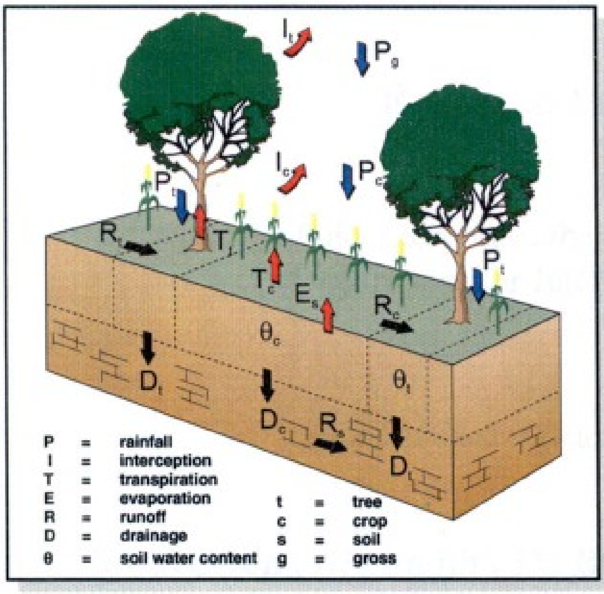
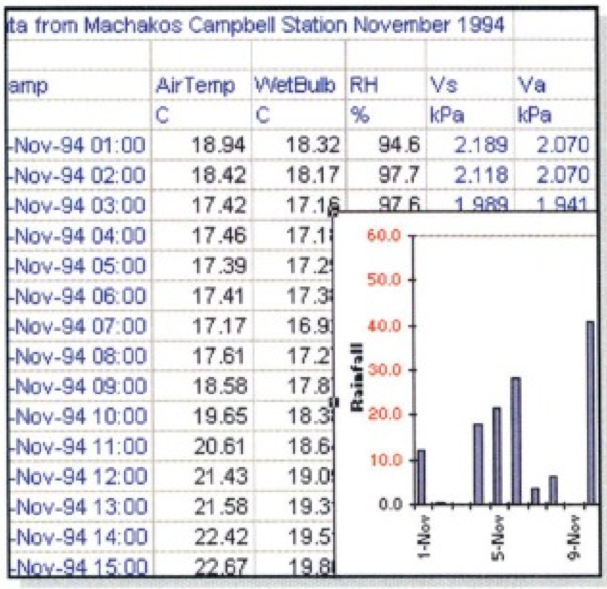
Water balance of agroforestry systems on hillslopes

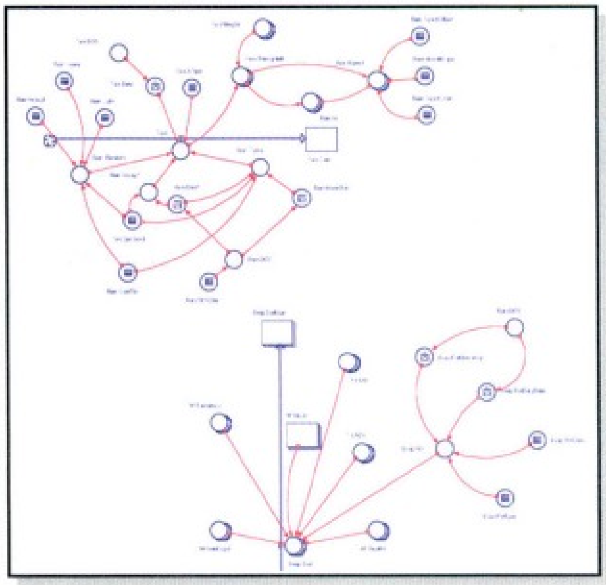
Department for International Development – Forestry Research Programme
Research Project R6364 – Final Technical Report





ta from Machakos Campbell Station November 1994

amp	AirTemp	WetBulb	RH	Vs	Va
	C	C	%	kPa	kPa
-Nov-94 01:00	18.94	18.32	94.6	2.189	2.070
-Nov-94 02:00	18.42	18.17	97.7	2.118	2.070
-Nov-94 03:00	17.42	17.16	97.6	1.989	1.941
-Nov-94 04:00	17.46	17.1			
-Nov-94 05:00	17.39	17.2			
-Nov-94 06:00	17.41	17.3			
-Nov-94 07:00	17.17	16.9			
-Nov-94 08:00	17.61	17.2			
-Nov-94 09:00	18.58	17.8			
-Nov-94 10:00	19.65	18.3			
-Nov-94 11:00	20.61	18.6			
-Nov-94 12:00	21.43	19.0			
-Nov-94 13:00	21.58	19.3			
-Nov-94 14:00	22.42	19.5			
-Nov-94 15:00	22.67	19.8			



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Water Balance of Agroforestry Systems on Hillslopes - Phase II

Research Project R6364

Final Technical Report to the Forestry Research Programme,
Department for International Development

Reporting Period: 1 October 1996 to 31 March 1998

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Executive Summary

Agroforestry systems have the potential to increase yields by effectively growing two crops at the same time on a single piece of land, and have been promoted as more sustainable agricultural production systems appropriate for developing countries. However, in many tropical areas the main factors determining the success or failure of agroforestry systems is usually either water availability, or other physical constraints such as poor drainage, shallow soil depth, steep slopes and gravelly soils. The addition of trees to a conventional cropping system may increase the water-use of the system, either directly or indirectly, but may lead to competition between trees and crops for available soil water resources.

Quantitative investigations of water-use in agroforestry systems are rare, and therefore the hydrological reasons for the success or failure of incorporating trees and crops in agroforestry systems are largely unknown. To address the DFID Forestry Research Programme goal of increasing the contribution of trees to the productivity of tree/crop based systems, agroforestry researchers are currently investigating the processes by which agroforestry systems can be sustained, adopting modelling approaches linked to field experiments to provide data to validate the models.

To address this need for data, the water balance of an agroforestry system comprising *Grevillea robusta* and maize was studied. The project was located at Machakos, Kenya, in a semi-arid region of the East African highlands. The site was sloping (22%), with shallow soils (< 2 m) and without a water table. Trees were planted in October 1991, and measurements were made from June 1993 until June 1997.

Individual components of the water balance (rainfall, runoff, evaporation *etc.*) were quantified in plots containing either trees or crops, as well in the agroforestry plots containing both. Plots containing trees showed a consistently greater water use than the comparable crop-only plots. As the trees grew larger, virtually no soil water recharge was observed below about 0.9 m depth, except in seasons where rainfall greatly exceeded the seasonal average. Therefore it is suggested that the bulk of the competition between tree and crop roots for available water resources took place in the surface soil layers.

Some of the water balance components (rainfall interception, evaporation) were strongly dependent on the tree canopy cover, responding dramatically to the pruning management regime. To allow for some degree of soil water recharge to depth, and to permit adequate crop establishment, it is suggested that at this tree planting density (0.083 tree m^{-2}), severe tree canopy pruning is required to ensure crop growth. The timing and severity of pruning can be determined by balancing tree and crop water demands with likely changes in soil evaporation (increases) and canopy rainfall interception (decreases) which follow pruning.

Data from the field experiment were used to parameterise ICRAF’s generic agroforestry model, WaNuLCAS, and the model was run over a number of seasons to investigate the water balance of the system. In its original form, the model greatly overestimated water input to the soil by ignoring rainfall interception by the tree (and crop) canopies. Runoff was also overestimated due to the model predicting runoff as a result of each and every rainfall event. Modifications were made to the model to remedy these problems, and the modified model was found to correctly simulate rainfall input to the surface soil layers. However, the submodels that simulated tree and crop water uptake from the soil could not be validated without direct estimates of tree water use efficiency. Once these submodels have been validated, it should be possible to use the model to enable agroforesters to solve management difficulties such as the question of pruning tree canopies.

1 Background

1.1 Importance of the researchable constraint

1.1.2 Relevance to strategic and developmental planning

The researchable constraint to which this project has relevance is how agroforestry can increase the efficiency with which limited natural resources are utilised, thereby producing more and/or more varied food and timber products. Agroforestry is one of the most promising forms of production system from which sustainable land use strategies might be developed to meet the demands for food and fuel of the increasing populations of the developing world.

It has been suggested that the establishment of agroforestry systems on hillslopes would reduce soil erosion and associated 'downstream' problems, *e.g.* siltation of river channels and dams. Alternatively, large-scale adoption of agroforestry in these areas might reduce soil water recharge and/or river flow. Therefore, the success or failure of the many possible tree/crop options depends to a large extent on the degree to which the components of the mixture are complementary in their use of natural resources, particularly water. There is therefore a need to develop a better understanding of the general principles underlying the partitioning of these resources in agroforestry systems in order to evolve solutions which have large scale application.

This strategy of generating improved basic knowledge about a system through a more rigorous approach to the key processes involved is in line with the revised DFID Renewable Natural Resources Research Strategy 1995-2005. The Forestry and Agroforestry Programme of the RNRRS has a remit to increase the contribution of trees to the productivity of tree/crop based systems and approaches this via the study of tree-crop interactions both above and below ground. In the long term the objective is to improve the output and increase the options available to resource poor farmers, in particular those who are cultivating marginal land on slopes. The current project will contribute to this area via the increased understanding it will generate about the water use of agroforestry systems on hillslopes.

1.2 Summary of significant previous research

Much of the previous research of use to agroforestry studies is from agricultural intercropping research where the understanding of controlling processes and interactions between the various components, is more advanced. From these studies it appears that successful intercropping systems are those which make 'better' use of resources. This can be by using more of a resource, by using it more efficiently, or both. The true definition of successful intercropping is a system where the two (or more) plant components access and exploit available resources in a 'complementary' rather than 'competitive' fashion.

It is possible that in a system where rainfall is not completely used, the incorporation of trees or shrubs may improve the rainfall use efficiency either directly, by using more of the rainfall as transpiration, or indirectly, by producing more dry matter per unit of water transpired. Increased rainfall use could be achieved by temporal 'complementarity' *i.e.* where trees might use rainfall falling outside the cropping seasons, or spatial 'complementarity' *i.e.* where tree roots might retrieve water that had drained beyond the reach of the crop roots. The presence of trees might also affect the rainfall use efficiency of the system by modifying the microclimate below the tree canopy. These two possibilities are discussed briefly below.

1.2.1 Direct effects: Increased water use by tree and crop combinations

Traditional farming systems in the semi-arid tropics generally utilise no more than half of the rainfall input as substantial losses of water can occur through runoff, soil evaporation and drainage. Many of these systems are characterised by relatively short cropping seasons, between which the ground is left bare. Often significant amounts of rainfall occur between cropping seasons and this rainfall is generally lost from the system. In the semi-arid regions of the Middle East and West Africa direct soil evaporation can account for 30-60% of rainfall (Cooper *et al.*, 1983, Wallace, 1991). On the Deccan plateau of India the best cropping systems only use 40% of the annual rainfall, while the rest is lost as runoff (26%) and deep percolation (33%) (Ong *et al.*, 1991).

Whilst the almost 'instantaneous' losses of water from the soil surface (*i.e.* runoff, evaporation) are relatively easily measured, drainage losses are more difficult to assess and often remain unquantified. As the extent of the tree and crop rooting systems is similarly difficult to measure, researchers often have little or no idea as to how much of the soil water is exploitable and thus where storage stops and drainage 'losses' from the system begin. Drainage may be one of the hydrological terms which can be most easily modified by the presence of trees, since they can utilise water outside the rooting zone of annual crops and also outside the crop growing season (*e.g.* Huda and Ong, 1989). Improved rainfall utilisation can also occur via the substantial reductions in runoff which can be achieved in agroforestry systems, particularly on sloping land (Young, 1989).

1.2.2 Indirect effects: Improved crop microclimate

Depending on the density of tree planting, the presence of trees in an agroforestry system may significantly modify the microclimate below the tree canopy. This can happen in several ways, some of which will increase the overall water use efficiency of the understorey crop, whilst others will decrease it.

If the tree canopy prevents a significant amount of direct solar radiation from reaching the soil surface, this may markedly reduce soil evaporation. This may be particularly true in the early part of the crop season under a rainfall regime of frequent and comparatively small storms. In addition, reduced wind speeds below the tree canopy should mean that a layer of warmer, more humid air will overlay the soil surface, reducing soil evaporation.

