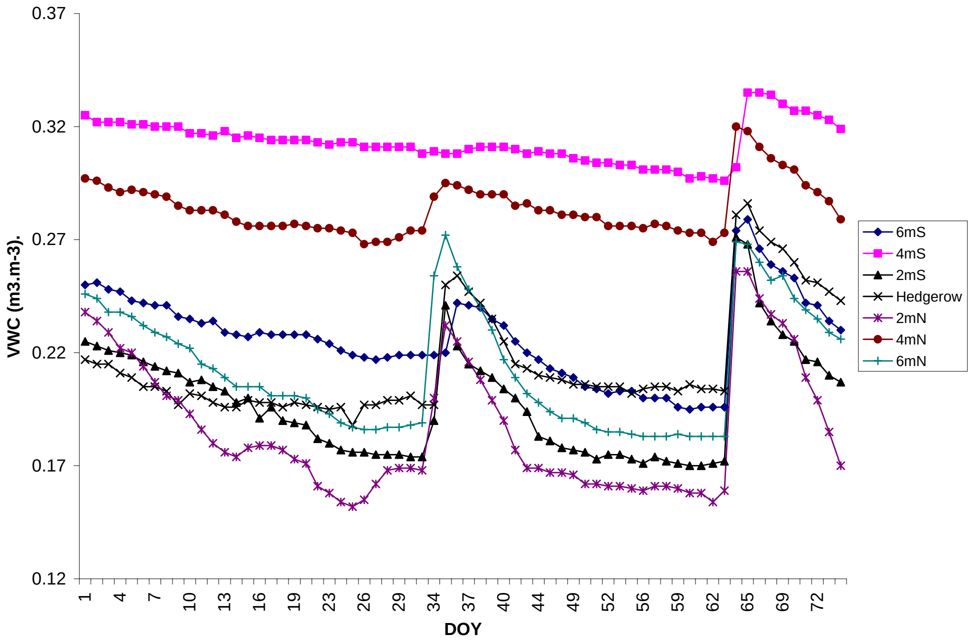

Figure 5.2.3 Daily volumetric water content of probes at depth 0.2 m

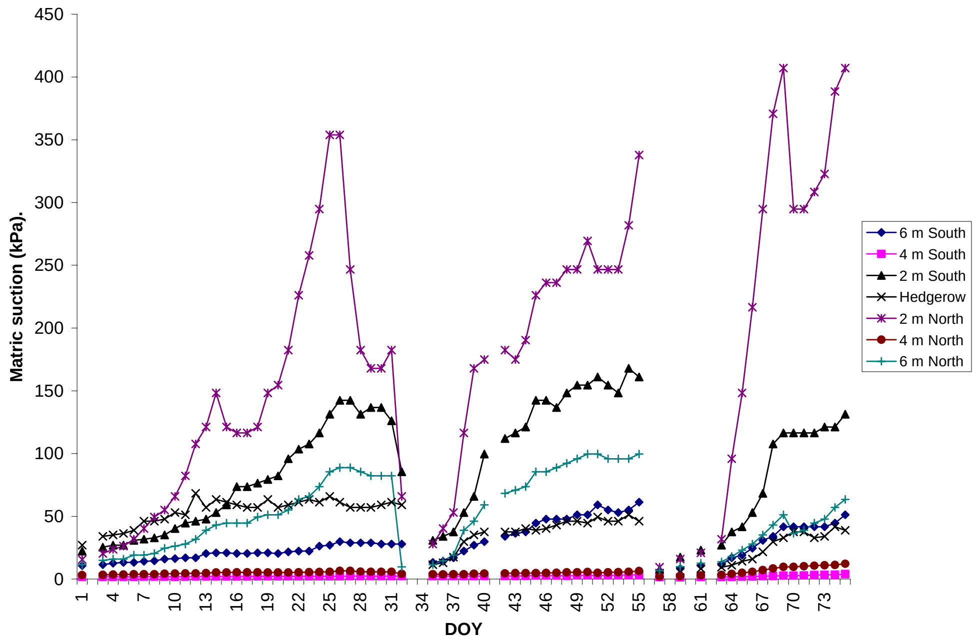

Figure 5.2.4 Daily matric suction (kPa) of probes at depth 0.2 m

Depth 0.6 m

VWC was lowest (Fig 5.2.5) in soil directly beneath the hedgerow for most of the observation period, suggesting that this zone is a major source of water for the hedgerow. The adjacent alleys (2 m N and S) showed similar water extraction and filling patterns throughout the observation period, but there was little similarity between N and S rows for the 4 m and 6 m alleys.

Comparison of Ψm values (Fig 5.2.6) emphasized the water stress in the hedgerow, with this soil zone experiencing Ψm below -100 kPa on 36 days, followed by 23 days for 6 m N and 10 days for 4 m S. Ψm never reached stress-indicative values in any of the other rows.

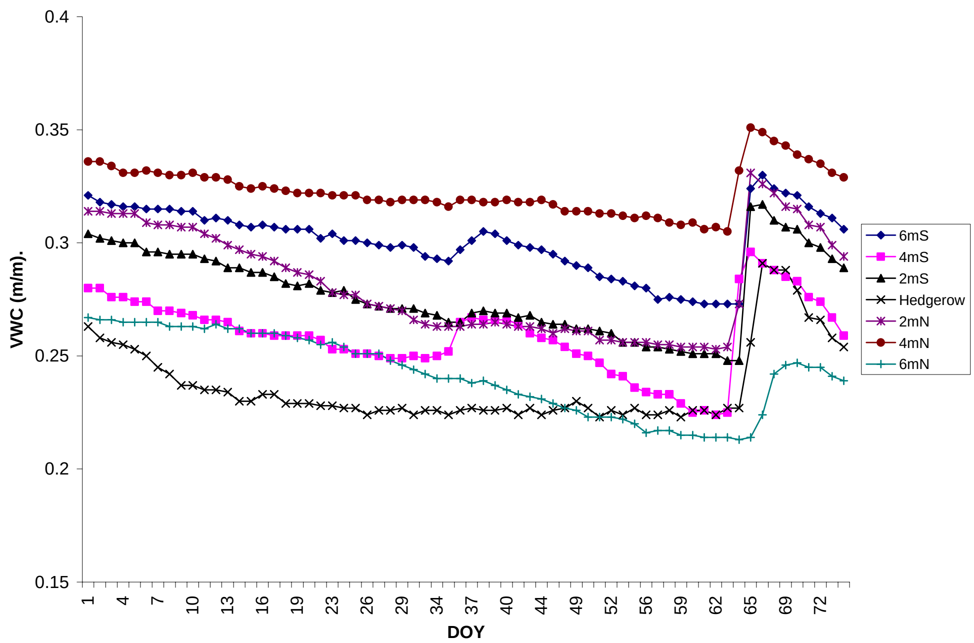

Figure 5.2.5 Daily volumetric water content of probes at depth 0.6 m

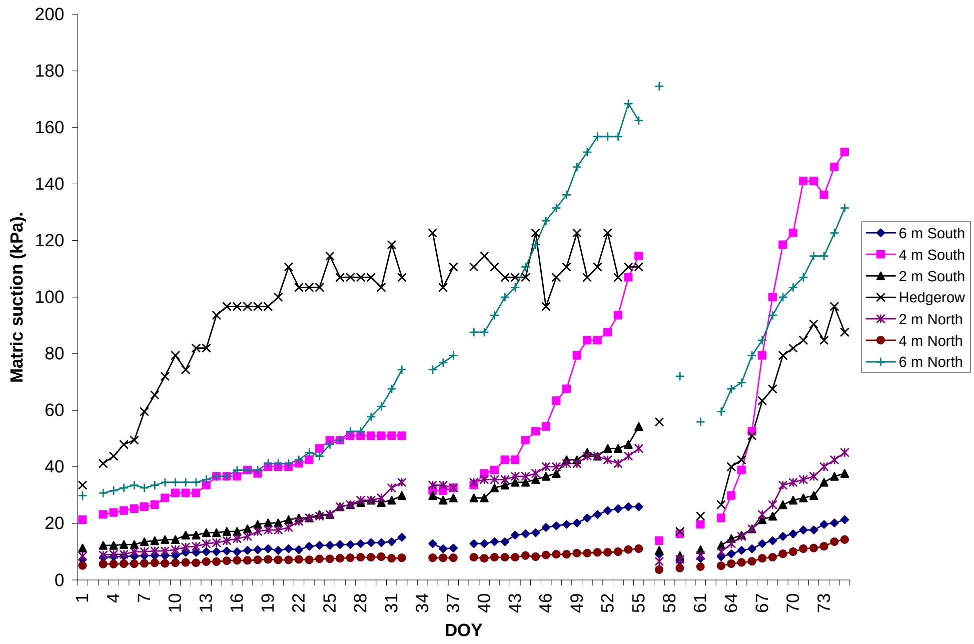

Figure 5.2.6 Daily matric suction (kPa) of probes at depth 0.6 m

Depth 0.9 m

Gravimetric soil sampling estimates for VWC_{FC} and VWC_{PWP} at a depth of 0.9 m were 0.357 and 0.209 $m^3.m^{-3}$ respectively.

At this depth, VWC (Fig 5.2.7) was lowest for the 2 m N row throughout the observation period. Depletion of soil water, in both rows adjacent to hedges, occurred at a rate matched only by the 6 m N row. Although the 2 m S row started wetter than the 2m N row, water extraction patterns in these rows were again very similar, confirming that most interspecific competition occurs in these rows.

Values for Ψm (Fig 5.2.8) were lower (drier) than at the 0.2 m depth. Both 2 m alley rows experienced values indicative of moisture stress. Stress days totalled 67 for the soil under the hedgerow, 46 from the 4 m N alley, 27 for 4 m S and 26 for 2 m S. Crop rooting depth for cowpeas was estimated at 0.5 m, suggesting that moisture stress at 0.9 m is predominantly from water absorption by tree roots. The 0.9 m results provide evidence that the hedgerow appeared to use the 2 m alley row at depth 0.9 m as a major source of soil water.

Significantly, VWC for the 0.9 m depth (Fig 5.2.8) in the 2 m N alley dropped below levels associated with permanent wilting point, reaching a minimum Ψm of under (drier than) -2500 kPa, and remaining below -500 kPa for 30 days of the observation period.

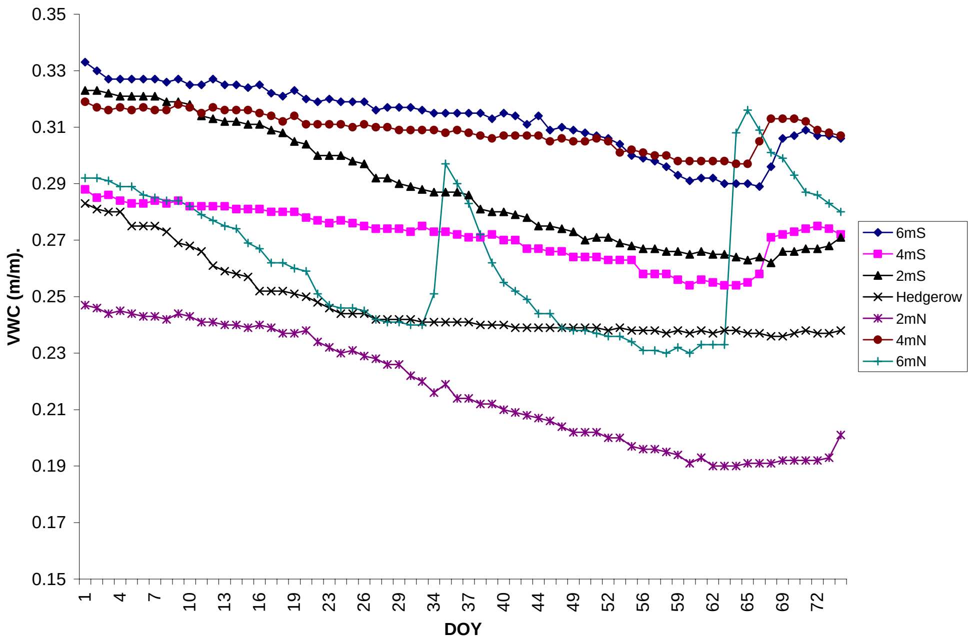

Figure 5.2.7 Daily volumetric water content of probes at depth 0.9 m (2000/2001)

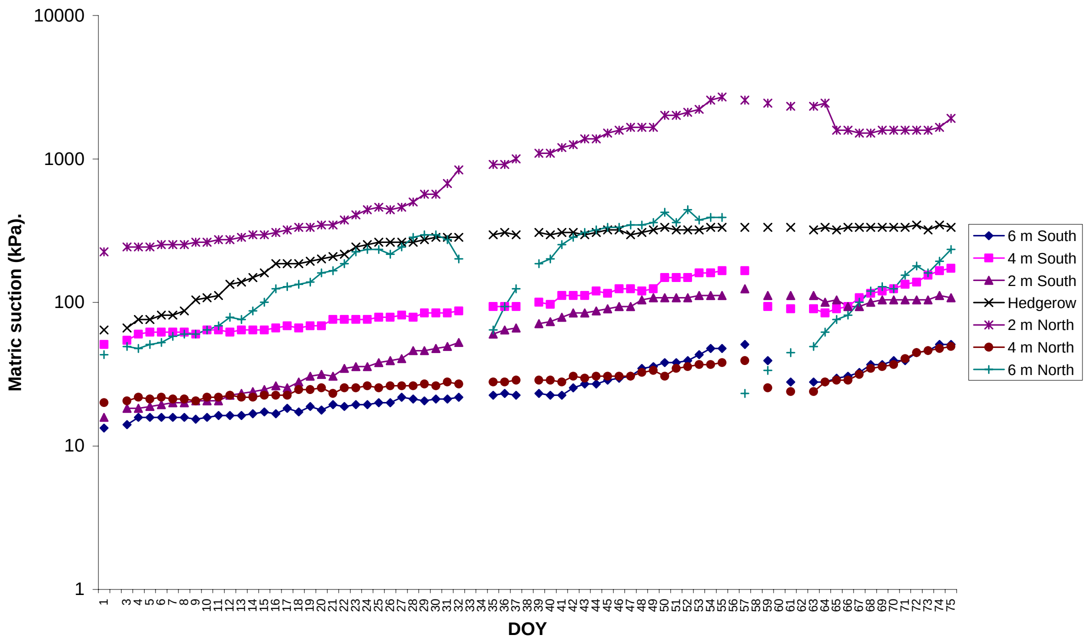

Figure 5.2.8 Daily matric suction (kPa) of probes at depth 0.9 m (2000/2001)

Depth 1.5 m

VWC (Fig 5.2.9) at the 1.5 m depth was lowest in alleys 2 m N and S throughout the season, and highest in alleys 6 m either side of the hedgerow. Soil under the hedgerow started the wettest, but dried more than the 4 m alleys. The 6m alleys began the season fairly wet and showed little decrease in VWC over the observation period.

Matric potential analysis (Figs 5.2.10) indicated water stress in both 2 m alleys throughout the season, with Ψm below (drier than) -100 kPa on all days observed. None of the other alleys experienced Ψm of below -100 kPa. The 2 mS alley experienced the most severe water stress, with Ψm below -900 kPa throughout, and decreasing to below (drier than) -5000 kPa by DOY 75.

Ψm for the soil under the hedgerow experienced Ψm associated with near-field capacity conditions throughout. Both 6 m alleys were marginally drier than the hedgerow and 4m alleys, but never reached Ψm close to stress conditions.

Data from this depth illustrates a clear contrast between preferred water sources for the hedgerow, with an obvious preference for water absorption from the adjacent rows at this depth. The near-field capacity conditions further from the hedgerow confirm that the assumption that shallow-rooting cowpeas obtain little, if any, water from soil at 1.5 m is correct.

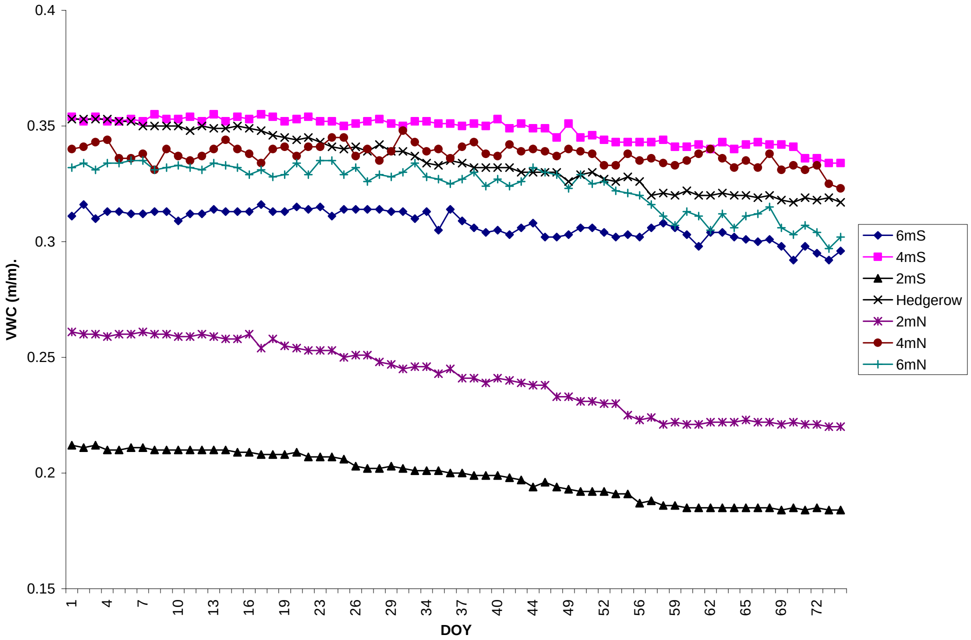

Figure 5.2.9 Daily volumetric water content of probes at depth 1.5 m (2000/2001)

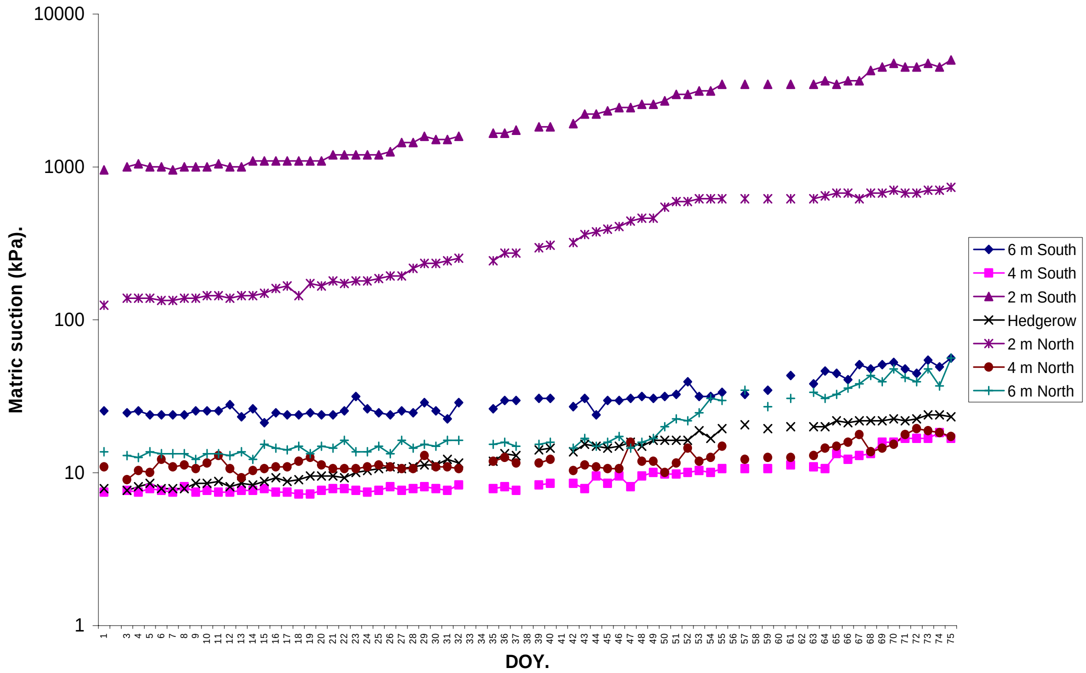

Figure 5.2.10 Daily matric suction (kPa) of probes at depth 1.5 m (2000/2001)

5.2.2 2001-2002 growing season

Rainfall for this season totalled 613 mm, with a major portion falling in November, December and January (respectively 132, 100 and 122 mm). Sorghum was planted in the alley. Literature suggests a rooting depth of 2 m, if soil depth allows (Bennie *et al.*, 1998).

Depth 0.2 m

The probe located 2 m N produced unreliable data, but data from the previous season suggest that soil water in the same position on the northern side follows the same extraction patterns as that on the southern side. Data collected for the 2 m S alley could, therefore, be used to reflect conditions in the 2 m N alley.

Although VWC (Fig. 5.2.11) for all probes did decrease gradually over the observation period, fluctuation was less dramatic than in the early part of the previous growing season for most soil zones at this depth, with the most activity evident under the hedgerow. The 2 m alley had the lowest VWC throughout the observed period, while the 4 m S alley had the highest VWC for most of the period observed. Soil under the hedgerow wetted and dried faster than the other rows. This comparatively dramatic fluctuation under the hedgerow could possibly be ascribed to rapid filling due to stem flow, followed by rapid uptake by the hedgerow. Ψm values (Fig. 5.2.12) suggest prolonged stress under the 2 m alley, with Ψm less than -100 kPa on all days observed. Ψm, however, never decreased to levels associated with permanent wilting point. Other rows, including the hedgerow, showed little sign of water stress, with Ψm remaining above -80 kPa in all other rows.

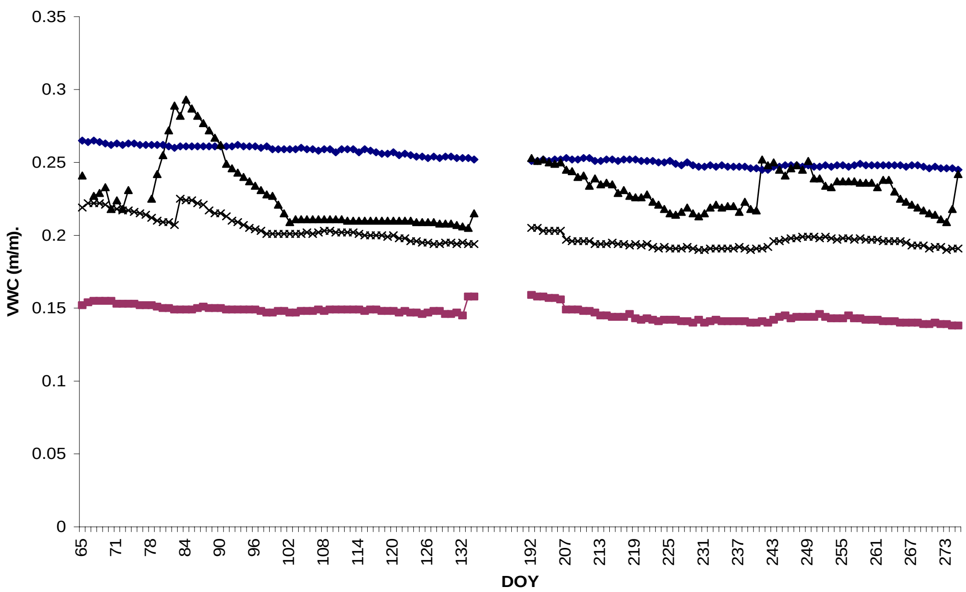

Figure 5.2.11 Daily volumetric water content of probes at depth 0.2 m (2001/2002)

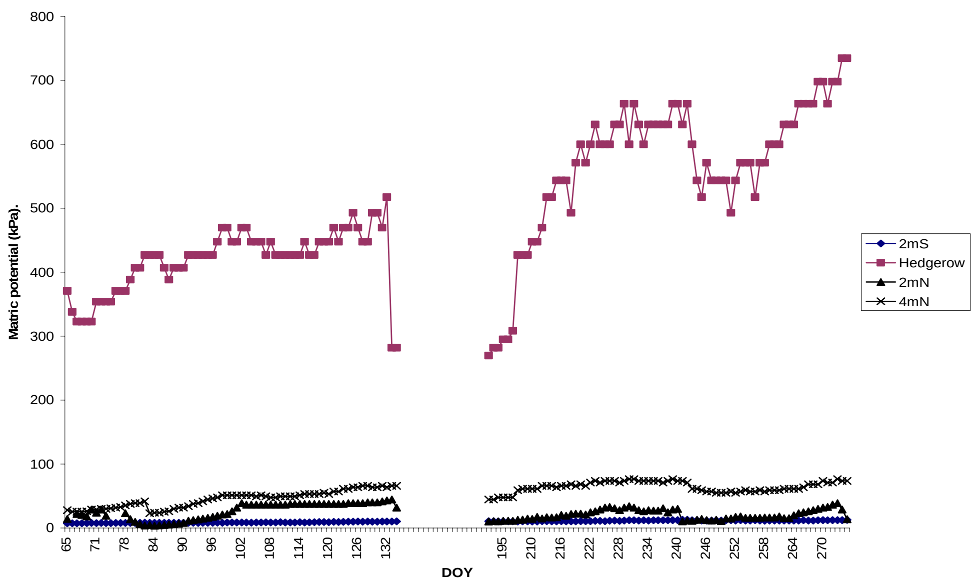

Figure 5.2.12 Daily matric suction of probes at depth 0.2 m (2001-2002)

Depth 0.6 m

The 2 m alley rows had similar VWC values (Fig. 5.2.13) for much of the observed period, although the 2 m N row reacted faster, and to a greater extent, to rainfall.

The 4 m N alley began the period the wettest, but dried consistently throughout the season, reacting little to rainfall. The 4 m S alley showed dramatic changes in VWC, with VWC increasing sharply after rainfall, followed by rapid decreases in VWC. This soil zone's rapid increases in VWC can be ascribed to its comparative dryness, allowing rapid entry of levels until near-saturation.

Despite its fairly high initial VWC, the row under the hedgerow wetted rapidly, suggesting effects of stem flow.

Matric potentials (Fig. 5.2.14) were much lower at 0.6 m than at 0.2 m (as with the preceding season). Both 2 m alleys experienced Ψm values associated with water stress in the earlier part of the observed period (DOY 65-134), with Ψm for alleys 2 m S and N below -100 kPa for 69 and 39 days respectively. From DOY 192 to DOY 275, these alleys were both water stressed throughout, although Ψm never declined below -200 kPa.

The 4 m S alley experienced the lowest Ψm, with 62 of 69 days between DOY 64 and DOY 134, being water stressed, reaching the lowest Ψm of -944 kPa. From DOY 192 to DOY 275 (a fallow period after harvesting of the intercrop) this alley dried the most, reaching near-permanent wilting point values on a number of days.

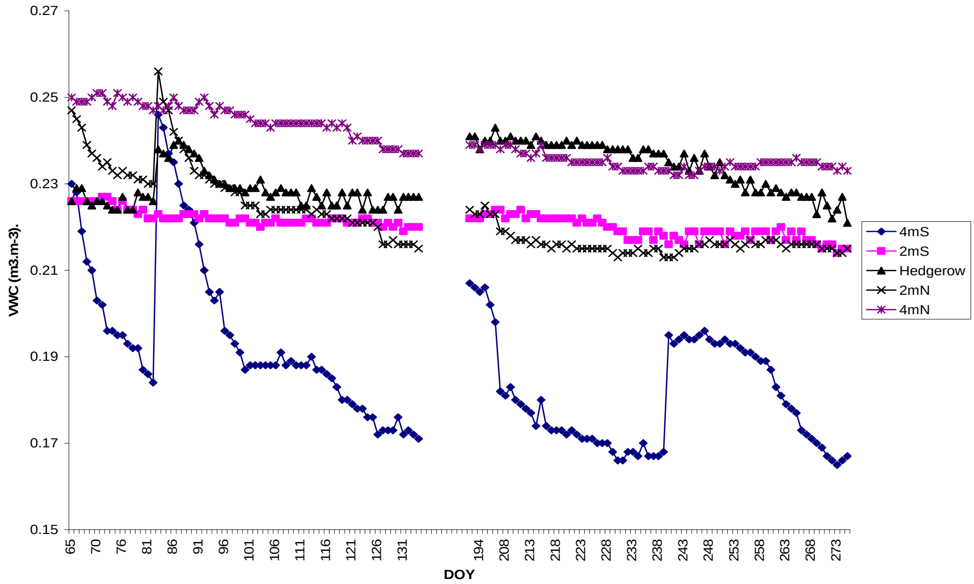

Figure 5.2.13 Daily volumetric water content of probes at depth 0.6 m (2001/2002)

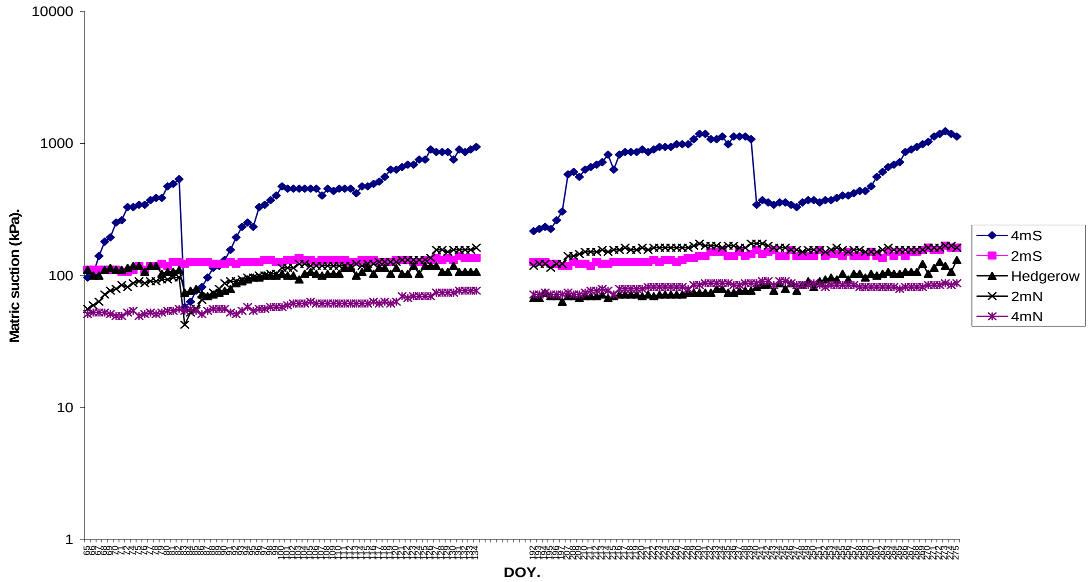

Figure 5.2.14 Daily matric suction of probes at depth 0.6 m (2001/2002)

Depth 0.9 m

All soil zones at the 0.9 m depth experienced severe water stress, both in the early part (DOY 65-134) and later part (DOY 192-275) of the observation period. VWC (Fig 5.2.15) in the 4 m S alley decreased gradually over the season, but the 4 m N alley and both 2 m alleys experienced relatively little change in VWC.

The greatest change in VWC (Fig. 5.2.15) was from DOY 65 -134 under the hedgerow. From DOY 192-275, VWC was mostly static for both the alley rows and the hedgerow.

Ψm (Fig. 5.2.16) was lowest in the 2 m N alley throughout the observed period. This zone experienced severe water stress, with Ψm generally below -1500 kPa. The 2 m S alley, although water stressed throughout the period, had higher values for Ψm than 2 m N.

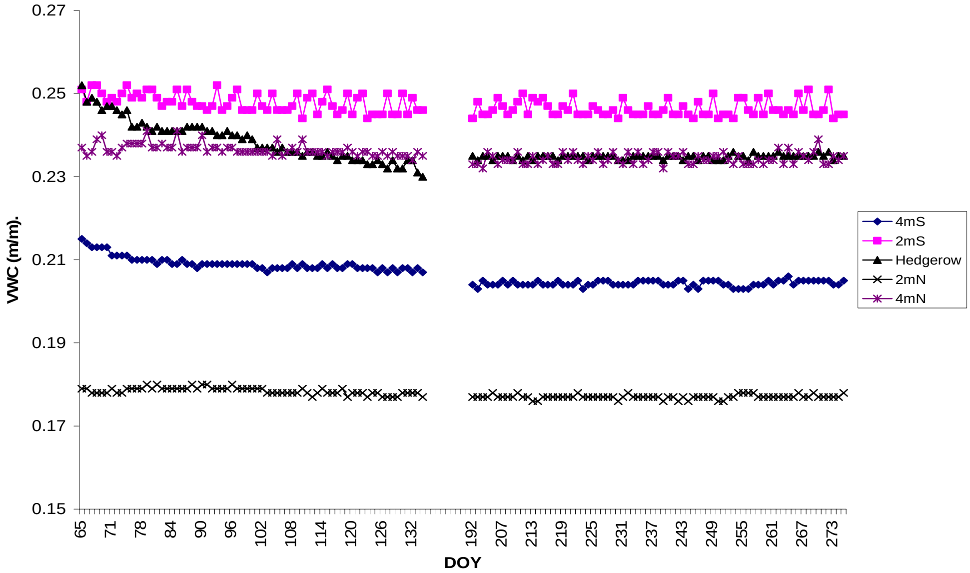

Figure 5.2.15 Daily volumetric water content of probes at depth 0.9 m (2001/2002)

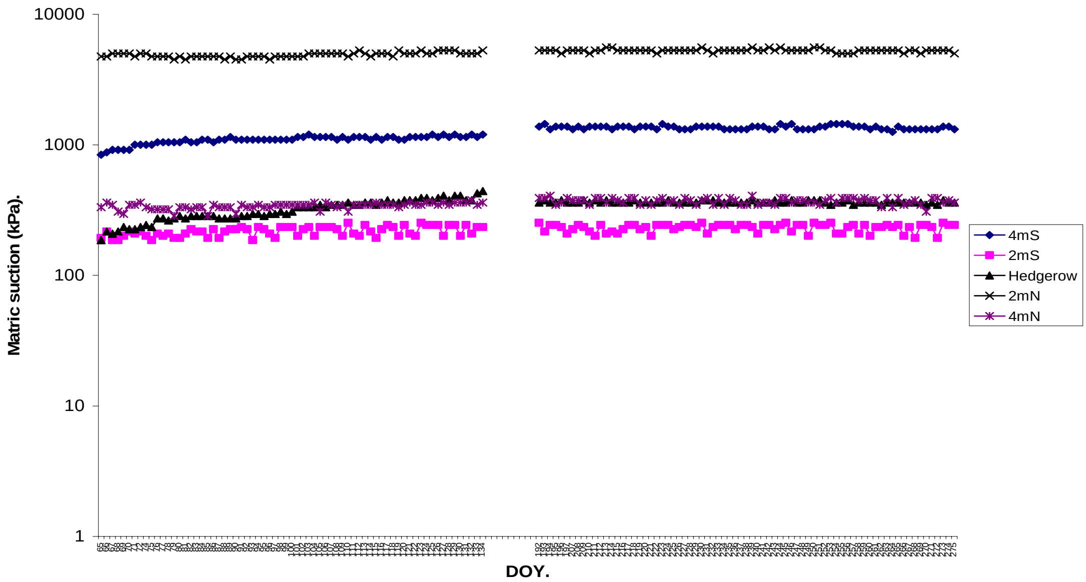

Figure 5.2.16 Daily matric suction (kPa) of probes at depth 0.9 m (2001/2002)

Depth 1.5 m

Both alley rows adjacent to hedgerows (2 m N and S) were severely water stressed at 1.5 m depth. VWC (Fig. 5.2.17) in these alleys was constantly at or below (gravimetrically-determined) permanent wilting point. This was particularly so in the case of the 2 m S alley, where matric potential values remained below -10000 kPa (Fig 5.2.18).

Ψm (Fig. 5.2.18) for both 6 m alley rows were lower than those for the 4 m alleys and hedgerow. Ψm for these alleys indicated water stress throughout the period observed (ranging from -120 to -170 kPa for the 6 m N alley, and -165 to below -300 kPa for 6 m S).

The 4m N alley was the only other alley to experience Ψm associated with moisture stress, with Ψm below (drier than) -100 kPa on 103 of the 152 days observed. The hedgerow was wettest throughout, with Ψm in this row ranging from -50 to -70 kPa.

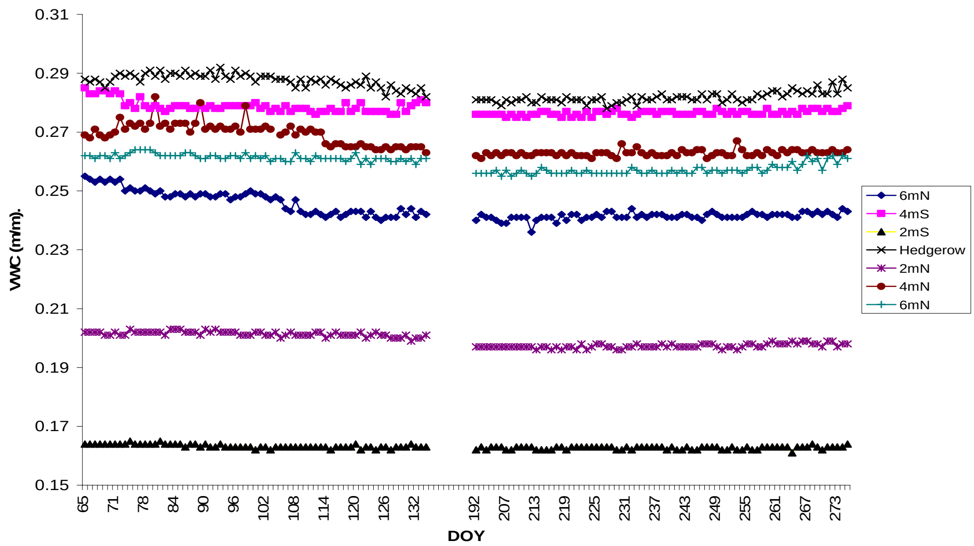

Figure 5.2.17   Daily volumetric water content of probes at depth 1.5 m (2001/2002)

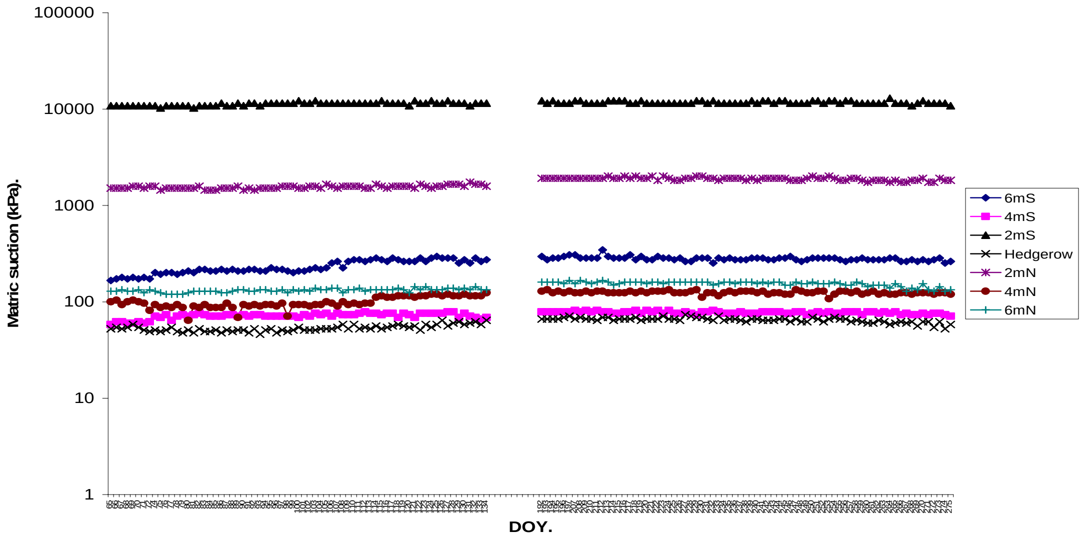

Figure 5.2.18   Daily matric suction of probes at depth 1.5 m

5.2.3   2002/2003 growing season

Depth 0.2 m

Rainfall in the 2002-2003 season totalled 524 mm, concentrated mainly in December, January and February (121, 135 and 111 mm respectively). Maize was planted as the alley crop in this season. The December to February rainfall was reflected in the fairly high water contents throughout the observed period.

VWC (Fig. 5.2.19) measured for the hedgerow was extremely erratic, making interpretation difficult. Again, the 2m alley row was much drier than other rows, with VWC dropping to below 0.15 $m.m^{-1}$. VWC for the 4 m S alley row was higher than 4 m N for most of the season. The 4 m N alley row exhibited the fastest drying and wetting.

Ψm analysis (Fig. 5.2.20) indicated that the 4 m S and 4 m N alley rows remained at near-field capacity (and even saturation) for most of the observed period, while the 2 m S alley frequently experienced water stress. Total water-stressed days for the 2 m alley rows was 29. None of the other alleys experienced days of water stress.