Significant ground cover by the tree canopy will lead to increased interception losses (*i.e.* rainfall that is trapped on foliage before it reaches the ground and subsequently evaporates). Increased interception will reduce rainfall use efficiency, often significantly. Even if intercepted water does eventually reach the ground (*e.g.* through stemflow), the overall distribution of rainfall may be significantly altered by the presence of trees, thus affecting individual crop plants. Finally, crop growth rates might react to the presence of trees if increased shading reduced leaf surface temperatures in super-optimal thermal conditions. In these situations, the introduction of shade may bring the system back closer to optimal temperatures and crop growth rates would recover.

1.3 How was the demand for the project identified?

Clearly, there are a number of ways in which agroforestry systems could use water more efficiently than agricultural sole crops, but a clear picture of how this actually happens in any system can only be obtained through a comprehensive water balance study. This was therefore the primary reason for setting up the current project.

The need for research in this area was identified and established as a priority in ICRAF's strategic program at a planning workshop held in Nairobi in January 1992, attended by independent consultants with a wide range of expertise. The University of Nottingham and the Institute of Hydrology were identified as international collaborators in ICRAF's resource utilisation program. The three institutes subsequently developed a coordinated program to improve our understanding of tree/crop interactions in established agroforestry systems over a five year period. In the longer term, the research was intended to improve productivity and sustainability and increase the opportunities for resource-poor farmers, particularly those working marginal land on hillslopes. The comprehensive experimental database obtained describing resource capture, tree and crop growth and hydrology over an extended period was also to be made available to members of the DFID Agroforestry Modelling Group to support the development of effective process-based agroforestry models, the testing of underlying assumptions and validation of model output. An important benefit of the close link with ICRAF is that the project results will be incorporated into their strategic programme to develop sustainable agroforestry systems and disseminated through the Agroforestry Research Network for Africa (AFRENA) and CGIAR.

2 Project purpose

2.1 The purpose of the project

To date, most agroforestry research in the semi-arid tropics falls into two categories. Firstly, studies of scattered trees in traditional parkland systems, which are mainly microclimatic and soil nutrient in emphasis (Kessler, 1992; Jonsson, 1995); and secondly, non-traditional systems such as alley cropping, involving closely planted trees or hedgerows (Ong et al., 1992). It has been suggested that by combining trees and crops in agroforestry systems, increases in productivity can be achieved, assuming that the trees can exploit resources currently under-utilised by crops (Cannell *et al.*, 1996). Previous observations in alley-cropping trials demonstrated the potential of intercropping for temporal complementarity in areas where significant rainfall occurs outside the normal cropping season.

As outlined in the background to the project, there are clearly several mechanisms by which agroforestry systems may utilise available water more efficiently than either woodlots or crop fields alone. However, with only short-term alley-cropping data to rely on, it is uncertain as to how these benefits are manifested over the lifetime of the trees, where below-ground competition for water and nutrients between trees and crops will inevitably occur, and/or with a significant variation in both seasonal and inter-seasonal rainfall.

Therefore the rationale for the project reported here was to collect data from field experiments which would be used to validate new and existing agroforestry models, and allowing the potential competition or complementarity of agroforestry systems to be compared. The study was conducted over a 5½ year period to quantify the impact of trees on the water use of the system. This report describes the experimental design, methods and results of investigating the various components of the soil water balance, and the modelling of resource utilisation using existing agroforestry models.

2.2 How the development constraint was addressed by the project

The project (R6364; ZF0030) formed part of the Renewable Natural Resources Research Strategy (RNRRS) of the United Kingdom Department for International Development (DFID) and, additionally, a major part of ICRAF's programme on **C**omplementarity **I**n **R**esource **U**se on **S**loping Land (CIRUS). Project R6364 continued the development and validation of field measurement and modelling techniques used to determine the water balance of trees and crops grown in combination on sloping land, initiated under RNRRS Project R4853. It was intended that these techniques would have broad applications in most tropical agroforestry systems, and that the development of water balance models would assist other scientists modelling such systems.

2.2.1 Collaboration with other Institutes

This project covered by this report formed part of a larger collaborative programme between the Institute of Hydrology (IH), the International Centre for Research in Agroforestry (ICRAF) in Kenya and the University of Nottingham (UNott). The three institutes were responsible for different areas of the investigation into long-term productivity and water use of a *Grevillea robusta*/maize agroforestry system:

- IH: Measurement of water balance components and development of tree and crop water use modelling.
- ICRAF: Establishment and management of the trial, routine growth analysis and measurement of tree transpiration.
- UNott: Measurement of light interception, tree and crop leaf area, crop transpiration and photosynthesis.

There was some overlap in these areas, and some activities were shared between institutes. For example IH and ICRAF were jointly involved in the measurement of soil moisture and runoff, and all three institutes have been involved in the various aspects of the analysis and modelling work. This report concentrates on the work done by IH and the complementary work done by ICRAF and UNott will form the basis of separate reports unless directly relating to the water balance.

2.2.2 Key project objectives

The project had the following key objectives:

- The **goal** level objective was to increase the contribution of trees to the productivity of tree/crop based systems.
- The **purpose** level objective was to improve knowledge of crop/tree interactions in the above- and below-ground environment and incorporate this knowledge into management strategies.

The scientific and technical objectives at **output** level were:

- Development and application of techniques to measure the water use of trees and crops when grown in combination as agroforestry systems.
- Evaluate the mechanisms by which agroforestry systems on sloping land can make better use of rainfall and hence increase yield.
- To develop a water balance model for agroforestry systems on sloping land which can form an integral part of a growth and yield model.

2.2.3 Amendments to key objectives

During the course of the project, contact was established with ICRAF partner scientists who were developing a generic agroforestry model (WaNuLCAS). There are currently many different agroforestry models available or under development. Given this, and because this project’s objectives specify that the water balance model must (i) form an integral part of a growth and yield model, and (ii) be both adopted and supported by ICRAF staff, the decision was taken to validate and, if necessary, improve ICRAF’s generic agroforestry model rather than continue developing an independent model of our own.

3 Research activities I : materials and methods

3.1 Site description

3.1.1 Site location

The fieldwork was carried out at one of ICRAF's experimental stations, located at Machakos, approximately 80 km southeast of Nairobi, Kenya (Figure 3.1). The station lies at 1°33' S, 37°8' E, and at an altitude of 1560 m (Kibe *et al*., 1981), and the area is geographically typical of the surrounding Kenyan uplands (Scott *et al*., 1971). The area of the station given over to the experiment is a southwest facing hillslope (Figure 3.2$_{a,b}$), above the Maruba River, with a slope of about 22%. Before the experiment was established in October 1991, the area was covered by scrub dominated by various *Acacia* species.

3.1.2 Soil type and physical properties

The soil at the site was extremely heterogeneous, both in terms of depth and textural composition. In general, it varies between 0.2 and 2 m and is composed of a series of shallow reddish-brown to brown sandy clay loams (well-drained alfisols) varying in clay content over the profile. A number of distinct horizons were identified. Below this, the soil is underlain by layers of first, weathered gneiss rock (saprolite) and then coherent gneiss rock. Figure 3.2$_c$ shows the results of a soil depth survey undertaken in 1993, which measured the depth to rock at each point on a 4 m I 4 m grid covering the site. A band of very shallow soils (0.2 to 0.6 m deep) ran across the site from the top northwest corner towards the bottom southeast corner. Soils were generally deeper (0.7 to 1.5 m) above and below this band. A water table was not observed at the site and excavations revealed that the bedrock was free of cracks deeper than 15 mm and that tree roots did not penetrate more than 2 to 3 mm into the weathered surface of the rock.

Four different soil horizons between the surface and the underlying rock were identified using data obtained from a series of soil pits dug

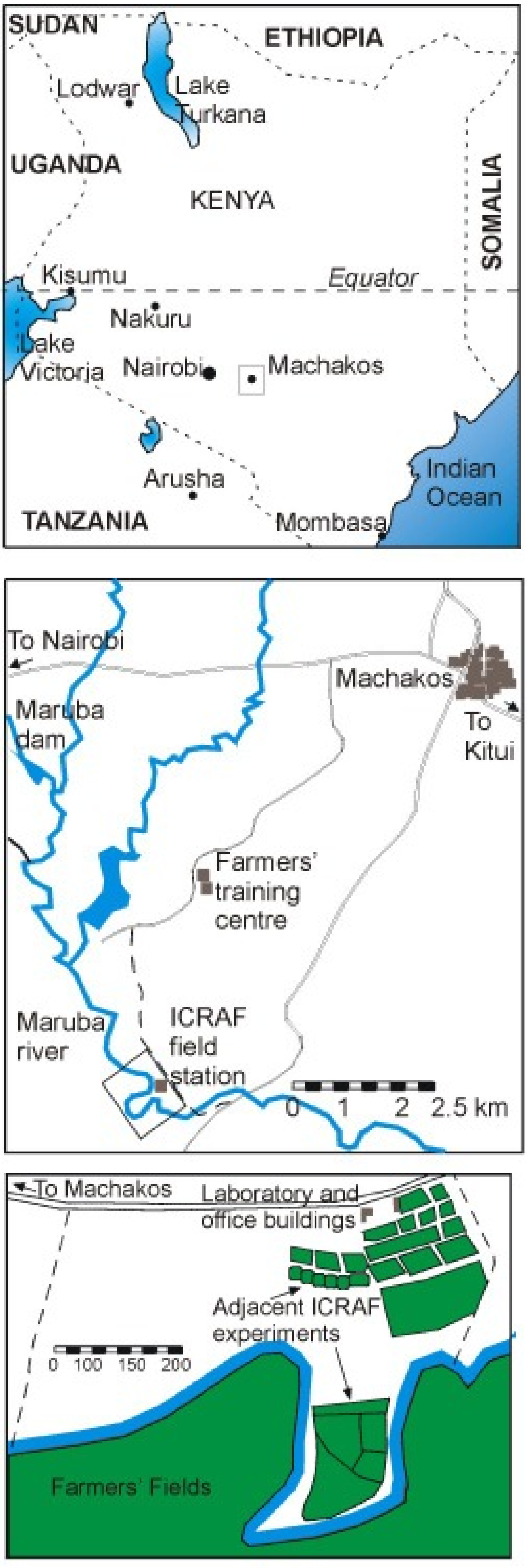
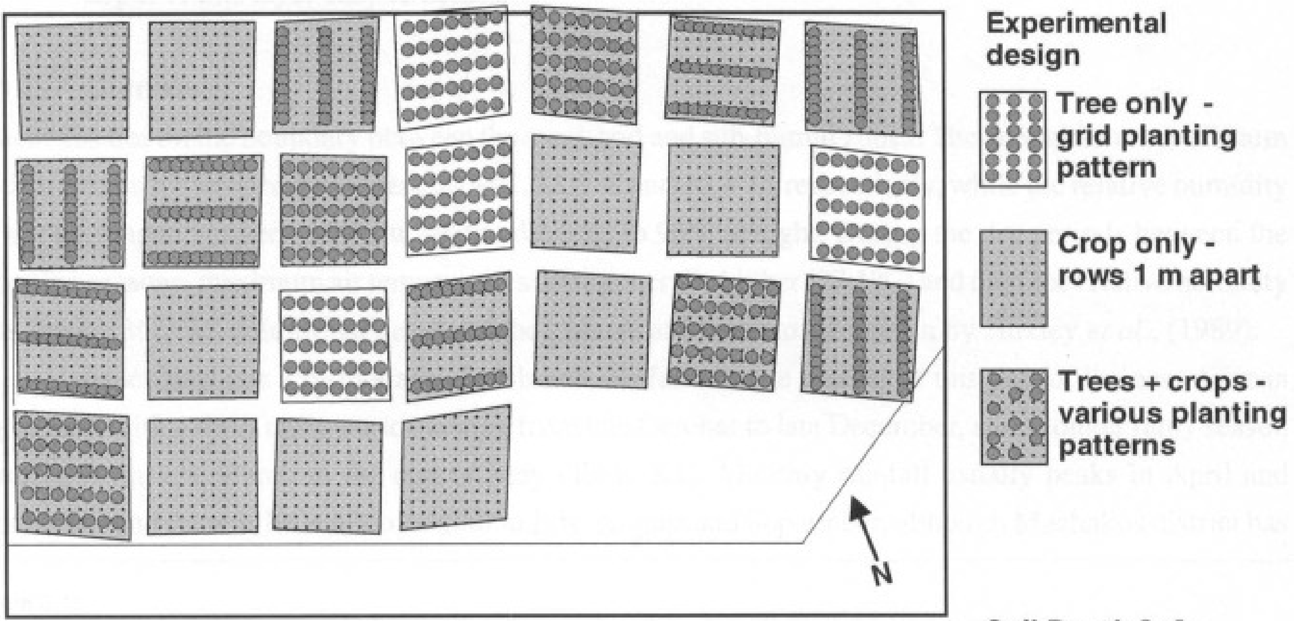
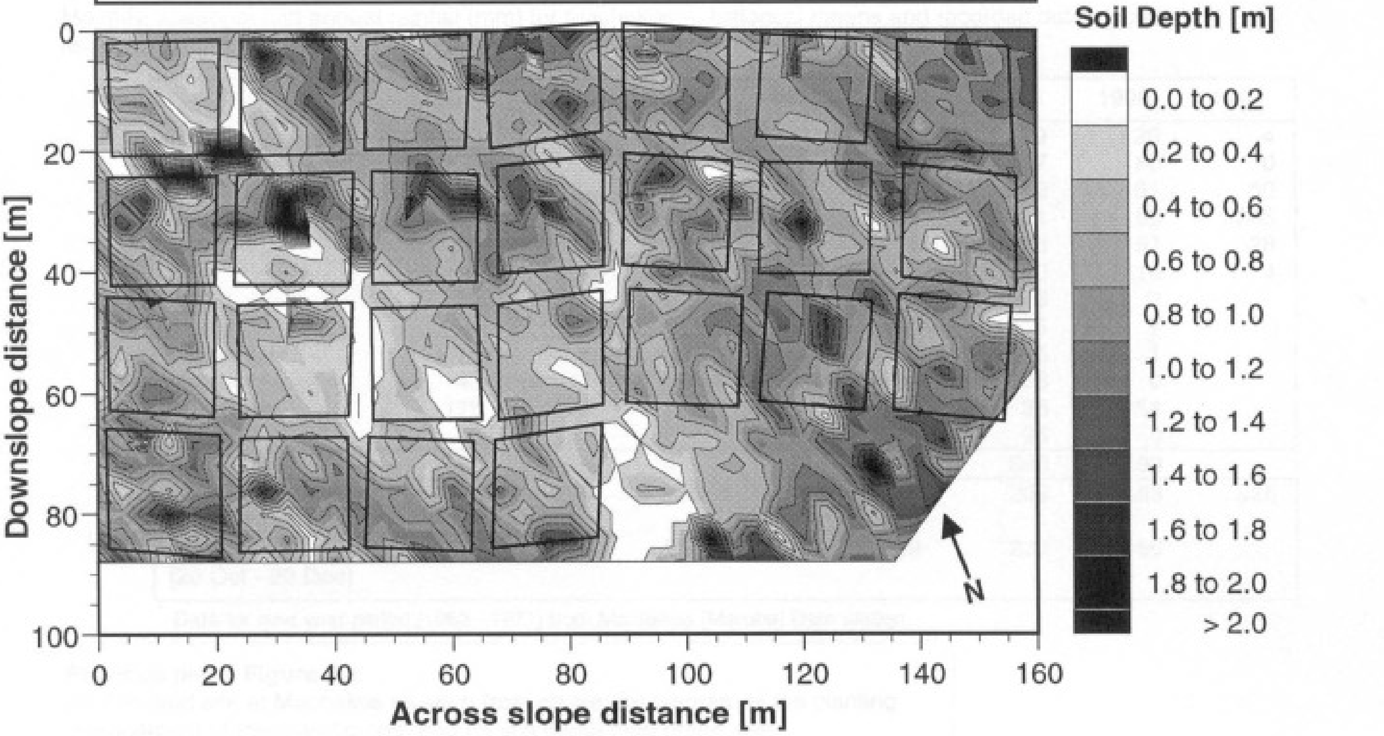


Figure 3.1:
The location of the ICRAF field station at Machakos, Kenya, and of the CIRUS trial within the field station.

Field site at Machakos seen from above



Experimental design



Soil Depth [m]

across the site for the installation of runoff collection tanks, and data from soil samples extracted during the installation of neutron probe access tubes :

- The surface soil or till layer; a layer of soil approximately 0.2 m deep regularly disturbed each season during the preparation of the ground prior to crop sowing, and occasional weeding.
- The subsoil; immediately below the till layer, this soil was undisturbed by any site management practices such as seedbed preparation. As it was observed to be more sticky when wet this suggested a higher clay content than the till layer above.
- Mixed soil/gravel layer; consisting of fragments of stone and occasional gravel pans found at depths between 0.8 and 1.2 m. This ‘stone layer’ was previously identified by the Ministry of Agriculture soil survey (Kibe *et al*., 1981).
- Eroded gneiss bedrock; the underlying bedrock was weathered to a layer between 150 and 300 mm thick over the entire site, producing a friable yellow sandy quartz material. The colour change between the yellow weathered material and the grey, uneroded gneiss underneath made the depth of this layer easy to define.

3.1.3 Climate

Machakos lies on the boundary between the semi-arid and sub-humid zones. The annual mean, maximum and minimum air temperatures were 20.1°C, 25.2°C and 15.8°C, respectively, while the relative humidity of the air ranged between 56% during the daytime to 96% at night. During the dry periods between the cropping seasons, maximum air temperatures were generally higher (27.1°C) and daytime relative humidity was lower (36.7%). Additional details of the climate at Machakos are given by Huxley *et al*., (1989).

Machakos has a bi-modally distributed rainfall climate typical of this part of the east African highlands, with a short rainy season lasting from late October to late December, and a longer rainy season running from late March to the end of May (Table 3.1). Monthly rainfall usually peaks in April and November and there is little or no rainfall in July, August and September, although Machakos district has

Table 3.1:
Monthly, seasonal and annual rainfall (mm) for Machakos – historical means and recorded data since the establishment of the trial.

	Mean*	1991	1992	1993	1994	1995	1996	1997
January	50	23	28	283	1	39	20	4
February	50	13	4	110	90	77	80	0
March	105	48	5	41	87	152	91	60
April	183	77	164	35	92	111	69	245
May	56	89	68	14	15	33	57	28
June	11	4	17	21	0	0	16	4
July	4	11	7	1	5	6	2	
August	4	11	1	3	5	5	7	
September	5	5	1	1	3	6	1	
October	43	47	40	10	61	106	0	
November	175	175	126	162	310	36	154	
December	96	150	214	118	141	95	0	
Annual total	782	651	672	797	811	666	499	
Long rains [20 Mar - 31 May]	~ 265	203	235	60	194	209	183	325
Short rains [20 Oct - 20 Dec]	~ 345	340	359	273	429	236	156	

* Data for nine year period [1963 - 1971] from Machakos [Maruba] Dam station.

Previous page. Figure 3.2:
(a) The field site at Machakos as seen from above; (b) diagram of the planting arrangement of trees and crops; and (c) soil depth map of the site

a very large inter-annual variation in monthly and seasonal rainfall. Huxley *et al*. (1989) reported that potential annual evaporation in the Machakos area was about 1450 mm, ranging between 95 and 165 mm per month.

3.1.4 Experimental design

Figure 3.2_b shows the layout of the 25 plots that comprised ICRAF's larger experiment (CIRUS), established in October 1991. Plots of size 20 m I 20 m were planted with *Grevillea robusta* (A. Cunn. ex R. Br.), a popular upperstorey tree species in East Africa (ICRAF, 1995), and/or maize (*Zea mays* var. Katumani composite) in five planting arrangements. For reasons of simplicity and experimental control, the water balance experiment concentrated on only three of these treatments:

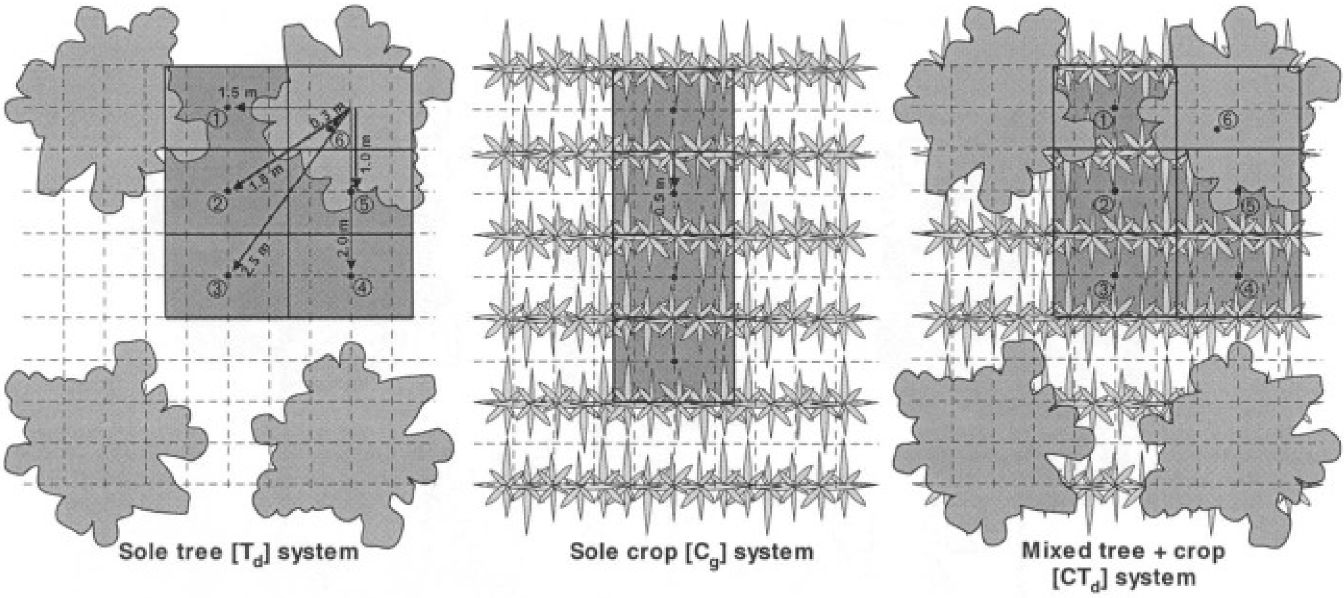
- Tree-only [T_d] treatment : *Grevillea robusta* trees planted in a 3 m I 4 m grid pattern without any understorey crop, simulating a traditional woodlot system.
- Crop-only [C_g] treatment : Maize planted following local farming practice, rows 1 m apart, approximately 0.3 m between plants in a row.
- Tree + crop [CT_d] treatment : *Grevillea robusta* trees planted in a 3 m I 4 m arrangement as in the T_d plots, but with an understorey of maize planted in the same arrangement as the C_g plots.

These three treatments (Plates 3.1 and 3.2) were chosen so that the water balance of trees and crops grown together could be compared with each grown separately. In addition, it was felt that the higher planting density of the 3 m I 4 m planting arrangement would lead to greater competition between the trees and crops, providing much-needed data on above- and below-ground competition and/or complementarity. Figure 3.3 shows a schematic representation of the three treatments used in the experiment. The total area enclosed by the four trees [from the base of each tree to the next] is 12 m^2 — *i.e.* a tree density of 0.083 trees m^{-2}. To facilitate comparison of measurements between treatments, the area between the trees was divided into smaller blocks of 1.5 m^2 (numbered 1 to 6 in Fig. 3.3) that ran between the maize rows [where present], with the measurements made at the centres of these blocks assumed to represent the entire block.

A strip of Vetiver grass (*Vetiveria zizanoides* (L.) Nash) was planted halfway down each of the plots (along the contours) to protect against possible soil erosion, especially in the establishment phase of the trial. This grass was regularly cut to ensure that its water use did not constitute a significant part of the water balance of the trials. The plots were weeded by hand

Plates 3.1 and 3.2:
Above: a view of the sole tree treatment (background) and sole crop treatment (foreground).
Below: one of the agroforestry [tree+crop] plots soon after the trees were pruned. The maize grows well after the trees are pruned.

before sowing the crop and occasionally throughout the growing season. The trees were pruned by removing the lower 1 m of branches three to four times a year. During the latter part of the project, some of the trees were attacked by termites which caused extensive damage, and which lead to tree death where the bark was completely removed. Where evidence of termite attack was observed, the trees and surrounding soil were treated with a locally available insecticide, and the lower 0.5 m of each trunk was treated with an insecticidal wood preservative.



Sole tree [T_d] system

Sole crop [C_g] system

Mixed tree + crop [CT_d] system

Figure 3.3:
Stylistic representation of the three treatments studied in this experiment - the tree-only plots, crop-only plots and the agroforestry treatment with tree and crop components combined. The small black circles (labelled -6 in plots containing trees) represent positions at which measurements *e.g.* neutron probe, TDR, rainfall interception *etc.*, were made.