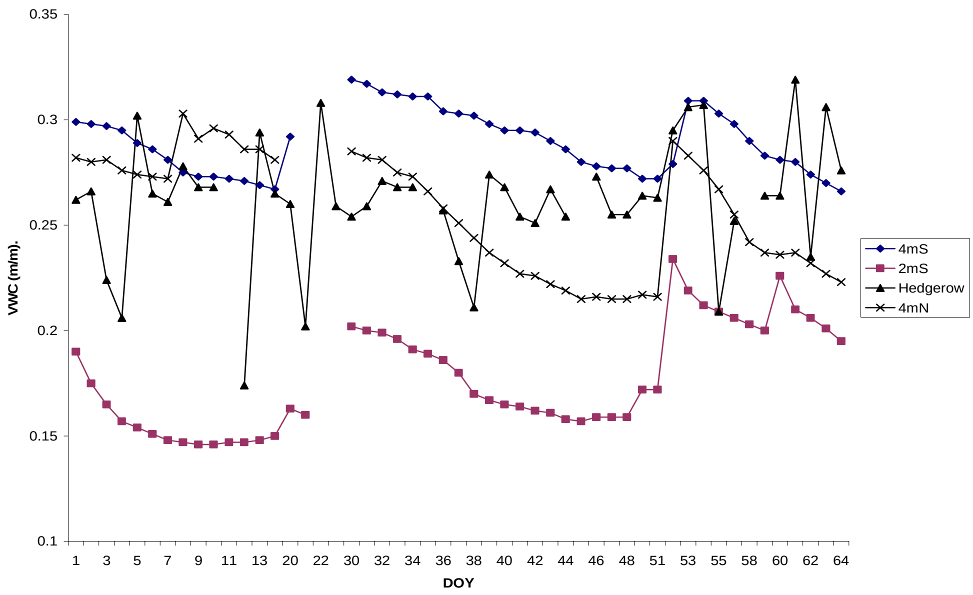

Figure 5.2.19 Daily volumetric water content of probes at depth 0.2 m (2002/2003)

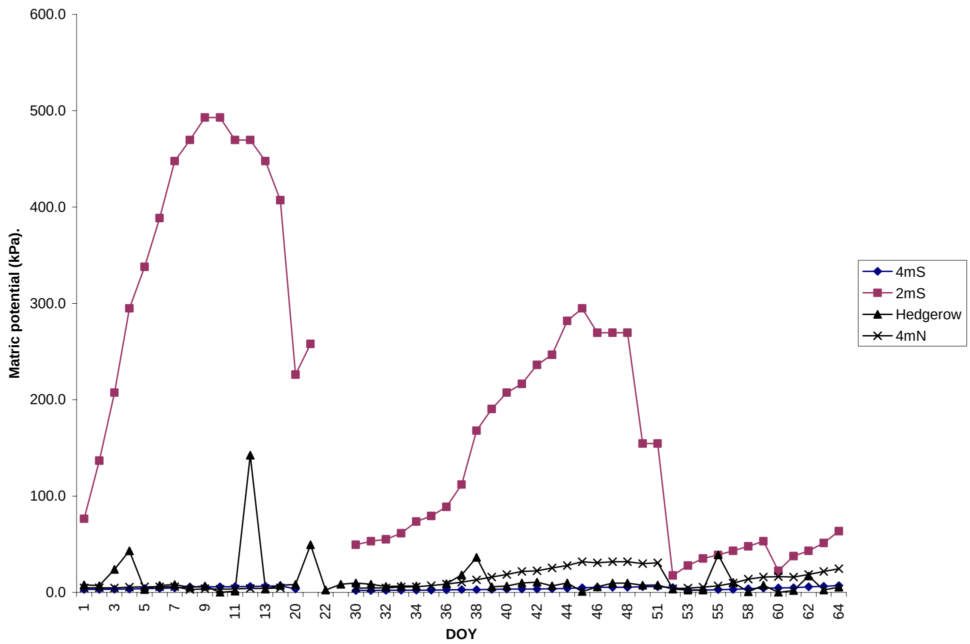

Figure 5.2.20 Daily matric suction of probes at depth 0.2 m (2002/2003)

Depth 0.6 m

VWC (Fig. 5.2.21) at the 0.6 m depth was highest in the 4 m N alley row for most of the season. The 4 m S alley started wet, but lost water faster than the other rows, quickly becoming the driest alley. This pattern of rapid wetting, followed by rapid drying after rainfall events suggested that alley crops obtained most water in this row. The 2 m N alley began drier than the 2 m S alley, but wetted quickly after rainfall. After this, both 2 m alleys showed almost identical water extraction patterns. Surprisingly, these rows ended the observation period the wettest – in contrast to the adjacent rows at depth 0.2 m. the most extreme increases in VWC after rainfall occurred in the hedgerow, suggesting stem flow.

Ψm analysis (Fig. 5.2.22) emphasized the rapid fluctuations in water content in the 4 m N alley row, with Ψm dropping to below (drier than) -300 kPa, and filling to near-field capacity levels. This was the only alley row to exhibit evidence of extreme water stress at this depth.

The hedgerow and 2 m S alley were the only other alleys that experienced Ψm below -100 kPa, but never at the same levels observed in the 4mS alley. Total stress days were 28 for 4 m S, 16 days for 2 m S and 31 days for the hedgerow. Overall, the southern side of the hedgerow was drier than the northern side.

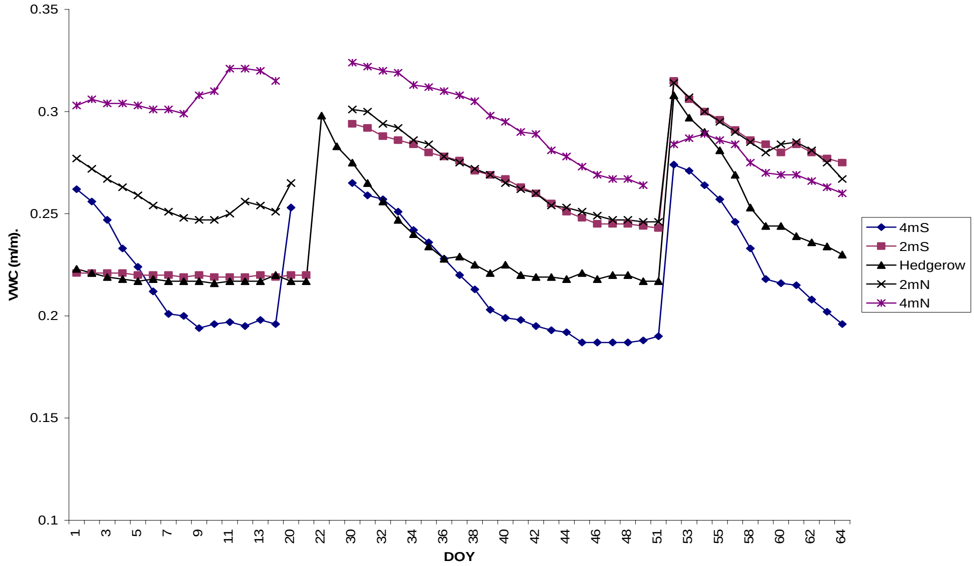

Figure 5.2.21 Daily volumetric water content of probes at depth 0.6 m (2002/2003)

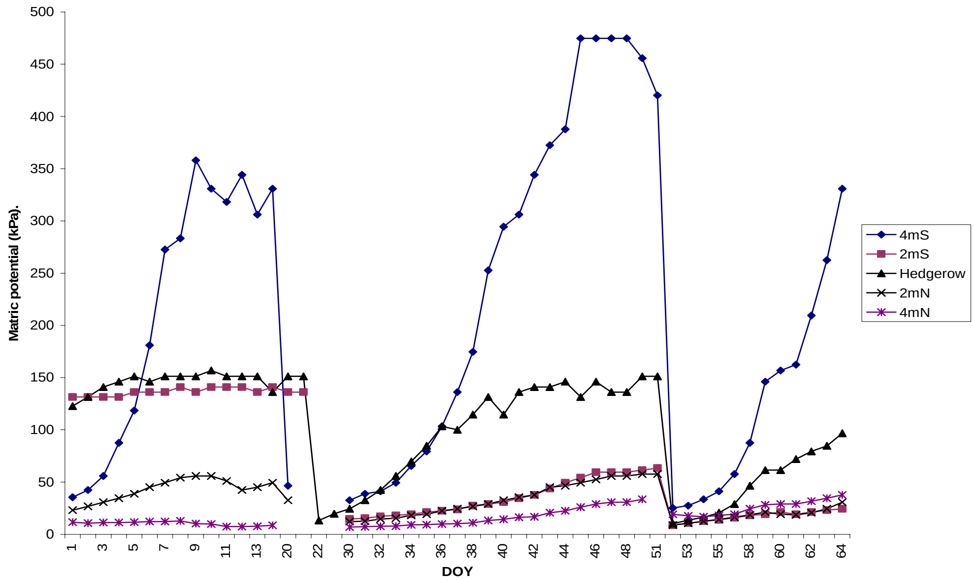

Figure 5.2.22 Daily matric suction of probes at depth 0.6 m (2002/2003)

Depth 0.9 m

At the 0.9 m depth (figures 5.2.23 and 5.2.24) all alley rows began the season at Ψm levels associated with water stress (ranging from -250 kPa in the 2 m S alley to below -4000 kPa in the 2 m N alley row).This was succeeded by rapid wetting to near-field capacity levels of VWC following a series of heavy rainfalls on DOY 22, 24 and 25 (respectively receiving 44, 26.5 and 32 mm of rain). After this, all alleys showed similar water extraction patterns. A downpour of 64.5 mm on DOY 49 filled the 2 m alleys and the hedgerow, but had virtually no influence on the 4 m rows. Dramatic fluctuations in the overlying 0.6m layer (discussed previously) in the 4 m S alley indicate that the high intensity precipitation may have filled the 0.6m zone, but made no impact on VWC at 0.9 m for the 4 m S alley. Lack of reaction at 0.9 m of the 4 m N alley row is unusual, since its overlying layer was already fairly wet.

Possible effects of stem flow were reiterated by rapid wetting under the hedgerows, at depth 0.9 m, after rainfall events.

Matric potentials (Fig 5.2.24) at this depth were lowest for the 2 m N alley throughout, increasing from levels suggesting severe water stress (<-4000 kPa) to higher levels (-180kPa), before decreasing again. This alley row did not experience any stressless days during for the observation period.

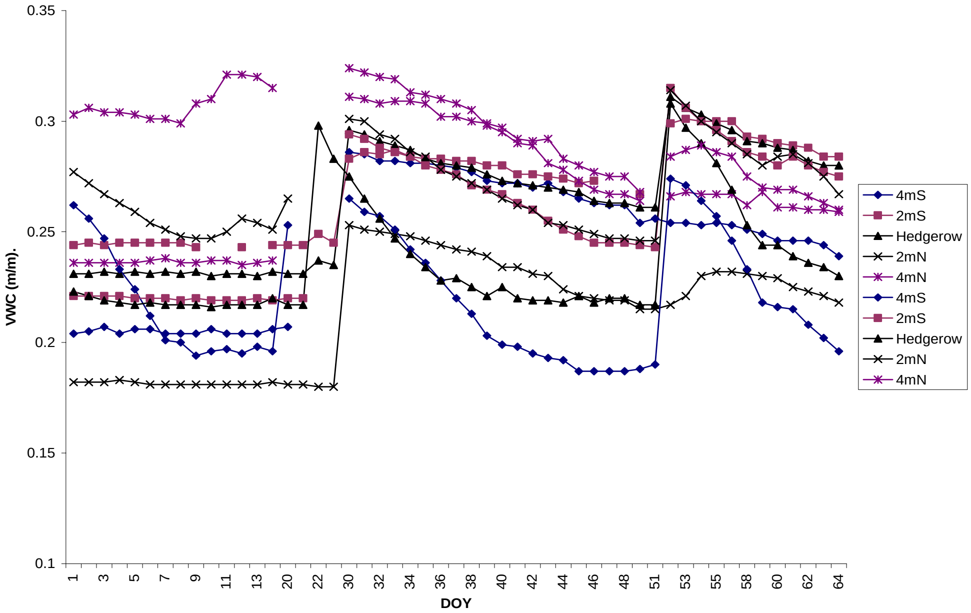

Figure 5.2.23 Daily volumetric water content of probes at depth 0.9 m (2002/2003)

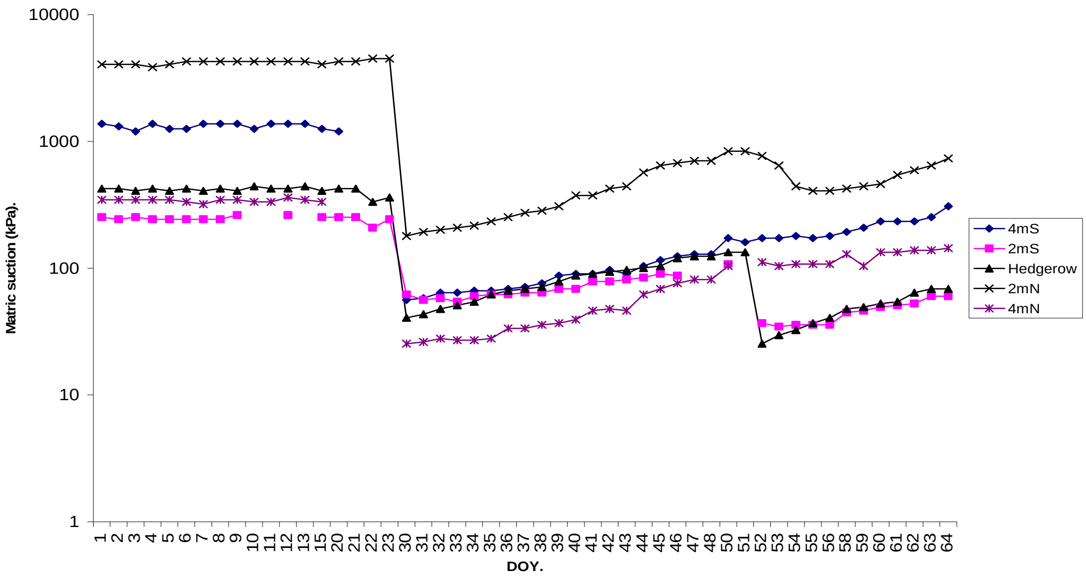

Figure 5.2.24 Daily matric suction of probes at depth 0.9 m (2002/2003)

Depth 1.5 m

VWC (Fig. 5.2.25) at a depth of 1.5 m was consistently lower in the 2 m N and 2 m S alleys than in the other rows. The 2 m S alley showed no response to rainfall, while response to rainfall in the 2 m N alley was only very slight. These results indicate that while heavy rains are capable of supplementing overlying layers in the rows adjacent to trees, they are incapable of contributing to water content at these deeper levels.

Matric potentials (Fig 5.2.26) for both adjacent rows indicated severe, prolonged water stress, with Ψm never exceeding (becoming wetter than) -10000 kPa in the 2 m S row, and gradually increasing in the 2 m N alley from around -2000 kPa at the beginning of the season to about -650kPa at the end of the period observed.

Other rows reacted rapidly to heavy showers in late January, mostly increasing to above-stress matric potentials.

A heavy rainfall on DOY 49 had a marked effect on the 2 m N alley row, but hardly any effect on the other rows, due probably to the already relatively high water contents in these rows. VWC and Ψm values for the adjacent rows at this depth provide strong evidence of extensive deep water extraction by the Leucaena hedgerow.

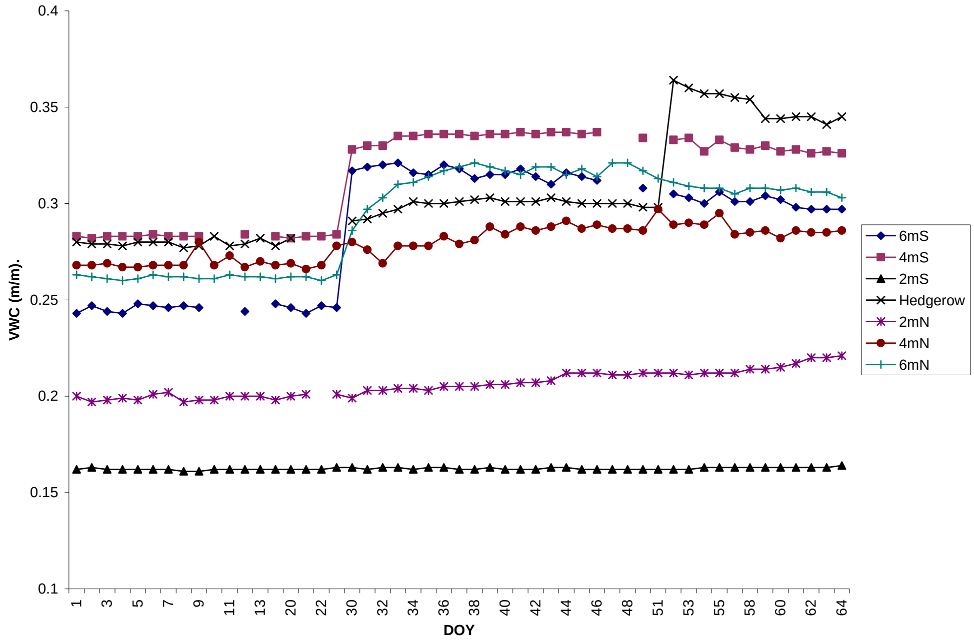

Figure 5.2.25 Daily volumetric water content of probes at depth 1.5 m (2002/2003)

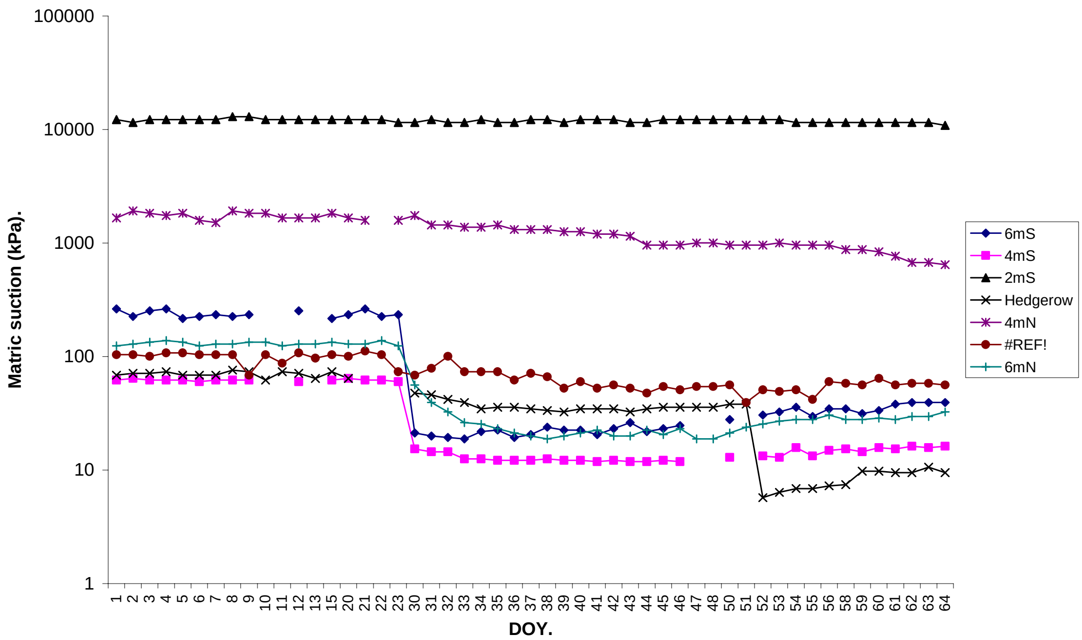

Figure 5.2.26 Daily matric suction of probes at depth 1.5 m (2002/2003)

5.2.4 Discussion

When results of the three seasons are combined (Fig. 5.2.27 to 5.2.30), the following tendencies in spatial and temporal water distribution patterns were repeatedly evident:

- Soil zones in rows adjacent to trees generally showed similar water extraction patterns. These alley rows had the lowest water contents in the 0.2 m and 0.5 m layers in all three seasons. At the 0.9 m depth, the 2 m N row experienced the lowest water contents throughout. Although cowpeas, sorghum and maize have different rooting depths, it is well-documented that the highest root length density, and highest water extraction for many agronomic crops is in the top 0.3 m of soil.

- Extremely low matric potentials (high matric suction) in all seasons in the rows adjacent to trees indicate the severity of this "adjacent row water crisis" in semi-arid regions. Moderate to low rainfall and high evaporative demand in these areas make water stress a hazard, even without the added moisture demand of interspecific competition. Low water contents in rows adjacent to hedgerows support the assumption that the deeper-rooting Leucaena uses water which would be unused in a monoculture. The question which arises is whether the Leucaena production, facilitated by hedgerow utilization of deep water, compensates for crop loss in adjacent alley rows, due to intense interspecific competition for water?

- In the first season (2000-2001) the already-dry adjacent rows at depth 1.5 m were comparatively quickly completely depleted of water. Measurements in the second season suggested extreme water stress throughout, and soil in this zone only refilled marginally after heavy rain in the third season. It appears that the hedgerow uses water at this depth extensively, when water is available, but relies on other sources of water once this deep water source is exhausted. If this water source is continually dry the assumption that deep-rooting trees can improve water use efficiency of the system by tapping reserves inaccessible to crops becomes irrelevant. In contrast it seems that, in semi-arid regions, water at depths inaccessible to crops in adjacent rows may be used almost completely by the hedgerow in the first season of intercropping, followed by extreme water stress in these soil zones in subsequent years. It is unlikely, with the high evaporative demand and low rainfall associated with semi-arid regions, that these soils can ever be filled (after the first season of cropping) to a level that sustainably provides enough water for trees to rely on.

- One or both of the rows 4 m on either side of the hedgerow registered the highest water contents for long periods at all depths in all three seasons, suggesting less interspecific competition at this distance from the hedgerow.

- VWC under the hedgerow, although often marginally lower than rows 4 and 6 m from the hedgerow, generally increased more rapidly after rainfall events, suggesting evidence of stem flow. Water content under the hedgerows was intermediate between the two and four metre alleys at all depths, except 1.5 m, where this row had the highest VWC at the end of the 2003 observation period. It appears that soil water content under the hedgerow is restricted to use by the hedgerow itself.

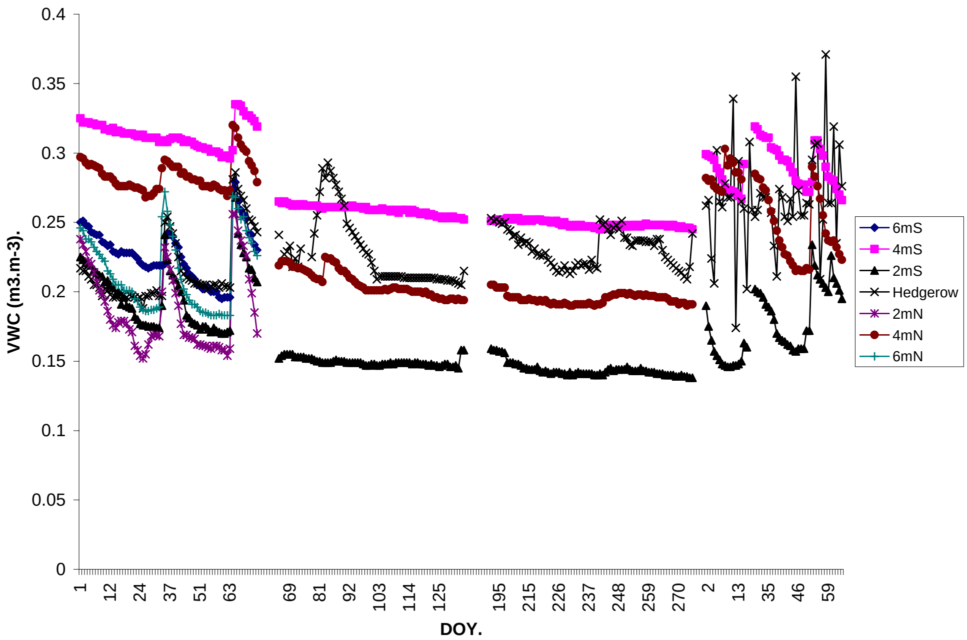

Figure 5.2.27 Daily volumetric water content for 3 seasons – 0.2 m

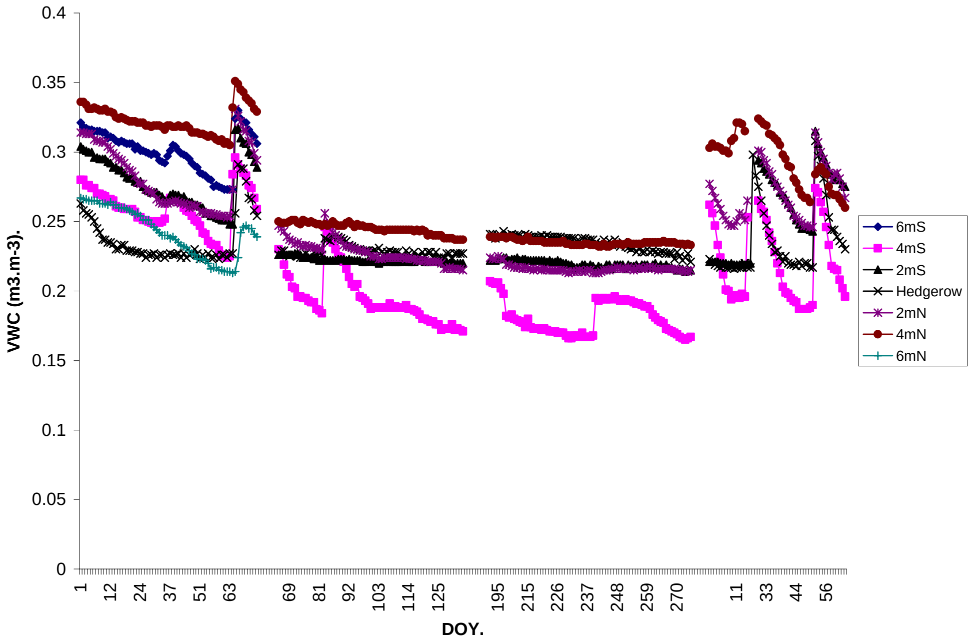

Figure 5.2.28 Daily volumetric water content for 3 seasons – 0.6 m

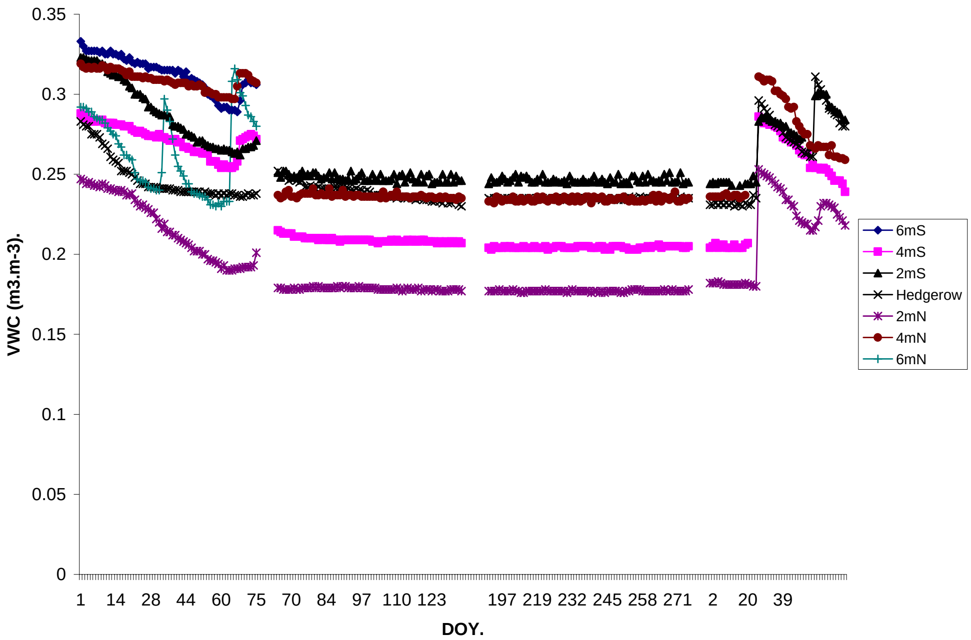

Figure 5.2.29 Daily volumetric water content for 3 seasons – 0.9 m

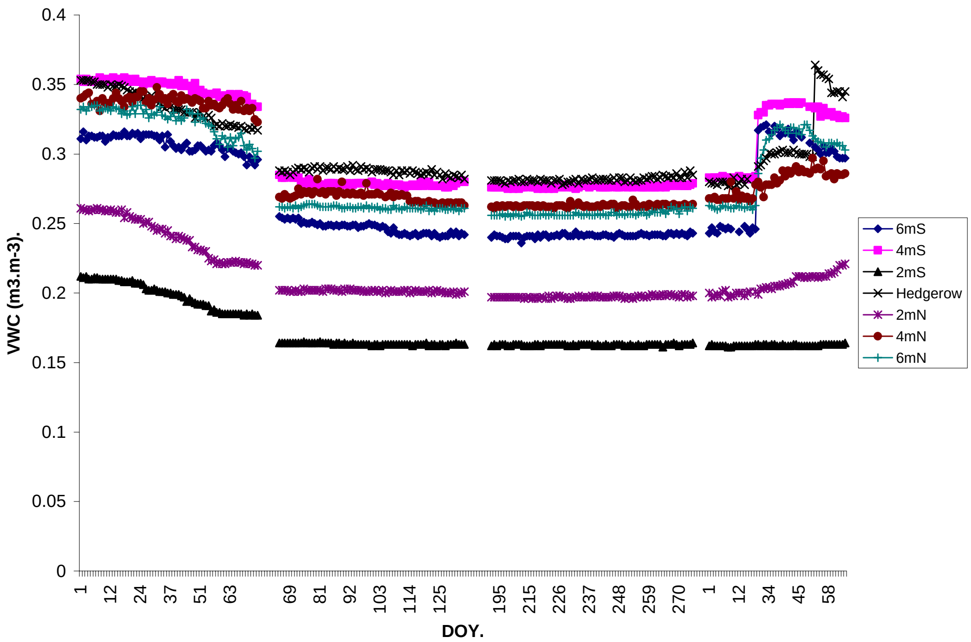

Figure 5.2.30 Daily volumetric water content for 3 seasons – 1.5 m

6 RESULTS AND DISCUSSION – AGRONOMIC CHARACTERISTICS – “ON-STATION TRIALS”

6.1 1999-2000 growing season

A Cowpeas

Average yield (Fig 6.1) in the alley rows (243 kg.ha^{-1}) was far lower than average pure stand yield (645 kg.ha^{-1}) in this season. There was little evidence of the expected yield reductions in alley rows closer to the hedgerows, with the exception of row 11.

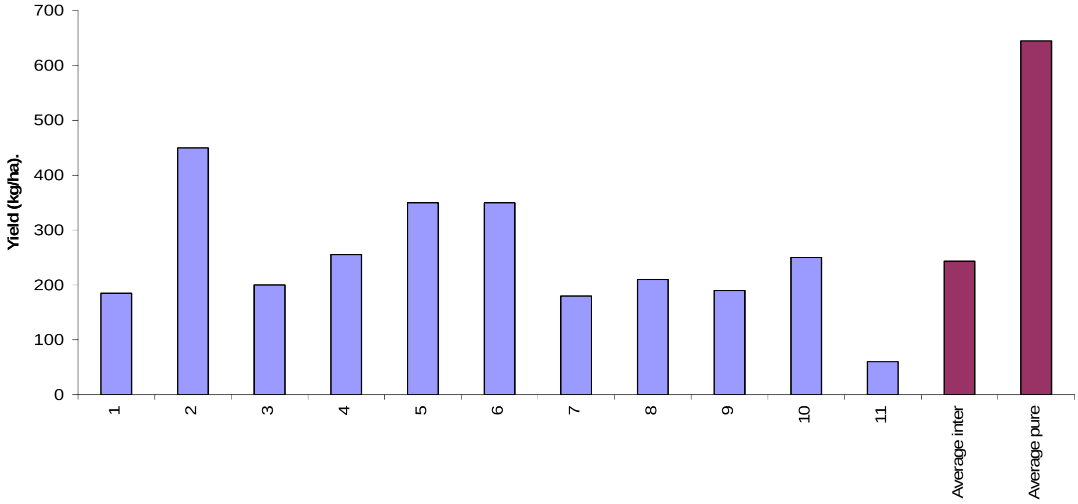

Figure 6.1 Yield of intercropped cowpeas, compared to pure stand (1999/2000)

B Sweet potatoes

Average yield (Fig. 6.2) in the alley rows (14.6 tons wet mass.ha^{-1}) was lower than that of the pure stand (17.3 t.ha^{-1}), although the difference was less dramatic than in the case of cowpeas. The central alley rows (further from the Leucaena hedgerows) yielded considerably more than the alley rows adjacent to the hedgerows, and also generally outyielded the pure stand.

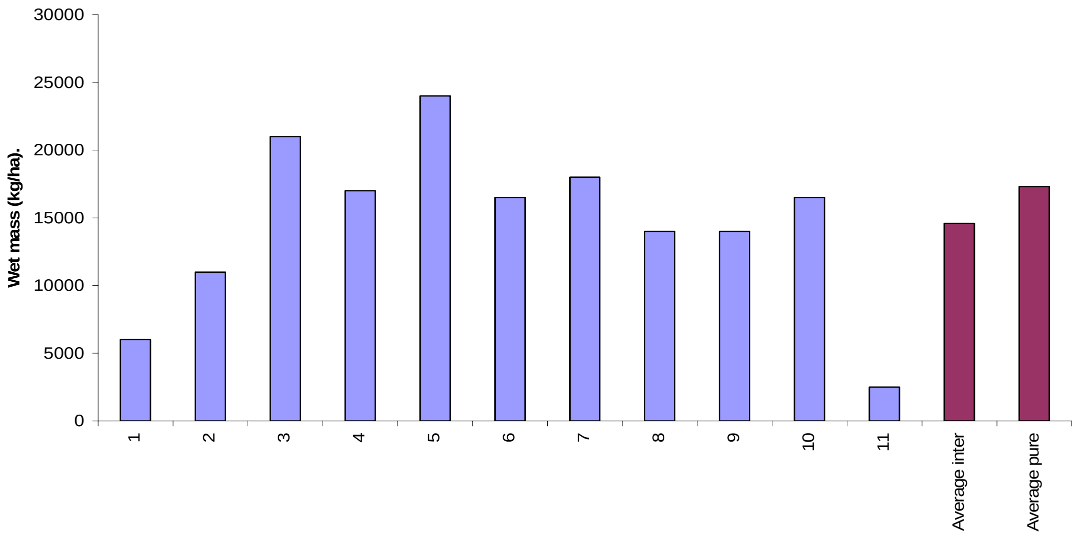

Figure 6.2 Yield of intercropped sweet potatoes, compared to that of a pure stand (1999/2000)

C Sorghum

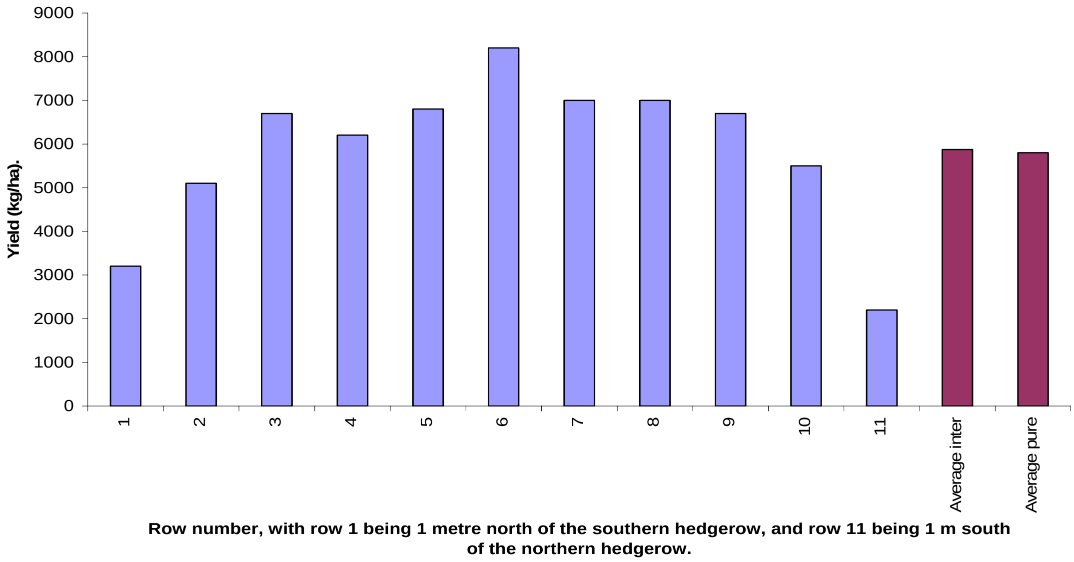

Figure 6.3 Fodder yield of intercropped sorghum, compared to pure stand (1999/2000)

Sorghum in the alley rows (Fig 6.3) yielded markedly higher in central alley rows than in those rows adjacent to trees (rows 1,2, 10 and 11), suggesting interspecific competition for water and/or light in rows closer to the trees. The average stover yield was virtually identical for intercropped and pure stand sorghum (5.9 and 5.8 t stover.ha^{-1} respectively). Sorghum grain was consumed by birds.

D Leucaena

L. leucocephala yields were low by international standards (total edible material of around 3.5 t.ha^{-1} for the pure stand). Kruger (1999) measured yields of edible material in Leucaena harvested in Nelspruit of 7 t.ha $^{-1}$ (contributing 2 t.ha^{-1} of protein). This, however, was achieved in a subtropical climate in an area with an average annual rainfall of approximately 700 mm and lower atmospheric demand due to higher air humidity. Yield of Leucaena per hectare for intercropped (Fig 6.4) Leucaena was 33 and 30% that of pure stand yield for the December and June harvests respectively. With four times the number of intercropped plants in the pure stand (pure stand planting density of 3333 plants.ha^{-1} compared to intercropped planting density of 833 plants.ha^{-1}), yield per plant was, however, higher for intercropped plants than for pure stand plants (Fig. 6.5).

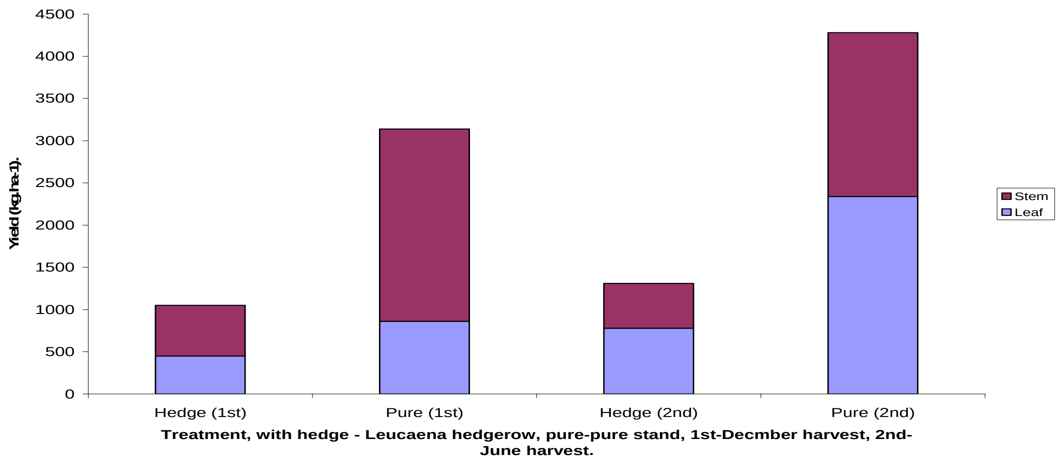

Figure 6.4 Leaf and stem yield per hectare of hedgerow and pure stand Leucaena (2000/2001)

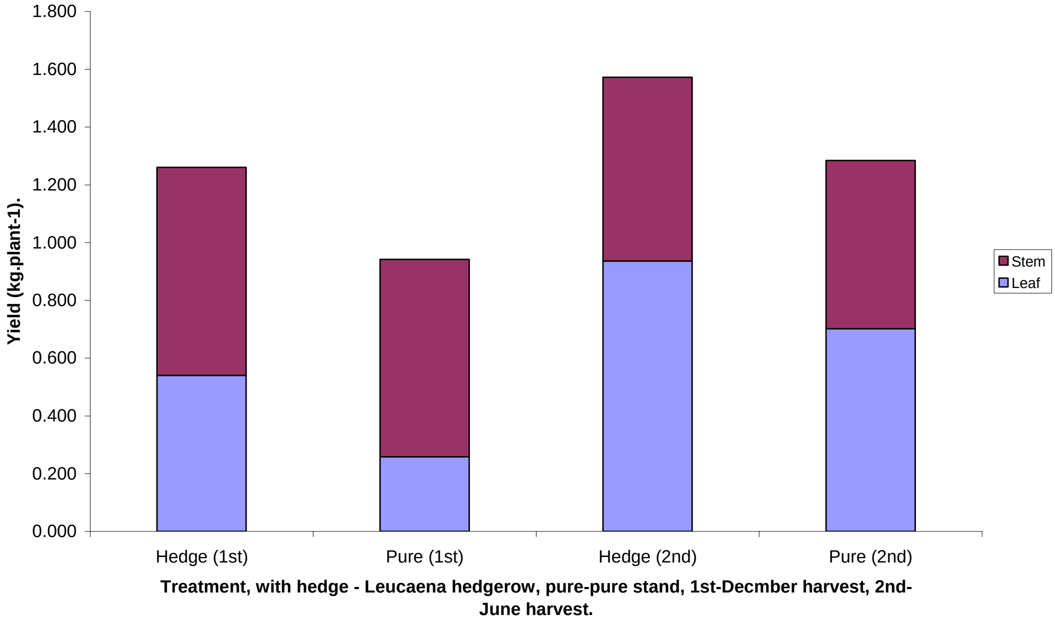

Figure 6.5 Leaf and stem yield per plant of hedgerow and pure stand Leucaena (2000/2001)

6.2 2000-2001 growing season

Total rainfall for this season was above the long-term average for Pretoria, at 728 mm. Distribution of rainfall was, however, erratic with an extremely wet October (180 mm), and fairly wet November (120 mm) and December (120 mm). Monthly distribution of rainfall is illustrated in figure 6.6.

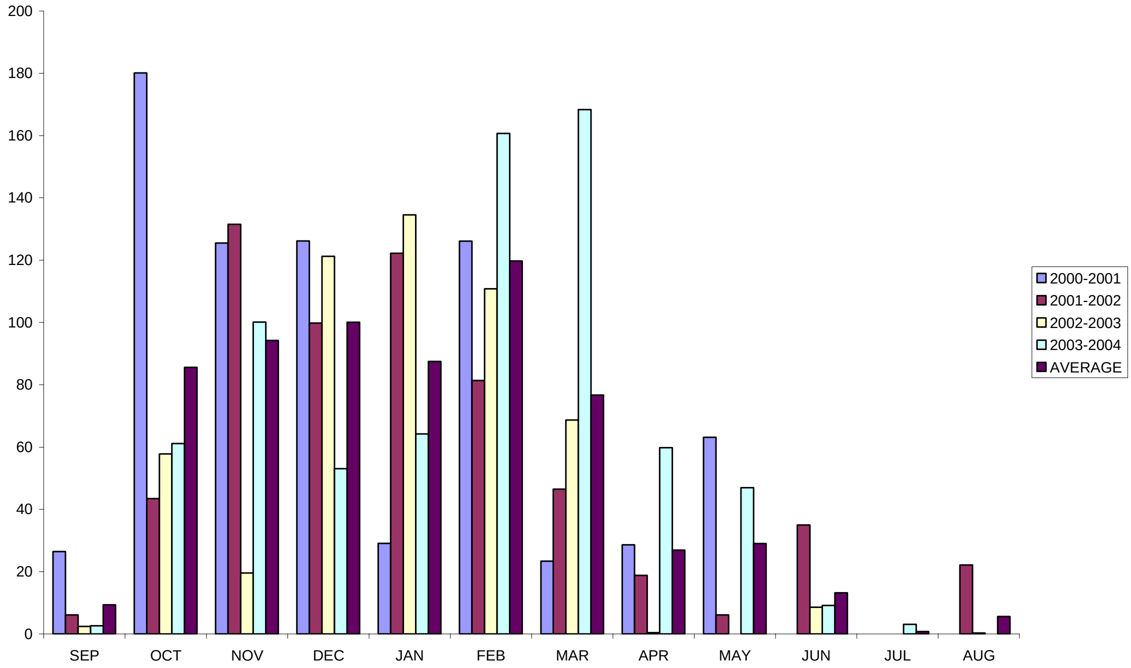

Figure 6.6 Monthly rainfall distribution for the cropping seasons 2000/2001 to 2003/2004

A Cowpeas

The average cowpea yields in the alley rows (0.88 t grain.ha^{-1}) was higher than for the pure stand (0.7 t grain.ha^{-1}) with yields in some alleys nearly double those in the pure stand (Fig. 6.7). As with the previous season, expected decreases in yields in rows adjacent to the hedgerows (rows 1,2, 10 and 11) were not as marked as with other alley species, except for row 11.

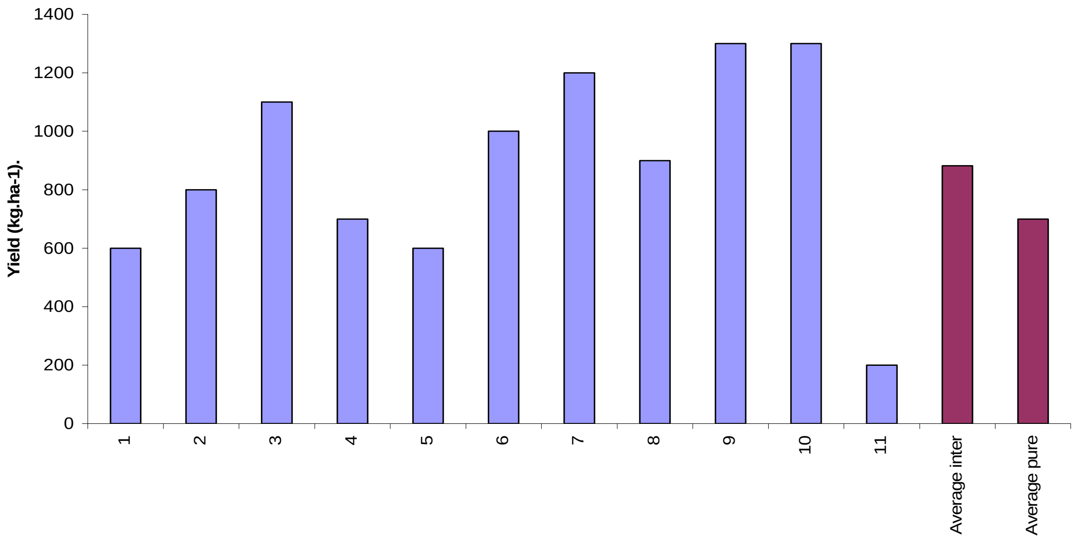

Figure 6.7 Grain yield of intercropped cowpeas, compared to pure stand (2000/2001)

B Sweet potatoes

As with the previous season, yield decreased in rows closer to the Leucaena hedgerows (Fig 6.8). Although yields in central alley rows (rows 3 to 7) exceeded the pure stand average, the average yield of intercropped sweet potatoes was the same as for pure stand due to yield losses in the rows closer to the hedgerows. Yields in the alley rows revealed the bell-shaped curve often associated with hedgerow intercropping.

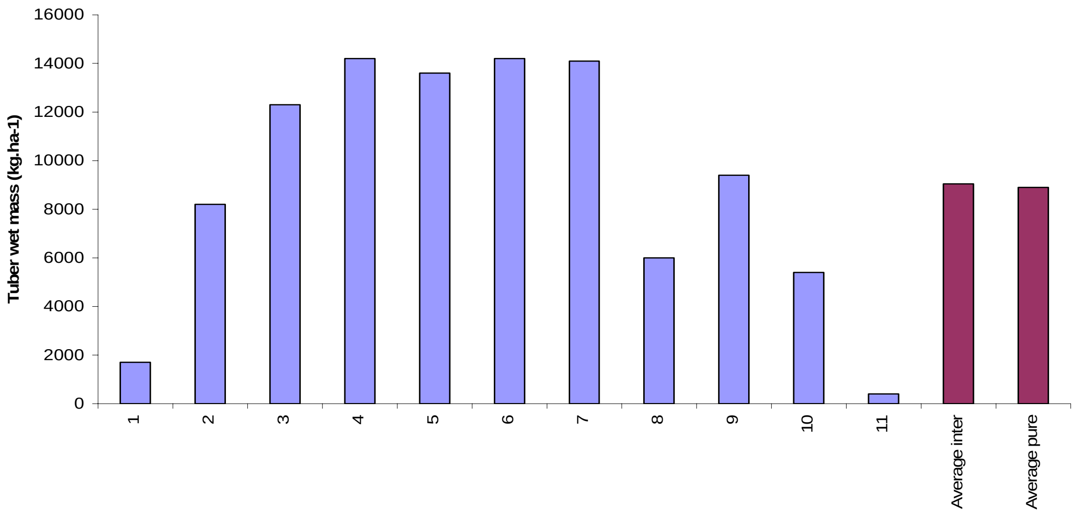

Figure 6.8 Yield of intercropped sweet potatoes, compared to pure stand (2000/2001)

C Sorghum

Yields in both alleys and pure stands (Fig 6.9) were very low in this season, with the average yield in alleys slightly higher (1250 kg stover.ha^{-1} and 280 kg grain.ha^{-1}) than in the pure stand (1250 kg stover.ha^{-1} and 220 kg grain.ha^{-1}). As in the previous season, yields in alley rows adjacent to the hedgerow were markedly lower than other rows.

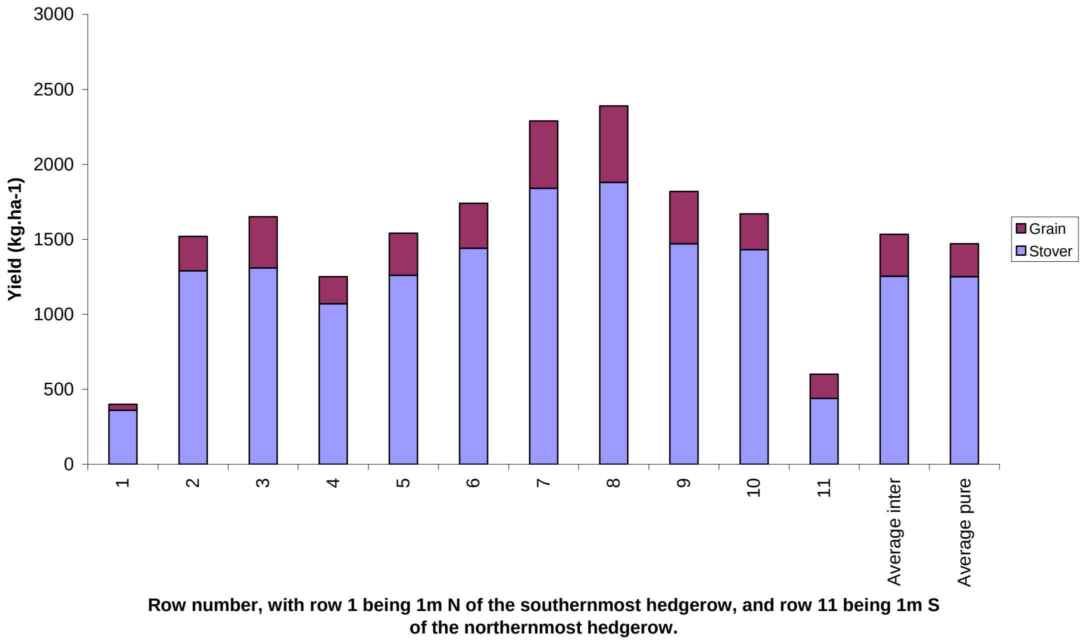

Figure 6.9 Yield of intercropped sorghum, compared to pure stand (2000/2001)

D Leucaena

Yield per hectare (Fig. 6.10) of Leucaena was higher for the pure stand (3333 plants.ha^{-1}) than for the hedgerow (833 plants.ha^{-1}). However, yields per plant (Fig. 6.11) were higher in the hedgerow in the 2nd harvest. This trend was also evident in the first season (1999/2000) and was repeated throughout most of the duration of the trial, suggesting that pure stands of Leucaena may experience greater yield losses through intraspecific competition than they do through interspecific competition with alley crops.

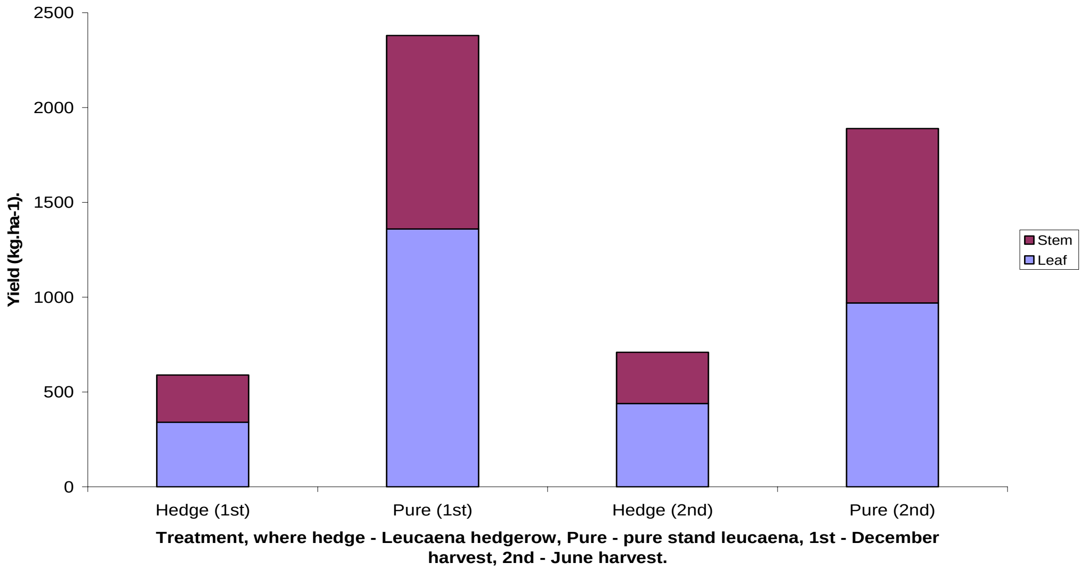

Figure 6.10 Leaf and stem yield per hectare of hedgerow and pure stand Leucaena (2000/2001)

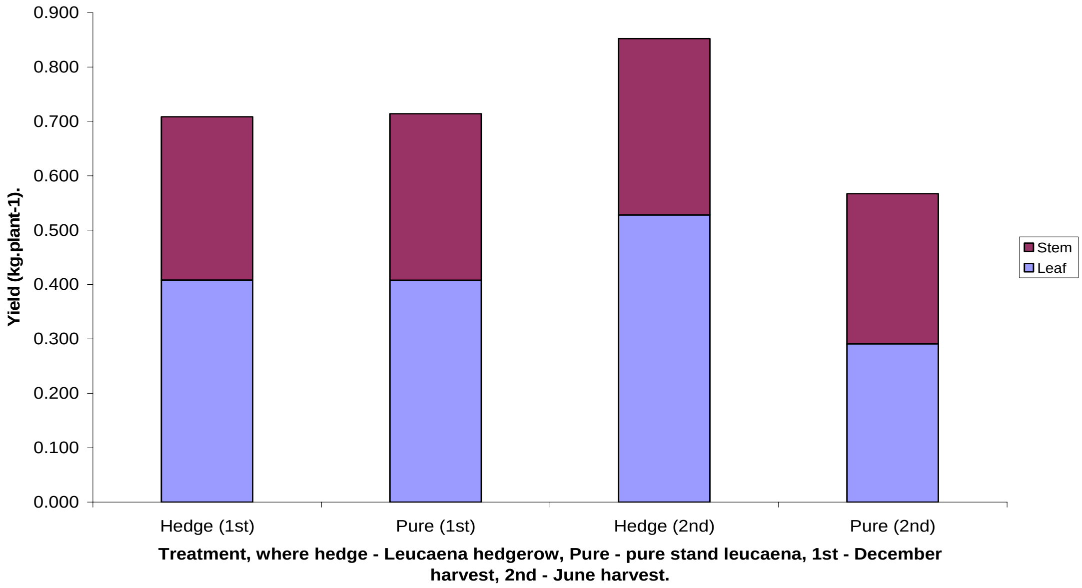

Figure 6.11 Leaf and stem yield per plant of hedgerow and pure stand Leucaena (2000/2001)

6.3 2001-2002 growing season

A Cowpeas

Statistical analysis of cowpea production in this season was carried out, but results showed no explicable tendency between yield and distance of hedgerow from alley-cropped cowpeas. Rows 1, 8 and 9 were significantly lower than row 2. Cowpeas in the 2001/2002 season were attacked by aphids, resulting in lower overall yields, and probably masking any yield loss due to interspecific competition. There was a marked difference (Fig 6.12) between intercropped (1070 kg grain. ha^{-1}) and pure stand (2020 kg grain.ha^{-1}) in terms of yield. Whether intercropped yield losses were due to intercropping or increased aphid prevalence is debatable, but aphid prevalence was lower in the pure stand.

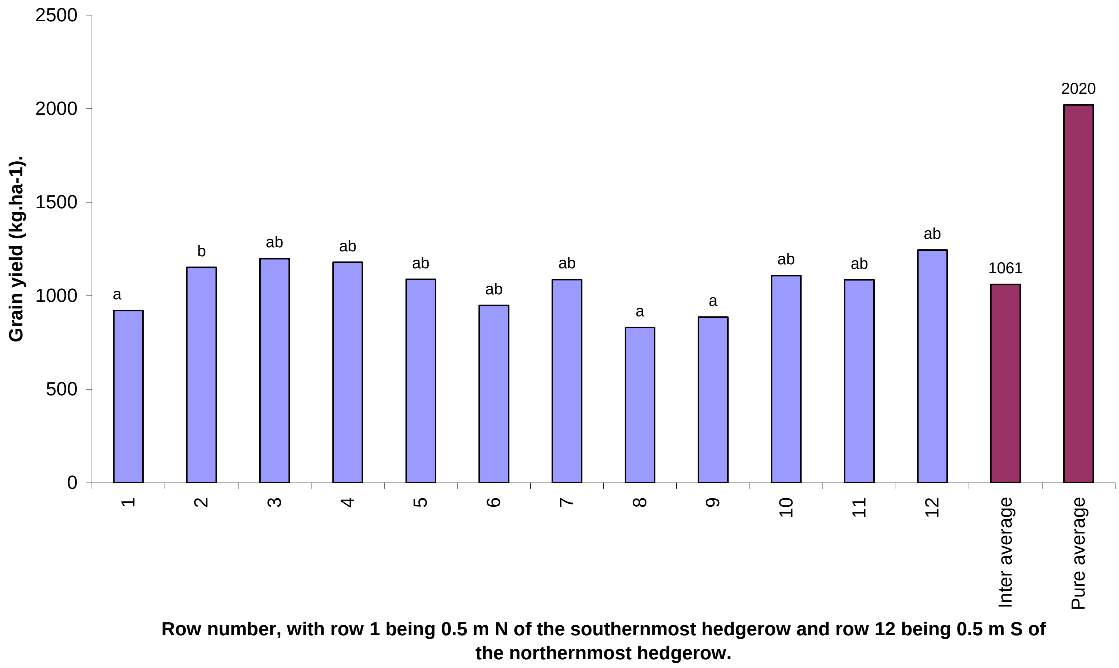

Figure 6.12 Grain yield of intercropped cowpeas, compared to pure stand (2001/2002)

B Sweet potatoes

Sweet potatoes were harvested in June 2002, after planting in mid-December 2001.The sweet potato yields were extremely low (around 2 t.ha^{-1} for a crop with an average dryland yield of 30-40 t.ha^{-1}). This was ascribed to combination of *Fusarium* fungus and comparatively lower rainfall. Sweet potato yields were not analysed statistically for this reason.

C Sorghum

Intercropped sorghum yield showed the typical bell-shaped curve when rows were compared, with the lowest yields in the rows closest to the hedgerows. Yields in alley rows 1 and 12 (i.e. the adjacent alleys) were significantly lower ($P \leq 0.05$) than all other rows. Yields were highest in rows 7 and 8 of the hedgerow, with the row 7 statistically higher than rows 9, 10,11 and 12. Although significantly higher than the rows 1 and 12, the alley 11 was significantly lower than most rows, including its equivalent row, row 2. Average per hectare yield (Fig. 6.13) was higher for pure stand sorghum (5992 kg total DM.ha^{-1} and 1797 kg grain.ha^{-1}) than intercropped (5631 kg total DM.ha^{-1} and 1498 kg grain.ha^{-1}).

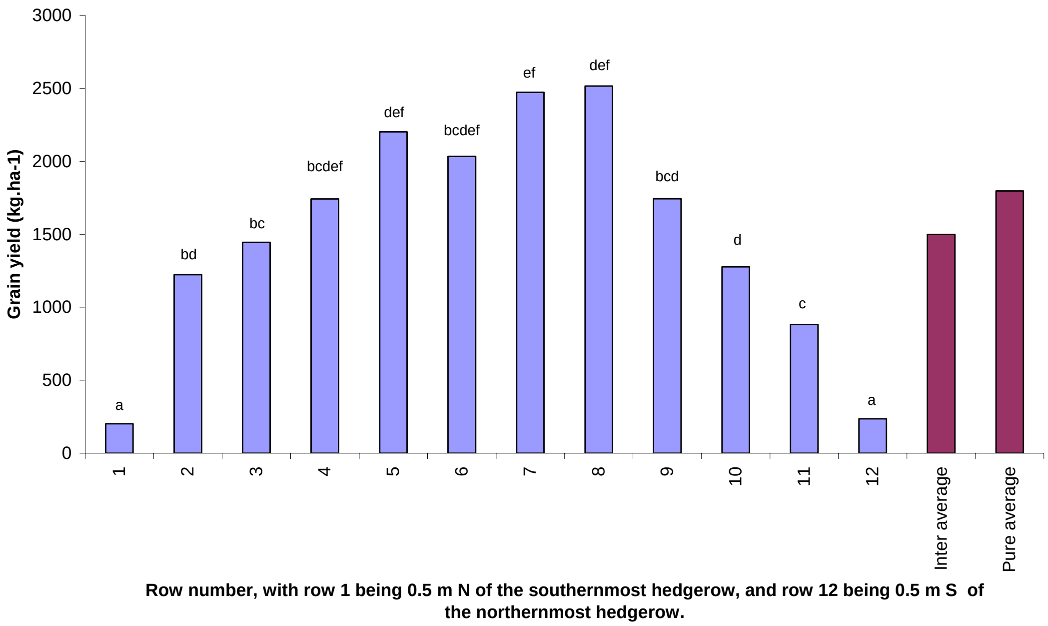

Figure 6.13 Grain yield of intercropped sorghum, compared to pure stand (2001/2002)

December 2001 yield

Average total DM yield (Fig. 6.14 and 6.15) of hedgerow Leucaena, harvested in December 2002, was 1265 g.plant^{-1} (1050 kg total DM.ha^{-1}), compared to 1065.5 g.plant^{-1} (3550 kg total DM.ha^{-1}) for pure stand trees. Yield differences between pure stand Leucaena and intercropped trees were not significant at a 5% level.

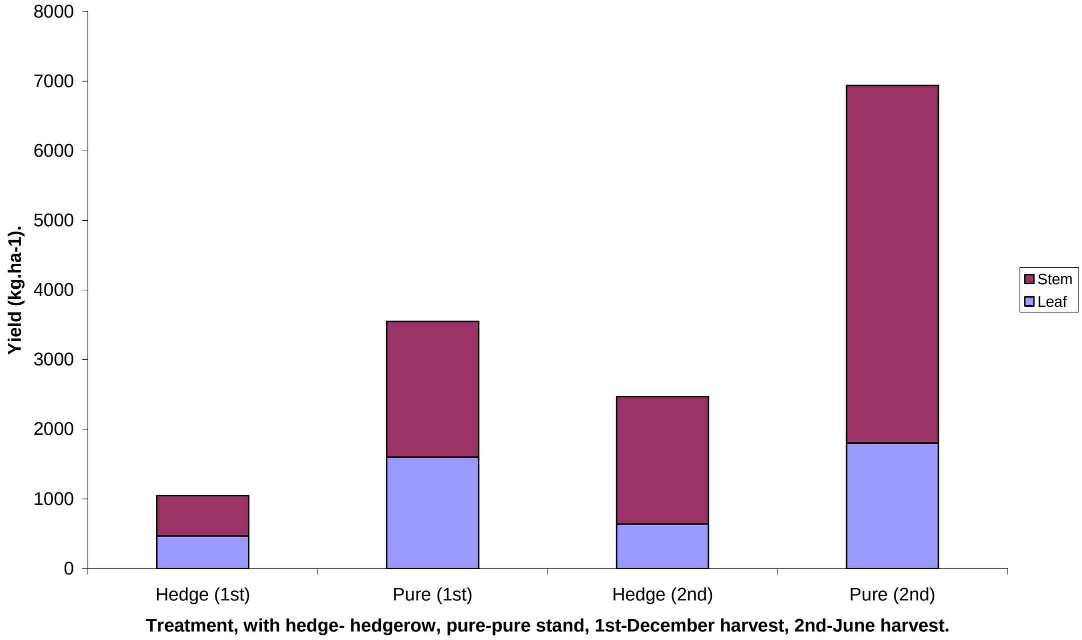

Figure 6.14 Leaf and stem yield per hectare of hedgerow and pure stand Leucaena (2000/2001) in the December harvest

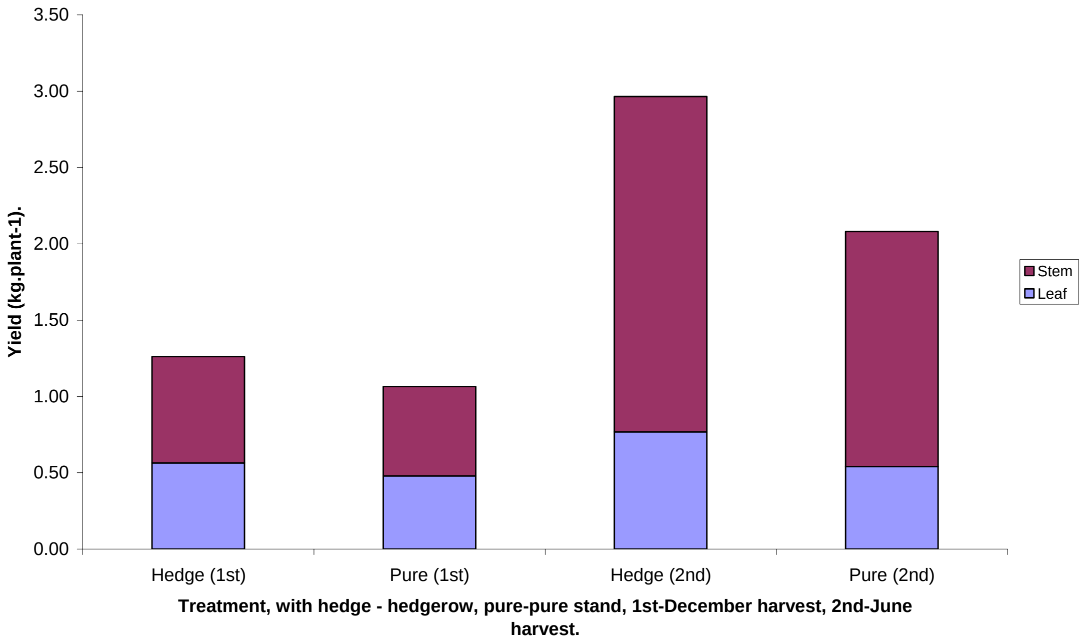

Figure 6.15 Leaf and stem yield per plant of intercropped and pure stand Leucaena (2000/2001) in the December harvest

June 2002 yield

Twenty Leucaena trees were sampled from intercropped and pure stands. Since sampling blocks were positioned differently spatially it was impossible to carry out statistical analysis, to compare pure stand and intercropped yield statistically. Instead, per plant total yields were compared to illustrate differences between pure and intercropped trees. The average yield per plant in hedgerows was 41% higher (2.95 kg total DM.plant^{-1}) than that of trees in a pure stand (2.09 kg total DM.ha^{-1}). When converted to yields per hectare, intercropped stands yielded 2470 kg.ha^{-1}, compared to 6936 kg.ha^{-1} for pure stands. Yield differences were statistically significant at a 5% level (LSD 0.909).

6.4 2002-2003 growing season

The major portion of rain in the 2002-2003 season fell between December and February, with monthly totals for December, January and February being 121, 135 and 111 mm respectively. Maize and sorghum were planted from 15 December. Simulations for the 2002-2003 weather conditions, with a 15 December planting predicted a potential maize yield of 6.1 tons.ha^{-1} grain, and 13.3 t.ha^{-1} total DM. Rainfall in the growing season was 398 mm. This season was fairly warm, with maize expected to reach maturity on 7 April.

As sweet potatoes, sorghum and cowpeas were replaced with maize and sorghum, the effect of previous crop was also analysed statistically. Treatments were thus row number (distance from hedgerow) and previous crop.

A Maize

Intercropped maize

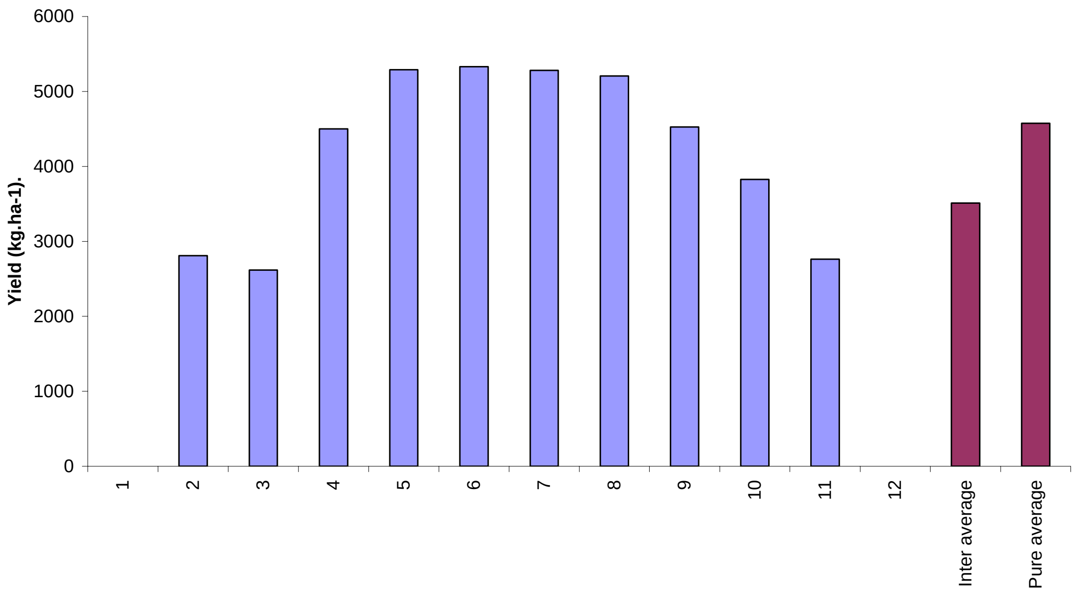

Figure 6.16 Grain yield of intercropped maize, compared to pure stand (2002/2003)

Table 6.1 **Significant differences between yields for different rows under intercropped** maize (2002/03 season)

Row number	Lower than	Higher than
1	4,5,6,7,8,9	
2	5,6,7,8,10	12
3	4,5,6,7,8,9	12
4		12
5		11,12
6		11,12
7		11,12
8		11,12
9		11,12
10		11,12
11		12

There was no significant interaction ($P \leq 0.05$) between row number and previous crop. The highest yields (Fig. 6.16) were obtained in treatments 17, 18 and 19 (rows 5, 6 and 7 previously cropped with sweet potatoes-see table 4.2).

Rows five to eight yielded significantly higher than rows one to three, and 11 and 12.

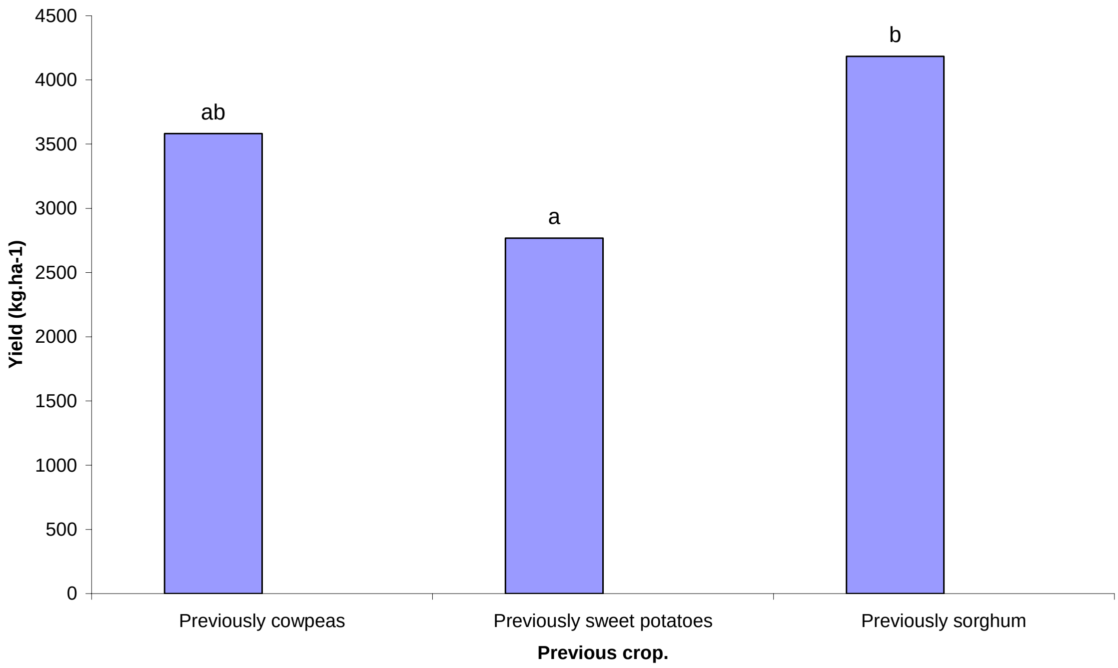

Figure 6.17 Intercropped maize production plotted against previous crop

Previous crop

The highest average maize yield was from plots previously cropped with sorghum (4184 kg grain.ha^{-1} and 9644 kg total DM.ha^{-1} – Fig. 6.17), which was statistically significantly higher than yields obtained in plots previously cropped with sweet potatoes. Plots previously cropped with sweet potatoes had the lowest yields (2768 kg grain.ha^{-1} and 6867 kg total DM.ha^{-1}). These results were contrary to the expected performance from the plots previously cropped with cowpeas, where residual N remaining from microbial fixation from this legume, as well as decomposing N-rich cowpea organic material was expected to benefit the subsequent crop. It is also possible that the high P requirements of the cowpeas depleted P levels more than the sorghum crop.

Pure stand maize

Although no statistical differences were apparent when maize yields were analysed in relation to previous crop, differences in yield averages did exist. Pure stand average maize yield was lowest on plots previously cropped with cowpeas (4189 kg grain.ha^{-1} compared to 4508 and 5029 kg grain.ha^{-1} on plots previously cropped with sweet potatoes and sorghum respectively (Fig 6.18).

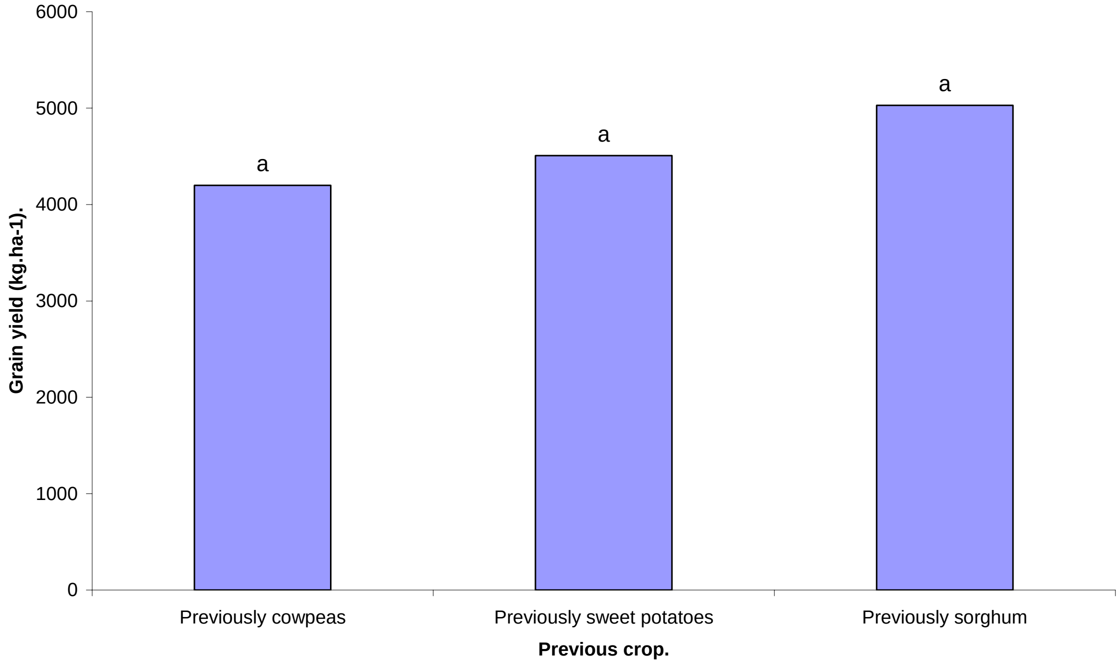

Figure 6.18 Pure stand maize production plotted against previous crop

B Sorghum

Intercropped sorghum

Sorghum yields were highest (Fig. 6.19) on plots previously cropped with sorghum, and lowest on plots previously cropped with cowpeas. Yields of sorghum on plots previously planted to cowpeas, sweet potatoes and sorghum were 9542, 10558 and 13465 $kg.ha^{-1}$ respectively. Differences were, however, not statistically significant. The overall average on intercropped plots was 11188 $kg.ha^{-1}$, markedly lower than the 16600 $kg.ha^{-1}$ measured on the pure stands (Fig. 6.20).

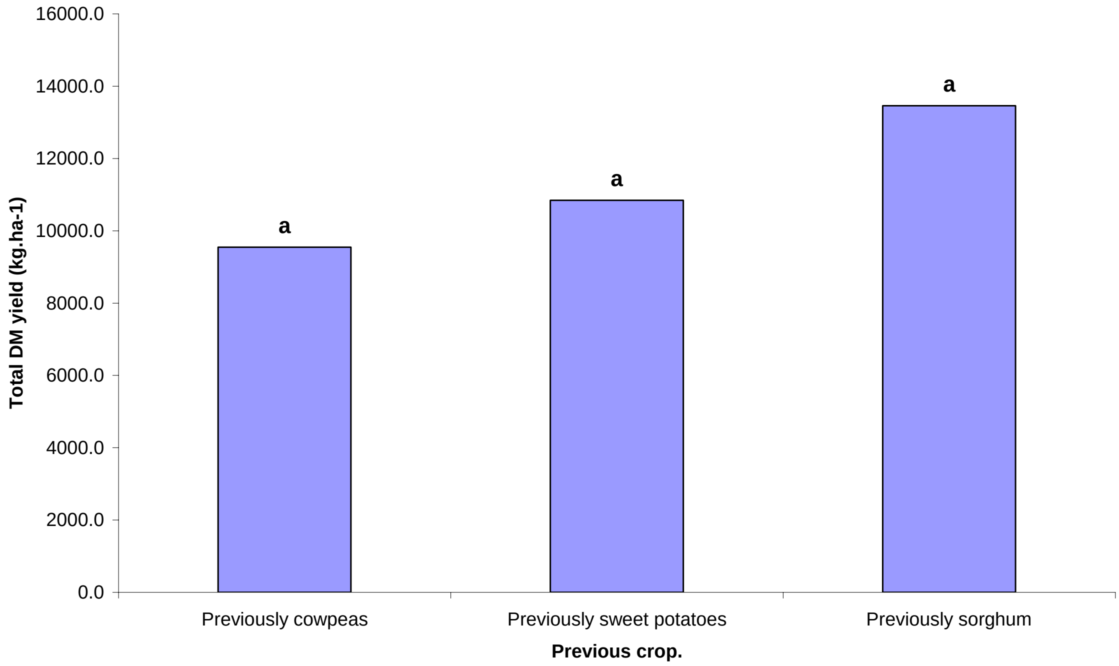

Figure 6.19 Intercropped forage sorghum production plotted against previous crop

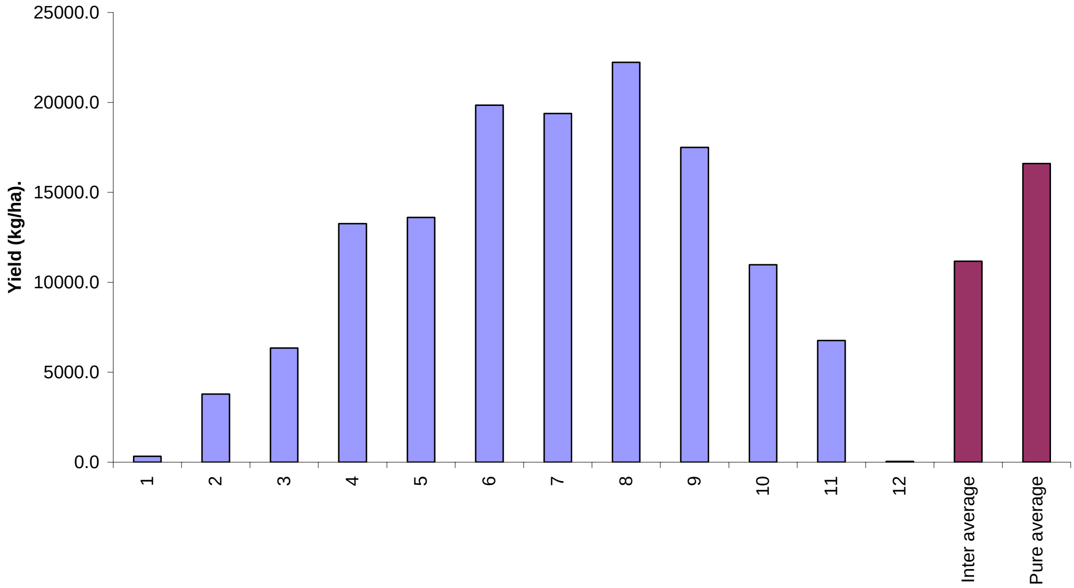

Figure 6.20 Total DM yield of intercropped sorghum, compared to pure stand (2002/2003)

Table 6.2 Significant differences between yields for different rows under intercropped sorghum (2002/03 season)

Row number	Lower than	Higher than
1	3,4,5,6,7,8,9,10,11	
2	4,5,6,7,8,9,10	
3	4,5,6,7,8,9,10	11
4	7,12	
5		11,12
6		11,12
7		10,11,12
8		11,12
9		11,12
10		12
11		
12		

The effects of competition between alley-cropped sorghum and Leucaena hedgerows was evident in the typical bell-shaped yield curve, favouring sorghum growth in the rows in the centre of the alley (rows five to nine). Although the overall average yield of intercropped stands was lower than pure stands, central rows often outperformed pure stands, with yields of over 20 tons.ha^{-1} for central rows in many cases. Adjacent row yield losses were, nonetheless, drastic enough to make intercropped sorghum less productive than pure stands on average. Highest yield was obtained in the three central rows (rows six to eight), and yield in rows five to nine were significantly higher than those of rows one, two, three, 10 and 11.