3.2 Water balance components

Figure 3.4 is a schematic representation of the water balance of an agroforestry system on a hillslope. As water progresses through the agroforestry system, its distribution is affected by several processes:

- The incoming rainfall or gross precipitation [$\mathbf{P_g}$] is intercepted by the tree and/or crop canopies, giving rise to losses [$\mathbf{I_t}$ and $\mathbf{I_c}$], where the intercepted water evaporates from the canopy without ever reaching the ground.
- The presence of tree and/or crop canopies modifies the spatial distribution of the remaining water so that the input to the ground (*throughfall*) beneath the trees [$\mathbf{P_t}$] is different from that beneath the crop [$\mathbf{P_c}$]. The effect of the tree canopy on spatial redistribution of rainfall may be even more intense if the angle between the branches and the trunk is less than 90°, allowing some of the water intercepted by the canopy to drain down the trunk (*stemflow*) to the ground around the tree [$\mathbf{S_t}$].
- Water reaching the ground will either infiltrate, run off, or evaporate. Water may infiltrate at different rates below the trees [$\mathbf{F_t}$] and crop [$\mathbf{F_c}$], due to the effect of tree roots on soil structure and composition, therefore producing different rates of surface runoff, [$\mathbf{R_t}$ and $\mathbf{R_c}$]. In some circumstances $\mathbf{F_t}$ may be sufficiently high not only to reduce $\mathbf{R_t}$ to zero, but also to absorb any runoff from the cropped area, $\mathbf{R_c}$.
- Water will evaporate directly from the soil surface at rates $\mathbf{E_t}$ and $\mathbf{E_c}$, from beneath the trees and crop respectively. During the first stage of soil drying, these rates largely depend on the net radiation reaching the soil surface, and therefore shading by tree and/or crop canopies may reduce evaporation rates.

- The water contents of the soil zones beneath the trees, $\boldsymbol{\theta_t}$, and the crop $\boldsymbol{\theta_c}$,, may lead to different rates of drainage to below the rooting zone, $\mathbf{D_t}$ and $\mathbf{D_c}$, due to the different surface fluxes and transpiration rates, $\mathbf{T_t}$ and $\mathbf{T_c}$. There may also be some lateral subsurface water movement, $\mathbf{R_{ss}}$, particularly if the soil reaches saturated water content $\boldsymbol{\theta_{sat}}$ for significant amounts of time.

In terms of the overall 'water use' of the tree and crop system, the combined transpiration is therefore:

$$T_t + T_c = P_g - I_t - I_c - E_t - E_c - D_t - D_c - R_t - R_c - \Delta\theta_t - \Delta\theta_c \tag{1}$$

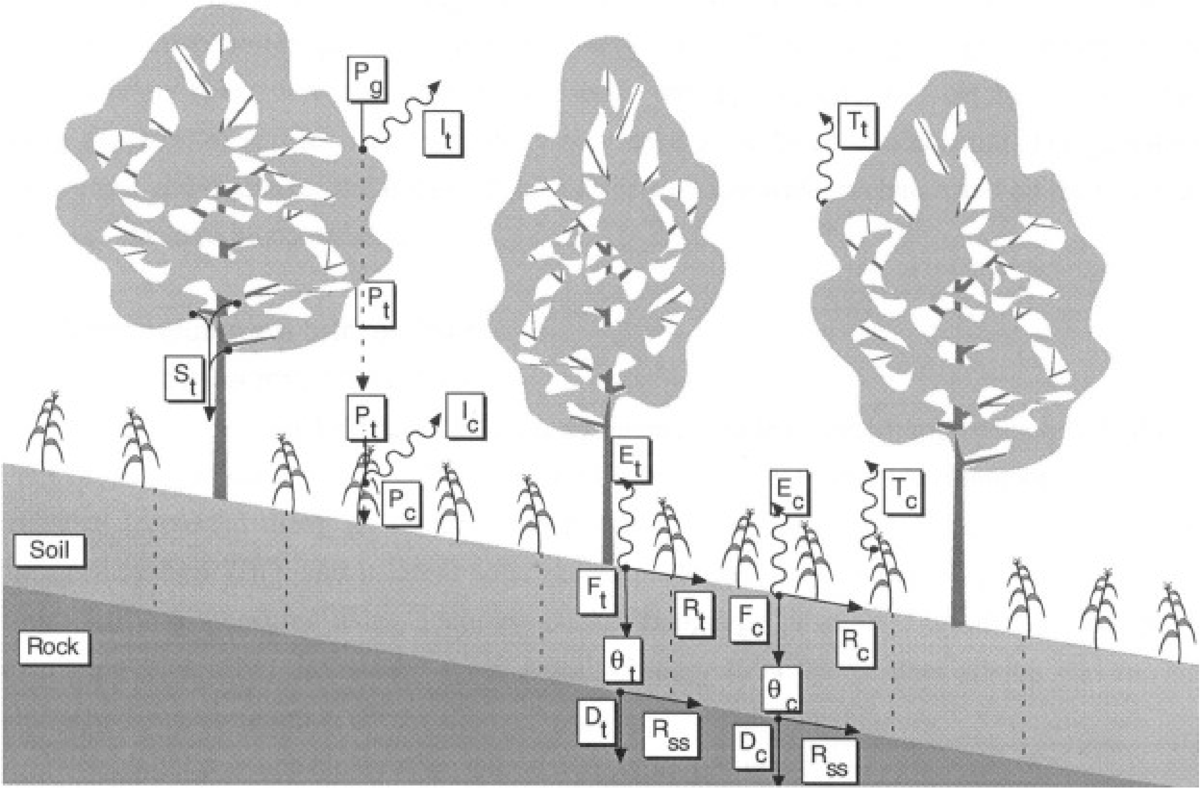


Figure 3.4:
The water balance of a tree+crop agroforestry system on a hillslope. Each of the water balance components is highlighted, and shown as separate items as affected by tree and/or crop canopies. The darker zone signifies the area below which neither crop nor tree roots are able to exploit resources.

In a conventionally cropped area on the same slope (*i.e.* without trees), the equivalent transpiration is

$$T_c' = P_g - I_c' - E_c' - D_c' - R_c' - \Delta\theta_c' \tag{2}$$

where the superscript (') indicates that these components can be significantly different in traditional cropping systems, where trees are excluded. The hypothesis that agroforestry systems can use rainfall more effectively assumes a synergistic effect of combining the tree and crop components, and can be expressed mathematically as

$$T_t + T_c \; > \; T_c' \tag{3}$$

This defines the way in which the different water balance components need to be managed in order to benefit from the addition of trees to a crop.

On the small-scale, *i.e.* the plot or farm level, net 'losses' to the system such as interception, soil evaporation, runoff and drainage should be minimised in the agroforestry system. This could be achieved via the utilisation of as much as possible of the traditionally 'nonproductive' components of the water balance of a crop-only farming system (*e.g.* E_c', R_c' and D_c'). In an agroforestry system, water balance components such as interception and soil evaporation are directly dependent on the amount of 'ground cover'. As this is provided primarily by the tree canopy, one such management practice of interest is that of pruning. A successful pruning strategy would lead to a situation where the canopy left after pruning is large enough to reduce soil evaporation (through shading) yet small enough to minimise rainfall interception losses. On a larger scale, where agroforestry is used in the upper reaches of a catchment, the effects of wholesale adoption of agroforestry technology may need to be taken into account. The possibility of reducing runoff and drainage, and the subsequent effects on soil water recharge and on the water supply 'downstream' need to be considered.

3.2.1 Canopy/climate interactions

Above- and below-canopy meteorology

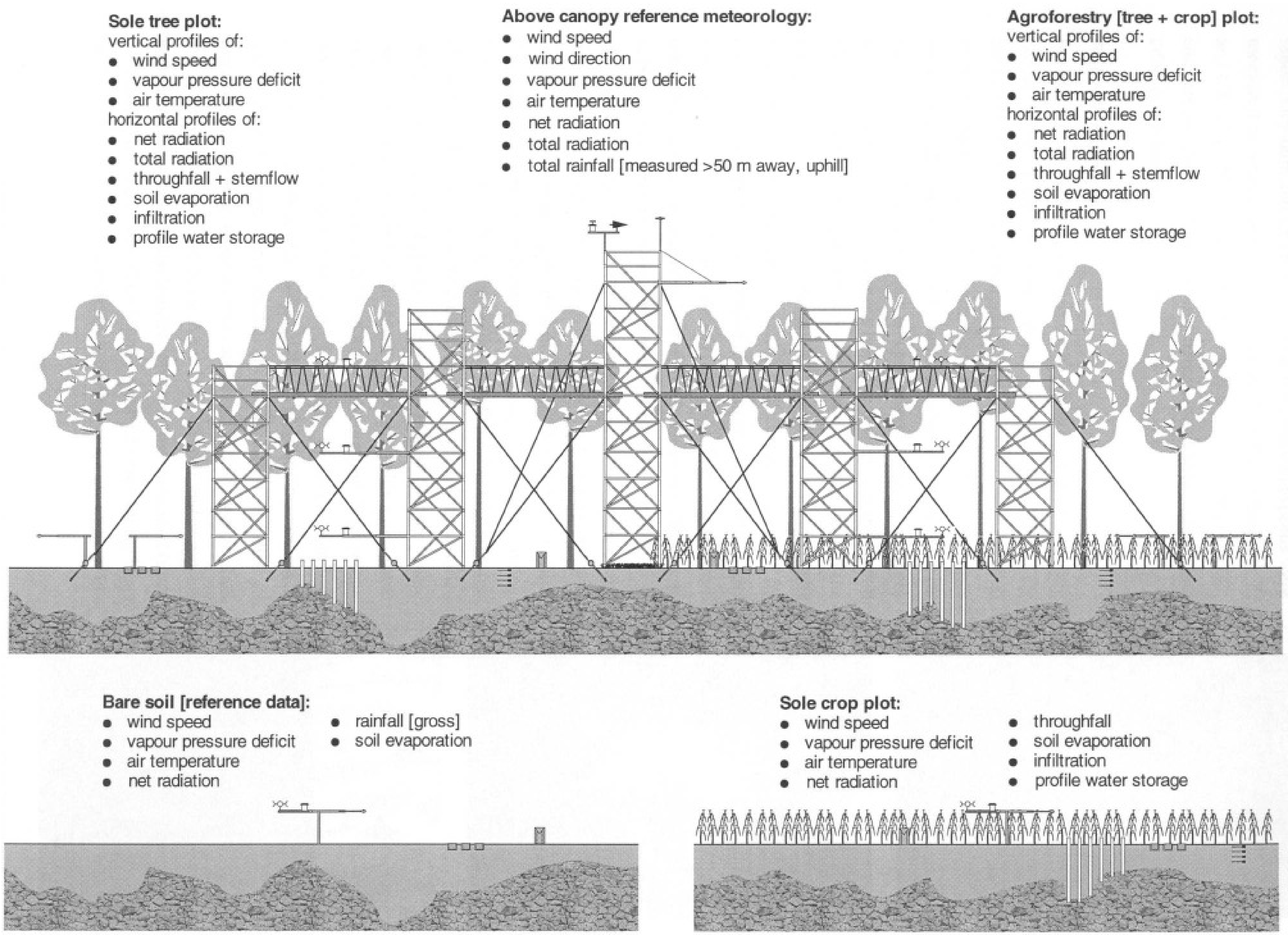
Between October 1992 and February 1994, an automatic weather station approximately 500 m away from the project site was used to collect standard meteorological data, including dry- and wet-bulb temperatures (recorded using an IH aspirated psychrometer); wind speed and direction (Campbell Scientific, Shepshed, UK); and incident solar radiation (Model CM5, Kipp and Zollen, Netherlands). Gross rainfall was measured using a tipping-bucket raingauge positioned uphill from the plots and approximately 20 m from the nearest trees. After February 1994 the weather station was moved and mounted above the tree canopy (Plate 3.3).

The height at which the weather station was positioned was adjusted each season to allow for the growth of the trees, ensuring that the height at which temperature, wind speed and humidity measurements were made was approximately + 2 m above the tree canopy. All variables (including those described below) were measured every 10 minutes and an hourly value (either average or sum) was stored on data loggers (Campbell 21X, Campbell Scientific Instruments, USA).