Pure stand sorghum

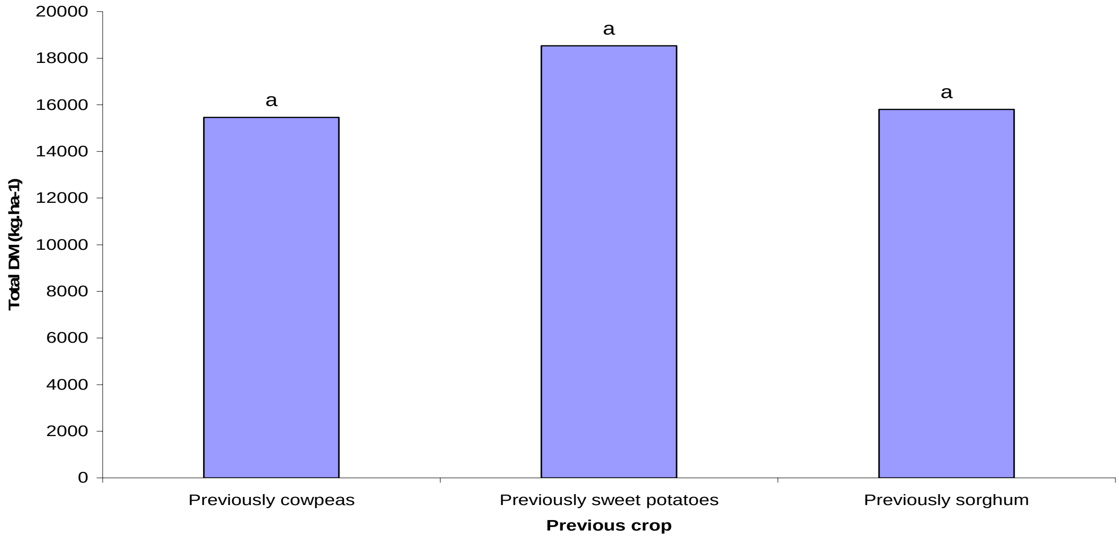

Figure 6.21 Yield of pure stand forage sorghum production plotted against previous crop

No statistical differences were obtained when sorghum yields were analysed relative to the previous crop. The average yield of sorghum on plots previously cropped with cowpeas (was marginally lower, while in contrast to intercropped and pure stand maize, the average yields of sorghum on plots previously planted with sweet potatoes were higher than those previously planted with sorghum. Yields were for total dry matter, since the sorghum cultivar was a forage cultivar. Fodder yields where previous crops were cowpeas, sorghum and sweet potatoes as a treatment were 15438, 15508 and 18531 kg.ha^{-1} respectively (Fig. 6.21). The overall average yield for pure stand sorghum (16600 kg.ha^{-1}) was higher than for intercropped sorghum (11188 kg.ha^{-1}).

C Leucaena

December 2002 yield

There were no marked differences between intercropped and pure stand leucaena yields per plant in the 2002/2003 cropping season. Average total DM yield per plant was 1.08 kg.plant^{-1} for the pure stand and 1.03 kg.plant^{-1}for intercropped trees (Fig. 6.22 and 6.23).

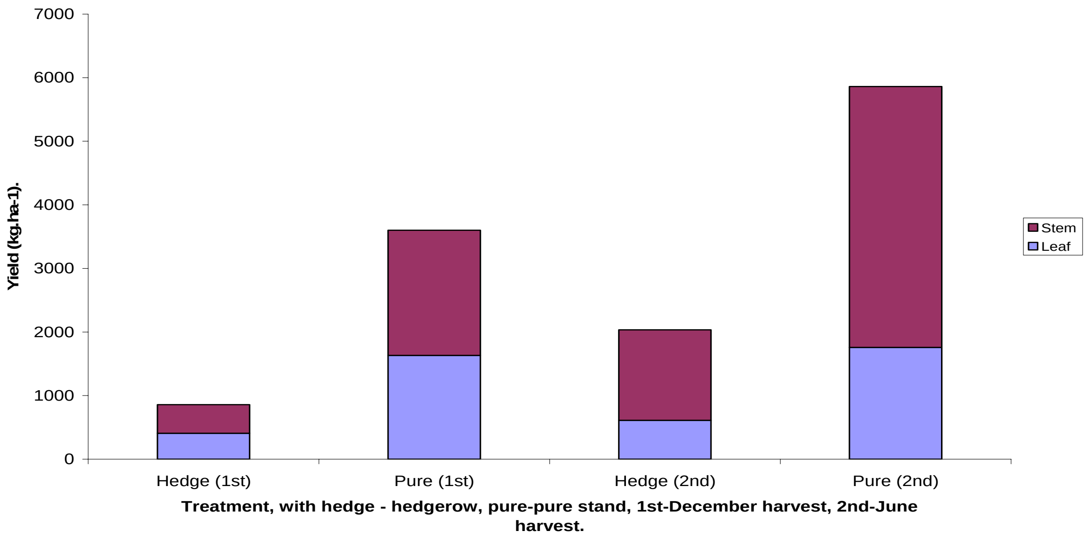

Figure 6.22 Leaf and stem yield per hectare of intercropped and pure stand Leucaena (2002/2003)

June 2003

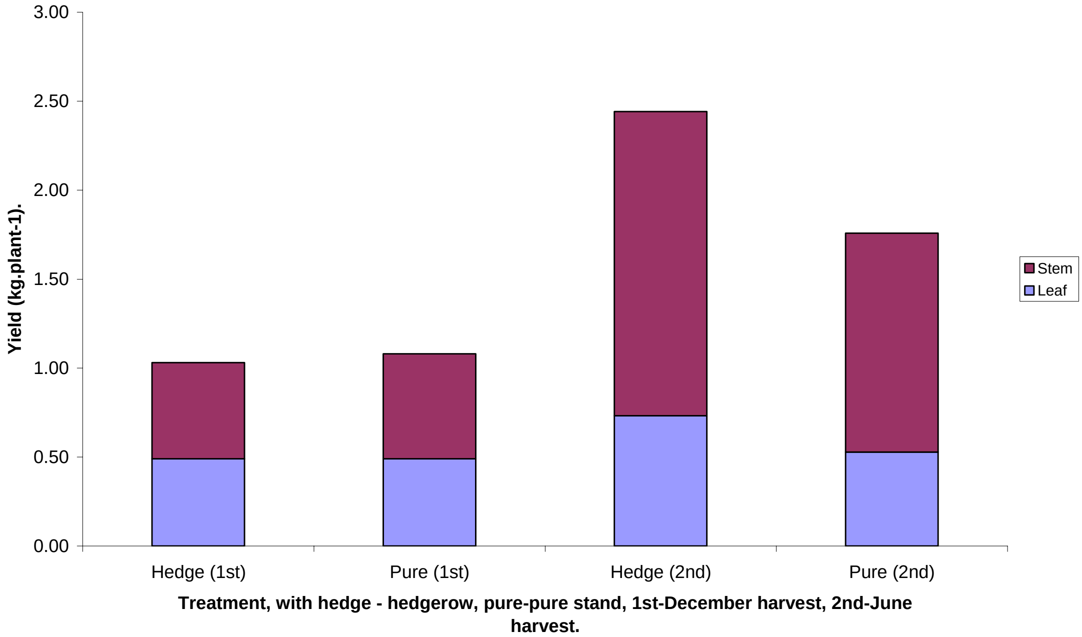

Figure 6.23 Leaf and stem yield per plant of intercropped and pure stand Leucaena (2002/2003)

June 2003 yield

In June (2nd harvest) pure stand Leucaena had lower yields than intercropped Leucaena per plant, confirming intraspecific competition between trees in pure stands. The average yield (total DM) per plant for pure stands was 1.71 kg compared to 2.45 kg for hedgerow trees. At respective densities of 833 and 3333 trees.ha^{-1} for intercropped and pure stands, total DM production per hectare at this stage was 5861 kg for pure stands and 2034 kg for intercropped trees. Overall, Leucaena yields in the second harvest were the lowest of the three seasons studied, probably as a result of the poor rains in the previous two seasons.

At this stage the proportional contribution of leaves to the total DM was lower than in the December cutting, with leaves contributing 26% to total yield in March, compared to 45% in December.

6.5 2003-2004 growing season

The 2003-2004 growing season was cooler and wetter than 2002-2003, with simulated maturity for maize, with a planting date of 15 December at 11 May, and a simulated yield potential of 4400 kg.ha^{-1} grain and 10500 kg.ha^{-1} TDM. Rainfall during the growing season was 495 mm, with the majority falling later in the season (161 mm and 223 mm for February and March respectively).

A Maize

Intercropped maize yields (Fig. 6.24) were higher in the central alley rows (rows 5 to 8) than in pure stands, with these rows consistently yielding above 6000 kg grain.ha^{-1} compared to average pure stand average of 3921 kg.ha^{-1}. Despite dramatic yield losses in rows adjacent to the Leucaena hedgerows (rows one, two, 10, 11 and 12) the average yield of intercropped maize (3730 kg.ha^{-1}) was higher than that of the pure stand (3550 kg.ha^{-1}). Yields in rows adjacent to the hedgerows were significantly lower than other rows, while rows three to nine yielded significantly rows one, two, 11 and 12.

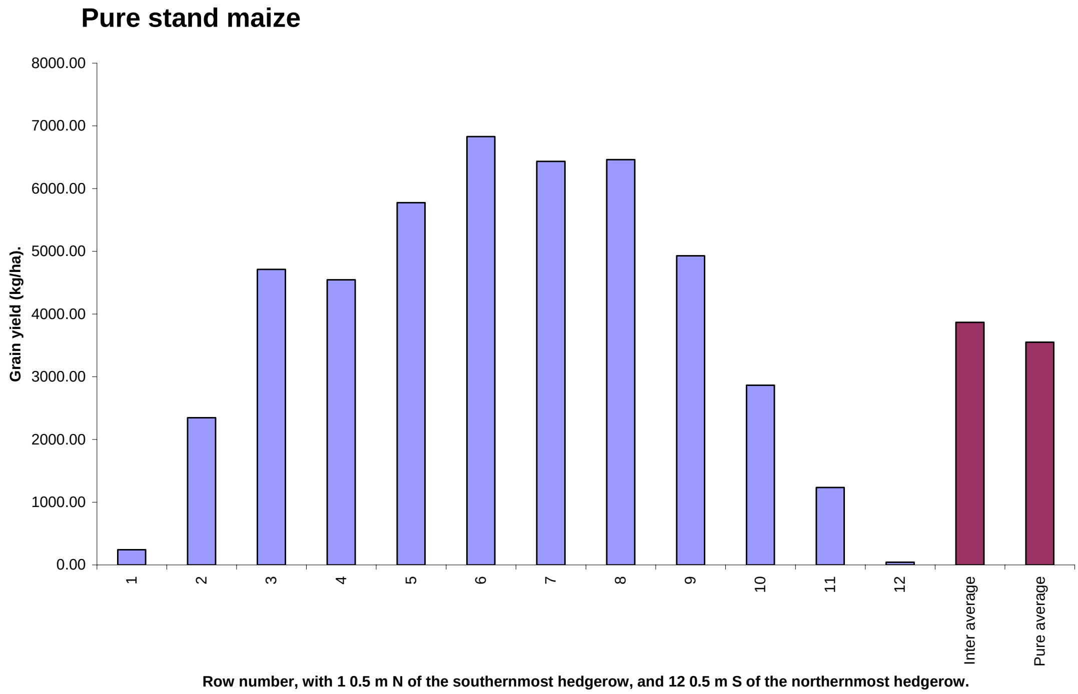

Figure 6.24 Grain yields of intercropped maize, compared to pure stand (2003/2004)

Table 6.3 Significant differences between yields for different rows under intercropped maize (2003/04 season)

Row number	Lower than	Higher than
1	2,3,4,5,6,7,8,9,10	
2	3,4,5,6,7,8,9	12
3	6	10,11,12
4	6,8	10,11,12
5		10,11,13
6		9,10,11,12
7		10,11,12
8		10,11,12
9		10,11,12
10		11,12
11		12

B Sorghum

Intercropped sorghum (Fig. 6.25) exhibited the same production tendencies as in the previous seasons, with rows adjacent to the trees (rows one, two, 10, 11and 12) yielding dramatically less than the inner rows. The yields of alley rows 1, 11 and 12 m N were significantly lower than other rows.

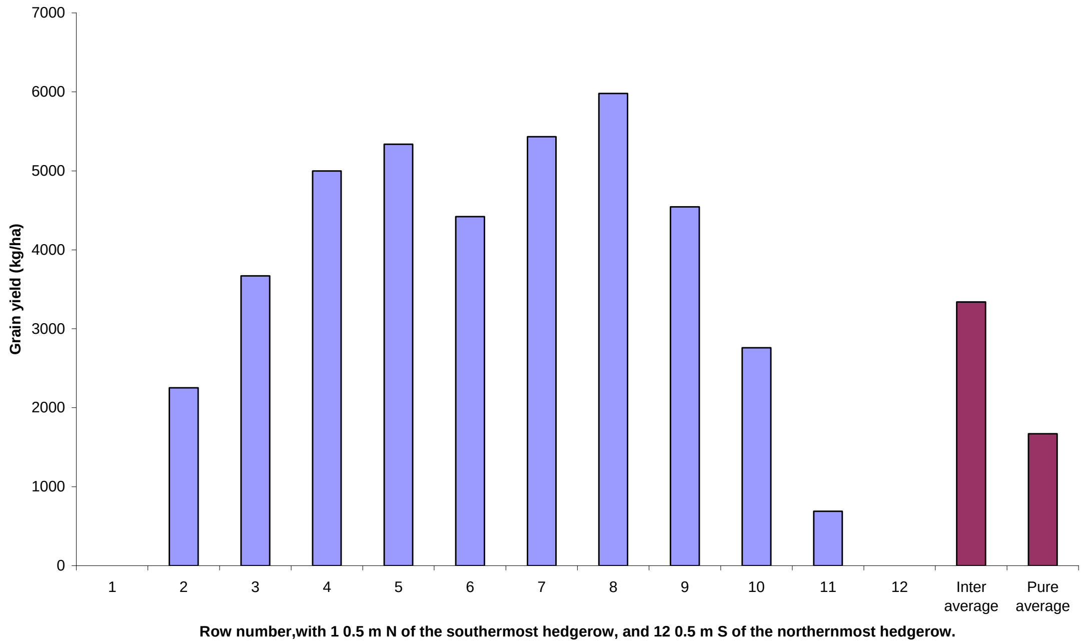

Figure 6.25 Grain yield per row of intercropped grain sorghum, compared to pure stand sorghum (2003/2004)

Table 6.4 Significant differences between yields for different rows under intercropped sorghum (2003/04 season)

Row number	Lower than	Higher than
1	2,3,4,5,6,7,8,9,10	
2	3,4,5,6,7,8,9	11,12
3		10,11,12
4		11,12
5		10,11,12
6		10,11,12
7		10,11,12
8		10,11,12
9		11,12
10		11,12
11		12

Pure stand sorghum

Sorghum grain yields in the intercrop (3374 kg/ha) were far higher than in the pure stand (1674 kg/ha).

C Leucaena

December 2003

The first (December) cutting in the 2003/2004 season (Fig. 6.26 and 6.27) yielded considerably higher yields per plant for the intercropped trees (0.89 kg total DM per plant or 741 kg total DM.ha^{-1}) than pure stand plants (0.57 kg.plant^{-1} or 1900 kg DM.ha^{-1}). This was also the lowest average yield per plant measured in the three seasons. This could possibly be ascribed to the steady decrease in water content in the deeper soil layers over the three growing seasons, and casts doubt on the ability of rain to recharge deeper soil levels in cropping systems combining shallow and deeper rooting crops under local conditions. Annual rainfall in the preceding two seasons (613 and 524 mm in the 2001/02 and 2002/03 seasons respectively) was considerably lower than the long-term average (± 700 mm), and this poor

December harvest possibly reflects the combined below average rainfall and intraspecific competition.

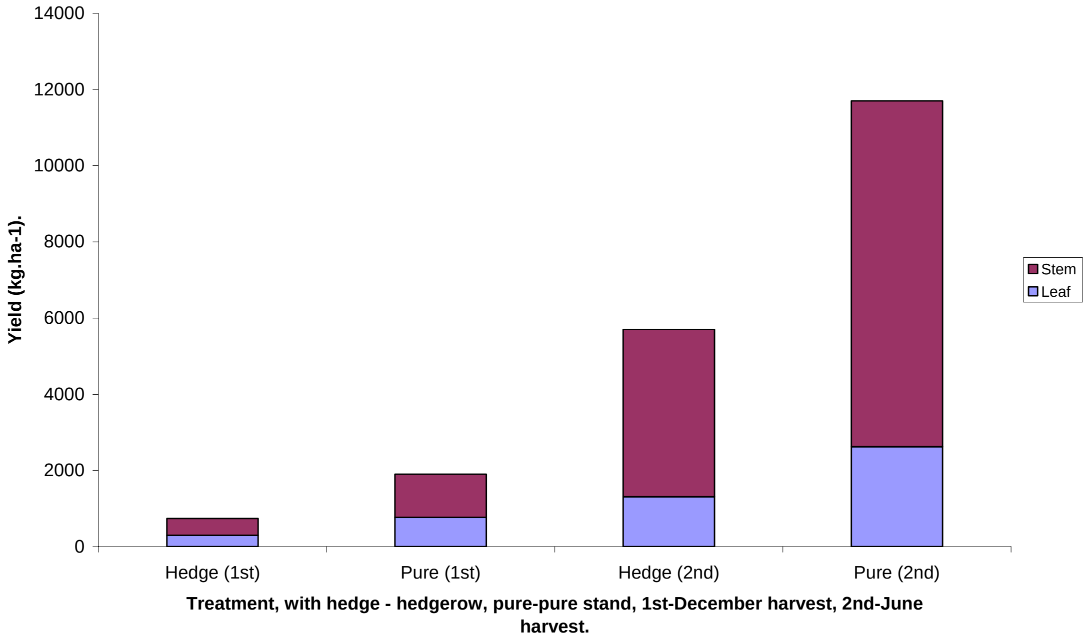

Figure 6.26 Leaf and stem yield per hectare of intercropped and pure stand Leucaena (2003/2004)

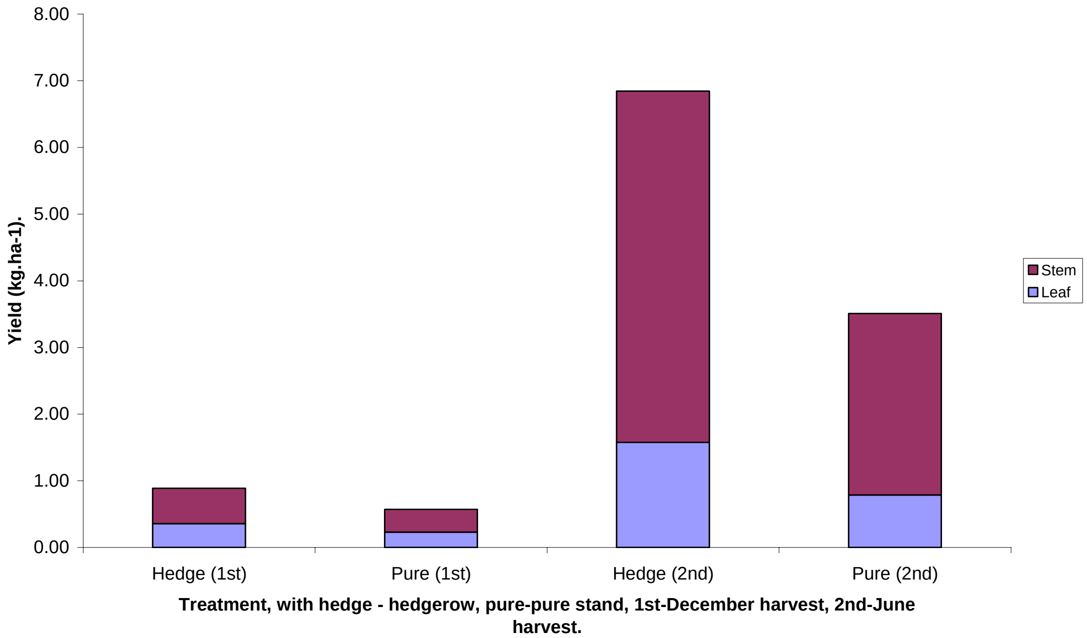

Figure 6.27 Leaf and stem yield per plant of intercropped and pure stand Leucaena (2003/2004)

June 2004

The second Leucaena harvest in the 2003/04 season, in June 2004, confirmed the yield advantage of intercropped trees above pure stands, with intercropped trees yielding twice that of pure stand trees (6.86 $kg.plant^{-1}$ for intercropped trees, and 3.51 $kg.plant^{-1}$ for pure stand trees). Respective yields per hectare for intercropped and pure stand Leucaena was 5.7 $t.ha^{-1}$ and 11.7 $t.ha^{-1}$. Yield in this harvest was higher than in previous seasons, reflecting the late rains of the 2003/04 season, when over 300 mm fell in February and March - months associated with maturity of grain crops, and the later part of the growing season.

6.6 Discussion

Grain and forage plants in pure stands outperformed intercropped plants in almost all cases. Although intercropped plants in the central rows outyielded pure stand plants in every season, yield losses in adjacent rows were too large to allow intercropping systems to perform as well as pure stands overall. The gradual, progressive drying of deeper soil zones over a number of seasons with, intercropping, appears to force hedgerow Leucaena to explore shallower soil zones for water, resulting in interspecific competition for water, resulting in moisture stress during crucial growth periods for forage and grain alley crops. The attempt to improve system productivity by maximizing soil profile water use, with complementary root systems of deeper-rooting hedgerow trees and shallower-rooting annual species, appears to be more appropriate to environments where hedgerow trees are less likely to experience water stress.

Leucaena production, on the other hand, was consistently higher in intercropped stands than pure stands, suggesting that leucaena yield is diminished less by interspecific competition than by intraspecific competition. In agricultural systems where firewood and nitrogen-rich fodder are as important as, or more important than, grain for human consumption, intercropping may be utilized productively.

7 RESULTS AND DISCUSSION – "ON-FARM" AND COMMUNITY DEVELOPMENT THRUSTS

7.1 Results – Sekakane

A survival rate of 90% was recorded for Leucaena saplings planted with supplementary irrigation in the 2002/2003 season – dead trees were replaced.

The influence of pruning to a single stem in comparison with the coppicing system on the production of Leucaena is reflected in Table 7.1

Table 7.1 The influence of pruning on the productivity of Leucaena at Sekakane in the 2003/2004 season

	Single Stem Trees	Multiple Stem coppice
Mean height	1.9 m	1.7 m
Canopy volume	3.86 m^3	3.55 m^3
Yield of fuel	95 $kg.ha^{-1}$	127 $kg.ha^{-1}$
Yield of leaves	40 $kg.ha^{-1}$	59 $kg.ha^{-1}$
Yield of pods	36 $kg.ha^{-1}$	73 $kg.ha^{-1}$

Coppice produced 35% more fuel, 48% more leaves and 103% more pods (With respect to the pods, while coppice plants had young immature pods in the winter the single stem trees had more mature pods (and hence a poorer quality) in the winter.

Table 7.2 The productivity of maize and leucaena in different systems at Sekakane in the 2003/2004 growing season ($kg.ha^{-1}$)

Crop Component	System		
	Mono-culture Maize	Leucaena trees X Maize	Leucaena coppice X Maize
Maize grain	2165$^{(1)}$	1655$^{(2)}$	1655$^{(2)}$
Maize stover	2000	1500	1500
Inedible Leucaena	-	95$^{(3)}$	127$^{(3)}$
Edible Leucaena	-	76	132
Total DM harvested	4165	3326	3414

(1) Maize yield from pure stand ($kg.ha^{-1}$)
(2) Maize yield from alley crop area of 0.7 ha
(3) Leucaena yields from hedgerows (single stem trees or coppice - $kg.ha^{-1}$)

The results, recorded in the 2003/2004 season (Table 7.2), were in the favour of monoculture maize in comparison with the maize x Leucaena coppice system. This must, however, be qualified by the fact that keeping the rows of maize a full 3m from the trees was a conservative error. Initially the idea had been to ensure that the maize intercrop should not stunt the trees in the early stages of development and also to ensure that the border rows of maize were not too negatively impacted by competition from the trees ("On-station" results obtained in Pretoria, under much better rainfall conditions, had indicated a strong competitive effect from mature Leuceana coppice; declining rapidly as the crop distance from the trees was increased from 0.5 m to 1.5 m to 2.5 m). At Sekakane in the second season trees had absolutely no impact on the maize and in fact the border rows of maize planted 3 m from the trees were the highest yielding rows. Furthermore the yields per 100 m intercrop row (or 0.7 ha or 0.9 ha) were as good and better than those from the control block (monoculture). In a "what if" scenario where maize was planted closer to the trees (adding an additional 4 rows to each alley intercrop) the combined yield of maize and Leucaena was 4144 kg $DM.ha^{-1}$ which is very comparable with the total DM production of maize from the monoculture (4165 kg $DM.ha^{-1}$).

Table 7.3 Hypothetical comparison of maize and leucaena yields from maize alleys of 0.7 m and 0.9 ha respectively cropped between coppiced leucaena hedgerows (the latter being based on an additional four rows of maize in each alley, which yielded considerably lower yields – based on Hatfield experimental results)

Crop Component	System		
	Mono-culture Maize	Leucaena coppice X 0.7 ha maize	Leucaena coppice X 0.9 ha maize
Maize grain (kg/ha)	2165	1655	1955
Maize stover (kg/ha)	2000	1500	1900
Inedible Leucaena	-	127	127
Edible Leucaena	-	132	132
Total DM harvested	4165	3414	4114

Of the three seasons evaluated "on-farm", the 2003/2004 season was by far the best. It would appear that the lower rainfall limit for considering maize (either as a monoculture or as an alley inter crop) would be 360 – 400 mm in the summer growing season although this could be adjusted according to soil properties. Under such conditions the choice between mono-culture maize and an alley cropping system would be determined primarily by the needs of the land user for grain, fuel wood, bulk roughage and protein supplements, and the relative values attached to such products.

In the 3rd season (2004/2005), when drought of disaster proportions (120 mm rainfall) was experienced, the maize crop was a total disaster (with no grain being produced, no surviving plants within 5m of trees and a very sparse stand of plants (0.3 – 0.4 m tall compared with 1.5 – 1.8 m tall in the previous season) on the remaining six intercrop rows and in the monoculture block. Yields of maize stem and leaves were estimated to only be 150 and 200 $kg.ha^{-1}$ from the alley and mono-crop systems respectively. In contrast, although the productivity of the Leucaena was negatively impacted, virtually all plants survived, with production of wood, leaves and pods being estimated at 80, 40 and 50 $kg.ha^{-1}$ from Leucaena coppice respectively.

The implications of these findings are that where rainfall conditions tend to be more arid than semi-arid (200 – 300 mm) perennial crops such as Leucaena with adapted grasses such as *Cenchrus* and *Anthephora,* would probably be a better bet than annual row crops such as maize. More drought tolerant sorghum and millet might still, however, be a consideration. The other consideration is to have mono-specific stands of row crops (with appropriate cultivar choice and agronomic practice for such dry conditions) and tree lots, but this would be the subject of further research.

7.2 Results – Chuene Maja

In the establishment season (2002/2003) 85% of the saplings survived, but had bucket watering not been provided the mortality would have been higher as hail, termites and shallow planting had had negative impacts and placed the saplings under stress.

Table 7.4 Assessment of Leucaena components in 2003/2004 at Chuene Maja as influenced by pruning

		Single Stem Trees	Multiple Stem coppice
Canopy:	Height (m)	1.70	1.52
	Diameter (m)	1.54	1.35
	Volume (m^3)	3.17	2.18
Mortality		15%	15%

Although the multi-stemmed coppiced plants were a lot smaller (as at Sekakane) they were leafier and physiologically younger. Unfortunately this edible material was not carried through to mid-winter, when such protein rich forage would be extremely valuable for livestock, because frost resulted in 90% of the surviving trees losing their leaves. Under such conditions Leucaena would only play a significant role in late summer and autumn, although it should be noted that this species is characterized by excellent spring re-growth (long before any other forage species), where it has been pruned to 0.3 m in winter, or where frost has caused significant top-kill.

Once again this trial site has demonstrated that where annual row crops might fail (because of drought or socio-economic reasons) the incorporation of perennial fodder trees has the advantage of providing a diversity of products to meet the needs of communities. Although winter frost resulted in top-kill of many plants in the winter of 2004, most of these plants re-grew in 2004/2005 resulting in a multi-stemmed coppice growth form, which would appear to be a desirable result under local conditions.

7.3 Results from Community Development Programme

(a) <u>Information days 2002/2003 season</u>

In May 2003 information days were held at the Sekakane and Chuene Maja sites. The responses of the attendees to the questionnaire were particularly relevant. Although virtually all participants recognized the contribution which trees could make to meeting the food, fuel, shade, shelter, fencing, etc. needs of rural communities this was not recognized as formal agriculture. The concept of agroforestry was not only not well known, it was virtually unknown. In fact if the questionnaire had preceded the short workshop on agro-forestry at these information days a total lack of knowledge about this concept would probably been reflected. If this concept of agro-forestry was compared with maize production, where farmers – both large and small scale – have been exposed to literally generations of extension inputs, but where the application of recommendations is still so poor, then it becomes evident that the team was probably overly optimistic about demonstrating alley cropping in this scenario (small scale farmers in semi-arid to arid conditions) and working on why acceptance of such concepts is a problem. The initial input should probably have been focussed on extension field staff, leading hopefully at a later stage to demonstration and education AND where necessary research. This project started at the other end – “on-station” research to determine whether alley cropping was a proposition with 600 mm of rainfall, moving to apply this concept with an average rainfall of 205 mm (a first in the world) and then coming up short, when crops failed 66% of the time. Under such rainfall conditions even the best agronomist would struggle to formulate, and put into practice, a strategy to produce maize in a mono-culture in a sustainable manner, let alone in a alley cropping system where interspecies competition for scarce resources would be a major consideration.

When asked what the major problems were facing rural communities, in such dry environments, water totally dominated the answers. At Sekakane 97% listed water (potable, irrigation, stock water) as the most important factor, while at Chuene Maja 71% regarded water as the most important factor. Still important, but not as overwhelming (20 – 40% of respondents), were pests and diseases (plant and animal), soil fertility and the availability of feed as grazing and fodder for their livestock. Between 10 – 15% also listed land, implements and availability and cost of seed as limiting factors. Less than 10% mentioned finances, fencing, firewood, water quality, stock theft, knowledge, electricity, dipping facilities or livestock remedies. From this it may be concluded that these communities would be particularly receptive to messages which emphasized water harvesting, water use efficiency of crops, or cropping systems which were drought tolerant and yielded something even in severe drought seasons, reduction of risk, etc. With respect to potential agro-forestry systems it is very evident that these communities have interests in both cropping (maybe because of the small intensive areas under irrigation) and livestock. Livestock feed is evidently important but increasing emphasis could possibly be placed on the synergies between row crops, tree crops and animals in terms of feed, fertility (especially using leguminous species and emphasizing the circulation of nutrients through the animals). Although fuel wood and fencing receive only passing mention as problems, the former (in particular) plays a major time-consuming role in the majority of households. If education programmes would lay emphasis on the savings (especially freeing up family members to improve their education and/or expand their inputs into home gardens or cottage industries) this would probably receive a positive response. Such an emphasis would change the perceptions about alley cropping and wood lots, especially if it was emphasized that such tree components could be selected for multi-purposes, thereby increasing diversity and reducing risk. Agroforestry systems would have to be developed for different ecological and socio-ecological conditions and should not be regarded as an end, or objective, in themselves but as a component of sustainable rural living. In this context this project probably missed the boat, coming into areas with a "new" concept and concentrating on the concept as such, without enough emphasis on a holistic approach. Agro-forestry is at least now known, especially amongst the extension staff and project members who participated in this exercise, but the concept needs to be integrated into crop and livestock extension programmes. While the alley cropping aspect of agro-forestry received attention in this project the questionnaire also indicated that livestock owners might be receptive to programmes emphasising livestock nutrition, ecto- and endoparasite control, provision of protein supplements, etc. In other words the impression was possibly created that the project team was promoting agro-forestry as such, while the communities involved have other perceived needs or priorities and agro-forestry should only be "marketed" as one of numerous alternative strategies to meet the communities perceived needs – a need-driven rather than a solution-driven programme.

In developing such a programme due regard should be paid to the local situation as illustrated by information collected by questionnaires and participatory rural appraisal techniques. For example in the two communities surveyed it was found that:

- 42% of respondents were pensioners or were unemployed;
- Only 3% regarded themselves as farmers;
- 22% had some land rights (presumably arable) in addition to homestead gardens;
- Although there was little interest in a planned programme of tree planting and use, 75% collected fuel wood from the veld; wood was the single most important source of fuel; there was considerable indigenous knowledge about which indigenous trees could be used for fuel and which should be protected for one reason or another; 70% harvested dead wood while only 30% used coppicing or pollarding harvesting techniques and
- 83% had planted trees, but these were virtually all fruit trees and were restricted (93%) to homestead gardens.

Using such information as the basis, education programmes could be developed, which stress how different trees could be incorporated into land use systems to meet the needs (perceived and unconscious) and solve the problems of the communities. In other scenarios attention may also be focussed on individual emerging (small scale, commercial) farmers, as compared with communal rural dwellers, who dominated these target communities.

<u>Determination of acceptability of agro-forestry technology</u>
Although some information was gleaned from the preliminary questionnaires, as described in the foregoing pages, the planned masters study, under the supervision of the Department of Agricultural Economics, Extension and Rural Development of the University of Pretoria, by Tebogo Mohlasedi, unfortunately was not completed when the student terminated his studies.

8 THE QUANTIFICATION OF AGROFORESTRY SYSTEMS

The land equivalent ratio, although a useful quantitative description of differences in biomass production between agricultural systems, gives no weighting for product value to the community using the system. For this reason it is necessary to include relative local values of products in order to ascertain the true benefit of the product to a particular community. This economic approach, similar to a Nett Present Value (NPV) approach, linked to LERs – termed by Terreaux and Chavet (2004) the NPV-LER – allows a calculation of value relevant to the individual and to the time. Alternatively, combustible energy can be calculated to indicate energy use efficiency.

8.1 Combustible energy

In a world where national energetics and carbon trading is becoming an international focus, it becomes relevant to express system productivity in terms of energy. The global unit for expressing per-capita energy use is the kg oil equivalent (where oil has an energy value of around 37 $MJ.kg^{-1}$ – Rosillo-Calle, 2003). According to the International Energy Agency (2004), energy use in high income countries has been fairly stable for the last decade or more, with energy use per capita of 622 kg oil equivalent in 1990, and 667 kg oil equivalent in 2001. In lower income countries, energy use per capita, although still considerably lower than in high income countries, has increased markedly since 1990 (38.2 kg oil equivalent in 1990, compared to 215 kg oil equivalent in 2001). In 2001, South Africa had a per-capita energy consumption of 269.6 kg oil equivalent, compared to 887.5 kg oil equivalent in the United States.

In a study on the energy profile of a rural community in south-western Kwazulu-Natal, South Africa, Lloyd *et al.*(2004) noted that 96% of the households surveyed cooked on wood collected free of charge in the vicinity, compared to 3% on paraffin, and 1% on LP gas. Paraffin was used as a light source in 30% of households, compared to 70% using candles. The average household consumed 12.1 bundles (between 300 and 400 kg) of wood per month. Wood collection was shown to be a virtually non-stop effort, ceasing only between midnight and 04h00. Although these trials were conducted in a drier environment than subtropical Kwazulu-Natal, the household dynamics and energy requirements of rural communities in Kwazulu-Natal and semi-arid areas are likely to be very similar.

In his overview of biomass assessment methodology, Rosillo–Calles (2003) assigned a “low heat” combustible energy value of 17.6 $MJ.kg^{-1}$ for dry crop residue, and 18.7 $MJ.kg^{-1}$ for dry wood. Using these values, and assuming a combustible energy value of 18.7 $MJ.kg^{-1}$ for dry, edible Leucaena leaves and branches, the energy values of the different cropping systems can be calculated (Table 8.1). Table 8.2 summarises the combustible energy production of the different systems in different years.

Table 8.1 Yields ($kg.ha^{-1}$) and combustible energy ($MJ.year^{-1}$) of different systems for five cropping seasons on Hatfield Experimental Farm, Pretoria

1999/2000 season

	PURE SORGHUM (S)	PURE COW PEAS (C)	PURE SWEET POTATO (SP)	PURE LEUCAENA (L)	INTER (S+L)	INTER (C+L)	INTER (SP+L)
Grain (alley) – $kg.ha^{-1}$		650	17300			225	13383
Fodder (alley) – $kg.ha^{-1}$	5800				5408		
TOTAL	5800	650	17300		5408	225	13383
Fodder (1st harvest) – $kg.ha^{-1}$				860	450	450	450
Wood (1st harvest) – $kg.ha^{-1}$				2280	600	600	600
TOTAL				3140	1050	1050	1050

Table 8 1 (Cont'd) 2000/2001 season

	PURE SORGHUM (S)	PURE COWPEAS (C)	PURE SWEET POTATO (SP)	PURE LEUCAENA (L)	INTER (S+L)	INTER (C+L)	INTER (SP+L)
Fodder (2nd harvest) – kg.ha^{-1}				2340	2340	2340	2340
Wood (2nd harvest)				1940	1940	1940	1940
TOTAL				4280	4280	4280	4280
Leucaena total DM (kg.ha^{-1})				7420	5330	5330	5330
Leucaena wood (kg.ha^{-1})				4220.0	2540	2540	2540
Energy (x1000 MJ.year^{-1})	102.1	11.4	60.9	140.2	195.9	104.7	91,7
Grain (alley) – kg.ha^{-1}	220	700	9000		257	807	8158
Fodder (alley) – kg.ha^{-1}	1250				1146		
TOTAL	1470	700			1403	807	8158
Fodder (1st harvest) – kg.ha^{-1}				1360	340	340	340
Wood (1st harvest) – kg.ha^{-1}				1020	250	250	250
TOTAL				2380	590	590	590
Fodder (2nd harvest) – kg.ha^{-1}				970	440	440	440
Wood (2nd harvest) – kg.ha^{-1}				920	270	270	270
TOTAL				1890	710	710	710
Leucaena total DM (kg.ha^{-1})				4270	1300	1300	1300
Leucaena wood (kg.ha^{-1})				1940	520	520	520
Energy (x1000 MJ.year^{-1})	25.9	12.3	31.6	80.7	49.3	38.8	53.3

2001/2002 season

	PURE SORGHUM (S)	PURE COWPEA (L)	PURE LEUCAENA (L)	INTER (S+L)	INTER (C+L)
Grain (alley)	1797	2020		1498	1070
Fodder (alley)	4195	4910		4133	2610
TOTAL	5992	6930		5631	3680
Fodder (1st harvest)			1600	470	470
Wood (1st harvest)			1950	580	580
TOTAL			3550	1050	1050
Fodder (2nd harvest)			1803	640	640
Wood (2nd harvest)			5133	1830	1830
TOTAL			6936	2470	2470
Leucaena total DM (kg.ha^{-1})			10486	3520	3520
Leucaena wood (kg.ha^{-1})			7083	2410	2410
Energy (MJ.year^{-1})	105.5	122	198.2	165.6	131.3

Table 8.1 (cont'd) 2002/2003 season

	PURE MAIZE	PURE SORGHUM	PURE LEUCAENA	INTER (M+L)	INTER (S+L)
Grain (alley)	4575			3512	
Fodder (alley)	5160	16600		4752	
TOTAL	9735	16600		8264	11188
Fodder (1st harvest)			1633	408	408
Wood (1st harvest)			1967	450	450
TOTAL			3600	858	858
Fodder (2nd harvest)			1758	610	610
Wood (2nd harvest)			4103	1424	1424
TOTAL			5861	2034	2034
Leucaena total DM ($kg.ha^{-1}$)			9461	2892	2892
Leucaena wood ($kg.ha^{-1}$)			6069	1874	1874
Energy ($MJ.year^{-1}$)	171.3	292.2	178.8	200.1	251.6

2003/2004 season

	PURE MAIZE	PURE SORGHUM	PURE LEUCAENA	INTER (M+L)	INTER (S+L)
Grain (alley)	3921	1473		3730	3374
Fodder (alley)	4710	3300		5426	6482
TOTAL	8631	4773		9156	9856
Fodder (1)			768	299	299
Wood (1)			1132	442	442
TOTAL			1900	741	741
Fodder (2)			2625	1312	1312
Wood (2)			9075	4388	4388
TOTAL			11700	5700	5700
Leucaena total ($kg.ha^{-1}$)			13600	6441	6441
Leucaena wood ($kg.ha^{-1}$)			10207	4830	4830
Energy ($MJ.year^{-1}$)	151.9	173.5	257	282.9	205.7

Where:

- Grain and fodder are grain and fodder production of the alley crop
- Fodder (1st harvest) and Wood (1st harvest) are fodder and wood product of Leucaena from the December harvest.
- Fodder (2nd harvest) and Wood (2nd harvest) are fodder and wood product of Leucaena from the June harvest.

Table 8.2 Ranked combustible energy values (x1000 $MJ.ha^{-1}.year^{-1}$) for different systems and seasons

1999/2000		**2000/2001**	
S+L	195.9	LEUCAENA	80.7
LEUCAENA	140.2	SP+L	53.3
C+L	104.7	S+L	49.3
SORGHUM	102.1	C+L	38.8
SP+L	91.7	SWEET POTATO	31.6
SWEET POTATO	60.9	SORGHUM	25.9
COWPEAS	11.4	COWPEAS	12.3

Table 8.2 (cont'd)

2001/2002		**2002/2003**		**2003/2004**	
LEUCAENA	198.2	SORGHUM	292.2	M+L	282.9
S+L	165.6	S+L	251.6	LEUCAENA	257
C+L	131.3	M+L	200.1	S+L	205.7
COWPEAS	122	LEUCAENA	178.8	SORGHUM	173.5
SORGHUM	105.5	MAIZE	171.3	MAIZE	151.9

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Where M+L - intercropped maize and Leucaena
S+L - intercropped sorghum and Leucaena
C+L - intercropped sorghum and Leucaena
SP+L - intercropped sweet potatoes and Leucaena
Sorghum, maize, cowpeas and Leucaena are the pure stands

Combining Leucaena and grain crops proved more profitable than pure stands (in terms of energy production) in most cases. The only instances in which monocultures produced more combustible energy than intercropped stands were with a pure stand of forage sorghum in 2002/03, and with a pure stand of Leucaena, consecutively between 1999/2000 and 2001/02. In the first two seasons, very low grain yields were recorded for cowpeas and sorghum, making the contribution of Leucaena to system success even more valuable. The pure stand row crops generally produced the least combustible energy compared with the intercropped stands in any of the seasons, the exception being the pure stand of sorghum in the 2002/03 season, when exceptional fodder yields were recorded for this crop (16600 kg fodder.ha^{-1}).

If the monthly wood requirement for a South African rural family is 300 kg (Lloyd, 2004), found, in the KZN energy studies, that rural households consumed 300 kg of firewood per month), one hectare of intercropped Leucaena provided firewood for eight, six and 16 months for the 2001/02, 2002/03 and 2003/04 seasons respectively.

Lindeque (1997), in a pioneering study to quantify the yield and quality of Leucaena, measured digestibility and yield of the Leucaena components at different phenological stages. A summary of these studies is presented in Figures 8.1 and 8.2. If yield or quality of alley crops is known, energy and land equivalent ratio calculations can be extended to the value of the different systems for livestock.

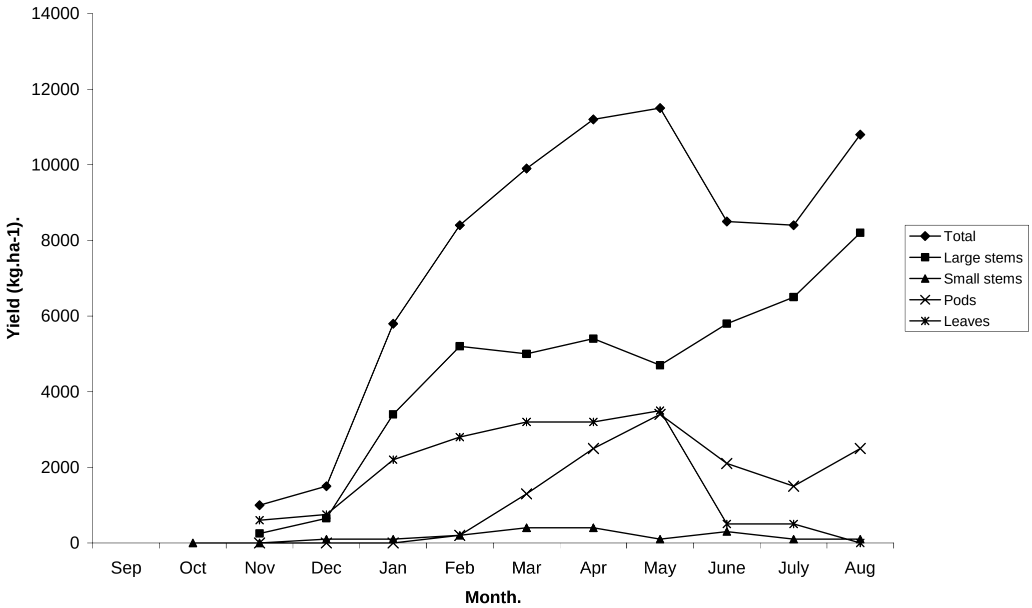

Figure 8.1 Cumulative production over the growing season of Leucaena components (Lindeque, 1997)

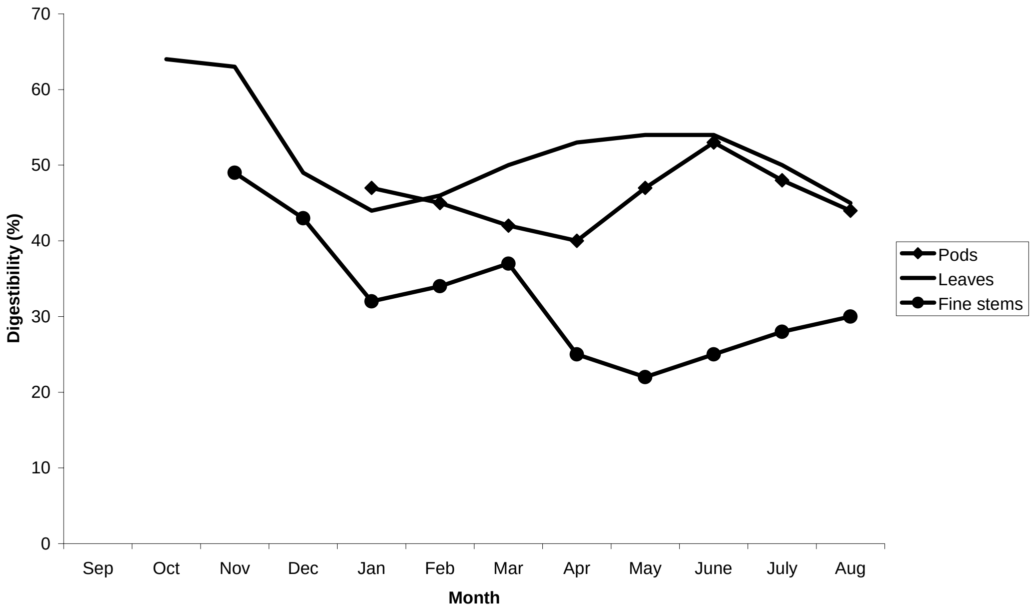

Figure 8.2 *In vitro* digestibility (%) over the year of Leucaena components (Lindeque, 1997)

8.2 Land equivalent ratios

Ong (1996) defined Land Equivalent Ratios as “the ratio of the area under sole cropping to the area under intercropping, at the same level of management, that gives an equal amount of yield”.

LER = (Xi / Xs) + (Yi / Ys),
Where X and Y are the component crops, i is intercrop and s is sole crop (monoculture)

A shortcoming of Ong’s evaluation has been that no weighting was given for the relative value of the crops to the community. In this study, plant components were evaluated economically and “economically-adjusted LERs” were calculated,

- Where LER_e = Sum of economic value of all plant components (intercropped) / Sum of economic value of all plant components (monoculture).
- LERe – economically-adjusted LER.

An economically-weighted LER is, thus, simply the area of sole-cropped land required to produce the same economic product as the intercropped land. Separate LER_e must, therefore be calculated for the pure stands of Leucaena and intercrops. These LERs are denoted as LER_{ea} (Land Equivalent Ratio for intercrop) and LER_{el} (Land Equivalent Ratio for Leucaena).

Assigning monetary values to fodder, grain and wood products of plants varies seasonally and socially/geographically. Everson (WRC Report 780/1/02, 2002) allocated prices to firewood at R280.ton^{-1} for bulk, or R400.ton^{-1} if firewood was bought per bundle. Maize, cowpeas and sorghum residues were valued at R250.ton^{-1}. Forage sorghum was valued at R400.ton^{-1} (higher than the residue value for maize, cowpea and grain sorghum, due to the higher quality of this forage), and Leucaena forage (due to its additional protein) was valued at R500. ton^{-1}. Cowpea and sorghum grain were given values of R1500.ton^{-1}. Maize grain was valued at R1000.ton^{-1} (all values summarized in Table 8.3). Sweet potatoes were not included in the calculations for the 2001/02 season – with failure of the sweet potato crop in this season due to *Fusarium*, the intercropped stand would have performed unusually better than the pure stand. Note should, however, be taken of the ability of intercropping to spread risk, diminishing effects of failure of one of the two intercropped species. In the 1999/2000 and 2000/2001 seasons sweet potatoes were assigned a monetary value of R2000.ton^{-1}.

Table 8.3 Summary of monetary values (R.ton^{-1}) assigned to plant components

Crop Component	R.ton^{-1}
Maize residue	250
Maize grain	1000
Sorghum grain	1500
Sorghum residue	250
Leucaena forage	500
Leucaena wood	280
Cowpeas grain	1500
Cowpeas residue	250
Forage sorghum	400
Sweet potatoes	2000

8.2.1 Calculation of LER$_{ea}$ (economically-weighted LER for inter crops)

In the 1999/2000 season (Table 8.4), alleycropping systems outperformed pure stands of cowpea and sorghum (respective LER$_{ea}$s of 1.57 and 1.3). Poor cowpea and sorghum yields were supplemented by higher Leucaena yields per plant in the alleys. The ability of intercropping to reduce exposure to crop failure (through product diversification) was emphasised several times during this trial. Interestingly, a pure stand Leucaena would have proved more profitable (at the values assigned) than intercropped cowpeas and sorghum.

The pure stand of sweet potatoes, however, performed better in financial terms than intercropped sweet potatoes (LER$_{ea}$ 0.8). Sweet potatoes could be considered a high value crop, and any decrease in sweet potato productivity, as a results of decreased area cropped or decreased average yield in alleys, had a drastic effect on the profitability of the system.

In 2000/2001, as with the previous season, with the high-value sweet potatoes, pure stands outperformed intercropped stands, and provided by far the most value in monetary terms. It is logical that “diluting” alley crops to allow product diversity by intercropping would be less successful with high value crops. With other alley crops (as in the previous season) Leucaena hedgerow yields boosted profitability of intercropped systems, resulting in land equivalent ratios of above 1 when compared to pure stands of crops. The pure stand of Leucaena was more profitable than a pure stand of sorghum (in a low yielding season for sorghum) and roughly the same as pure stands of cowpeas.

At the valuations described (if wood value was set at R280.ton^{-1}), in the 2001/02 season, intercropped sorghum had a LER$_{ea}$ of >1 (1.2) while intercropped cowpeas had a LER$_{ea}$ of 0.82. In the 2002/03 season, monoculture was more profitable at these valuations for both maize (LER$_{ea}$ 0.98) and sorghum (LER$_{ea}$ 0.83). In the 2003/04 season, intercropping was clearly more profitable at these valuations than monoculture, with LER$_{ea}$ 1.42 and 1.71 for intercropped maize and sorghum, respectively.

When firewood is valued at R400.ton^{-1}, economically-weighted LER$_{ea}$ for the 2001/02 season becomes 1.28 for intercropped sorghum and 0.89 for intercropped cowpeas. For the 2002/03 season, LER$_{ea}$ would be 1.02. for intercropped maize, and 0.86 for intercropped forage sorghum, while in the 2003/04 season, intercropped maize and sorghum would have respective LER$_{ea}$ values of 1.53 and 1.9. When the maize grain price is increased to R1500.ton^{-1}, monoculture became more profitable in the 2002/03 season, with LER$_{ea}$ of 0.97. Intercropped sorghum and maize, however, were the more profitable cropping systems in all scenarios in the 2003/04 season. Unless the wood and forage value of Leucaena becomes virtually negligible, these systems consistently proved more productive than their monoculture equivalents, both energy-wise and economically.

Table 8.4 Produce value and economically-weighted Land Equivalent Ratios, calculated according to monetary values assigned in table 8.3

Season		VALUE (Rands)	LER_{ea}	LER_{el}
1999/2000	Sorghum (S)	1450		
	Cowpeas (C)	975		
	Sweet potato (SP)	34600		
	Leucaena (L)	2782		
	S+L	2283	1.57	0.82
	C+L	1268	1.30	0.46
	SP+L	27698	0.80	9.96
2000/2001	Sorghum (S)	643		
	Cowpeas (C)	1050		
	Sweet potato (SP)	18000		
	Leucaena (L)	1708		
	S+L	886	1.38	0.52
	C+L	1746	1.66	1.02
	SP+L	16852	0.94	9.87
2001/2002	Sorghum (S)	3744		
	Cowpeas (C)	4258		
	Leucaena (L)	3685		
	S+L	4510	1.20	1.22
	C+L	3487	0.82	0.95
Season		VALUE (Rands)	LER_{ea}	LER_{el}
2002/2003	Maize (M)	5865		
	Sorghum (S)	6640		
	Leucaena (L)	3395		
	M+L	5734	0.98	1.69
	S+L	5509	0.83	1.62
2003/2004	Maize (M)	5099		
	Sorghum (S)	3035		
	Leucaena (L)	4554		
	M+L	7244	1.42	1.59
	S+L	5192	1.71	1.14

8.2.2 Calculation of LER_{el} (economically-weighted LER for Leucaena)

For the 2001/02 season, LER_{el} was 1.22 for sorghum and 0.95 for cowpeas, with Leucaena wood valued at R280.ton^{-1} and maize grain at R1000.ton^{-1}. The added value of Leucaena wood, at these prices, was insufficient to offset the financial losses due to dramatically lower cowpea grain production (1070 kg.ha^{-1}) of the intercropped stand. In this case, a pure stand of Leucaena would offer more financial reward than combining cowpeas and Leucaena.

LER_{el} for the 2002/03 season favoured intercropping of both maize (LER_{el} 1.69) and sorghum (LER_{el} 1.62). Although pure stand sorghum and maize both outyielded these crops in alleys, the additional value of Leucaena firewood and fodder made the intercropping systems more profitable at the monetary values discussed.

For the 2003/2004 season, LER_{el} was higher than 1 for maize (1.69) and sorghum (1.14). The success of intercropping in this season had much to do with intercropped Leucaena outyielding pure leucaena per plant, particularly in the second harvest, when intercropped Leucaena yields (5700 kg.ha^{-1}) were half those of pure stands of Leucaena (11700 kg.ha^{-1}), despite being only a quarter the planting density.

8.3 Discussion

Land equivalent ratios, as traditionally defined, are unfortunately often inadequate to assess value of intercropping systems for the targeted communities. Although monetary values are variable, the value of systems can be put into better perspective if plant products are economically-weighted. At the monetary values assigned to the products of the systems included in this study, intercropping systems outperformed pure stands in terms of perceived financial value to the community in eight of the 12 comparisons with pure Leucaena, and seven of the 12 comparisons with pure stand annual crops. The poor performance of intercropped cowpeas, in all three seasons, and sorghum, in the first two seasons, resulted in an overall advantage to the pure stand, while the higher yields of intercropped Leucaena in the 2003/04 season ensured the superiority of the intercropped stands above the pure stands.

In terms of energy, the contribution of Leucaena to total system energy ensured that intercropped stands produced more combustible energy than pure stands in most cases. Systems that produce maximum combustible energy do not necessarily produce maximum economic value (as evident in the 2001/02 season, where most energy was provided by Leucaena, but not the greatest monetary value). Although Leucaena has a slightly higher combustible energy per unit mass than the alley crops, this difference is small enough to make system evaluation in terms of energy similar to traditional agronomic biomass evaluation. In this respect, although combustible energy calculations provide an insight into the ability of a system to meet a community’s energy requirements, it still gives little indication of the true value of the system to the community.

9 THE USE OF MODELS TO EVALUATE AGROFORESTRY SYSTEMS

Agricultural and agroforestry models fulfil roles beyond those encompassed in the previous chapter (agroforestry system quantification) and are thus considered separately. Agroforestry systems are by their very nature, multi-faceted and often more complex than monoculture systems, making computer-driven decision support systems extremely important in the evaluation of agroforestry systems, or in planning before implementation.

9.1 Overview of WaNuLCas

The reference to the WaNuLCas manual and a more detailed summary of this model's purpose and inputs are included in the appendices. This model is input intensive and an abbreviated description follows:

- WaNuLCas was developed by Betha Lusiana and Meine van Noordwijk (ICRAF International Centre for Research in Agroforestry – Indonesia), and was formulated in Stella Research Modelling Environment. The model combines internal parameterization and input with an external MS Excel file to describe an array of agroforestry scenarios.

- WaNuLCas is open to modifications, both internally (with source code or equations available), as well as to the Excel file that runs much of the weather and crop units.

- WaNuLCas lays particular emphasis on below-ground interactions. It derives parameters of the Van Genuchten equations of soil physical properties via a "pedotransfer" function from the soil texture, bulk density and organic matter content.

Some of the key biophysical elements of WaNuLCas are as follows:

- Use of root length density of crops and trees to calculate water and nutrient (N and P) uptake, together with plant demand factors and diffusion at a given soil water content.

- Growth of trees and crops is calculated daily by multiplying daily growth potential with four stress factors, namely:

1. Shading
2. Water limitation
3. N
4. P

- System geometry consists of 4 soil zones – trees in zone 1 or 4. (e.g. half alley + 1 hedgerow – Zone 1, whole alley + 2 hedgerows – Zone 4), and crops in the remaining 3 crop zones.

- Can simulate simultaneous or sequential agricultural systems (for example the user may choose five consecutive crops).

- The user may specify a number of events to occur chronologically.

- Crop root length density decreases exponentially with increasing soil depth.

- Light capture calculated using leaf area indices of trees and crops, as well as plant height. Interception by leaves and stems is calculated with only leaf-intercepted radiation used by plants.

9.2 Overview of the Soil Water Balance (SWB) model

SWB was developed from the NEWSWB model of G.S. Campbell (Washington State University, Pullman, WA, USA – Annandale *et al*., 2000). SWB models water balance and crop growth mechanistically, using a weather unit driven by a modified FAO Penman-Monteith formula for calculation of grass reference evapotranspiration, and thermal time-based plant phenology. Further reference to this model is made in the appendices – see Literature on modelling.

Advantages of SWB for use in agroforestry decision support in this country are as follows :

- Local (in South Africa) technical support
- Mechanistic nature of the model allowing application of the model in a wide range of environmental conditions.
- Comparatively simple inputs and user-friendly interface. SWB is a generic crop growth model, simplifying crop parameterisation, and is simple to run.

9.3 Overview of BECVOL

BECVOL, an empirical model originally devised to estimate browse contribution to livestock nutrition, offers a simple method of quantifying tree parameters non-destructively. While this model was not earmarked for decision support in agroforestry, it may provide information on canopy characteristics which could then be used to better describe non-measured tree inputs for models such as SWB and WaNuLCas.

9.4 Discussion

Agroforestry presents numerous complexities not considered with monoculture. Best practise manuals should be based on integration of measured data with scenario simulation using computer models. The Soil Water Balance model combines a sound mechanistic biophysical basis with user-friendly interface and simple inputs, and probably offers the best possibility for agroforestry modelling in South Africa. WaNuLCas addresses numerous agroforestry management and biophysical scenarios, but may be too input-intensive to be locally practical at this stage. BECVOL should be seen as a supporting model for a more comprehensive agroforestry model.

In general, agroforestry (due to its inherently complex nature) is well-suited for computer simulation and scenario-driven decision support. For this reason, sound agroforestry models could be hugely valuable to this developing field of agriculture.

10. CONCLUSIONS AND RECOMMENDATIONS

Although intercropping reduced alley crop yields in most instances, the benefits of diversity often lead to financial advantage of the system above pure stands. In rural, semi-arid areas, (where it is more likely that communities will cultivate traditional annual cash crops such as maize rather than high value crops such as sweet potatoes) intercropping offers the community a safer and, in many cases, more lucrative alternative to monoculture.

Benefits of intercropping in these drier areas cannot be ascribed to crop complementarity, with regard to utilisation of water, light and nutrients. For crop root complementarity to provide maximum benefit, deeper soil zones (with tree roots) need to be refilled with water a number of times in a season to prevent tree (hedgerow) roots from competing with alley crop roots for water. This will seldom occur in the arid environments targeted for this study. High evaporative demand and comparatively low rainfall in these areas ensures that the little water available in the system is mostly used in transpiration or evaporated, allowing little deep drainage, and replenishment of deeper soil horizons/layers.

Water balance and other agroforestry models which simulate interspecific competition offer valuable insight into the mechanisms of agroforestry systems, and are potentially powerful tools for decision support in systems which are often too complex to allow simple planning.

11 CAPACITY BUILDING

11.1 ON-STATION - Hatfield Experimental Farm

Undergraduate and postgraduate students in BSc Agric, MSc Agric, as well as B Inst Agrar, B Inst Agrar Hons and M Inst Agrar degree courses have been exposed to this agro-forestry project as part of the practical in the Planted Pastures and Fodder Crops Courses.

Specific students have also learnt how to collect, tabulate and analyse data on crop production, light interception, soil water records and weather data. These include:

- Johan Cronje – who started a PhD study using data from this project in 1999/2000 and 2000/2001 but who left for greener pastures in the middle of 2001. His MSc concentrated on the use of tree leaf material as a green manure or mulch.

- Chris Keen – who collected data for an MSc from this project, has subsequently used his experience with predictive models to secure a position in the private sector and who has now virtually completed his thesis.

- Solomon Ghezehei – who has had an invaluable introduction to agro-forestry modelling, while working in this project, and who has moved on to work on another WRC agroforestry project with Dr Colin Everson and Prof John Annandale for a PhD.

- Freddie Rabothata, who was doing practical work towards his B Tech degree from TUT.

- Sanet Briel, who participated on a part-time basis in the monitoring of light interception by both trees and intercrops whilst completing her BSc Agric.

- Willem Jansen van Rensburg, a BSc Agric student who participated in a part-time capacity in the monitoring of the Hatfield alley cropping trial.

- John McLea who worked on project maintenance and data collection while working on his B Inst Agrar degree.

- Melake Fessehazion; and

- Michael Gebru, two MSc Agric students from East Africa, who were of particular help in the quantification of tree characteristics used in the BECVOL model and light interception studies.

11.2 ON-FARM - Limpopo Province

Although the team did not persist with their participation in the Sylvopastoral/Alley system in Venda under subtropical/sub-humid conditions, Johan van der Walt, of the Field Crop Section on the Hatfield Experimental Farm, gained valuable field experience of agro-forestry. Probably even more important was the co-operation with the TUT, lecturers and students of that institution, local extension officers and, most importantly, community members, all of whom received exposure for the first time to concepts of agro-forestry, targeted - in this case - at a small scale dairy enterprise.

At Sekakane the main beneficiaries of this co-operative effort were the extension staff (who gave invaluable assistance in the site selection, preparation for information day and regular support for the community group which participated in planting, maintenance and harvesting of the demonstration block). The chairman of the community group was a prime example of how important it is to select the right person for the job. Without his inputs this would have been a complete failure.

This latter situation arose at Chuene Maja, where the local manager played a vital role in the establishment of the demo block and the organizing of the information day. When, however, this person left the group our inputs were largely wasted.
At both Chuene Maja and Sekakane the information days organized and conducted by Ms C Botha and C Keen of the University of Pretoria, with excellent co-operation from the co-operators and local extension staff, were very positive in terms of educating local people about agro-forestry, learning about their needs, problems and perceptions and how such communities (as compared with individual land holders) function. The exposure of educators and learners to such "new" technologies to help solve "old" problems will probably yield long term benefits. The big disappointment at these two centres was, however, the failure of the student in agriculture and rural development, to deliver on his project. In the short time that he was involved he learnt a lot about agro-forestry and also helped in collecting production data from the co-operative sites. Unfortunately, he left the project and his graduate studies before conducting his extension survey. The project team did, however, learn from the experience, namely that the "natural sciences" are much easier to research then the "human sciences" and that technology is often easier to generate than to transfer.

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APPENDIX A

Contents

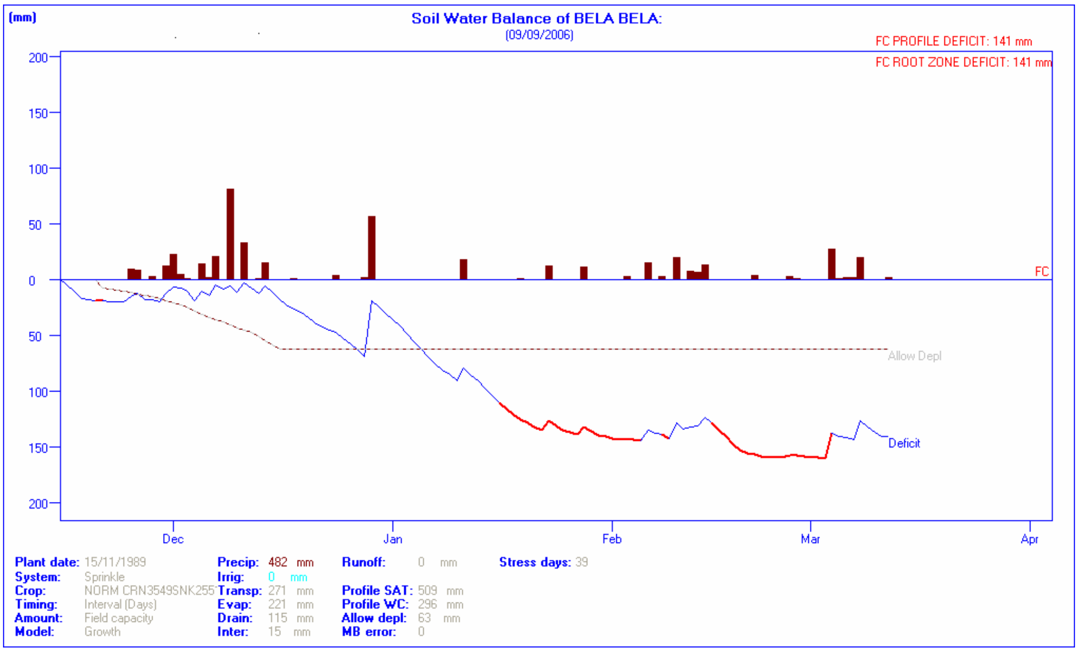

Figure A 1 Water balance for simulations for Bela Bela (1989/90)

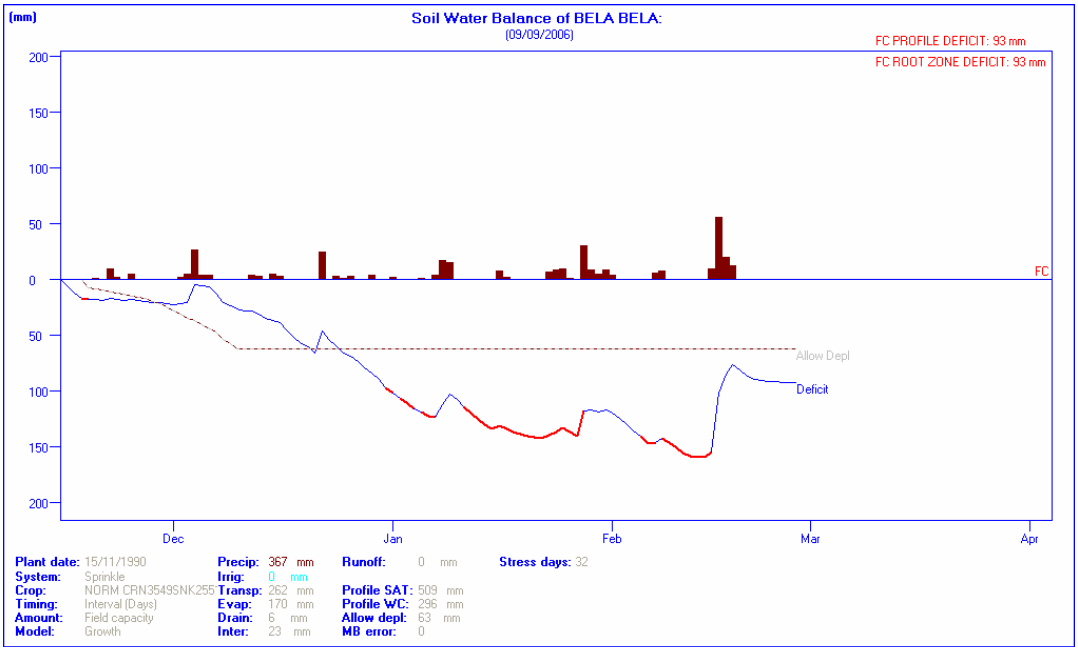

Figure A 2 Water balance for simulations for Bela Bela (1990/91)

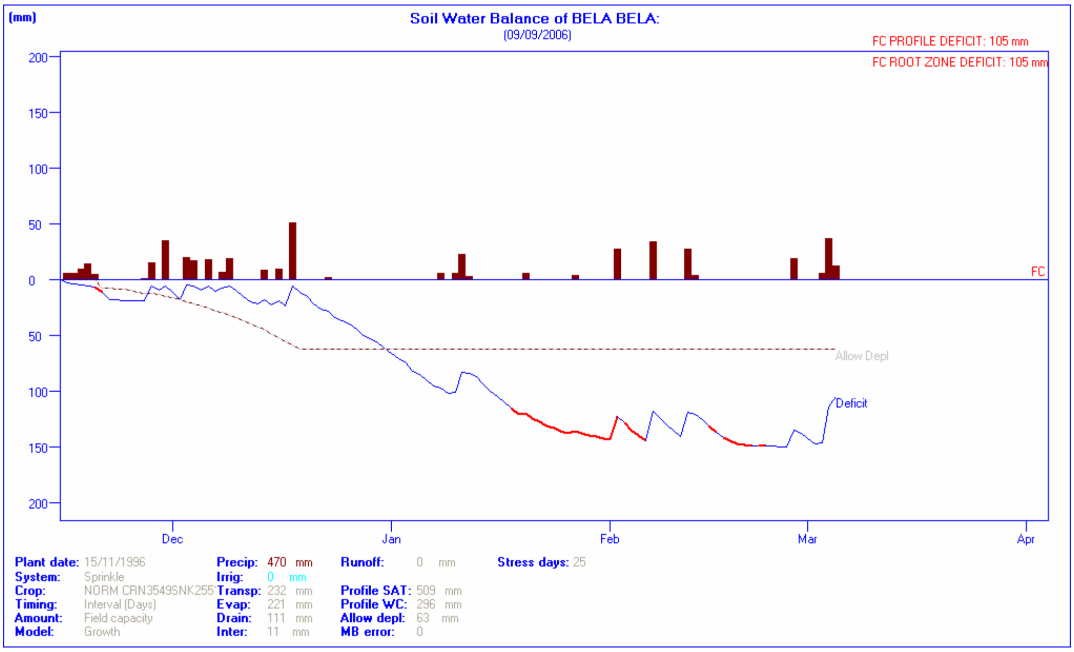

Figure A 3 Water balance for simulations for Bela Bela (1996/97)

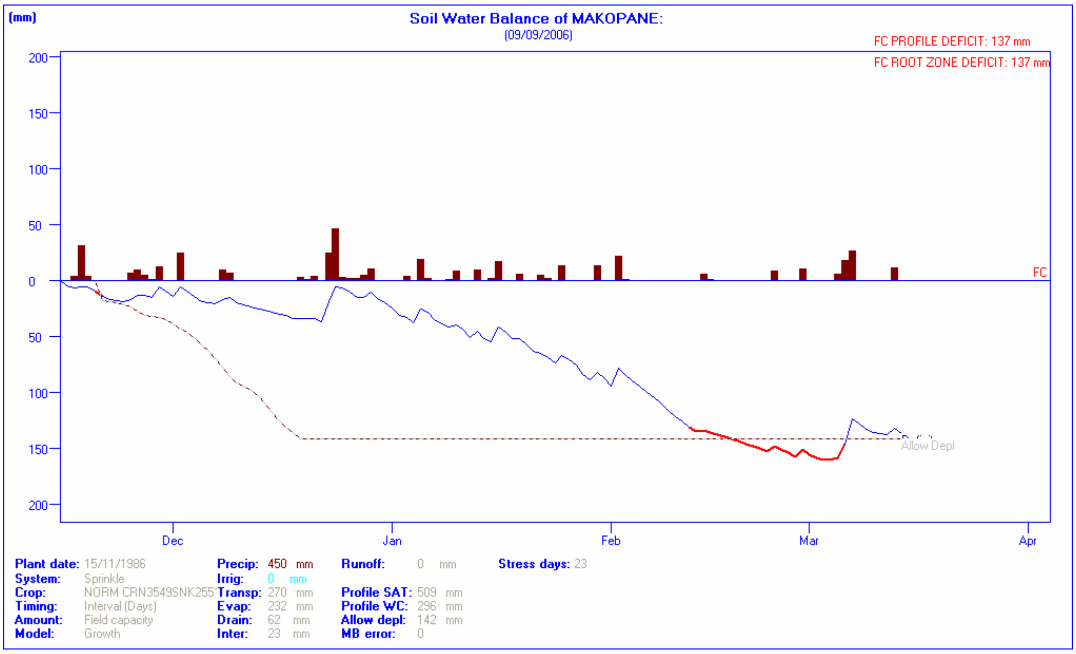

Figure A 4 Water balance for simulations for Makopane (1986/87)

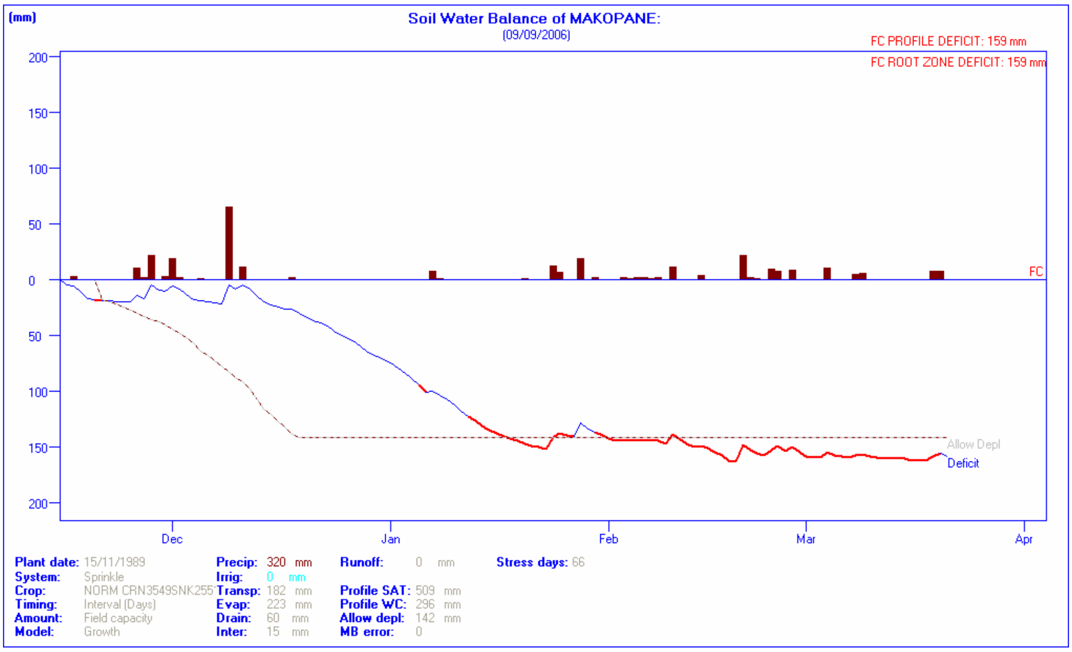

Figure A 5 Water balance for simulations for Makopane (1989/90)

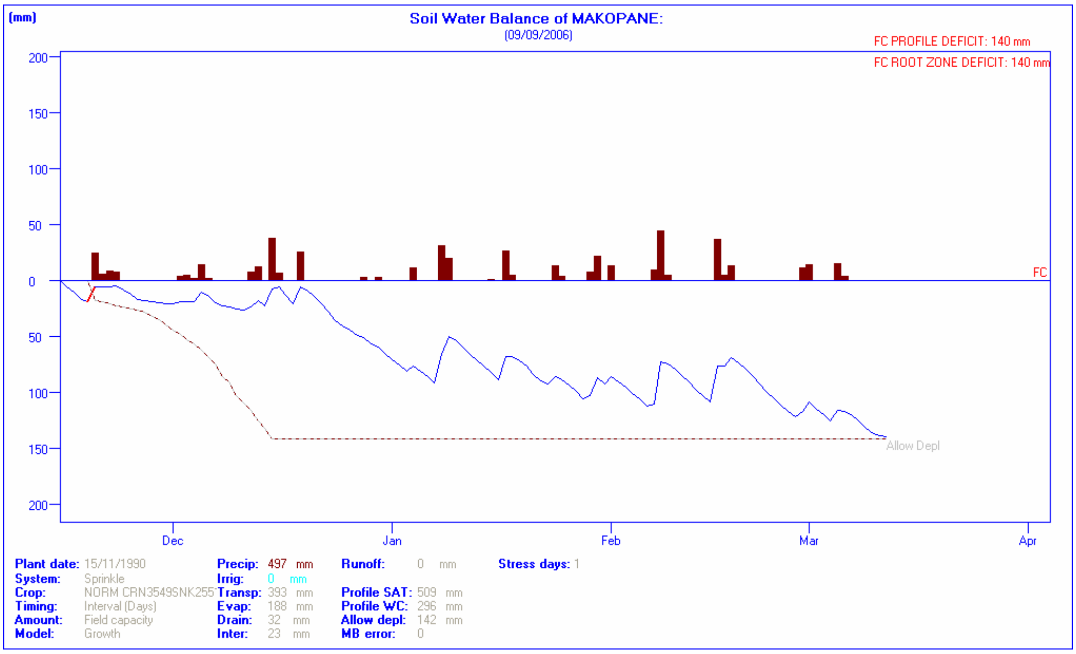

Figure A 6 Water balance for simulations for Makopane (1990/91)