As the trees grew larger and their canopies had more pronounced effects on the local environment, the microclimate below the tree canopies was measured and compared with similar measurements made in the sole crop (C_g) treatment, and over bare soil. Figure 3.5 shows the network of towers and walkways installed at the site, which was used both to house equipment measuring below-canopy microclimate and also permitting access to the tree canopy for other manual measurements described elsewhere in this report. Dry-bulb and wet-bulb temperatures, and wind speeds were measured at several points along a vertical profile in both the T_d and CT_d plots (Plates 3.4 and 3.5), and at a single height in the C_g and bare soil

Plate 3.3:
The automatic weather station positioned above the tree canopy in the middle of the field site. The height was adjusted seasonally to compensate for increases in tree height. See text for details of instrumentation.

Next page. Figure 3.5:
The netowrk of towers and walkways used to gain access to the *Grevillea robusta* tree canopy at the Machakos site. Equipment installed in each of the treatments is illustrated and listed.


Sole tree plot:
vertical profiles of:
● wind speed
● vapour pressure deficit
● air temperature
horizontal profiles of:
● net radiation
● total radiation
● throughfall + stemflow
● soil evaporation
● infiltration
● profile water storage
Above canopy reference meteorology:
● wind speed
● wind direction
● vapour pressure deficit
● air temperature
● net radiation
● total radiation
● total rainfall [measured >50 m away, uphill]
Agroforestry [tree + crop] plot:
vertical profiles of:
● wind speed
● vapour pressure deficit
● air temperature
horizontal profiles of:
● net radiation
● total radiation
● throughfall + stemflow
● soil evaporation
● infiltration
● profile water storage
Bare soil [reference data]:
● wind speed
● vapour pressure deficit
● air temperature
● net radiation
● rainfall [gross]
● soil evaporation
Sole crop plot:
● wind speed
● vapour pressure deficit
● air temperature
● net radiation
● throughfall
● soil evaporation
● infiltration
● profile water storage

plots (0.75 m, ~ ¾ crop height), equivalent to the lowest point in the tree-plot vertical profile.

Rainfall Interception

In order to relate changes in surface soil water content to varying rainfall input, rainfall interception was measured using manually recorded raingauges. Three gauges (125 mm diameter) were installed in the C_g plot, midway between the maize rows. Six raingauges were installed in each of the T_d and CT_d plots around trees with average heights, basal diameters and projected canopy. The gauges were situated at various distances from the tree in both the T_d and CT_d plots (Plate 3.6), and midway between the maize rows in the CT_d plot. After each rainfall event, the volume in each gauge was measured and the fraction of rainfall intercepted calculated by comparing the net rainfall recorded at each point P_t with the gross rainfall P_g recorded by the met station raingauge. The volumes were converted to mm equivalents of throughfall. Measurements began in November 1994 and were continued to June 1997.

One effect of the tree canopies is to channel some of the rainfall intercepted by the foliage down the trunk and into the soil immediately surrounding the base of the tree. The degree to which this occurs is strongly influenced by the shape of the tree canopy, but in the case of *Grevillea*, observations confirmed that the volumes of water involved can be substantial. Stemflow gauges were installed on trees in the T_d and CT_d plots. These consisted of a flexible plastic collar which was sealed to the trunk of the tree with a non-toxic silicone compound about 0.75 m above the ground. The collars drained to plastic jerry-cans of 35 l capacity. Eighteen stemflow gauges were installed, nine in one of the T_d plots and nine others in one of the CT_d plots. Three gauges in each plot were installed on trees of average size, three on trees at the top end of the size class and three on the smallest trees. After both rainfall and stemflow had ended, the volume in each collection vessel was measured (Plate 3.7) and converted to stemflow [mm] expressed either on the basis of the 12 m^2 of ground occupied by each tree, or on the basis of the 1.5 m^2 block of soil around the base of the tree, into which stemflow was observed to infiltrate.

Plates 3.4, 3.5 and 3.6:
3.4 (**top**) and 3.5 (**middle**) - Institute of Hydrology psychrometers and anemometers used to measure vertical profiles of air temperature, humidity and wind speed. 3.6 (**bottom**) - measuring rainfall interception using the network of raingauges below the tree canopy

Both interception gauges and stemflow gauges were moved regularly to sample as many trees in the experiment as possible [temporal replication]. As both the measurements of throughfall and stemflow were related to tree size classes it was expected that we would be able to scale up to a plot area average for both of these water balance components given the tree size class distribution for each of the plots and treatments.

Radiation interception

Net radiation [R_n] was measured using net radiometers (Model Q6, Radiation Energy Balance Systems, Seattle, USA), to provide input data required to calculate potential rates of soil evaporation to compare with observed rates. Measurements were made at 0.75 m above the ground (~ ¾ crop height) over bare soil and in the C_g plot, and at two positions near to (0.3 m) and further from (2.5 m) a tree in both the T_d and CT_d plots (Plate 3.8). Another net radiometer was attached at the same height as the weather station (¾ tree height + 2 m) to measure net radiation immediately above the tree canopy.

In order to attempt to extrapolate from fixed-point estimates of R_n to the area average value across the 12 m^2 between four trees (see Fig. 3.3), more detailed measurements of light interception by the tree canopy were made using an array of six Kipp dome solarimeters. These were mounted on a 3 m arm which was moved over the area of ground between four trees (Plate 3.9). This provided 48 measurements over the 12 m^2 area between trees, which were compared to simultaneous measurements made with a seventh solarimeter that was unshaded by the canopy. This allowed us to map the areas of light and shade beneath the trees (Plate 3.10).

Plate 3.7:
Measuring the amount of rainfall that was channelled down to the soil along the trunk (stemflow).

3.2.2 Soil surface processes

Surface runoff

Runoff plots were installed in three of the four replicate plots from the T_d, CT_d, and C_g treatments, and measured from April 1993 until the end of the experiment. The runoff plots measured 2.5 m x 20 m giving a total area per plot of 50 m^2, and contained 5 trees. The plots terminated in a collection trough and which channelled the runoff to a collection tank of 1 m^3 capacity, allowing runoff events of up to 20 mm (Plate 3.11) to be measured. After rainfall and runoff ceased, the volumes collected in the tanks were measured (Plate 3.12). Sub-samples of the resulting water/soil slurry were collected and the water evaporated to give a

Plates 3.8 and 3.9:
3.8 (above) Patterns of shade cast by the tree canopies, together with the two net radiometers measuring radiation close to (0.3 m) and further away from (2.5 m) from the tree. 3.9 (below) The array of solarimeters used to measure the patterns of radiation reaching the soil surface. The boom is 3 m long.

correct measure of the water in the entire sample and an estimate of the amount of soil eroded. Runoff volumes were converted to depth equivalents [mm], on the basis of the runoff plot area.

Infiltration

Time Domain Reflectometry [TDR] was used to measure rapidly occurring changes in surface [0 - 0.4 m] soil water content [θ_v] in the T_d, CT_d and C_g plots. Measurements made on an hourly basis allowed rapid changes in θ_v due to infiltration to be studied during and immediately after rainfall events.

A site-specific calibration was determined, relating θ_v to the dielectric constant of the Machakos soil, details of which are given in Jackson and Wallace, (1998_a). This equation was very similar to both the conventional Topp *et al.* (1985) multi-site calibration and to the built-in calibration used by the TDR unit. The waveforms obtained in the soil in this trial were sufficiently well defined to be able to rely on the existing automatic waveform interpretation.

A Soil Moisture Corp. Trase System I (Goleta, CA, USA) was used, comprising 60 sensors multiplexed to a central signal processing and recording unit. The sensors were installed at various positions in sets of four, at depths 0.05 m, 0.15 m, 0.25 m and 0.35 m. Since there was only one TDR central processing unit available, sensors could only be installed in one representative plot from each of the T_d, CT_d and C_g treatments. The positions chosen for the TDR sensors were as follows :

- T_d and CT_d plots - sets of four TDR sensors were installed at the centre point in each of the 1.5 m^2 soil blocks detailed in Fig. 3.3. These positions mirrored the placement of the rainfall interception gauges, and allowed us to compare the infiltration with the total volume of water reaching the soil surface rates at each position.
- C_g plots - three sets of four sensors were placed midway between the maize crop rows at the centre of the 1.5 m^2 soil blocks shown in Fig. 3.3.

All 60 TDR sensors were logged hourly from November 1, 1993 to June 10, 1997. Readings were stored in the central TDR unit memory and downloaded approximately weekly using a portable computer.

Plate 3.10 (above):
Patterns of shade cast by the tree canopies in a sole tree plot.
Plate 3.11 (below):
Runoff event occurring within a runoff plot in one of the sole tree plot
Plate 3.12 (bottom):
Runoff plot and collection tank (uncovered).

Soil evaporation

Direct evaporation of water from the soil [E_s] was measured using twenty-four small soil lysimeters. The design of the lysimeters followed the recommendations of Daamen *et al*. (1993), with a few modifications (Jackson and Wallace, 1998_b). Each of the lysimeters was made up of several parts :

- An aluminium 'holder' which was permanently installed in the soil.
- An inner 'casing' made of perforated UPVC pipe. 200 of these lysimeter casings were installed in the soil at the start of each rainy season, and were excavated and used, as required, after a rainfall event. Pre-installation of these casings allowed the extraction of lysimeter cores without breaking the surface soil crust which develops after drying.
- A base plate made of UPVC sheet.
- A strip of thin polythene used to seal the walls of the lysimeter casing.
- The soil core inside the lysimeter casing — a volume of approximately 0.0018 m^3.

The 24 lysimeter liners were permanently installed in bare soil, CT_d, T_d, and C_g plots as follows, and as shown in Figure 3.6:

- CT_d and T_d : two sets of four lysimeters in each treatment, around the base of a tree, and the other set at similar orientations around the midpoint between four trees (Plate 3.13). In each set of lysimeters two were located on a crop row (where present) and two were positioned midway between crop rows (again, where present).
- C_g : a set of four lysimeters arranged as in the CT_d plot, with two lysimeters on a crop row and two midway between the crop rows (Plate 3.14).
- Bare soil : a corner of one crop plot was left unplanted and a set of four lysimeters was arranged away from any possible shading from adjacent tree or crop plots.

After each rainfall event occurring during the crop growing seasons, each of the lysimeters was weighed, at dawn and dusk every day, using a portable, battery powered electronic balance [AMS model FX 6000] with a resolution of 0.1 g, equivalent to a depth of 0.006 mm of water. Occasionally, measurements were continued on

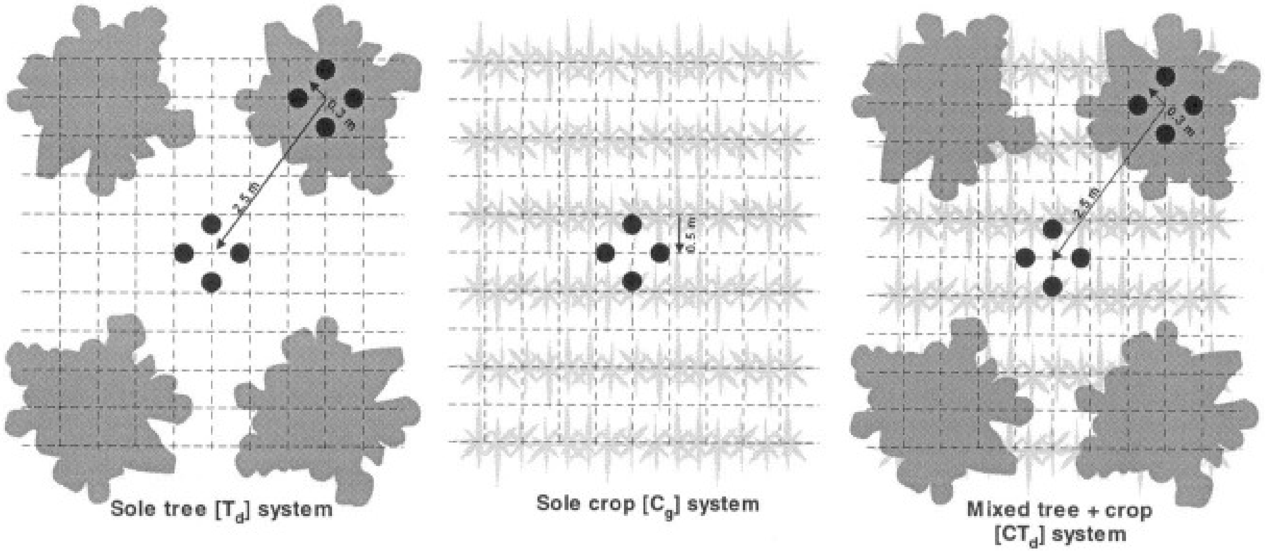


Figure 3.6:
The arrangement of the lysimeters in the three treatments being studied. Lysimeters were arranged in groups of four, arranged north, east south and west about a central point either 0.3 m or 2.5 m away from the base of the tree (where present). Each of the small squares measures 0.25 m on a side.

into the dry seasons to follow the dry-down dynamics of the Machakos soil. Following the recommendations of Daamen *et al.* (1993) the lysimeters cores were replaced each morning for the first six days after rainfall, after which the lysimeters were weighed as before, but were only discarded and replaced every two days. If it had not rained again after 10 - 12 days, measurements were stopped and were only resumed again after the next rainfall had occurred. Using this process the water content of the lysimeters was kept representative of that in the surrounding field.