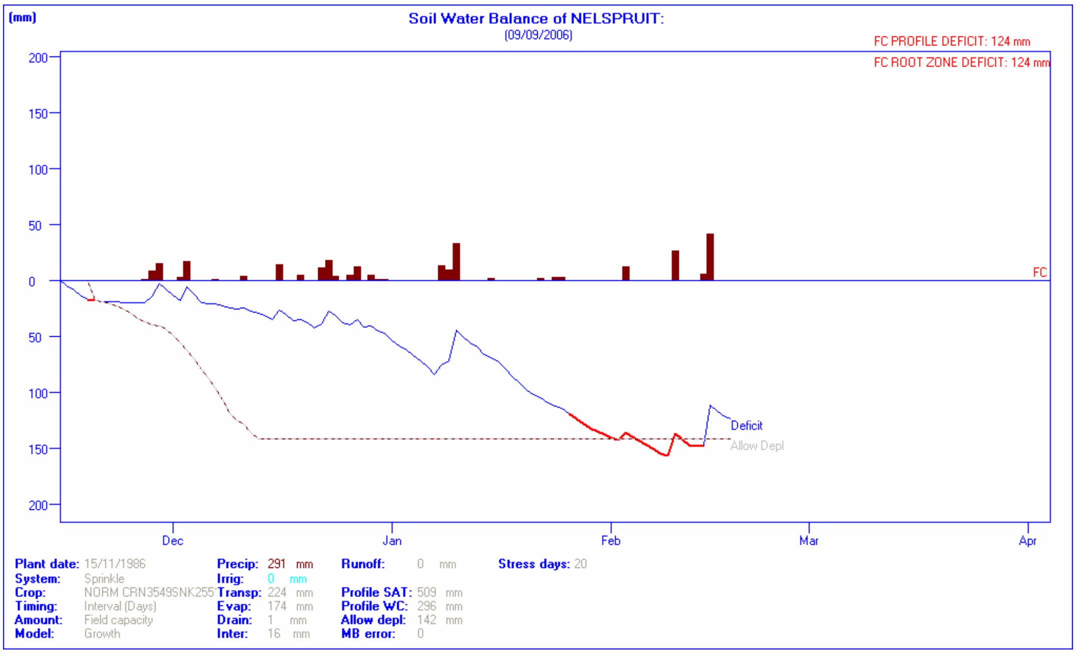

Figure A 7 Water balance for simulations for Nelspruit (1986/87)

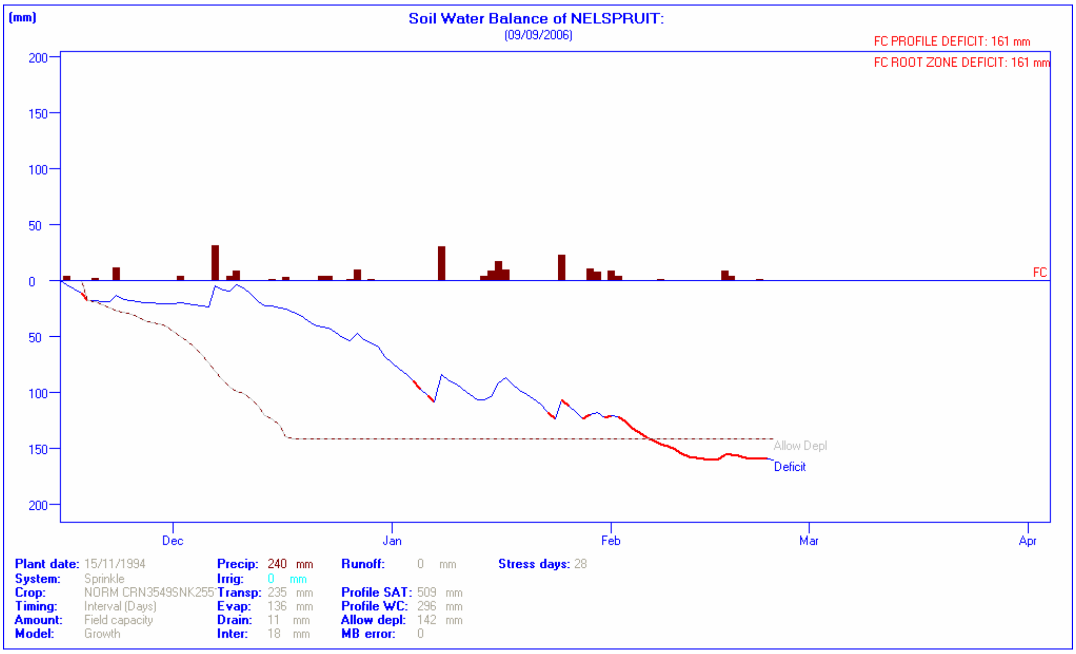

Figure A 8 Water balance for simulations for Nelspruit (1994/95)

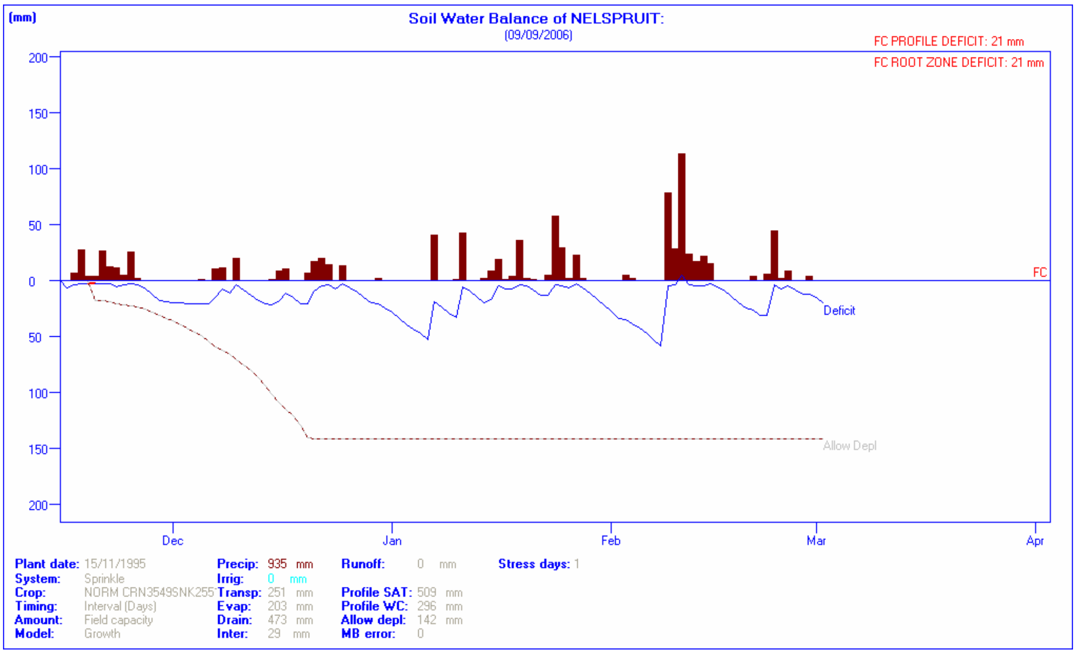

Figure A 9 Water balance for simulations for Nelspruit (1995/96)

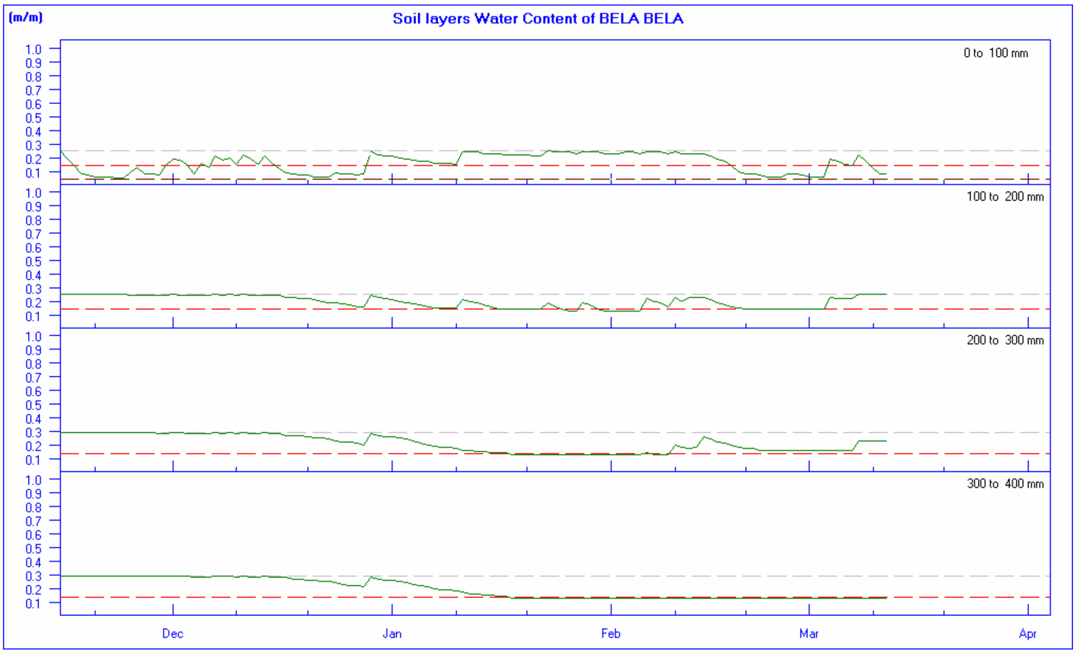

Figure A 10 Volumetric water content (depth 100 to 400 mm) for simulations for Bela Bela (1989/90)

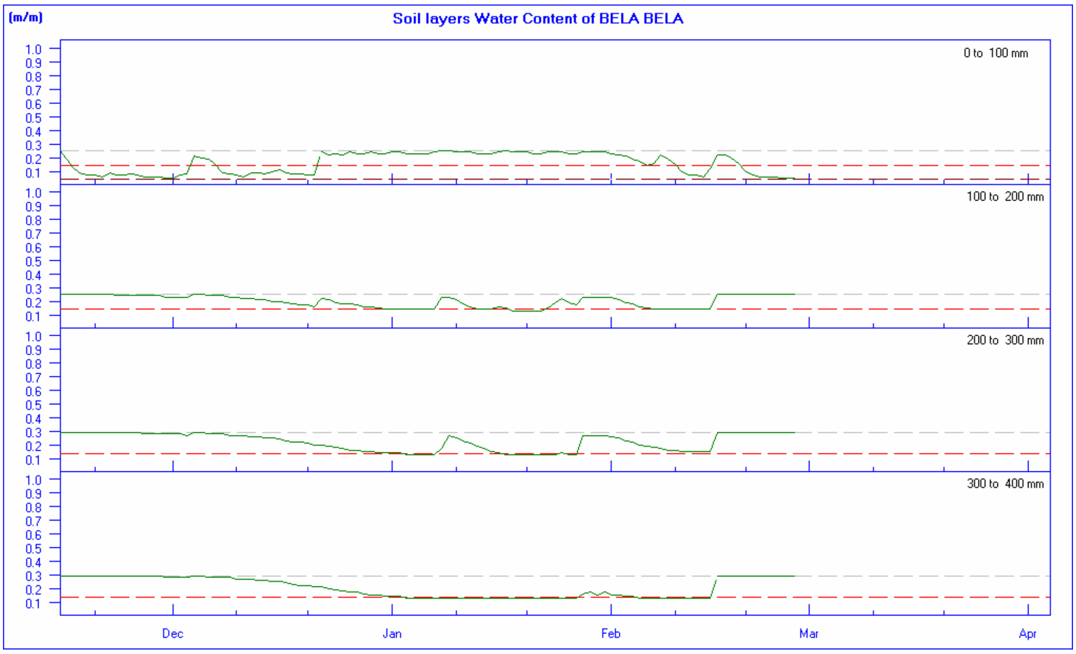

Figure A 11 Volumetric water content (depth 100 to 400 mm) for simulations for Bela Bela (1990/91)

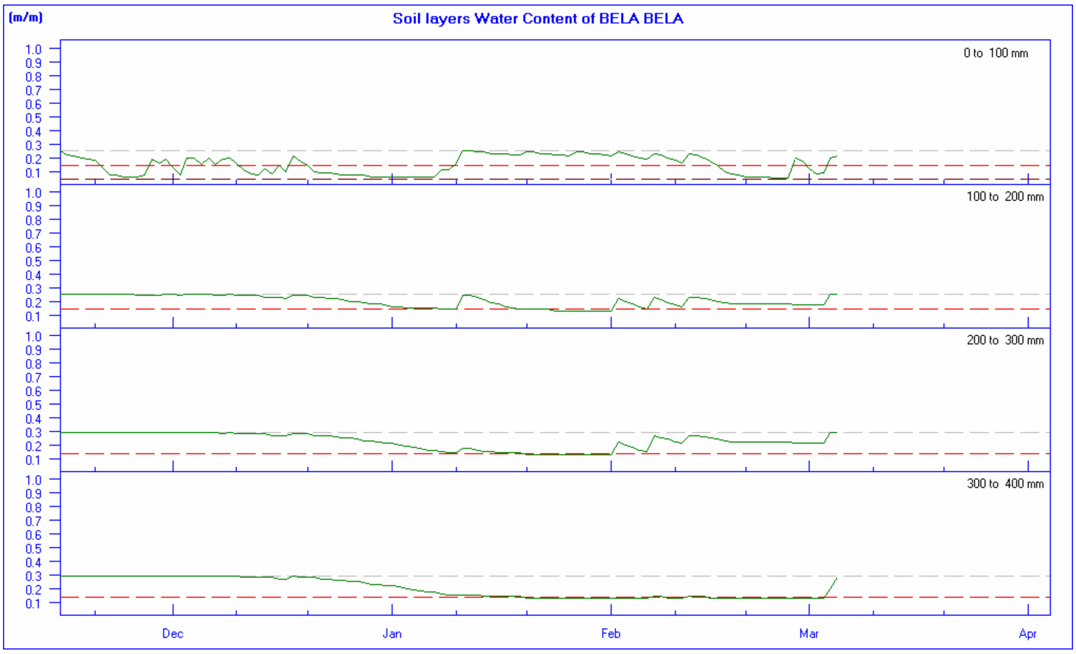

Figure A 12 Volumetric water content (depth 100 to 400 mm) for simulations for Bela Bela (1996/97)

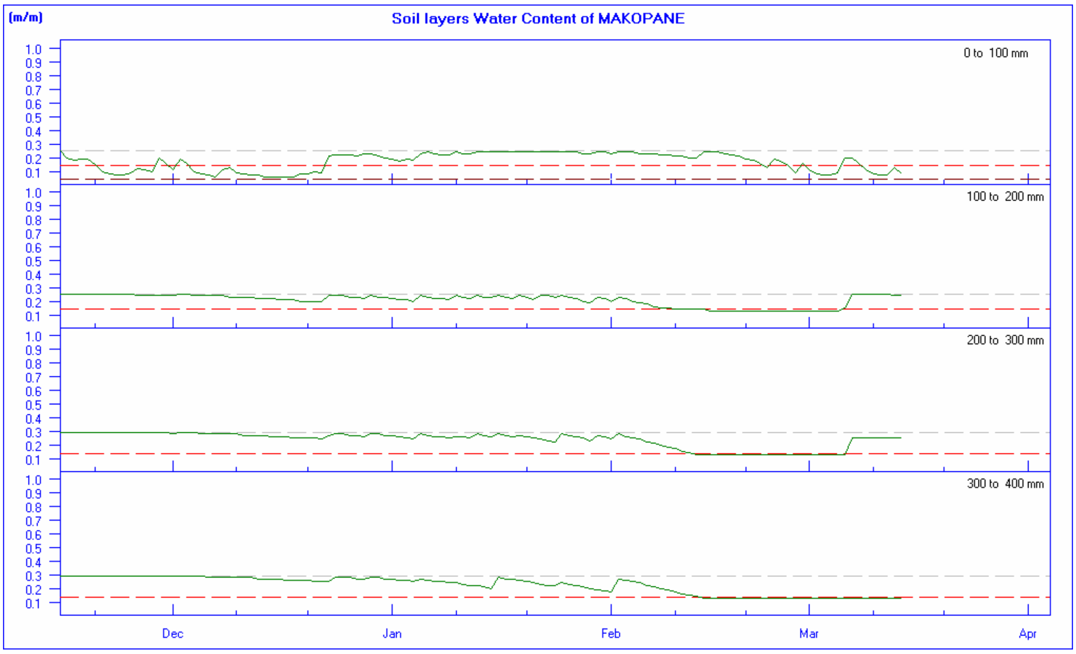

Figure A 13 Volumetric water content (depth 100 to 400 mm) for simulations for Makopane (1986/87)

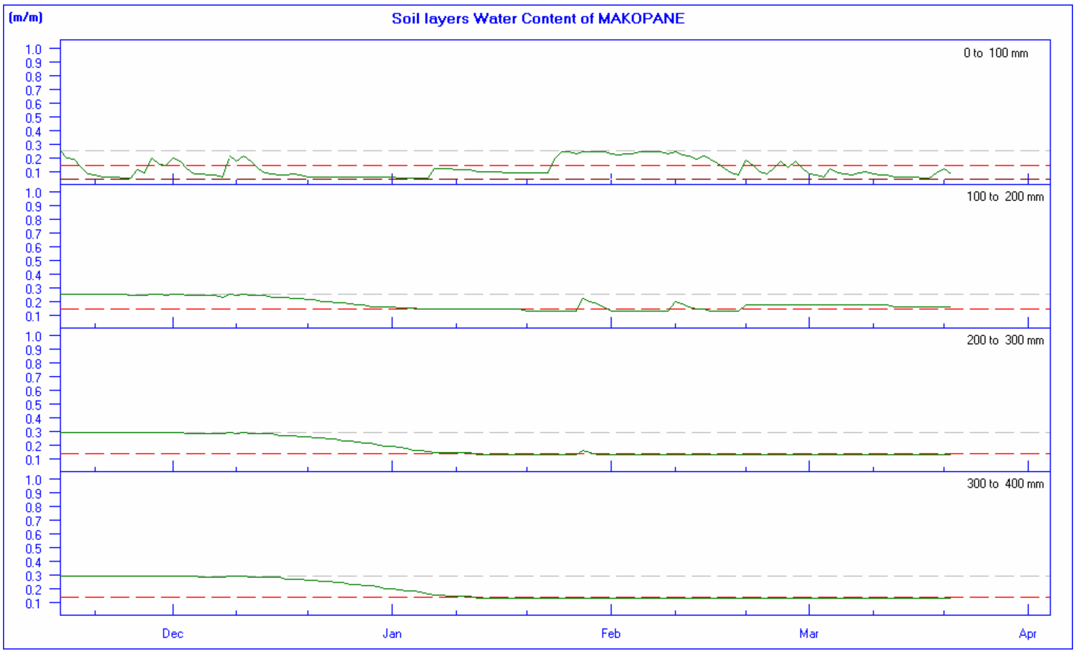

Figure A 14 Volumetric water content (depth 100 to 400 mm) for simulations for Makopane (1989/90)

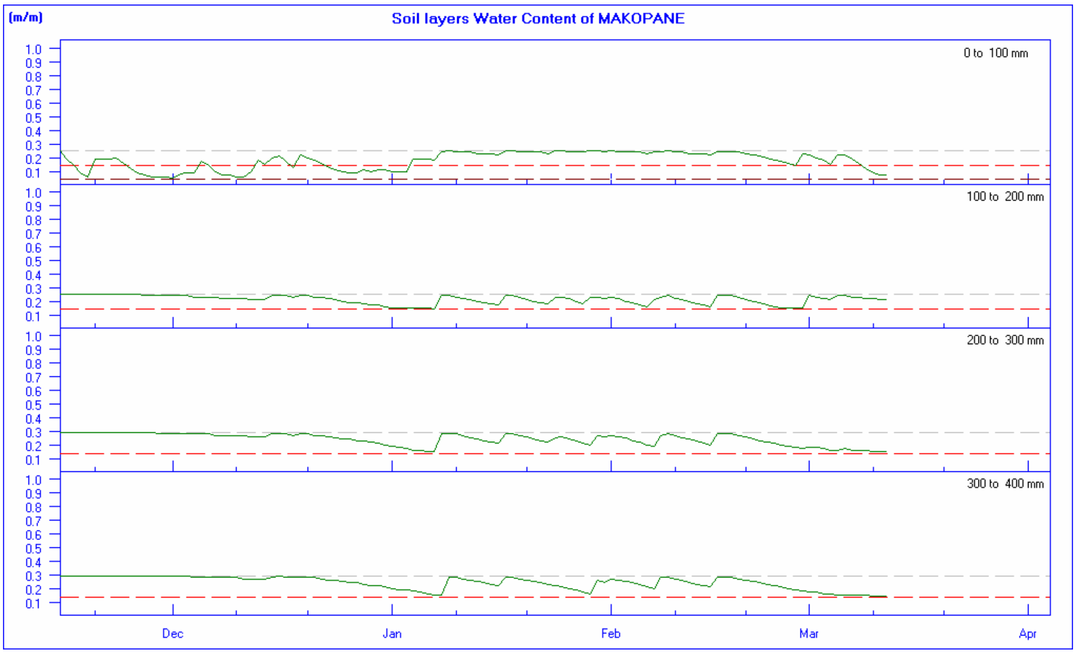

Figure A 15 Volumetric water content (depth 100 to 400 mm) for simulations for Makopane (1990/91)

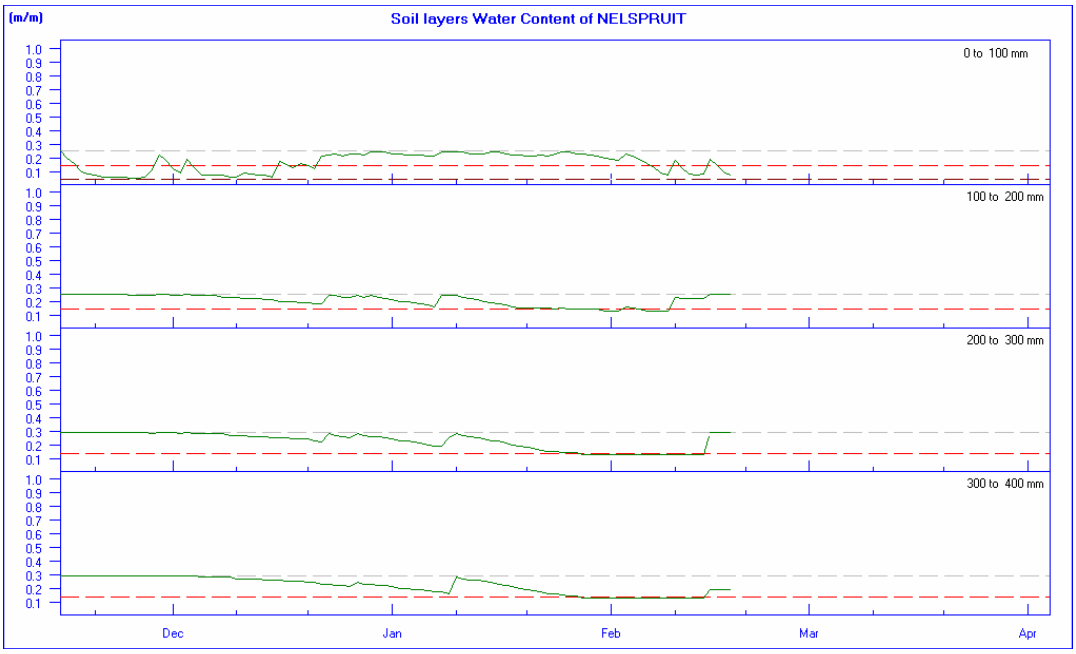

Figure A 16 Volumetric water content (depth 100 to 400 mm) for simulations for Nelspruit (1986/87)

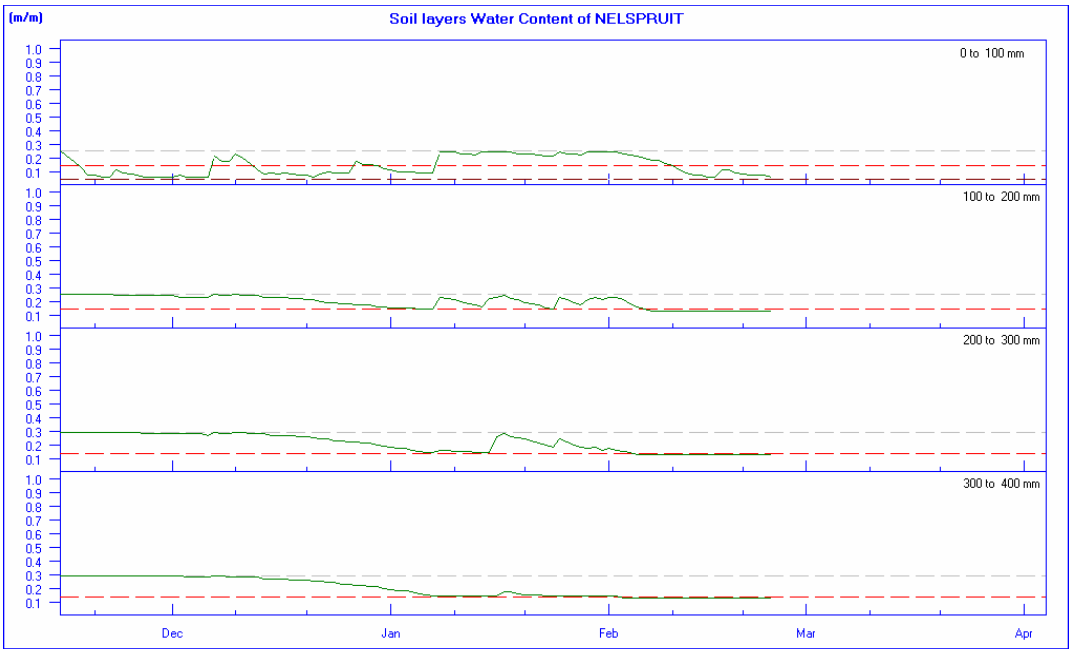

Figure A 17 Volumetric water content (depth 100 to 400 mm) for simulations for Nelspruit (1994/95)

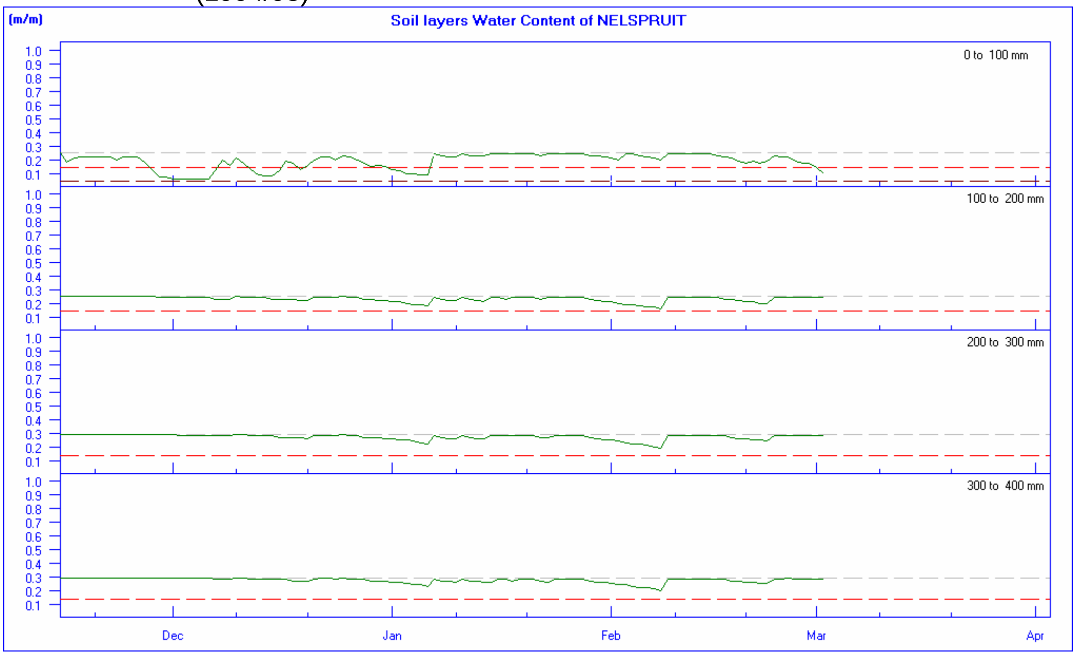

Figure A 18 Volumetric water content (depth 100 to 400 mm) for simulations for Nelspruit (1995/96)

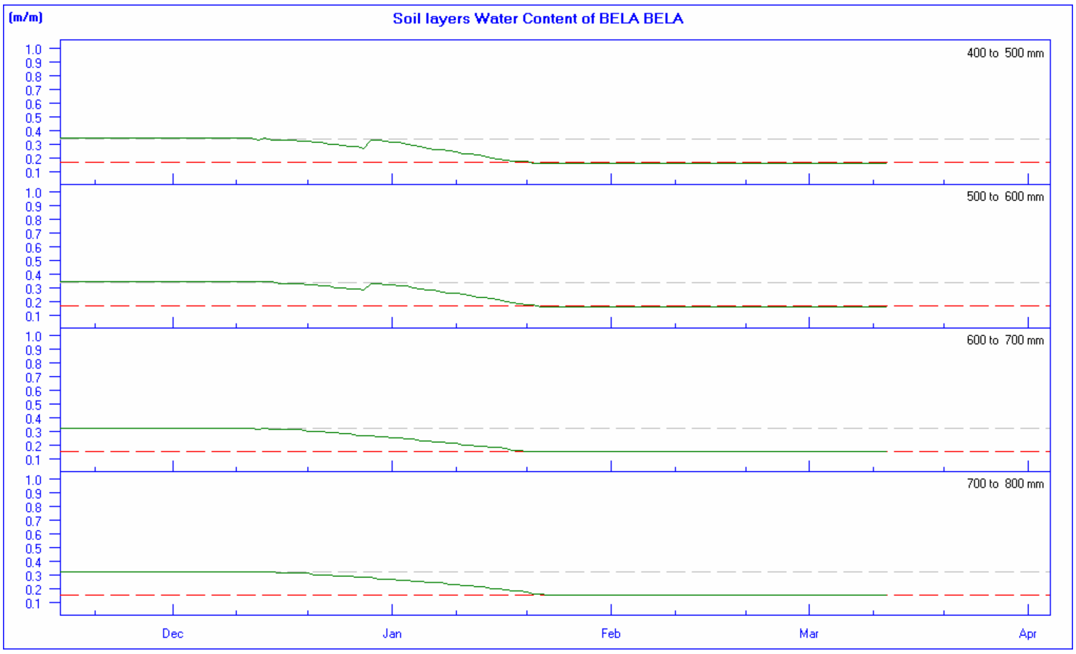

Figure A 19 Volumetric water content (depth 500 to 800 mm) for simulations for Bela Bela (1989/90)

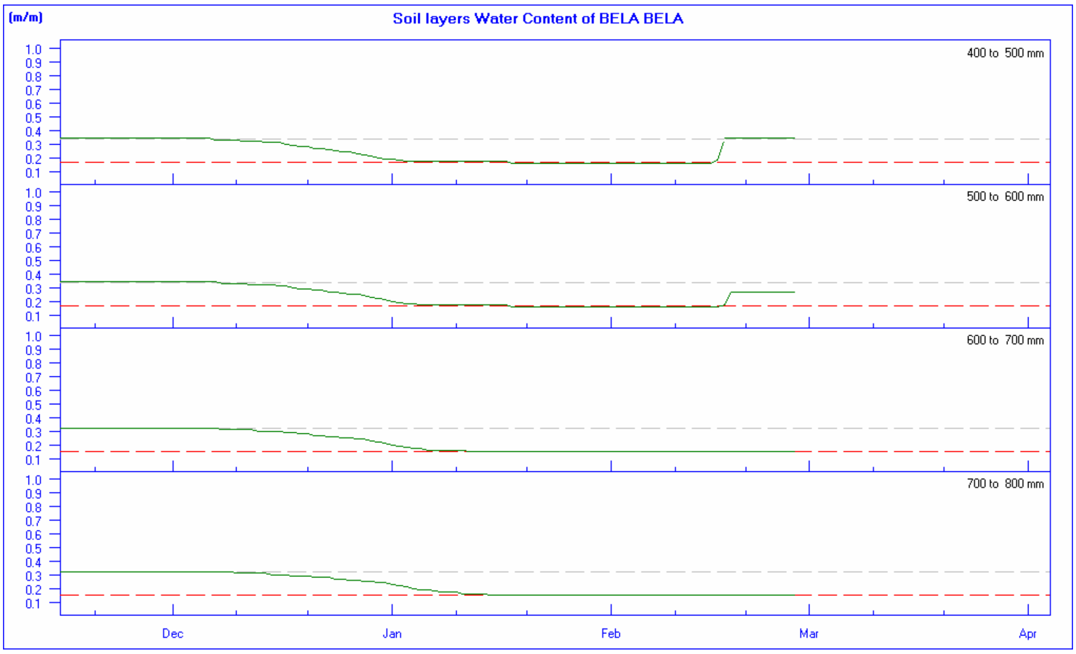

Figure A 20 Volumetric water content (depth 500 to 800 mm) for simulations for Bela Bela (1990/91)

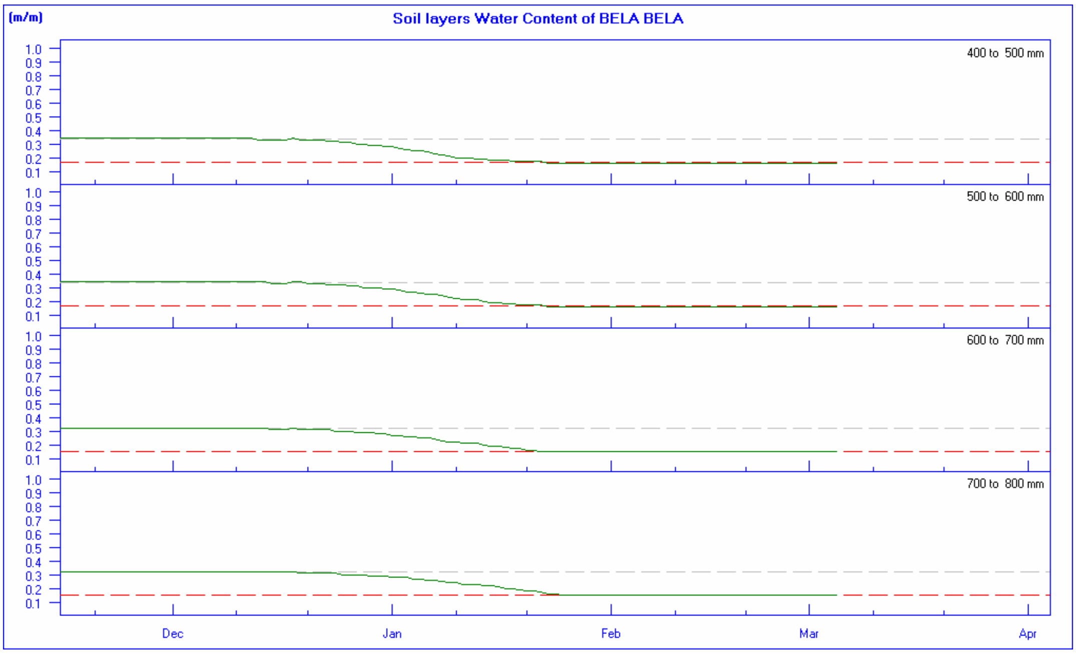

Figure A 21 Volumetric water content (depth 500 to 800 mm) for simulations for Bela Bela (1996/97)

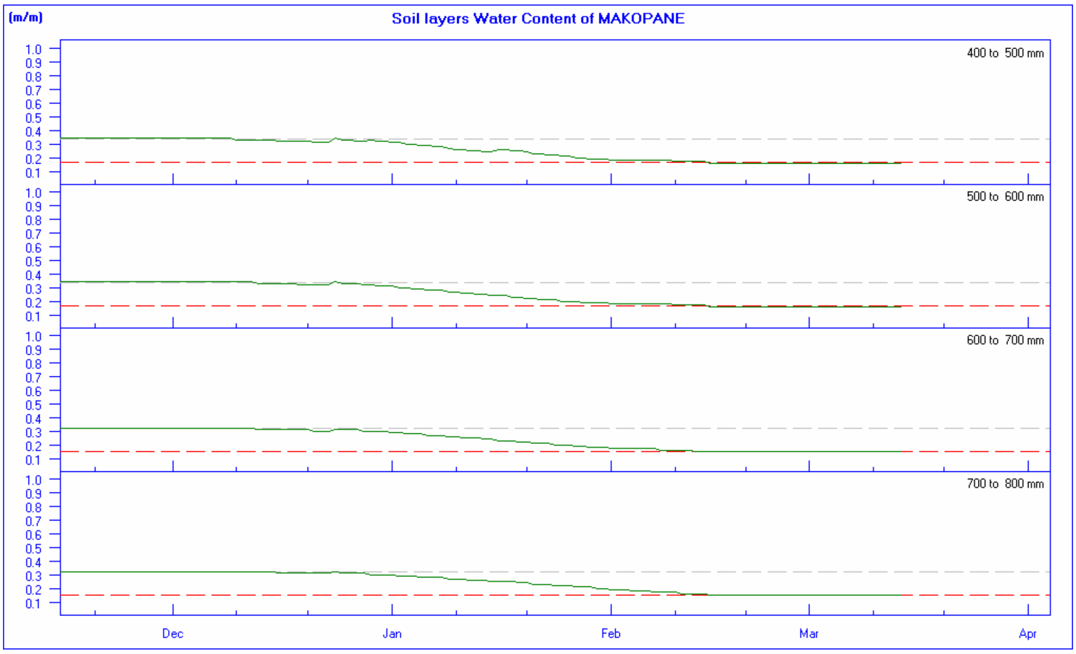

Figure A 22 Volumetric water content (depth 500 to 800 mm) for simulations for Makopane (1986/87)

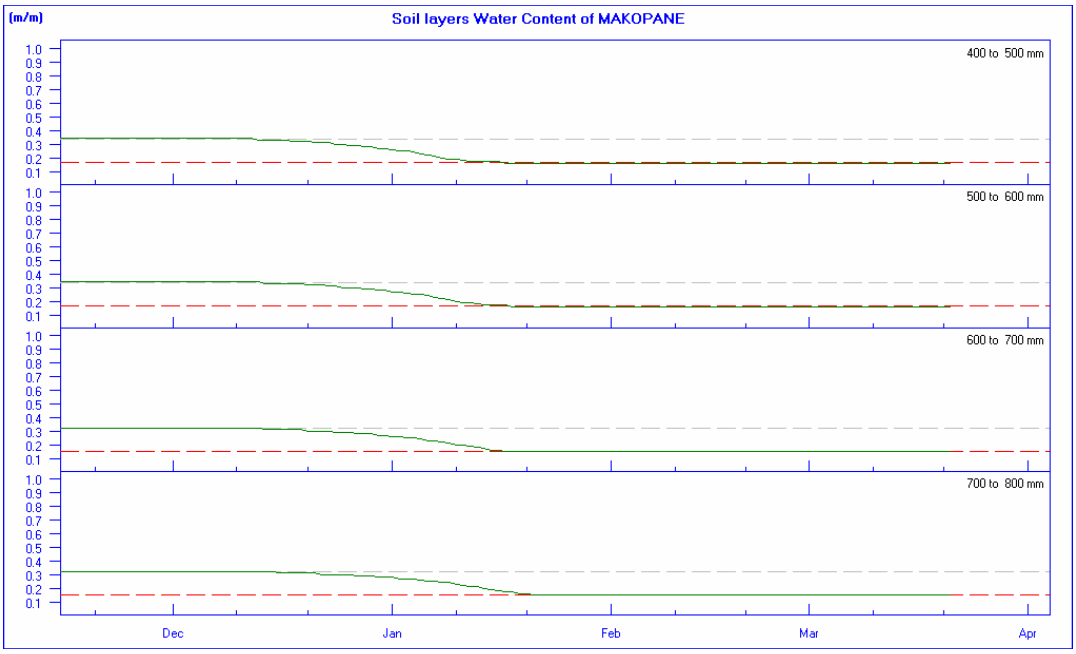

Figure A 23 Volumetric water content (depth 500 to 800 mm) for simulations for Makopane (1989/90)

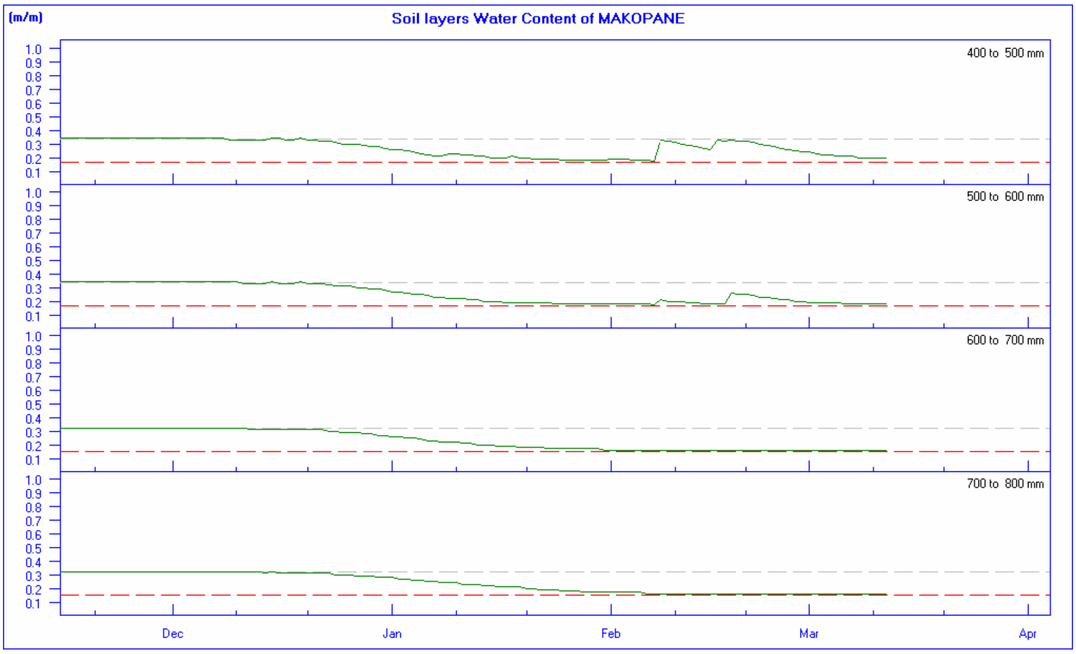

Figure A 24 Volumetric water content (depth 500 to 800 mm) for simulations for Makopane (1990/91)

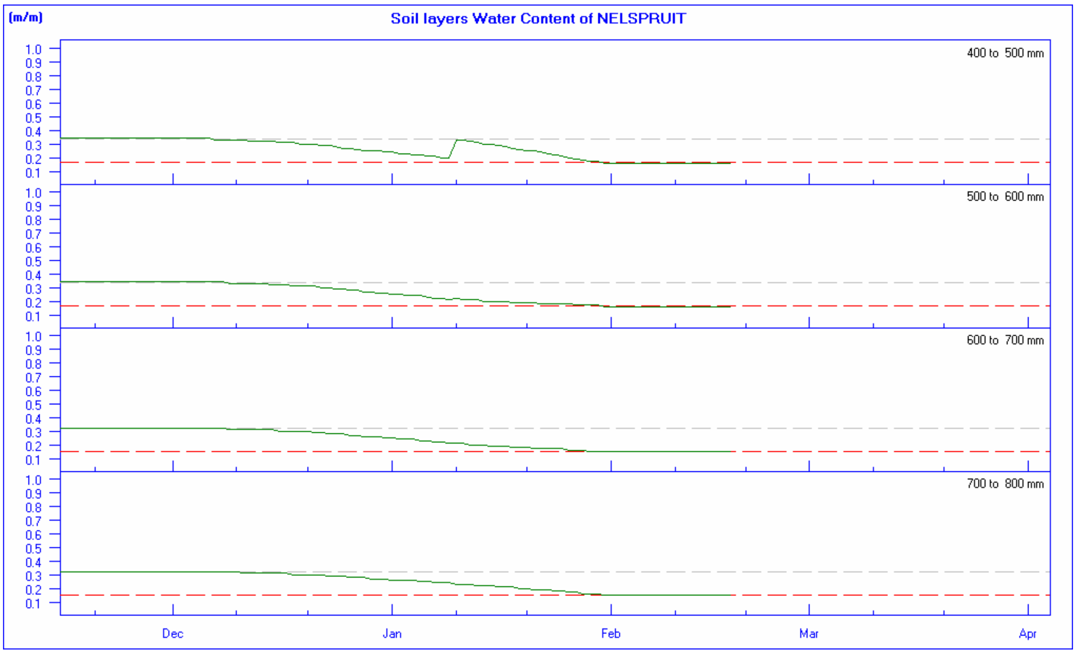

Figure A 25 Volumetric water content (depth 500 to 800 mm) for simulations for Nelspruit (1986/87)

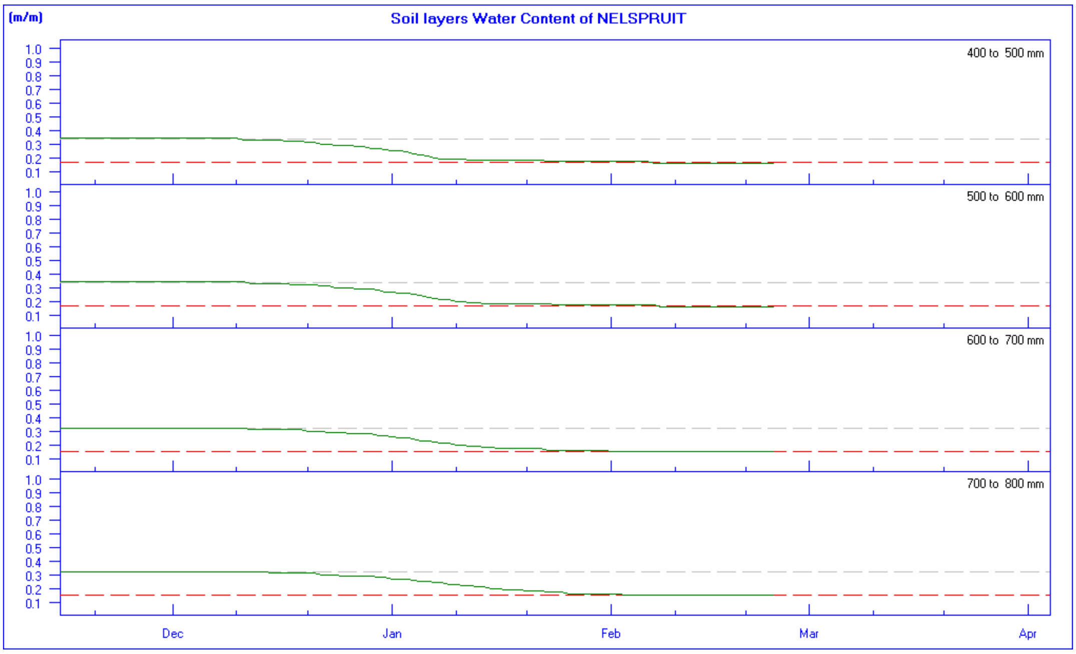

Figure A 26 Volumetric water content (depth 500 to 800 mm) for simulations for Nelspruit (1989/90)

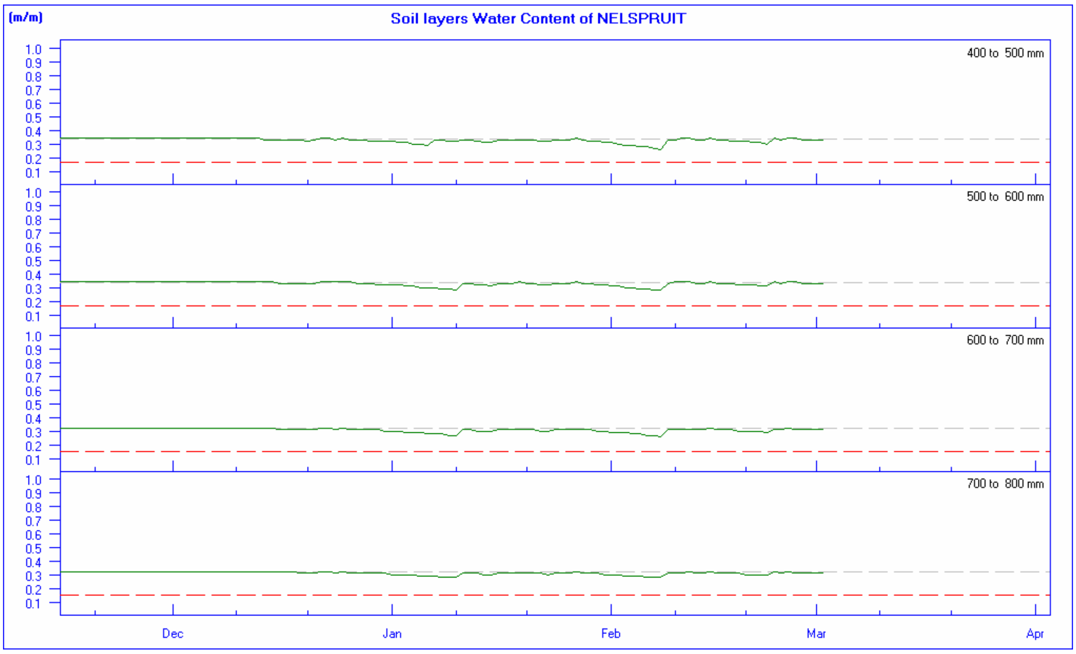

Figure A 27 Volumetric water content (depth 500 to 800 mm) for Nelspruit (1996/1997)

APPENDIX B

An addendum document to WRC project report entitled,
"WATER EFFICIENCY OF MULTICROP AGROFORESTRY SYSTEMS, WITH PARTICULAR REFERENCE TO SMALL-SCALE FARMERS IN SEMI ARID AREAS"

by

SOLOMON BEYENE GHEZEHEI

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1 MONITORING AND MODELLING RADIATION INTERCEPTION AND WATER BALANCE IN ALLEY-CROPPING SYSTEMS

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ABSTRACT

Monitoring and modelling factors and processes in agroforestry systems require extra perspectives and details to that of monocultural systems. This document reviews the main concepts and modelling approaches in water balance and radiation interception in agroforestry systems. To achieve this, the document explores interspecies interactions and plant-environment interactions in agroforestry systems in detail. The review also investigates water budgeting as well as radiation interactions and utilisation by the different plant components in agroforestry systems. Finally, it discusses major modelling approaches in water balance and radiation interception in agroforestry developed thus far, by referring to applicable modelling approaches of mixed-plant systems

INTRODUCTION

Agroforestry

Agroforestry is the science/practice of simultaneously or sequentially incorporating woody and non-woody perennials and/or annuals within the same land management unit. It, then, serves to offer multiple outputs in the form of products and/or services (Huxley, 1999). It is a joint application of agriculture and silviculture. The sustainability of an agroforestry system is only justified when its benefits outweigh its risks for an extended period of time. This is achieved upon keen understanding of the physical and biological factors involved in the system (Berlyn & Cho, 2000; Ong *et al.*, 2000).

The benefits of agroforestry include better recycling of nutrients, maintenance of soil fertility, improvements in the microclimate, higher yields, better resource utilisation efficiency, reduced nutrient leaching, soil erosion and promotion of soil organisms (Kang, 1997) as well as the provision of wind-breaks (Garrett and Buck, 1997; Oteng'I *et al.,* 2000). On the other hand, risks and problems, such as competition for radiation, water and nutrients between trees and crops, higher evaporative losses due to rain-water interception by the tree canopies and the resulting potential decrease in rain water utilization efficiency, occur in agroforestry (Ong *et al.*, 2000).

Modelling in Agroforestry

A model is defined as a diagrammatic, word or mathematical method of representing a system by accommodating the major processes of that system (Huxley, 1999). Models differ in their types, purposes and degrees of complexity. 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 major conventional ways of developing agroforestry models: A model is developed and its predictions are compared with independent field data. Depending on the extent of agreement, the model and its predictions are accepted or modified. An alternative way involves modifying agricultural, forestry, soil or economic models. To mention some: plant-growth simulations based on climate, soil and plant type (e.g. CERES - DSSAT set of models); plant growth predictors based on plant-climate and plant-soil empirical relationships (e.g. PLANTGRO, BIOL-CLIM and ECOCROP); soil erosion models (e.g. Erosion Productivity Impact Calculator - EPIC); soil water modelling (e.g. CROPWAT); soil organic matter modelling (e.g. Rothamsted Carbon model); nutrient cycling models; land evaluation models (e.g. Automated Land Evaluation System – ALES); and modelling shells like STELLA II (Young, 1997). At the programming level of modelling, model modules and subroutines in the model programming can be related to enable module flexibility in loading data structures. Such an approach offers advantages that agroforestry concept modelling can benefit from including, ease of model designing, implementation and modification, clearer structural configuration and possibility of exploring subroutines/ modules independently (Muetzelfeldt, 1995).

There are different types of agroforestry models: radiation and shade models, rainfall and growth simulation models, soil (process and property) models, economic models as well as combined biophysical and economic models (Young, 1997). Agroforestry models can provide crucial help in understanding system functioning, mechanisms of component interactions, recognising uncertainties in biophysical and social and economic aspects of agroforestry systems, interpretation of experimental results, designing of new systems and future trends and responses of the system (Lawson *et al*., 1995; Muetzelfeldt, 1995; Young, 1997). They can also be used in research, education, planning and development as well as in management and extension decision-making (Lawson *et al*., 1995).

Objectives

The objective of this document is to investigate theories and modelling approaches applicable to radiation interception and water balance in agroforestry.

CHAPTER – 1 INTERACTIONS IN AGROFORESTRY

1.1 Tree - Crop Interactions

These refer to the ways a component species affects the performances of the other component/s and the system as a whole (Nair, 1993). They are affected by**:**

1. Biological factors: Genotype, phenotype (genotype × environment), phenology factor and plant forms (Huxley, 1996, Ong *et al.*, 2000).

2. Environmental and hydrological factors**:** Temperature, nutrients, water, light, (Huxley, 1996: Huxley, 1999), slope of the land (Garrity, 1996) and interrelations between these factors

3. Management: Tree canopy pruning, (Droppelman *et al.*, 2000), tree root pruning, (Schroth, 1995; Ong *et al*., 2000) planting time and density of the understorey crop, fertilizer application, irrigation (Huxley, 1996) and selection of component species (Ashton & Ducey, 2000).

There are three major biological interaction types in agroforestry, namely: complementary, supplementary and competitive. Figure 1.1 illustrates relationships between tree and crop outputs in these interactions. In complementary interactions, there is a positive relationship between the outputs of both components as opposed to the competitive interactions, in which high output of a component is obtained when the output of the other is very low. In supplementary interactions, the component outputs do not affect each other.

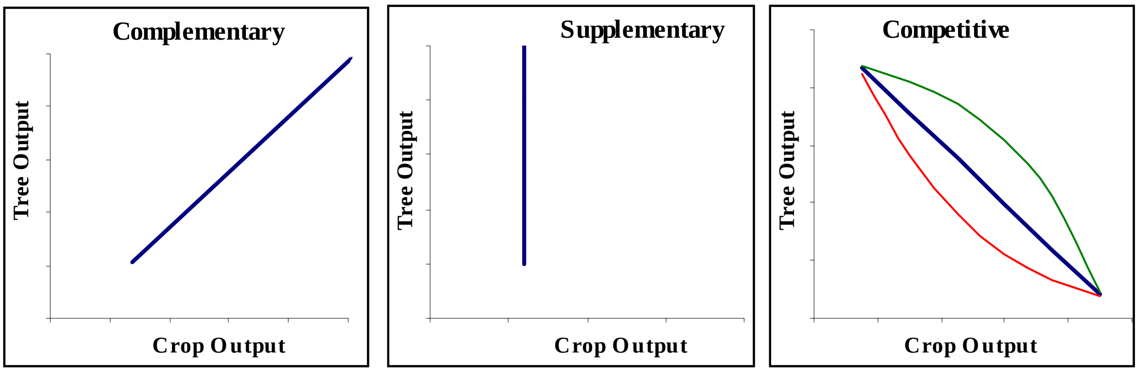

Figure 1.1: Common types of biological interactions in agroforestry (Nair, 1993)

Complementarity between components species should be ensured both spatially and temporally (Huxley, 1999; Ong *et al.,* 2000). Trees provide water and soil conservation benefits (Nair, 1993). Trees may also reduce weed competition with crops by blocking radiation from reaching shade-sensitive weeds and suppressing their growth (Nair, 1993; Ong, 1996). High resource use complementarity and efficiency necessitates that trees and crops mainly utilise different resources or extract resources from different zones, both belowground and aboveground**.** Microclimate may be improved because of the tree shading effects resulting in improved air temperature, air humidity and air movement, as well as soil temperature and soil moisture (Nair, 1993: Ong *et al.,* 2000). The changes, together with better efficiency of water use, imply higher expected productivity from agroforestry than sole cropping (Ong *et al*., 2000).

Competition for a resource in agroforestry is dictated by plant requirement and extractability potential for the resource and availability of the resource (van Noordwijk & Purnomosidhi, 1995). Competition in agroforestry includes: competition for radiation, water (Nair, 1993, Droppelman *et al*., 2000, Ong *et al.,* 2002), and nutrients; allelopathy (suppressing competing components by discharging chemicals) and the improvement of the microclimate to pests and disease-causing organisms, for which one component is resistant (Nair, 1993). Figure 1.2 illustrates possible ways competition can take place between components: one direct and two indirect ways. Selection of compatible species and carefully designing tree spacing and density minimise competition (Ong, 1996; Ong *et al.,* 2002).

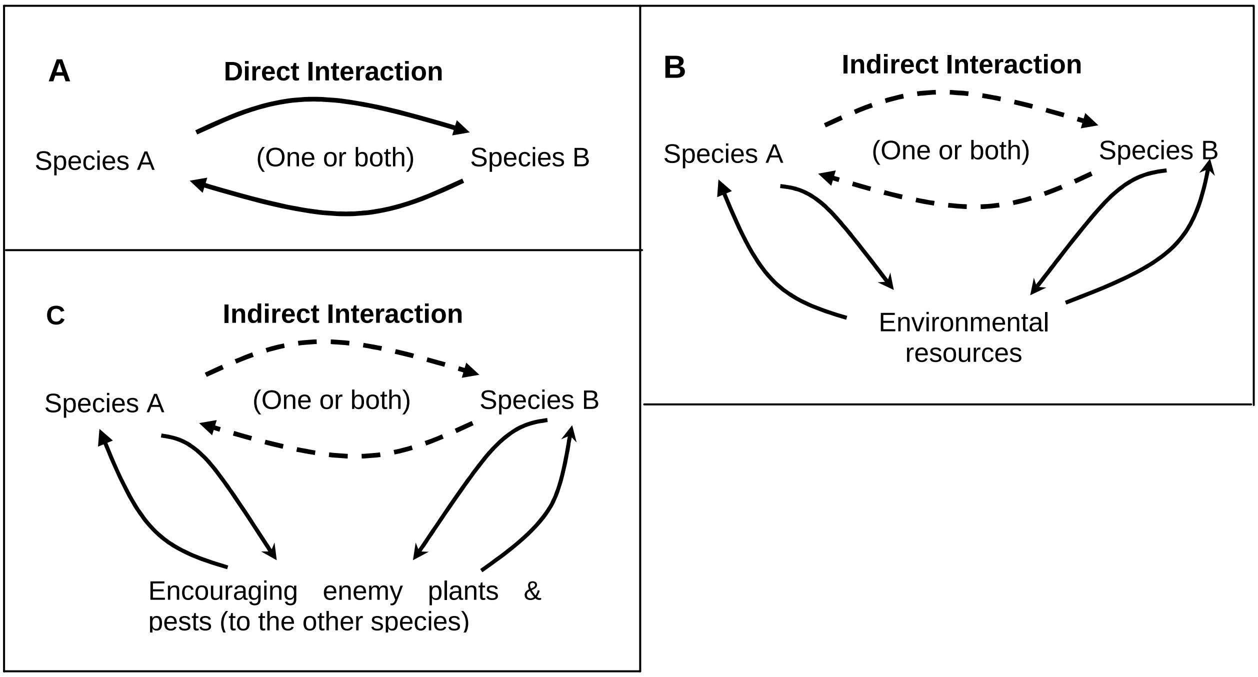

Figure 1.2: Forms of competition (Huxley, 1999)

The effect (*I*), which the interspecies interactions may have on crop yield, is quantified by:

$$I = F - C \pm M + P + L \qquad \textit{Eq. } (1.1)$$

Where: *F* is the effect on soil fertility and microclimate, *C* is for effects on crop yield reduction owing to competition, *M* denotes the effect on above-soil microclimatic with "±" sign showing possibility of having total positive or negative effect and the applicable sign being that of the dominant effect., *P* is the effect on soil properties and *L* for reduction of water or nutrient loss. Each of these variables is determines as a fraction of a control crop (Ong, 1996; Huxley, 1999).

Table 1.1 summarises positive and negative effects of tree-crop interactions. The positive effects are denoted by (+), the negative effects are denoted by (-) and the effects that have not been evidenced or experimentally verified are represented by (0).

Table 1.1: Major effects of tree-crop interactions (Nair, 1993; Ong, 1996

Effects	**Direct Evidence**	**Indirect Evidence**
Higher overall productivity	+	+
Soil fertility improvement	+	+
Nutrient cycling	+	+
Soil conservation	+	+
Microclimate improvement	+	+
Competition	-	-
Allelopathy	0, ?	-
Weed control	0	+
Sustainability and stability	0	+
Pests and diseases	0	-, +

Initially, slower tree growth (figure 1.3) and reduced crop growth may be expected in agroforestry systems than in monoculture systems, as a result of competition between trees and crops. The difference in tree growth between agroforestry and monoculture, however, decreases as the trees mature (Ong *et al.,* 2000)**.**

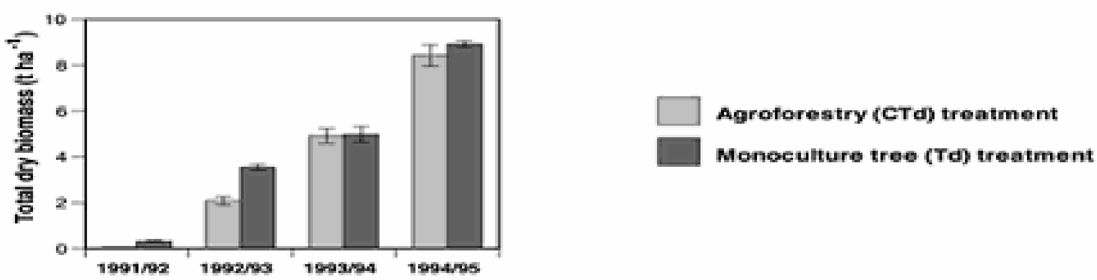

Figure 1.3: Comparison of total above-ground dry biomass increments between trees in monoculture & those in agroforestry (Ong et al., 2000)

1.2 Plant - Environment Interactions

Plant growth and survival is affected by solar radiation, temperature, water and nutrients. There are interrelationships, as shown in figure 1.4, among these factors and the perennial presence of trees in agroforestry only the magnitude of these interrelations is affected. For the radiation, nett radiation reaching a given environment is determined as the difference between total incoming radiation and total outgoing radiation before being partitioned into evapotranspiration energy, energy that warms up the air, as well as the energy that heats up the ground (Huxley, 1999).

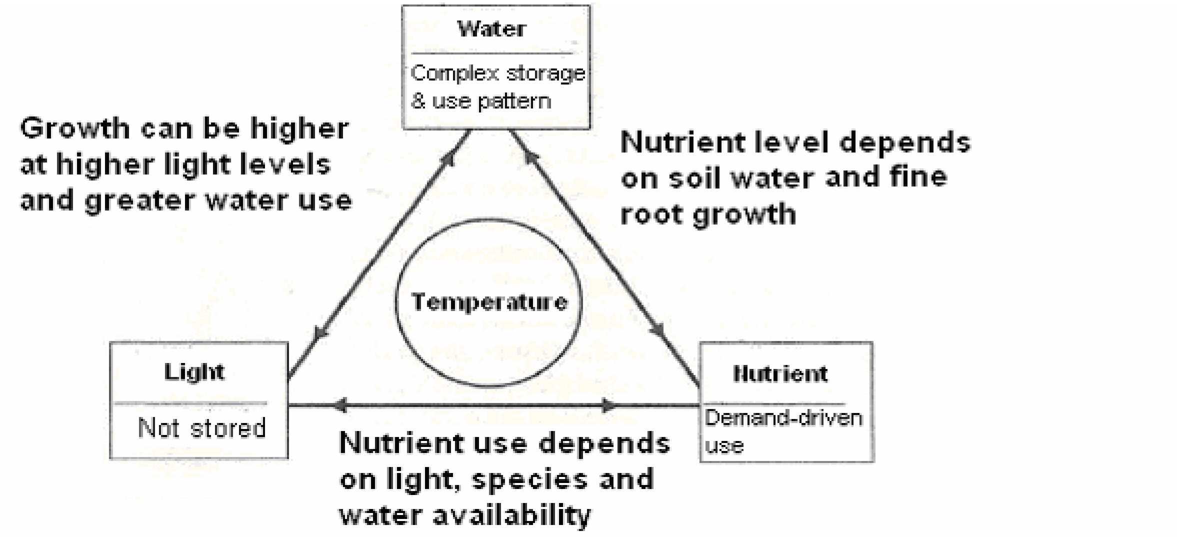

Figure 1.4: Interrelationships between environmental resources (Huxley, 1999)

Growth of tree roots is dictated by soil water content and hence varies seasonally. By trapping and/or extracting water and nutrients while descending down soil profile and nutrient pumping, tree roots reduce leaching loses and enrich the soil nutrient pool (Schroth, 1995). The following are the major positive effects of plant-environment interactions in agroforestry to the environment (Nair, 1993; Sanchez, 1995; Young 1989):

- Biological soil conservation benefits;
- Enhanced soil fertility and organic matter content of the soil and cutting down soil nutrient and organic matter losses;
- Enhanced biodiversity by reducing forest clearing and imitating natural succession;
- Reduced land degradation and rehabilitating degraded lands by reducing or protecting from soil acidity, alkalinity and salinity; and
- Reduced microclimatic extremes, such as wind, temperature, radiation, etc;

On the other hand, the following negative impacts upon the environment as a result of plant – environment interactions may result:

Release of growth-deterring chemicals by some components of the system;
Nutrient losses due to the harvest of trees or their products (Huxley, 1999);
Reduced groundwater recharge as a result of plants intercepting rainwater. Interception in an Eucalypts plantation was between 10 – 25 % of the total rainfall; and
Reduced groundwater recharge as a result of plants utilising water available in the soil (Schofield, 1990).

CHAPTER 2

WATER AND RADIATION UTILISATION AND BALANCE

The manners of utilisation and competition for water and radiation between component species vary in agroforestry systems because un-utilised water may still remain in the system, whereas light is either utilised or wasted (Kropff, 1993a; Kropff, 1993b). Water and irradiation utilisation and balance in agroforestry is discussed below.

2.1 Water Use and Balance

Ong *et al*., (1996) and Wallace, (1996) hypothesised that agroforestry would be more efficient in terms of the utilisation of rainwater than sole (crop or tree) cropping. They balanced transpiration of component species in an agroforestry system as:

$$T_t + T_c = P - (I_t + I_c) - (E_t + E_c) - (R_t + R_c) - (D_t + D_c) - (S_t + S_c) \qquad \textit{Eq. (2.1)}$$

Where: T denotes transpiration, P denotes precipitation, I stands for interception, R represents run off, D denoted deep drainage, E stands for soil evaporation, S denotes soil water, t denote trees or beneath them and c denotes crops or beneath them.

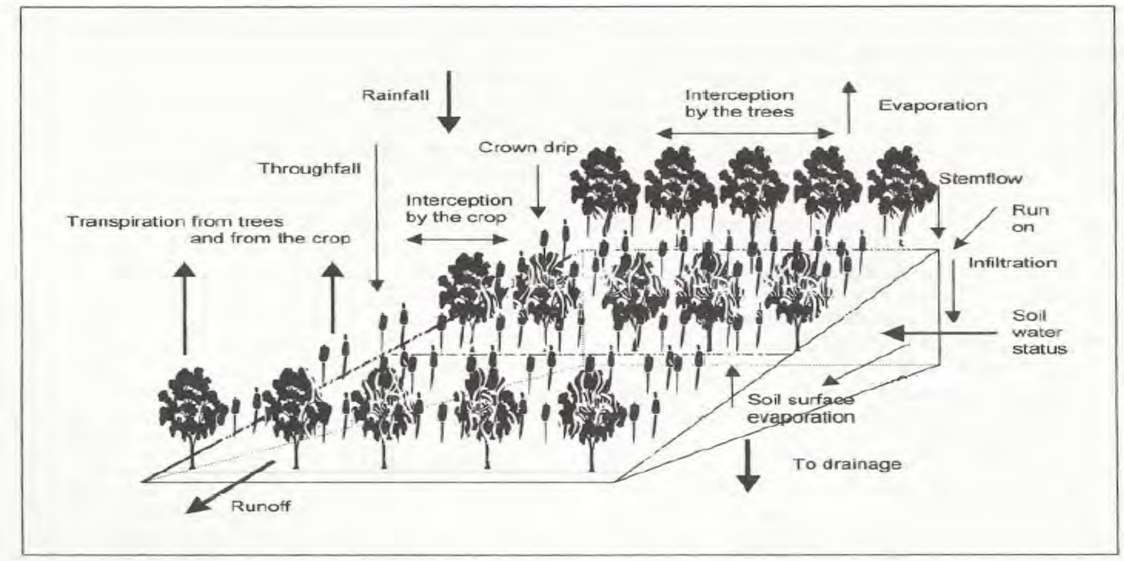

Figure 2.1: Components of water balance in agroforestry (Huxley, 1999)

Rainwater distributes asymmetrically on the windward and leeward sides trees. The presence of perennial woody species in agroforestry alters the kinetic energy raindrops, depending on the rainfall intensity. When rainfall is heavy and the raindrops are large, tree foliage reduces raindrop impact, whereas in the case of lighter rains and raindrops, tree canopies have the effect of combining the small droplets to form bigger ones. Provided that the trees are tall, these raindrops fall with similar speed to the original, thus attaining even higher kinetic energy (Wallace, 1996).

Water evaporation from soil, in cases where there is no energy limitation, takes place as a three-phase process. Evaporation takes place at a potential rate on wet soils. After this phase, soil water evaporates as a function of soil diffusivity and time. Lastly, it takes place as a function of water vapour diffusion through the top layers of the soil. Agroforestry has a potential of reducing evaporation to less than the potential rate in the first phase while the last case is insignificantly small. Mulching also reduces evaporation in agroforestry by shielding the soil from radiation and wind (Wallace, 1996).

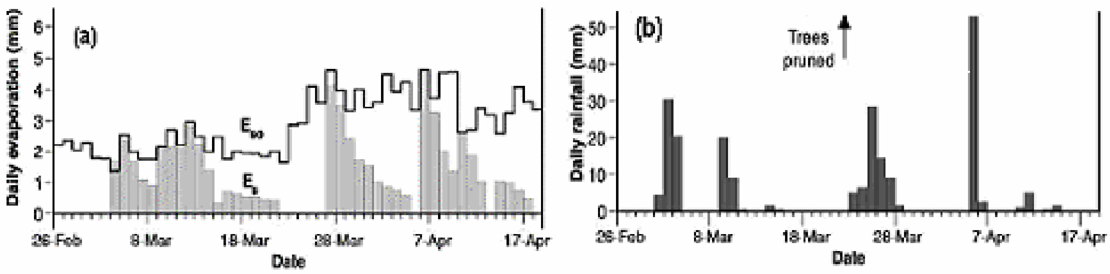

Figure 2.2: Soil evaporation (E_s, solid bars) & potential soil evaporation (E_{so}, stepped line) (a) soil 0.3 m from the base of trees in agroforestry (b) timing & quantity of rainfall (Ong *et al.,* 2000)

Agroforestry may be expected to have better water use efficiency than monocropping. On the one hand, agroforestry has the benefit that the woody components can utilise residual water in the crop rooting horizon, when the understorey crops are harvested. It also utilises water from rainfall between crop growing seasons. It reduces the amount of water losses by runoff, evaporation and deep percolation (Ong *et al.,* 1996; Lott *et al.,* 2003). According to an experiment carried out by Lott *et al.* (2003), the amount water used by trees between crop growing seasons was as much as 25% of the total annual tree water use and 16% of the annual rainfall.

Despite the above, however, more water is lost by canopy interception in agroforestry than in monoculture. A fraction of this interception is evaporated. The rest falls through plant canopies depending on the rainfall intensity and atmospheric evaporative demand (Ong *et al.,* 1996; Wallace, 1996).

In mixed plantings, competition for water takes place in two ways: directly, when there is limited available water and the component with the better rooting system dominates; and indirectly in which potential growth of components, when water is not limited, dictates potential competition for water when water is limited at later stages (Kropff, 1993b). The attainment of maximum water related benefits from agroforestry, therefore, requires implementing optimum tree planting density and arrangement (Ong *et al.,* 1996).

The water content in the soil beneath trees and beneath crops differs in agroforestry systems. The main reasons are differential runoff, infiltration and plant water uptake. Stored water remains in the soil until plants use it or until part of it is evaporated. If soil water storage capacity is exceeded, water drains below the root zone (Wallace, 1996; Huxley, 1999). Figures 2.3 & 2.4 illustrate how variations in water stored in the soil at various distances from trees at different soil depths resulting mainly from differential rainwater distribution and uptake

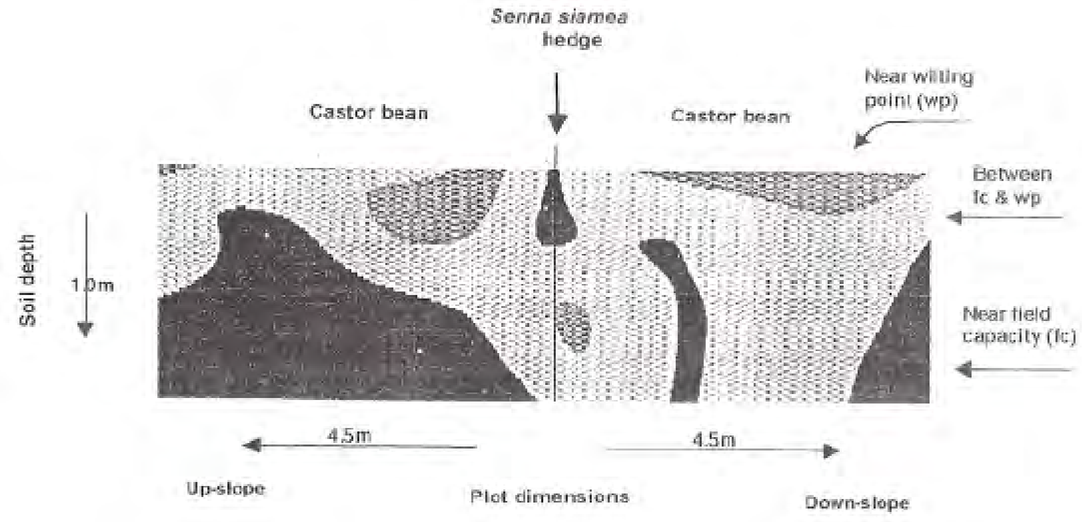

Figure 2.3: Variation in soil water content beneath tree and crops in *Senna siamea* - castor bean agroforestry system (Huxley, 1999)

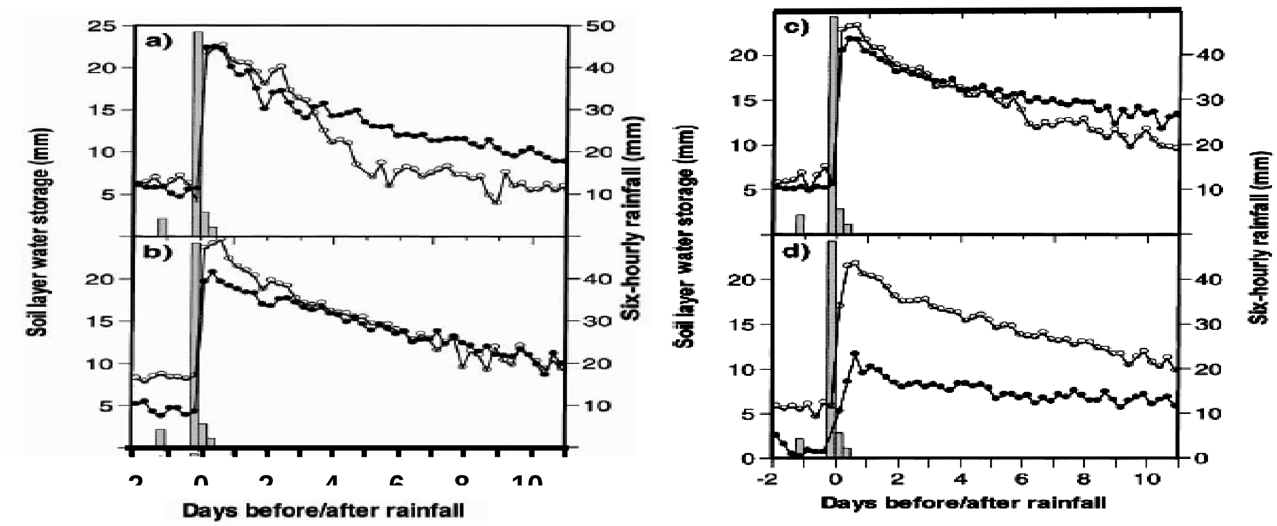

Figure 2.4: Soil water content after rainfall (indicated by vertical bars) at distances of 0.3 (●) & 2.5m(O) from trees in an agroforestry system at soil layers: (a) 0–0.1 m, (b) 0.1–0.2 m, (c) 0.2–0.3m & (d) 0.3–0.4 m (Ong *et al.*, 2000)

If rainfall intensity exceeds infiltration rate of the soil surface, water starts to accumulate on the surface until the surface storage is exceeded, after which water starts to run off. In agroforestry, runoff is reduced and infiltration of the soil is higher due to the effects of the woody vegetation. These effects include: modification of kinetic energy of raindrops; reduced effect of soil crusting; improved soil hydraulic conductivity and mulching, which encourages soil faunal and floral communities that work to modify soil physical characteristics such as soil structure and permeability (Wallace, 1996).

- Trees affect crop transpiration by affecting water availability to crops in two ways (Wallace, 1996):
- Positively, by enhancing soil physical properties, concentrating allowing intercepted rainwater in stem flow and get more opportunity time to infiltrate, and decreasing water losses via run off and evaporation, and
- Negatively, by intercepting rain and by competing for water with the field crops in the crop root zone.

Even when water is not limited, trees also affect crop transpiration by affecting the limiting resources in an environment, irrespective of the direct effect of trees on water available to crops (Kho, 2000). According to van Noordwijk *et al.*, (1996), apart from transpiration losses, water can be lost from plant roots to the surrounding soil when the plant roots have a higher water potential than the soil in their vicinity. This occurs, for instances, when water absorbed by deeper roots ascends through a section of the root system that comes into contact with soil with lower water potential, in the upper soil layers.

Transpiration in mixed planting can be quantified by: modelling water use by components using radiation interception models; by gauging total transpiration (using soil water balance method) and water utilised by a component from which water use by the other component is determined as the difference between the two; or by gauging water uses by individual components (Ong *et al.,* 1996).

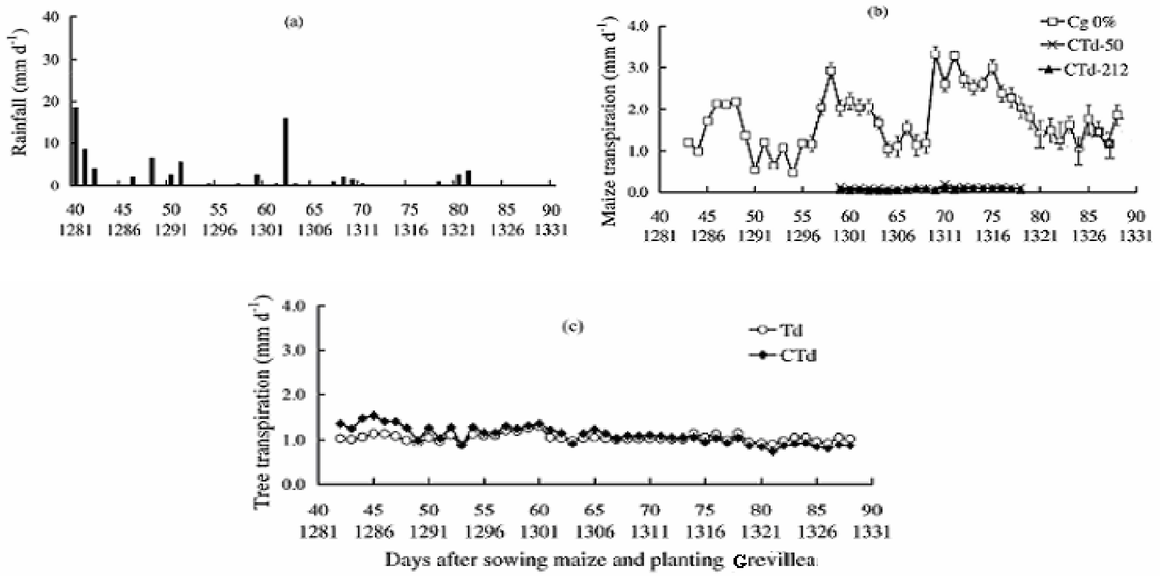

Figure 2.5: (a) rainfall; (b) transpiration by unshaded sole maize (Cg 0%), in agroforestry systems at distances 50 (CTd - 50) & 212 cm (CTd-212) from nearest tree; (c) transpiration by sole Grevillea (Td) & agroforestry (CTd) systems (Lott *et al.*, 2003)

2.2 Radiation Interception and Balance

Altitude, canopy structure, clouds, latitude, time of year, time of day, and topography are all factors that dictate the quantity, quality and duration of radiation intercepted by plants (Berlyn & Cho, 2000). In addition, the amount of solar energy received, duration of the plant canopy and fractional interception affect the amount of radiation that plant canopies intercept (Ong *et. al.*, 1996).