Potential rates for evaporation of water from the soil were calculated using meteorological data collected in identical positions to the lysimeters (see Figs. 3.5, 3.6) according the Penman-Monteith equation (Monteith, 1965) with a surface resistance of zero, *i.e.:*

$$\lambda E_{so} = \frac{\Delta(Rn_s - G_s) + \rho c_p D / r_a}{\Delta + \gamma} \qquad (4)$$

where: λ is the latent heat of vaporisation of water , Rn_s is the net radiation above the bare soil

G_s is the soil heat flux, ρ the density of air, c_p the specific heat of air at constant pressure
D is the vapour pressure deficit of the air, r_a the aerodynamic resistance to evaporation
Δ is the rate of change of saturated vapour pressure with temperature, γ is the psychrometric constant

Plate 3.13 (top):
Arrangement of lysimeters around the base of one of the *Grevillea robusta* trees in a tree-only plot.
Plate 3.14 (above):
A group of four lysimeters in one of the sole crop plots, arranged with two lysimeters 'in-line' with the crop row, and two others offset midway between crop rows.

In the present study in Kenya daily total values of E_{so} were calculated using Equation 4 and hourly measurements of temperature (needed to calculate D), humidity and wind speed (u). G_s was taken as a fixed fraction of Rn_s (*i.e.* $G_s = 0.2\, Rn_s$) and r_a was estimated using the formula for neutral atmospheric conditions, *i.e.:*

$$r_a = \ln^2\{(z-d)/z_0\}/k^2u \qquad (5)$$

where:

z is the reference level height (0.75 m)

d the zero plane displacement (0 for bare soil)

z_0 is the roughness length (0.01 m for bare soil)

k is von Karman's constant (0.41) and u is the wind speed at height z

Further details of the microclimate measurements are given by Wallace *et al.*, (1995).

3.2.1 Profile water storage

Soil water content

Water storage over the soil profile was determined from weekly measurements of soil water content made using a neutron probe. Aluminium access tubes were installed between May and November 1993, in three of each of the T_d, CT_d, and C_g plots using standard IH practice (Bell, 1987) in the following arrangements:

- In each of the T_d and CT_d plots, six access tubes were installed 1 m apart, so that they would be located between the rows of the maize crop (where present) at various distances from the base of the tree, in identical positions to where the TDR sensors and interception raingauges were positioned (see Fig. 3.3)
- In the C_g plots, four tubes were installed 1 m apart (Fig.3.3), so that they would be located between the crop rows.

This arrangement was considered to give good spatial coverage of the lightly shaded areas shown in Figure 3.3, while providing a number of radial distances from the tree from which a functional distribution of water content might be derived. Due to the heterogeneity of the soil depth across the site, the tubes ended up with varied lengths of between 0.4 and 1.8 m. It was ensured that at least one tube per plot reached the maximum depth of 1.8 m. As each access tube was installed, the depth at which each of the soil horizons appeared was recorded. In each case, the access tube was installed at least 0.1 m into the uneroded gneiss bedrock. Neutron probe readings were taken every 0.2 m from 0.2 m depth to the bottom of each tube. Readings started in June 1993 and continued at weekly intervals until June 1997 (Plate 3.15).

It was determined that a rigorous calibration was required for the following reasons. The soil was both shallow and texturally heterogeneous; the accurate estimation of soil water content [θ_v] was necessary both to fully quantify the water balance of the agroforestry system; and reliable values of θ_v were essential in order to accurately calculate soil matric potentials [Ψ_m]. Separate calibrations were determined for each 0.2 m depth interval in each of the 48 tubes (over 300 separate calibrations), using the neutron scattering technique (Couchat *et al.*, 1975). Data were obtained from field measurements made using a gamma probe (Model 306, Nuclear Enterprises, UK), and from soil samples sent to the Centre d'Études Nucleaires de Cadarache in France. Further details of the calibration procedure are given by Jackson (1998).

Tree water demand

Tree transpiration was measured primarily using a modification of the stem heat balance technique (Ishida *et al.*, 1991), where a heating element supplies heat around the circumference of the trunk which is then dissipated by the transpiration stream. Using thermocouples the dissipation rate can be measured and the mass flux of water calculated. Further details of the technique are given by Khan and Ong (1995). Dataloggers (CR21X, Campbell Scientific, Shepshed, UK) were used to control three heat balance gauges and record their outputs as hourly

Plate 3.15:
Measuring the volumetric water content of the soil profile using the neutron probe. Measurements were carried out weekly by ICRAF personnel.

mean sap fluxes for each tree. Two loggers were used to monitor three randomly selected trees within one of the T_d plots and one of the CT_d plots at any one time. The gauges were left installed on individual trees for no more than a week to ten days, in order to avoid damage to the cambium and phloem caused by growth of the trunks. Measurements were made routinely during each cropping season and intermittently during the dry seasons between the 1992/93 short rains and the 1996 long rains.

Whole tree transpiration was also measured occasionally using a modification of the deuterium [^2H_2O] tracing technique (Calder, 1992), where ^2H_2O is injected near to the base of the tree and is then dissipated along the transpiration stream over a number of days. Transpired water is collected and analysed to determine the mean mass flux of water over the period studied. A good agreement was obtained between the transpiration rate (mm d^{-1}) and the basal cross-sectional area of the tree (m^2). Stomatal conductance [g_s] measurements were made using a porometer (model AP4, Delta-T instruments**,** UK) on individual tree leaves either immediately after excision from the tree canopy, or measured *in situ*, when the towers and walkways were in position (Plates 3.16 and 3.17). Measurements of leaf water potential [Ψ_l] were made on the same leaves used for measuring g_s, using a pressure bomb apparatus (IH design, UK).

Plate 3.16 (top):
One of the walkways that provided access to the *Grevillea robusta* tree canopy.
Plate 3.17 (above):
Measurements being made of tree stomatal conductance using a porometer/gas exchange system. Up to twenty separate trees could be accessed by using the walkways.

Crop water demand

As the heat balance system could not be successfully deployed on maize plants until they reached a certain size, approximately a third of the way into the growth season, different measurement techniques were adopted for estimates of crop water demand. UNott staff used a portable infrared gas analyser (CIRAS 1, PP Systems, Hitchin, Herts, UK) to measure instantaneous transpiration [E_t] and stomatal conductance [g_s], on individual crop leaves. The IRGA was used intensively during the 1995 long and the 1995/96 short rainy seasons. IH staff measured crop g_s and Ψ_m at the same time that measurements were made on the trees (as described above). As soil water deficits developed, maize leaf extension rates were recorded.

Percolation and deep drainage

Losses to the system occurring through percolation and drainage are usually calculated as the residual of the water balance equation (Wallace *et al.* 1995). This approach is prone to both under- and overestimation as the errors associated with each component are summed. It is possible to model the movement of water through the soil if the relationship between θ_v and Ψ_m is accurately determined for each soil layer. Intact soil cores were collected from each of the horizons from a number of soil pits at various locations across the site. These were analysed by the Soil Survey and Land Research Centre (Derby, UK) for bulk and particle densities, and to obtain soil-moisture release curves (Hill, 1995).

The nature of the bedrock underlying the site was investigated by excavating the soil from around a single *Grevillea robusta* tree of average height and girth in one of the tree+crop [CT_d] plots, removing all the soil from around the tree. 12 m^2 of rock were exposed, the surface brushed down and examined for fissures. Over the entire area only three fissures were located, with a mean length about 300 mm and each less than 20 mm deep. Bedrock infiltration measurements were made using a standard set of infiltration rings located over one of the rock fissures.

Hydraulic conductivities and surface infiltration rates

In order to model the progress of water through the soil it is important to determine both the infiltration rate and the hydraulic conductivity [*K*]. Various methods area available to do this, but one of the most rigorous, accurate and well tested is that of the instantaneous profile method, where both θ_v and Ψ_m are measured in a sealed block of soil as it is artificially wetted up and left to drain. The relationships between the two variables can be determined for each soil layer required, and *K* calculated from Darcy's Law.

This method involves the horizontal isolation of a block of soil (shown in Fig. 3.18 using heavy duty polythene), thus ensuring that the water added to the profile is distributed over a known volume of soil. The progression of the wetting front as it moves down the profile is monitored using the neutron probe and tensiometers.

Two soil blocks were used, each approximately 2 I 3 m in ground surface area. As we suspected that there might be differences in infiltration rate between soil where the trees had been growing for several years, and soil in which only maize had been planted, one soil block was in a sole crop [C_g] plot, and one was sited in an adjacent sole tree [T_d] plot, covering most of the shaded area marked out in Fig. 3.7, *i.e.* with a tree at the top right-hand corner. The tree was felled at approximately 0.5 m above the ground to make the experiment easier to conduct, and to ensure that changes in both θ_v and Ψ_m were due to drainage alone and not to root abstraction.

One neutron probe tube (1.8 m) was installed in the middle of each block, together with sixteen tensiometers installed in a circular arrangement around the access tube at 0.1 m depth intervals. The tensiometers consisted of a porous ceramic pot attached to a PVC tube. At the top of the tube there was a thinner piece of clear acrylic tube which allowed the height of water inside the tensiometer to be observed

Plate 3.18 (top):
Excavation of one of the blocks used in the instantaneous profile experiment to detail the soil physical characteristics.
Plate 3.19 (above):
a view of the soil block once it had been wrapped in polythene and the surrounding ditches were refilled. The three neutron probe tubes and the circle pattern of tensiometers is visible in the centre of the block.

(and topped up if necessary). The top of each tensiometer tube was cleaned of any dirt or dust and capped with a rubber septum which could be repeatedly punctured without losing vacuum. The tensiometers were filled with degassed distilled water and as water moved out of the ceramic pot and into the surrounding soil a vacuum would develop, the pressure of which corresponded to the total water potential of the soil surrounding the ceramic pot.

Two extra access tubes were installed (without accompanying tensiometers) close to, and further away from, the base of the tree. This allowed a comparison of the rate of infiltration of water into the soil profile in relation to distance from the tree. Once a trench had been excavated around each of the blocks (Plate 3.18), the sides were wrapped in heavy gauge polythene and the trenches repacked with soil (Plate 3.19). The polythene was necessary to ensure that when a known amount of water was used to wet up the block, none of it dispersed laterally into drier soil.

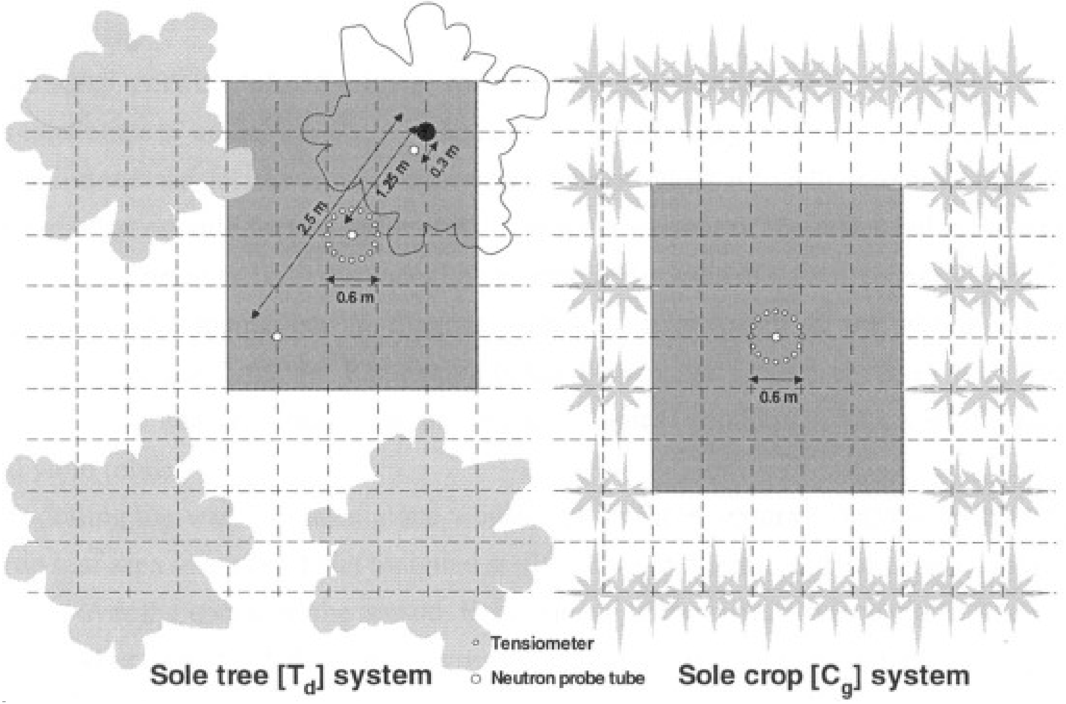


Figure 3.7.
Stylised representation of how the tensiometers and neutron probe access tubes were deployed in the two soil blocks used in the instantaneous profile experiment - one block sited in one of the tree+crop plots, another in one of the crop-only plots

Each of the soil blocks was irrigated with the equivalent of 25 mm of water using watering cans, over approximately 3 hours. Measurements of soil water content were taken at 0.1 m intervals, using a neutron probe, and of soil water potentials (0.1 m) using tensiometers and a digital Tensimeter™. The Tensimeter™ consisted of a needle which punctured the rubber septum, and a pressure transducer which measured the vacuum which had developed inside the tensiometer column. Neutron probe readings were calibrated using existing calibrations for the different soil horizons at the Machakos site, and the tensiometer readings were adjusted to take into account the height of the water column above the ceramic pot in each instrument, which affects the extent of the vacuum in each tube.