Trees intercept a portion of the radiation that would reach the field crops as a function of leaf area and extinction coefficients in their canopy layers at different times (Ong *et al.*, 1996). Then, shading (or light interception) on field crops, in agroforestry is a function of such factors as: closeness to the trees, nature and structure of the overstorey canopy (sparse or dense), solar angle, some management aspects such as timing of pruning of trees (Ong *et. al.*, 2000) as well as planting geometry of all the component species (Berlyn & Cho, 2000). Three-dimensional heterogeneity of the canopy structures and constant variation of canopy architecture in agroforestry also dictate the fraction of the radiation that is intercepted by component canopies (Ong *et al.,* 1996).

In mixed plantings, interception of light is determined by leaf area indices of the components and leaf characteristics determining light absorption (Kropff, 1993a). When a species, at its optimum density is grown with another species resulting in high total planting density, the total canopy can be divided into multiple horizontal strata, the interception of each of which is determined by (Ong *et al.,* 1996):

$$S_I = S\left(1 - e^{-\left(\sum_{A=1}^{m} k_{IA} L_{IA}\right)}\right) \qquad \text{Eq. (2.2)}$$

Where: S denotes solar radiation reaching surface of a given canopy layer (I) and S_I denotes solar radiation intercepted by the same canopy layer; m is the number of species in a given canopy layer; k and L denote extinction coefficient and leaf area index respectively; and A denotes a species in layer I. Total interception per component species at given time ($S_{A,Total}$) is given by:

$$S_{A,\,Total} = \sum_{I=1}^{n} S_{IA} \qquad \text{Eq. (2.3)}$$

$$Where: S_{IA} = S_I \frac{k_{IA} L_{IA}}{\sum_{A=1}^{m} k_{IA} L_{IA}} \qquad \text{Eq. (2.4)}$$

Where: n is the number of canopy layers, S_{IA} is the amount of radiation intercepted by species A in layer I; and that of the other species is obtained in the same way (Ong *et al.,* 1996). A portion of solar radiation gets reflected by the plant canopy. According to Kropff (1993a), this reflected portion from a green-leaved canopy (ρ), the leaves of which are randomly distributed in a spherical fashion, can be given by (Goudriaan, 1977):

$$\rho = \left[\left(1 - \sqrt{(1-\sigma)}\right) \Big/ \left(1 + \sqrt{(1-\sigma)}\right)\right] \bullet \left[2 \Big/ (1 + 1.6\sin\beta)\right] \qquad \text{Eq. (2.5)}$$

Where: σ is the scattering coefficient of a leaf for the visible range of the radiation (mean value for crops σ =0.2) and β is elevation of the sun. Using this reflectivity value, Kropff (1993a) described the cumulative radiation attenuated by canopies in a mixed plantation with differing heights as:

$$S_H = (1-\rho)S_o \exp\left(-\sum k_A L_{H,A}\right) \qquad \text{Eq. (2.6)}$$

of which

$$S_{Absorbed,\;H,A} = k_A (1-\rho) S_o \exp\left(-\sum_{A=1}^{m} k_A L_{H,A}\right) \qquad \text{Eq. (2.7)}$$

Where: L_H denoted the cumulative leaf area index above a certain height, H and S_o is flux of visible radiation at canopy top. According to Marshal and Willey (1983) and Ong *et al.,* (1996), the fractional interception of photosynthetically active radiation, S_p, can be determined by the equation:

$$\ln\left(1 - S_p\right) = 1.4 \cdot \ln\left(1 - S\right) \qquad \text{Eq. (2.8)}$$

Where: S is fractional interception of radiation

The overall plant utilisation of light depends on orientation (angle and angle distribution), shape, thickness, internal and external structures, moisture content, nature of mesophyll, cuticle and epidermis of leaves and the distribution of light absorbing leaf pigments (Kropff, 1993b; Berlyn & Cho, 2000).The proportion of intercepted photosynthetically active solar radiation and the species/cultivar-specific conversion efficiencies of plants play vital roles in determining light absorption and utilisation by plants (Ong *et al.,* 1996)

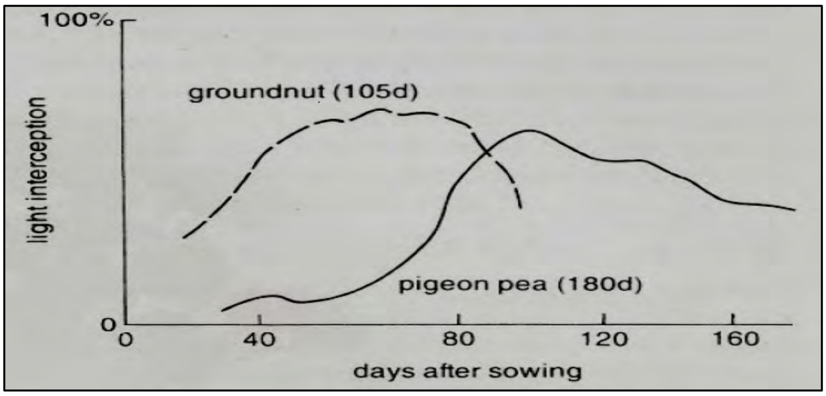

Figure 2.6: Temporally complementary pigeon pea and groundnut (Willey *et al.,* 1986; Huxley, 1999)

Once absorbed by plants, radiation takes part in photosynthesis, spatial and temporal orientation plants, stomatal closing and opening, leaf morphology and physiology, branching, crown orientation and shape, characterising leaf pigmentation, photoperiodism, enzyme activation, light driven reactions and cold hardiness (Berlyn & Cho, 2000).

In Figure 2.6, the canopy of the groundnut developed earlier after which the canopy of the pigeon pea developed. Thus the utilisation of light by these species was at different times and the two species were temporally complementary (Huxley, 1999). The amount and spatial allocation of light transmission to an agroforestry floor is dependent on overstorey spacing and orientation (North - South or East - West), height, architecture and structure of canopy as well as latitude (Ong *et al.,* 1996).

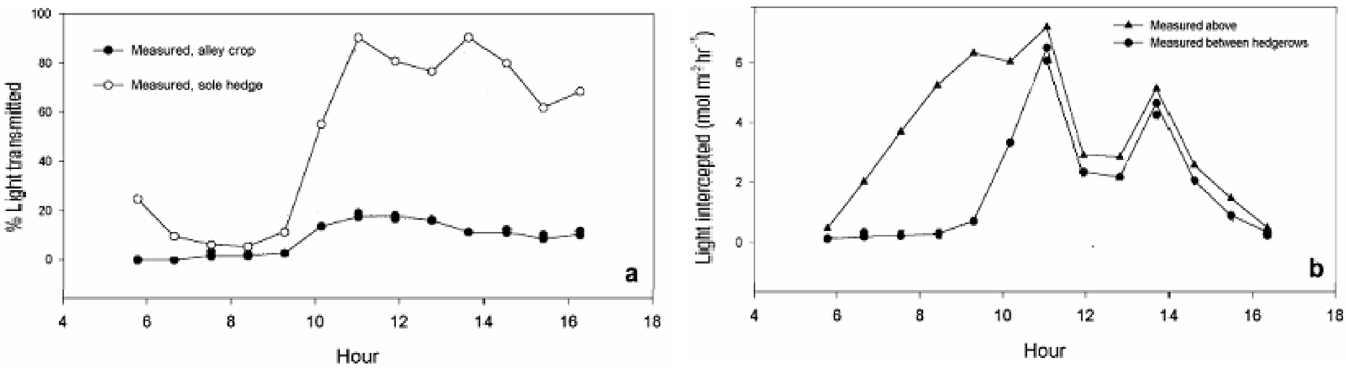

Figure 2.7: (a) Percent transmitted light to alley floor & (b) total incident on a sunny day (Friday and Fownes, 2001)

Monitoring of light interception should include selection of representative spots or sites for instrument placement to enable the tracking of spatial and temporal patterns, careful and accurate determination of photosynthetically active radiation (which is quantitatively and qualitatively affected by the heavy overstorey shading) and considering continuous variations between component interactions as well as longer timescale than with sole cropping. Measurements of radiation can be done using instruments, such as tube solarimeters, over both the overstorey and the understorey components of the system (Ong *et al.,* 1996). Depending on system design, composition and maturity, complexity of component interactions will vary and so will the complexity of monitoring light interception. As a general technique, however, light interaction with component species (interception, transmission, absorption and/or reflection) can be monitored by gauging the parameters involved across the component interfaces (Ong *et al.,* 1996).

CHAPTER 3

MODELLING RADIATION INTERCEPTION AND WATER BALANCE

3.1 Modelling Approaches

Here are models which are relevant to modelling soil water balance and radiation interception under agroforestry systems:

- Simulation of Hedgerow Intervention against Erosion and Land Degradation (SHIELD) is a model to simulate infiltration, runoff, soil water availability, erosion and consequences for crop yield as a function of soil water as driven by daily rainfall amount and intensity. It is based on measured infiltration, hydraulic conductivity, and soil water changes across the zones, runoff and erosion (Young, 1997).

- HyPAR is a tree and crop growth, as well as resource (light nutrient and water) utilisation model developed by merging two models namely: a forest (hybrid) and a crop (PARCH) models. HyPAR modifies crop growth by competition and stresses and models two tree canopy options: either uniform throughout the year or heterogeneous in three dimensions, also referred to as “disaggregated” (Mobbs *et al.,* 1999).

- Water, Nutrient and Light Capture in Agroforestry Systems: (WaNuLCAS) model - predicts resource capture under competition. For belowground tree-crop competition, it considers relative root length densities of trees and crops (van Noordwijk and Lusiana, 2000).

Van Noordwijk *et al.,* (1996) listed different complexity levels applicable in approaching water uptake modelling:

1. Modelling with implicit roots making use of measured or estimated uptake efficiencies;
2. Modelling uptake efficiencies with measured root densities and scaling up of single root functions to system levels;
3. Modelling that applies curve fitting methods to spatial and temporal root growth;
4. Modelling following functional equilibrium between root growth and nutrient and water status of the plant; and
5. Modelling root growth responses as differentially affected by variable distribution or availability of nutrients, water, oxygen, mechanical impedance, etc.

Different radiation interception modelling attempts have been made for pure-tree stands. To mention some:

- A sophisticated model for calculating the absorption profiles within a homogeneous vegetation canopy, based on the Nilson–Kuusk canopy reflectance model (Nilson and Kuusk, 1989);
- Radiation attenuation models by rectangular or triangular hedges proposed by Smart (1973) and Jackson and Palmer (1979);
- Charles-Edwards and Thorpe (1976) proposed a model that estimates radiation absorption and penetration in an apple orchard assuming the canopy to be parallel rows having ellipsoidal cross sections;
- Cohen and Fuchs (1987) proposed a two-dimensional model to predict attenuation of solar radiation by an orchard canopy having partial transmission.
- Berliner’s (1988) model that considered the orchard canopy to be made of parallel gapless, opaque cylinders with infinite length and circular cross-section a certain height above the ground.

Another valuable model, known as is Two-dimensional energy interception and water balance model for hedgerow tree crops (SWB-2D), has been developed and validated. The model has satisfactory accuracy. It has four fully substantiated and accurate sub-components, namely: tree radiation intercepted estimator, predictors of soil evaporation and transpiration tree, as well as soil water redistribution modeller. (Annandale *et al*., 2002; Annandale *et al*., 2003; Annandale *et al*., 2004)

Previous radiation models in mixed cropping systems have considered from horizontal canopy homogeneity (Sinoquet and Bonhomme, 1992) to vertical and horizontal uniformity of foliage distribution (one-dimensional models) (Rimmington, 1984; Sinoquet *et al.,* 1990). One model considered the mixed plant stand as a multi-layer stand with one layer representing each component, which is assumed to be horizontally homogeneous (citations by: McMurtrie and Wolf, 1983; Spitters and Aerts, 1983; Rimmington, 1985; Graf *et al.,* 1990; Ryel *et al*., 1990). Other models considered various solar angles and distribution of foliage; determination of intercepted radiation by deducting the proportion of radiation beam reaching a certain canopy depth before interception (or gap fraction) and so on. Nilson (1971) also described light penetration in a non-randomly distributed foliage, making use of the Markov chain model (Ong *et al.,* 1996).

In an agroforestry system, due to canopy heterogeneity, all of the above assumptions are highly unreliable. The canopy heterogeneity is not only across the tree-crop interface but also between adjacent trees in the tree row. The consequent reduction in accuracy of two-dimensional models led to the need to devise three-dimensional models.

Some of the three-dimensional models proposed include: the model by Mann *et al.*, (1980), which considered individual cotton plants as spheres. Their assumptions included random plant spacing in a row, infinite field dimensions (no edge effect) taking only direct solar beam and equal probability of solar ray reaching at any side in the crown. The model output was the prediction of the proportion of the whole area which light reaches, but with no detailed description of the spatial distribution. Another three-dimensional model was proposed to predict periods of shadow below an opaque tree canopy by disregarding edge effects and diffuse radiation (Quesada *et al.,* 1989). Chen *et al.,* (1993) used a computer generated poplar tree stand to look into leaf area index (LAI) and gap frequency as well as light distribution assuming that the source of light to be directly overhead.

Reid and Ferguson (1992) commented on assumptions by Mann *et al*. (1980) as follows:

- Agroforestry systems generally use smaller plots and the edge effects should not be ignored;
- Annual crops growing in agroforestry systems use diffuse radiation, especially during overcast and cloudy conditions;
- There is a lower probability of leaf interception of radiation for edge leaves than those the middle of tree crown; and
- Detailed modelling of spatial radiation distribution under the tree canopy, in agroforestry, is crucial to determine light requirement of the understory crops

They then modelled radiation transmitted through a discontinuous or overlapped canopies of an agroforestry system three-dimensionally:

- Assuming even stand spacing and cone-topped canopy as well as separate transmittances for direct and diffuse radiation;
- Considering different directions and edge effects;
- Determining gap fractions from photographs of tree crowns; and
- Using crown dimensions and not LAI and leaf inclination.
- The model predicted spatial and temporal distribution of solar radiation at any time and/or at any point under tree canopy in an agroforestry system.

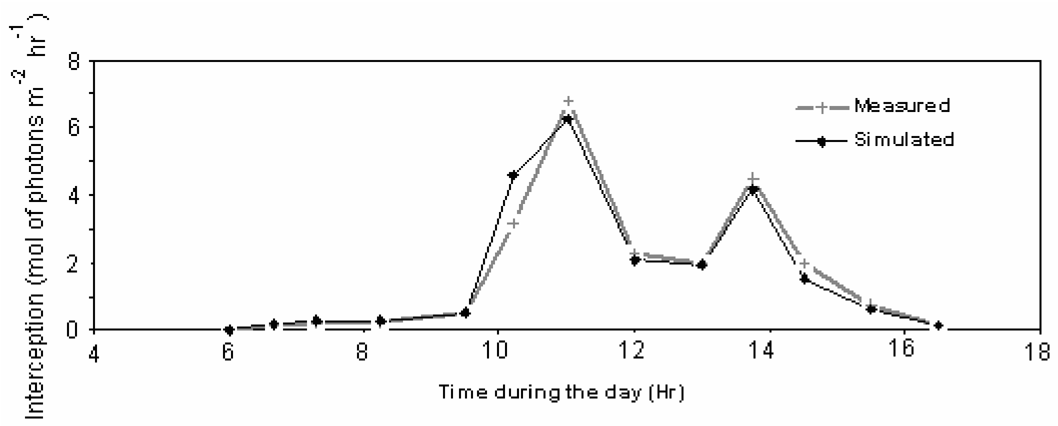

Figure 3.1: Simulated & measured incident radiation between hedgerows in agroforestry (Friday & Fownes, 2001)

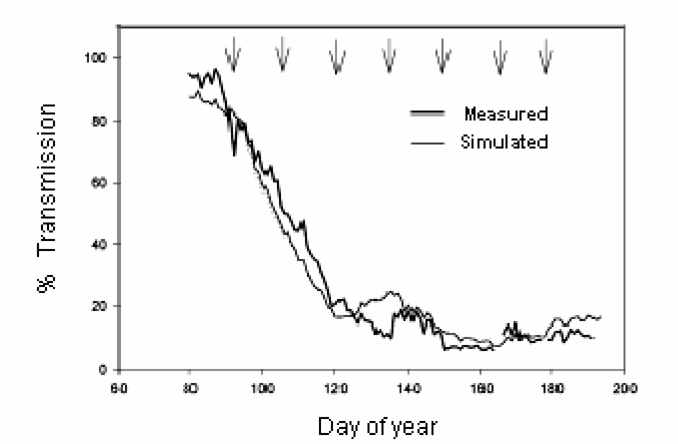

Figure 3.2: Measured & simulated percentage light transmission to the soil surface in an alley cropped system during the cropping period (Friday & Fowne, 2001)

Figures 3.1 & 3.2 illustrate comparisons of the predictions of a light interception and transmission model by Friday & Fowne, (2001) and actual measurement. Their model predictions showed better agreement with measurement when the interception of light was simulated with measured tree (hedgerow) dimensions than with simulated dimensions.

To correctly and accurately predict water balance and light interception in agroforestry, focus should be on the interspecies interaction of the component species. For the water balance modelling root distribution, availability of water and the demand of per component species need to be accurately characterized. The extent of canopy growth of both, as well as the relative dominance of component canopy, also determine water use by the components and thus affect the water balance of the whole system. Water not utilized by a component at a certain time may be used by the other component. For light interception, however, there is no storage in the system and accurate allocation is vital. The overestimation of light capture by a component will imply excess growth as well as over utilization of resources, which, according to the model, can be at the expense of the other component. Therefore, for accurate predictions, root and canopy distribution, relative canopy and root densities at a certain (overlap) zone, accurate determination of component demands for the resources, relative positions of the components, accurate growth predictions, nature of component interactions and climate are the main aspects that should be determined (Mobbs *et al.,* 1999)

3.2 Model Parameterisation and Performance Testing

Some unique features in agroforestry include: multiplicity of system components, the presence of some components and their effects perennially, aboveground and belowground tree-crop interactions and transfers, differences in soil development and erosion under the components as well as multiplicity of outputs. These need careful consideration when estimating any parameters (Young, 1997).

Parameters can be obtained from literature. Such parameterisation may not be exact, but only an approximation, or average for a range of conditions. For reliable applications, these parameters need to be tested under the conditions they are required to operate. Parameters can also be determined experimentally. Once the models have reliable parameters they are tested for their performances by comparing model predictions with actual measurement (Jorgensen, 1986). Recalibrating the model and its parameters every time the model is applied under a different environment assures model performance.

4 SUMMARY

This review focuses on the modelling of water balance and radiation interception under agroforestry and overstorey–understorey interactions between component species. These interactions may be complementary or competitive. These interactions, along with the resource status in the system, determine water budgeting and ell as light interaction with plants. Tree-crop interactions are also influenced by the environment, which in turn is influenced by the system components.

Water use by crops is mainly affected by trees, water availability and transpiration demand by the crops. As trees have more developed root systems, they are likely to dominate water competition under stressful conditions, thereby experiencing lower yield depression than crops. After crops are harvested, trees can use excess intercropping period rainwater and the residual water in the crop zone. This makes agroforestry more efficient in utilising rainwater than monocropping, though interception losses may be lower in the latter case.

For light interception, overall canopy behaviour of component species determines the nature of light interaction with these components. The understorey crops are affected by the nature of overstorey - radiation interactions.

The last section concentrates on the water balance and light interception modelling approaches developed thus far. Water balance mainly focuses on plant root distribution and water demand by the components. For radiation interception modelling, various attempts (One, two or three - dimensionally) have been made with viable assumptions. Relative positions of components, as well as overall canopy characteristics of the components are the main aspects to consider, when accurately modelling light interception. Light and water related models may adapt parameters from literature after these parameters are calibrated for the specific purpose or use experimentally determined parameters. Once developed, models need to be tested for their predictions against actual measurements.

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2 A SUMMARY OF THE HYPAR MODEL

HyPAR Model

HyPAR is a tree and crop growth as well as resource capture model. It is a process-based, generic and predictive but non-simulation model. It was developed by merging two process-based models, namely: a tree model, known as Hybrid, and a crop model, called PARCH. It models three cultivars of sorghum, one cultivar of maize and up to eight tree species, by considering light, nutrient and water resource utilisation at various overstorey foliage management (pruning) and fertiliser applications.

HyPAR has four main components: climate, tree modelling, crop modelling and soil modelling. It requires inputs such as soil, crop, tree and weather data as well as latitude and longitude and foliage management of tree, to produce outputs, including tree canopy nett primary production, crop growth and potential grain yield and capture of growth resources at daily and annual time-steps. It tracks production, soil carbon, and nutrient levels periodically to evaluate sustainability of the systems.

The model is written in FORTRAN 77 computer language. It has window interface and is linked with excel. Its computations are undertaken following sequences. Despite the absence of interface with user, it is open for improvement or addition of parameters and analysis with excel. Growth modelling of component species is done in response to day-to-day weather. It carries such shortcomings as no nutrient and livestock representation, and a small number of plant species. It grows one understorey crop per annum. Trees and crops are assumed to experience the same ambient temperature and humidity.

The following are the main components of the HyPAR model:

1 Climate: Daily weather data are required. Alternatively, HyPAR generates shortwave radiation, rainfall, maximum and minimum temperature, as well as vapour pressure, for each day of the year. To do this the model needs latitude, longitude and monthly measured data including: the ratio of number of rainy days in a month to the number of days in that month; amount of rainfall in each of the rainy days; highest and lowest temperature extremes; solar radiation and vapour pressure (or relative humidity).

2 Tree modelling – predicts tree nett primary production (NPP) as a function of: weather, modelled overstorey interception of light and nett photosynthesis; tree water balance; stomatal conductance and respiration. There are two options of tree canopy that are maintained (by the model) for the whole year of modelling: uniform foliage distribution or a three-dimensional foliage (regarding trees as isolated plants). Tree roots are deeper than crop roots and extract water as a function of: transpiration requirement; water content in the soil and root length density. It involves mass balance technique for carbon, nitrogen and water and predicts fluxes of CO_2 and water accurately.

The model applies Beer's law to compute photosynthetically active radiation (PAR) and short-wave interception by tree foliage after dividing the foliage into one-metre deep layers, each of which has distinct values of reflection and extinction coefficients of PAR and shortwave radiation. It applies radiation absorption estimated at the foliage-top to determine nett photosynthesis and stomatal conductance. The model, essentially, relates respiration with temperature and assumes different values of the ratio of carbon to nitrogen for sapwood, foliage and fine roots.Evaporation from tree foliage is determined using the Penman-Monteith method.

According to HyPAR, litter production is expressed as a fixed fraction of biomass from the woody parts of the tree while for the leaf and root components of the tree, 'turnover' is, also, accounted. The aboveground biomass of trees can be reduced by pruning, coppicing and thinning. The removed parts of the trees may partially or fully be added to the soil or removed. Subsequent to pruning or/and coppicing, trees replenish their shoot biomass from assimilate deposits in the sapwood. Allocation of assimilates in trees is performed presuming correlations between stem diameter and stem carbon; canopy area and 'sapwood' area; as well as constant canopy carbon content expressed relative to 'fine-root' carbon. A fixed portion of available assimilate is, firstly, allocated to the trunk, while the remained is used to add to underground and canopy biomass. In this way, carbon is allocated first and nitrogen follows, by obeying constant ratios of carbon content relative to nitrogen content (C/N) between canopy and sapwood as well as between canopy and roots.

Tree root distribution options are homogeneous or three-dimensional depending on the light capture option selected. Maximum root extensions horizontally (in three-dimensional option) and vertically are determined as a function of height of tree. In both cases, there is an exponential decrease in the belowground biomass away from the tree base.

From irradiance, soil water potential in the soil, ambient temperature and vapour pressure deficit, the model calculates stomatal conductance of the upper-most foliage layer, which in turn, is used to calculate foliage conductance and potential transpiration. Daily transpiration is determined as the lower of the potential transpiration and water acquired by tree roots. Biomass fraction that the model allocates to roots is converted to root length density assuming equivalence between one-milligram root and a millimetre of root length.

In the case of the three-dimensional option of tree radiation interception, basic ellipsoid tree foliage is considered. The field is divided into square plots, each of which may locate a tree at its centre. Beer's law is then used to characterise radiation interaction with tree foliage. Reflection is not, however, included. From an "Overcast Sky Model", radiation reaching the tree foliage directly and amount absorbed by the foliage are determined. The difference between these values gives an indication of the extent of shade beneath the foliage of each tree. The model maintains this profile of radiation, or shade intensity (estimated bi-dimensionally) until the foliage density changes significantly.

3 <u>Crop modelling</u>: This is applicable to crops common in arid and semi-arid lands, such as sorghum, maize or millet, to determine their maximum harvest as a function of understorey microclimate. After harvest, crop roots are assumed to stay in the soil, whereas aboveground biomass of crop may be left on, or removed from the soil. Only one crop, which is planted either when topsoil water content is higher than a minimum amount or at the start of a rainy season. Depending on the selected overstorey canopy option (uniform or discontinuous), modelling may be performed in only one plot per field (assuming uniformity all over the field) or by dividing the field into square plots. Growth of crops and their roots is limited in their respective plot.

Growth to harvest is determined phenologically. Dry matter added every day is based on availability, or crop interception, of growth resources, with the least available resource dictating the daily growth rate. Transpiration is determined from biomass production, saturated vapour pressure and a factor relating biomass production, vapour pressure and transpiration rate (known as crop transpiration equivalent). For radiation limited growth, dry matter production is determined from radiation interception (determined by leaf area index and extinction coefficient), radiation use efficiency, solar radiation and temperature modifier. When water limits growth, biomass production is estimated from the highest water supply rate of roots; crop transpiration equivalent and saturated vapour pressure deficit. Nutrient limitation is assessed using factors showing limitations for nitrogen and phosphorous. These factors are compared and the lesser of the two is multiplied by radiation-limited growth to determine resource limited growth.

Maximum of stresses related to temperature, water and nutrients is considered to modify crop phenology and growth. Stress effects on specific crop leaf area index and recovery from stress of crops can also be modelled. The model determines crop interception of light by modifying Beer's law to accommodate reduction in leaf area index in response to stress. It also includes a set of assumptions and a logistic curve to modify leaf area index for predicting light intercepted by non-closed crop canopy.

Development of crops keeps track of differences between mean daily and minimum growth temperatures and a factor that is related to stress and phenology. Crop development passes through three stages: between emergence and panicle initiation; between panicle initiation and anthesis; and from anthesis to harvest. Priority in assimilate allocation is given to roots and this proportion increases as stress increases and declines to nil from anthesis onwards. Allocation to leaves decreases linearly from 90 % of the proportion allocated to shoot part early during the crop development to 10 % during anthesis and 0 % in the post-anthesis development. The model assumes a transitional time between the end of anthesis and the start of maturity, during which assimilate is allocated to hulm only. During maturity, hulm takes 10 % and grain takes 90 % of assimilated carbon.

HyPAR converts assimilate to leaves into leaf area. In addition to assimilate allocation, the model takes stress effects on leaf growth into consideration. It includes the prediction of senescence of leaves tracking thermal time and stress-caused shedding of leaves. Quantity of grain is a function of rate of growth during the early stages of development. If the rate of grain production exceeds supply, carbon and nitrogen are redistributed from other organs, such as stem, into any assimilate in excess of the amount required for grain production goes.

Assimilate addition in the form of root mass is converted to root length using the conversion 1 mm mg^{-1}. Specific values for maximum root length density per depth and root depth per crop as well as the proportion of daily root death are used to predict the expansion of roots.

4. Soil modelling: The soil profile may stretch to a depth of 15 m. The soil profile is divided into 15 layers, each of which may have a distinct soil features. The model allows crop roots to extend to the ninth layer. In the multiple layers, it predicts redistribution of water, infiltration, drainage, soil evaporation, rainfall interception and evaporation, unidimensionally. Prediction of water movement may be performed using one of four methods, namely: tipping bucket, Brooks-Corey, van Genuchten as well as a method that combines Campbell's approach with Darcy's equation solved using a finite difference technique. These methods may obtain parameters from one of four pedotransfer functions, namely: Campbell; Rawls; Mishara and Tomasella; or Hodnett. It also predicts plant uptake and competition for water. Leaf area indices are used to determine the interception of rain water by tree foliage. This fraction of rain water is evaporated using the Penman-Monteith equation and if the holding capacity of foliage is exceeded, throughfall takes place. Water is assumed to be 'pooled' on the surface briefly, after which it either runs off, infiltrates or evaporates.

5 Crop and tree water requirements for water are calculated, per soil layer, from the ratios of available and maximum water content and root length density and maximum extraction rate per layer. The requirement for each species is computed by summing the products of its 'demand' per layer and layer depth, while total water amount required (by trees and crops) per layer is compared with the existing amount of water. This allows competition to modify uptake per species per layer, if available water per layer is lower. In such a case, water is allocated to each species as a function of the fractional contribution of its root length from the total per layer as well as relative demands (as a proportion of the total). Species attempt to recover water shortage in a soil layer from the next (deeper) layer.

6 Extraction of nutrients by trees and crops is represented by nitrogen and phosphorous uptake. Nitrogen extraction per layer is determined from: the ratio of available to maximum water content; the ratio of actual to maximum root length density per layer; the nitrate content per layer and the status of nutrients in the crops. These per-layer nitrogen requirements are added to give demand for nitrogen per plant, under favorable conditions. The nitrogen content of aboveground and belowground plant parts is computed separately for use in determining their requirements, the sum of which is multiplied with the demand for nitrogen per plant (under favourable conditions), to obtain actual nitrogen requirement. If the sum of actual requirement for trees and crops exceeds the amount available, competition modifies the uptake by trees and crops. The model amends the total nitrogen requirement per layer by replacing individual species root density by total root length density and excluding the nitrogen status of plant of the equation of determining optimal nitrogen requirement. Nitrogen is, then, allocated between trees and crops using the corrected collective 'demand' and the ratios of their original requirement to the original total requirement. Plants try to make up for scarcity in one layer from underlying soil layers. Phosphorous uptake is determined in the same

manner. For each of these nutrients, a factor reflecting its (limiting) effects on growth is calculated by subtracting the ratio of its degree of scarcity in the shoot biomass to the difference in nitrogen content at optimal and wilting conditions, from unit.

7 Soil nutrient and organic mater modelling: Nitrogen may be added as a mineral fertilizer or organic manure. Nitrates in the soil may be carried away by drainage water or extracted by plants. Organic nitrogen breakdown is determined as a function of soil moisture, temperature and the ratio of carbon-to-nitrogen, as is nitrogen immobilisation. Inorganic nitrogen, humus, organic matter in the soil, as well as manures prior to cropping season, are assumed to be homogeneous within tillage depth and declining exponentially to half a metre below this layer, below which it is limited to only 1 %. The model divides soil organic matter into five organic matter reservoirs with distinct mineralisation rates and an additional reservoir containing humus. It predicts breakdown of organic matter in the soil into mineral components per pool and conversion of mineral nitrogen into inaccessible (organic) form.

References

MOBBS, DC, LAWSON GJ, FRIEND AD, CROUT NMJ, ARAH, JRM. and HODNETT, MG (1999) *HyPAR – Model for Agroforestry Systems*, Technical manual of Model Description for Version 3.0. DFID Forestry Research Programme.

3 A SUMMARY OF THE 'WATER, NUTRIENT AND LIGHT CAPTURE IN AGROFORESTRY SYSTEMS' (WANULCAS) MODEL

WaNuLCAS Model

The WaNuLCAS model was developed to achieve the following objectives:

- To synthesise information regarding plant interactions for resources in agroforestry units;
- To develop soil water and nutrient balances and plant growth models to further examine these plant interactions;
- To depict interactions between species as a function of plant physiology and structure
- Being applicable to both spatial and temporal agroforestry systems;
- Promoting use of universally available and applicable parameters;
- Achieving high flexibility of manipulating system management alternatives;
- Enabling extrapolation of plant, climatic and soil features;
- User-friendliness and open-endedness to reasonable upgrading, and
- Employing and providing outputs in contemporary software.

The model assumptions are acceptable and operational in the context of agroforestry, though the quantitative model validation aspect has not been fully developed. It plays the role of null-hypothesis of the principal plant-soil interactions that are common to various agroforestry systems, allowing users to add more (specific) interactions.

Model Features

The most defining characteristics of WaNuLCAS is the extraction of water, nitrogen and phosphorous by trees and crops, in agroforestry systems. This is performed as a function of tree root length density, crop root length density and soil supply of water and soil supply of nitrogen and phosphorus at particular soil water contents.

It characterises an agroforestry system as a system on 16 'soil cells', as defined by four profiles and four lateral segments. In each of these cells, WaNuLCAS performs simulations of water, nitrogen and phosphorous balance and extraction by component species. It applies to sequential as well as simultaneous agroforestry systems and takes tree management and characteristics into account.

Inputs of the WaNuLCAS model include the following:

- Soil input data: Including field capacity per layer, soil clay and silt percentages, organic matter content and bulk density. The model applies these inputs and the Van Genuchten 'pedo-transfer function' to obtain soil water release characteristics and matric flux potential, which in turn are used to determine potential plant uptake.

- Temperature data: May be entered as constant, daily or mean monthly values.

- Potential evapotranspiration: Inputs may be constant values or daily values calculated from weather data. This rate is used in the determination of evaporation and transpiration from soil, understorey plants as well as living and non-living overstorey plants.

- Rainfall: As an input, rainfall is entered as one of the following options: daily measured, mean monthly or model generated.

- Rainfall trapped by foliage of plant components: is determined as a product of amount (mm) water in the foliage and leaf area index and simulated to be lost at a maximum water loss rate.

- Soil movement to and from an inclined unit area, wherein tree lines are planted along the contour, is determined, daily, as a function of the quantity of addition to, removal from and translocation in the unit. From these values and original slope, periodic variation in land gradient can be determined.

It has the following major components:

Climate: includes rainfall data (input or generated), mean temperature and radiation.
Soil: includes four layers, depth, physical and chemical characteristics as well as water and nitrogen contents of which have to be specified prior to simulation.

Water balance: Encompasses daily rainfall and/or irrigation; infiltration and drainage; horizontal solute transport and vertical bypass flow; soil evaporation; day-time plant water extraction and night-time soil-root 'hydrostatic equilibration'; and lateral water redistribution through runoff and run on. Infiltrated water descends through the soil profile in such a way that water fills the current horizon to field capacity before flowing into the horizon underlying it (the current layer). Soil evaporation is predicted as a function of the water holding capacity of the top-most soil layer and leaf area index of the plant to -1500 KPa. For all the 'soil-cells' altogether residual water is balanced as the difference between the additions and losses. Water is added in the form of precipitation, irrigation, lateral flows into cells and run-on; whereas the losses from the 'cells' is in the form of runoff, drainage, horizontal outflow and evapotranspiration from plants and soil.

Water redistribution between soil 'cells' at different moisture contents can also be simulated using the WaNuLCAS model. It simulates water movement on lands with gradients presuming that water flows out of a soil unit after the unit's field capacity is reached, depending mainly on saturated hydraulic and slope. Likewise, runoff is predicted if rate of water flux into the surface of a soil exceeds that of infiltration or the saturated hydraulic conductivity of the profile. Saturated hydraulic conductivity may change from its initial value resulting from soil macropores changes due to effects of soil worms, plant roots, etc.

Plant water extraction is quantified using root length density, amount of water contained in the soil and amount of water requirement (by plants). The calculations involve determining likely-extractible amount for each layer and adjusted actual requirement, using water potential of the plant and potential evapotranspiration. Once actual extraction is determined as the lower of the adjusted actual requirement and the amount the soil can provide, it is partitioned to the layers that contributed in proportion to their potentially extractible water. The actual extraction is then used to update the soil water balance and determine 'stress' due to water. The latter is compared with stresses due to nitrogen and phosphorous, to determine the most limiting growth resource. Competition for water in a common 'soil unit' is determined as a function of the proportions of root length densities and demands of the occupying species.

Nutrient (nitrogen and phosphorous) balance: includes fertiliser application rate, fixed atmospheric nitrogen, decomposition of organic matter and mulches, phosphorous characteristic relocation, plant extraction, plant parts applied as residues and nitrogen and phosphorous leaching, all determined for each soil layer. At a system level, nutrient balance is determined by accounting method between soil and plant nutrient status at the beginning, additions via fertilisers, nitrogen fixation and water entering the system as well as eventual nutrient status in the soil and plants and removals via harvesting and water escaping the system. The simulation of nutrient extraction by plants using the WaNuLCAS model entails determining the ideal content of nitrogen and phosphorous in the plants. The difference between this value and available amount is nutrient shortage. A portion of nitrogen shortage is offset by 'nitrogen fixation', whereas the rest of nitrogen shortage and all of the phosphorous shortage is extracted from the soil, as nutrient requirement. Actual nutrient extraction by a species is determined from nutrient requirement or 'potential uptake' per zone and total maximum extractible amount. The model assumes plant extraction and leaching of nitrogen to be in nitrate and ammonium forms. For phosphorous, extraction by plants takes into consideration the possibility of plants modifying accessibility of fixed phosphorous as well as root effects, through modification of the chemistry of the soil, on adsorption of phosphorous. The WaNuLCAS model supposes that both crop and trees can incorporate nitrogen (from the environment) into the soil, in which nitrogen fixation is either a preset proportion of shortage in plants or a function of plant nitrogen content and growth resource reserves.

Plant extraction nitrogen and phosphorous is determined as a function of root length densities and demands of the component species and supply of the soil for the nutrient (nitrogen or/and phosphorous). Plant demand for nitrogen is empirically determined as a function of stress-free nitrogen extraction and biomass production and extractions to make-up for previous nutrient stresses. Competition between component species for the above growth resources is determined as a function of the proportions of their root length densities and demands in the overlap “soil-cell”. This principle can be applied to a total of four component species, of which only one is an understorey crop.

Growth includes daily tree and crop growth. Calculation of growth is determined by reducing the maximum allowable growth under a given climatic condition by the most limiting of three factors, namely: light stress, water stress as well as nutrient (nitrogen and phosphorous) stress. The crop root growth per layer is determined using an exponential equation till flowering, during which it grows to a potential size not exceeding a value of maximum root specified as an input, after which the roots deteriorate. Also, assimilate allocation following aboveground and belowground functional equilibrium as well as preferential root growth following resource availability, are included. Tree root growth may be taken as homogeneous in all soil cells or be simulated using elliptical relationships between root growth and distance from the base of the tree, both vertically and horizontally. An option of modifying the elliptical equation using functional equilibrium and preferential root growth is also availability.

Light capture per zone: By component species is determined as a function of their leaf area index and relative heights.

Soil organic matter, according to the WaNuLCAS model is balanced and allocated into five different pools. Some of these pools are for immediate access while two of the pools are accessed and released at low rates. In other words, from residual and input carbon contents, nett system photosynthetic and growth demands are met and gaseous loss of carbon is deducted after which the updated residual soil carbon content in the soil is determined.

Management: Tree canopy and spacing management and application of soil nutrients can be assessed for hedgerow agroforestry systems.

Model Organisation

The WaNuLCAS model is profiled as: input, parameter modification and output display section; flow diagram and equations section; and a section of equations and comment.

Zoning in the model is such that trees occupy the first of the zones and influence the rest of the zones (occupied by crops) by their roots and foliage. Alley cropping, on either slopes or ‘level’ lands, is simulated. The difference between the two is in the difference in water balance though runoff and run-on and depth of the top-most soil layer. Its calculations are performed as mass balance per area per zone or/and by obtaining weighted mean for the whole system. The model needs users to specify the depth of ‘soil-cells’. Simulation of components such as litter fall, pruning of trees, fertilisers and plant residues is dependent on user-specified ‘input weight’ values. The assumption is that these values remain uniform for each zone, giving the zones values according to their respective contributions in the total area.

A succession of crops and respective fertiliser applications (per zone) can be entered, so as to simulate growth of a crop following the harvest of the current crop. The maximum level of growth of crops on a daily basis and light use efficiency of each growth stage of each of the crops needs to be entered. Weed growth simulation is also simulated, without the effect that the weeds have on the crops that they grow with.

For trees, planting and aboveground (foliage) management may be specified, before the start of simulation, so that the model grows trees empirically and prunes these trees according to the pre-set calendar, checking the co-existence of trees and crops and the extent, or if maximum allowable biomass limit is reached (provided as input). Pruning is skipped when crops are past their development stage or if there are no crops. The fraction of foliage biomass to be pruned or harvested may also be indicated by the user. The ‘pruning’ may either be left on the soil or used for animal feed.

References

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