Readings were made before irrigation was commenced and then at close intervals until the top 0.5 m of soil had wetted up to saturation. After that point readings were made every 0.5 h for 2 hours, then every hour for the next six hours, and then every 3 hours and so on. Readings continued at lesser intervals until the profile had been judged to have stopped draining (approximately seven to ten days).

Profile water storage changes

Comparisons of soil moisture profiles from week to week allowed us to determine whether there was any movement of water to below the soil/rock interface. Drainage to below the deepest point at which θ_v was measured could be determined from comparing successive soil moisture profiles and observing whether the lowermost points remained coincident from one measurement period to the next, or the values of θ_v decreased over the same period.

3.3 Modelling

3.3.4 'Nested' versus 'stand-alone' modelling approaches

If we were to attempt to model the water balance of the agroforestry system in isolation, that is to say to create a 'stand-alone' model, we would be faced with the problem as to where to draw the boundaries of the model, *i.e.* what outside factors indirectly affect a component of the water balance so much that it itself needs to be incorporated into the water balance model for sake of completeness. Figure 3.4 outlined the water balance components, but the diagram represents a 'snapshot' of the system, when in reality agroforestry systems are dynamic. For example, the percentage ground cover of both tree and crop components increase and decrease according to physiological conditions, which would form part of a growth and yield model.

Modelling the water balance alone would require these 'exterior' factors such as tree growth, tree and crop leaf area index *etc.* to be assigned static values at the start of each season, rather than have them changing over the course of the season. Furthermore, if the water balance model was developed in isolation from other aspects of the system (growth, nutrients, light interception *etc.*) it might prove too difficult to combine these separate models at a later date. These subsequent difficulties range from relatively simple problems, such as models being written in different programming languages, up to fundamentally different approaches to things such as scaling factors and the question of aggregation/disaggregation.

Clearly a nested modelling design is the more realistic option, allowing researchers with the relevant experience to develop sub-models appropriate to specific areas, but all operating within an environment that permits a modular approach.

3.3.2 Modular programming and Stella™

Agroforestry is by definition, the interface between two disciplines, combining aspects of both agriculture and forestry. Therefore models developed to simulate systems where trees and crops are combined often rely on incorporating parts of older models originally developed for one or other of the more traditional land-use systems. While this is understandable, and avoids much of the unnecessary duplication of effort required in modelling aspects of agroforestry systems that are common to crops or trees grown separately, this approach can also lead to difficulties. Possibly the greatest of these problems is a result of the way in which models have traditionally been implemented as line-code computer programs such as BASIC, FORTRAN *etc.* The larger a line-code program becomes, the more difficult it is to modify it further, either by addressing new areas of research or by reusing sub-models developed by other groups.

Therefore there are many advantages to using a 'systems dynamics' programming environment to develop the water balance model, especially in a situation where several institutes are involved in modelling different aspects of the same agroforestry system, as in the case of the CIRUS project. Several systems dynamics modelling environments are currently available, either commercial products such as Modelmaker™ or Stella™, or public domain software such as the DFID-funded Agroforestry Modelling Environment [AME]. These programming environments all take a similar approach to modelling and it is possible that models developed in one environment could be transferred to another with relatively little difficulty. Indeed, although WaNuLCAS (described below) was developed using Stella™, it is already planned to implement it within AME (Muetzelfeldt and Taylor, 1997).

3.3.2 WaNuLCAS

The WaNuLCAS model was developed by ICRAF researchers as a generic model, capable of simulating **Wa**ter, **Nu**trients and **L**ight **C**apture in **A**groforestry **S**ystems, of both simultaneous and sequential types (Van Noordwijk and Luisana, 1997). The model was constructed using the Stella™ dynamic systems modelling environment, and provides a mechanistic description of both above- and below-ground interactions in a two-component agroforestry system, although greater emphasis is placed on below-ground resource capture.

The Stella™ modelling environment allows the model to be as accessible as possible to users generally unfamiliar with modelling techniques. This is achieved by representing the structure of the model graphically as a flowchart (the ‘map’ layer). This is dynamically linked to the part of the model which contains the mathematical relationships between parameters (the ‘equation’ layer’). The input to the model is provided through a ‘control panel’ layer where parameters are set one by one, or links specified to data stored elsewhere (*e.g.* on external spreadsheets). The model is broken up into different sectors which interact, and which can be improved and modified individually without requiring a complete overhaul of the model. Both inputs to and outputs from the model are in a conventional spreadsheet format (Microsoft Excel™).

General model structure

WaNuLCAS incorporates a soil sub-model divided into 4 horizontal ‘zones’ and four vertical ‘layers’, in which roots from both components (*e.g.* tree and crop) exploit the soil. A simple vertical water balance model is contained (a ‘tipping-bucket’ approach) , where input from precipitation enters the uppermost soil layer and drainage (if present) accounts for water leaving the lowermost soil layer. Horizontal redistribution of water is allowed, through canopy rainfall interception and/or soil surface runoff. Subsurface lateral movement of water is not modelled at present.

In WaNuLCAS, rainfall is considered to be the only possible input of water to the system, *i.e.* the systems modelled are rain-fed rather than depending on a water table. While this is appropriate for the agroforestry system at Machakos, the model will need to be modified in the future to deal with systems that rely on groundwater and/or significant inputs of surface run-on (*e.g.* if planted on lower slopes of steep hillsides). Daily rainfall input to the model (Figure 3.8) can be either in the form of real data obtained from a weather station and input via the spreadsheet, or else it can be generated either as a function of monthly average precipitation (tabulated and again entered via the spreadsheet) or using a built-in rainfall generator.

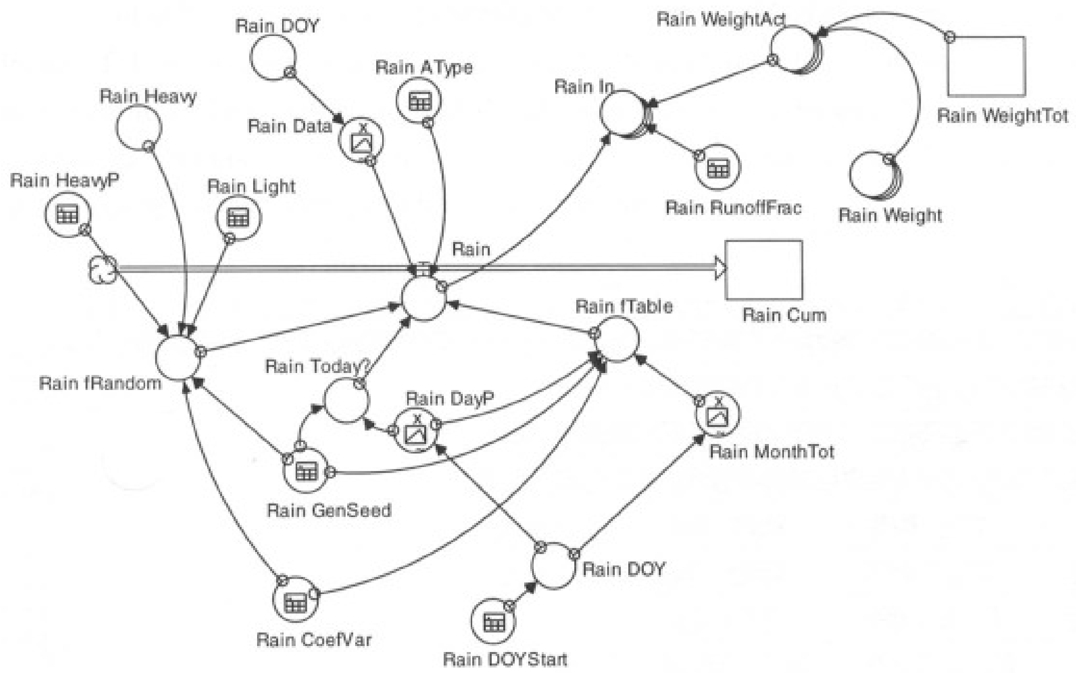


Figure 3.8:
an example of the StellaTM modelling structure. The rainfall ‘sector’ in the WaNuLCAS model that allows for rain to be either input as daily data, or generated from either monthly mean data or using a built-in rainfall generator.

Each of the soil layers has an initial water storage value and specific soil physical properties. These include the matric flux potential, hydraulic conductivities and the relationship between the soil water potential and the water content. At present, the model derives these ‘Van Genuchten’ parameters using a pedotransfer function developed by Wösten *et al.* (1995), based on data from temperate soils. A simultaneous DFID-funded project involving Institute of Hydrology staff has attempted to derive pedotransfer functions for a range of tropical soils, including the soil at the Machakos site. In the future, we intend to use these parameters when running the model with data from Machakos.

Rainfall enters the uppermost layer and raises the soil water content. When this exceeds the specified saturated water content θ_{sat} the excess water becomes the input for the soil layer below. The rest of the water in the uppermost layer is lost through either evaporation or abstraction by the trees and crops. Potential rates of below-ground resource uptake (water and nitrogen at present) are calculated using ‘zero-sink’ functions derived by De Willigen and van Noordwijk (1994), based on the total root length of each species present. Resources are shared between tree and crop components proportionally, according to the effective root length of each component.

‘Real’ uptake rates are determined by summing the potential uptake rates over all the soil layers and comparing these with the current ‘demand’, which is a function of the plant biomass. In turn, this biomass, and tree and crop growth, is controlled by resource availability (light, water and/or nitrogen). Within the model the trees and crops interact mainly in terms of competition for below-ground resources, but also through above-ground competition for light. Nutrient cycling, plant physiological sub-models and other aspects of WaNuLCAS such as light interception are outside the remit of this investigation and therefore the scope of this report; however they are discussed more fully by van Noordwijk and Luisana (1997).

4 Research activities II : results and discussion

The CIRUS trial is one of the most highly instrumented agroforestry experiments anywhere in the world. Due to the nature of this report, only key examples of data from the Machakos dataset will be presented as other forms of dissemination (papers, annual IH and ICRAF reports *etc.*) explore each area of the investigation more fully. Data will be presented with respect to the parameterisation of the WaNuLCAS model, the input parameters of which are listed in Tables 4.1 to 4.5 (at the end of section 4.2), and are highlighted in bold text where they are refered to in the following text.

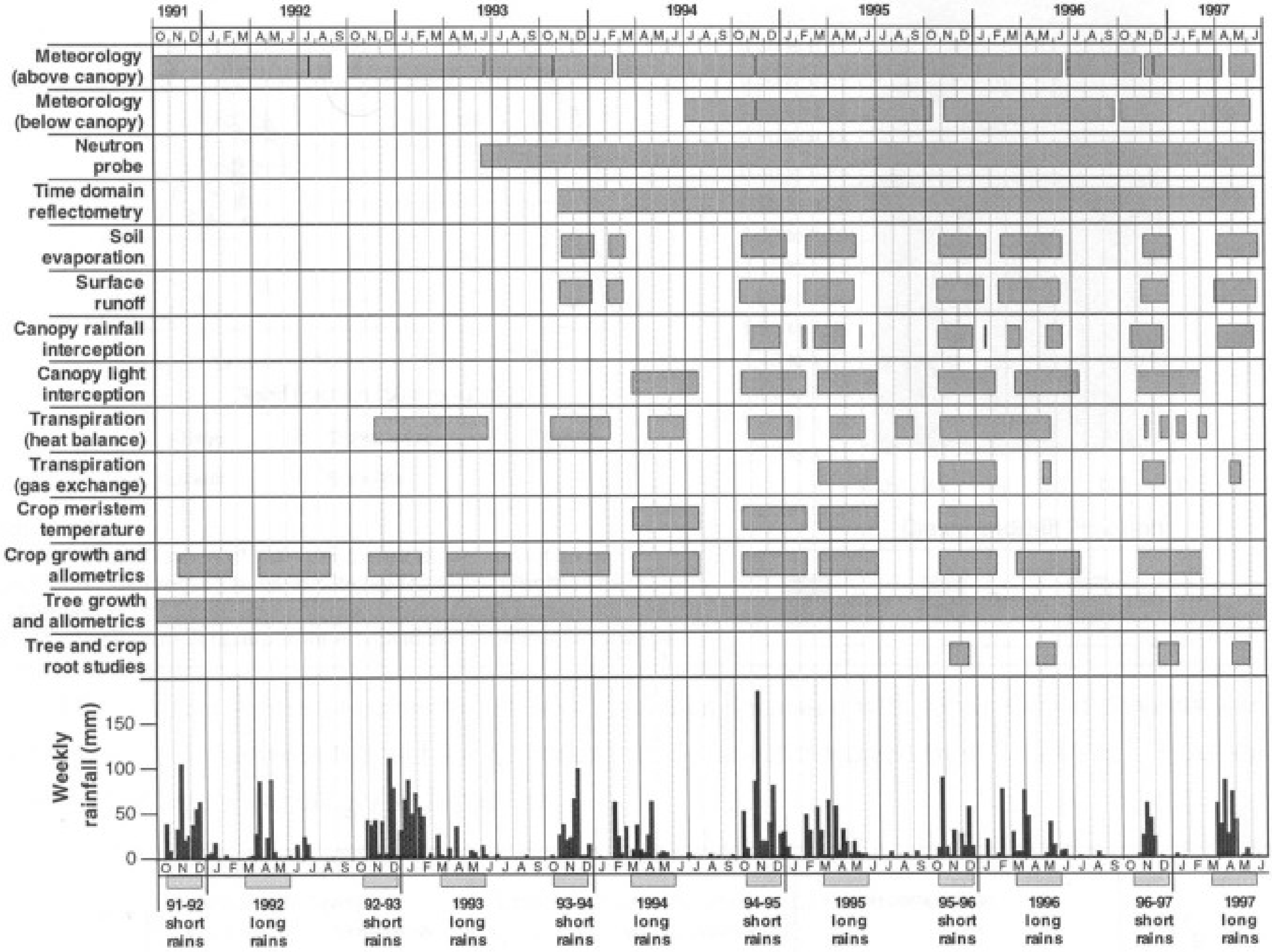


Figure 4.1:
Time series of the major categories of measurements made during the experiment, relating them to timing of rainfall (weekly) and crop seasons. The period shown is from when the *Grevillea robusta* trees were planted through to the end of the experiment in June 1997.

Figure 4.1 summarises the data collected during the experiment — the main categories of measurements of the water balance components, and their duration, together with the seasonal rainfall which determined the length of each crop growing season.

4.1 Site description

4.1.2 Soil type and physical properties

As one of the important contributions to be made to the modelling process was that of parameterising WaNuLCAS for a tropical soil, considerable effort was put into determining the physical characteristics of the soil at the field site. The soil was extremely heterogeneous both in terms of depth and texture. However, given that in many areas of the semi-arid tropics agroforestry is confined to marginal areas, data from this sort of soil is likely to be useful for modelling purposes.

Textural analysis of intact soil cores from the site showed that the dry soil bulk densities increased with depth from 1.19 kg m^{-3} at the soil surface to 1.44 kg m^{-3} for the eroded gneiss bedrock (saprolite). Particle analysis demonstrated that, in common with many tropical soils, the Machakos soil had high sand contents and low silt contents (Figure 4.2), suggesting that infiltration and drainage rates would most likely be high. Clay content increased below the till layer, and then decreased with depth. Gravel contents were highest (20-35%) between 0.8 and 1.4 m. Mean particle densities ranged from 2.49 kg m^{-3} in the soil layers to 2.62 kg m^{-3} for the gravel layer.

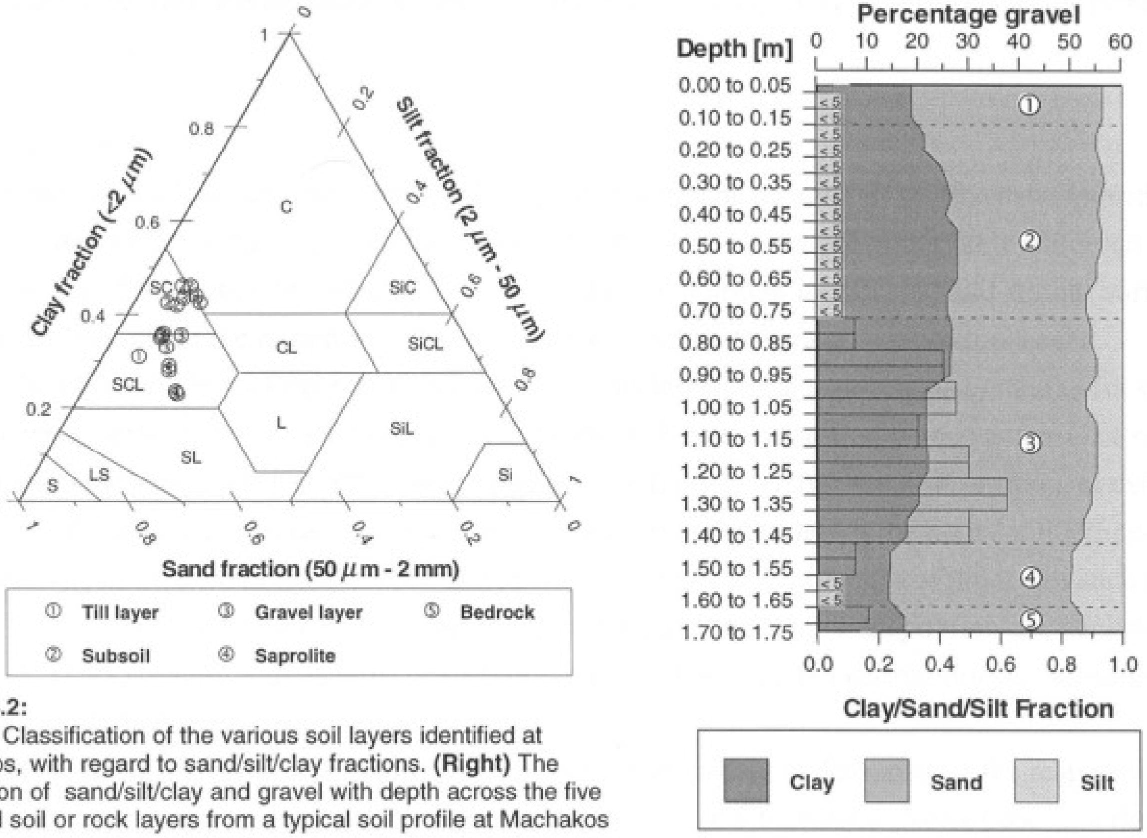


Figure 4.2:
(Above) Classification of the various soil layers identified at Machakos, with regard to sand/silt/clay fractions. **(Right)** The distribution of sand/silt/clay and gravel with depth across the five identified soil or rock layers from a typical soil profile at Machakos

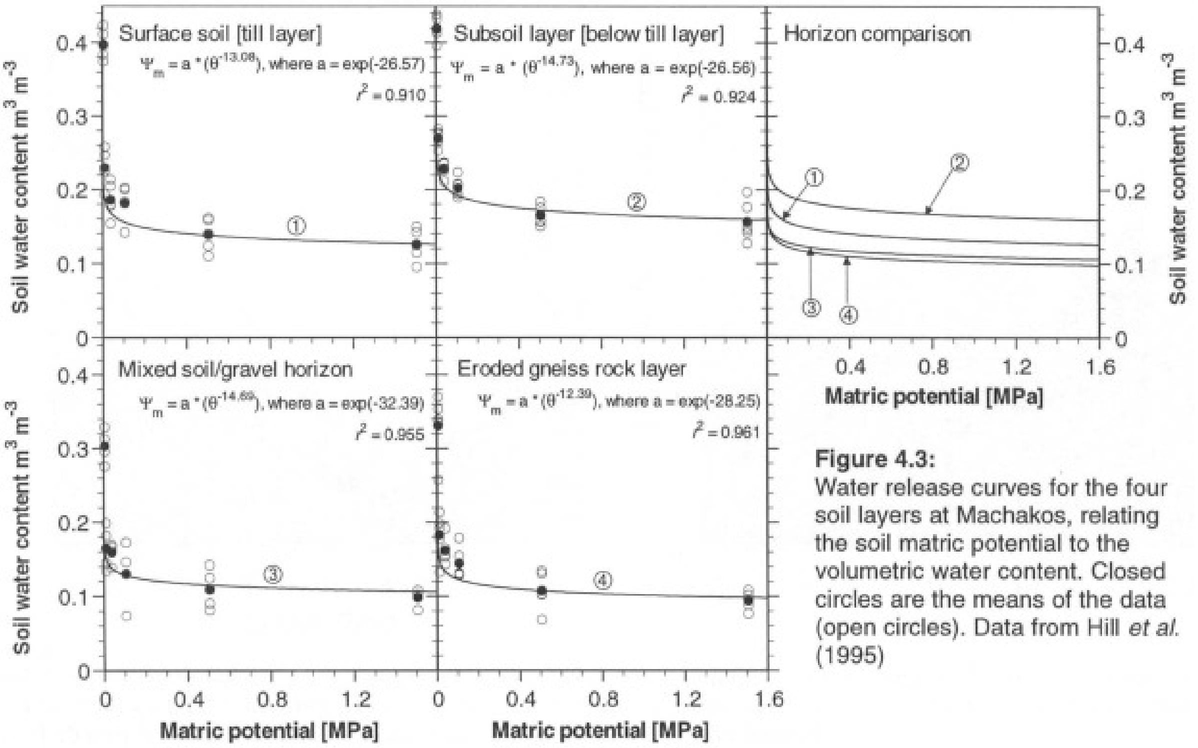


Figure 4.3:
Water release curves for the four soil layers at Machakos, relating the soil matric potential to the volumetric water content. Closed circles are the means of the data (open circles). Data from Hill *et al.* (1995)

The results of the water release measurements are shown in Figure 4.3, indicating that all the soil horizons exhibited the abrupt change in water content with soil matric potential that is a characteristic of sandy soils. The soil/gravel layer and the eroded bedrock had very similar water release curves, whereas the subsoil retained more water at a given matric potential, because of its higher clay content. More detailed information on the water release characteristics is given in section 4.2.3, with the results of the instantaneous profile experiment.

4.1.3 Climate

Of all the meteorological variables recorded during the experiment, the rainfall was the most immediately relevant to the scope of this water balance investigation. As there was no water table observed at the Machakos site, fluctuations in rainfall, at the scale of hours through to seasonal and annual variation, necessarily determined the rates at which other processes within the water balance proceeded.

The WaNuLCAS model is designed to run in daily increments, requiring daily rainfall (or similar ‘daily’ data generated from monthly means *etc.*) as input. Therefore, at first glance patterns of rainfall distribution at the hourly level would seem to be unimportant. However, figure 4.4 shows that, for example, the amount of rain and the intensity of the storms tends to be greater during the hours of darkness. This would suggest that the majority of rain falling on the site occurs when the rates of processes such as soil evaporation, evaporation of intercepted rainfall, and both tree and crop transpiration are negligible or even zero. The long-term implications of such trends in temporal rainfall distribution are uncertain, but we intend to study them in greater detail in the future.

One of the aims of the experiment was to accumulate data to demonstrate the response of the trees and crops to above- and below-average rainfall. During the 5½ years covered by the experiment, it was observed that rainfall both exceeded, and fell below the seasonal average for both the long and short rains. For example, in 1994 the site experienced ‘long-rains’ precipitation of ~26% *below* average and

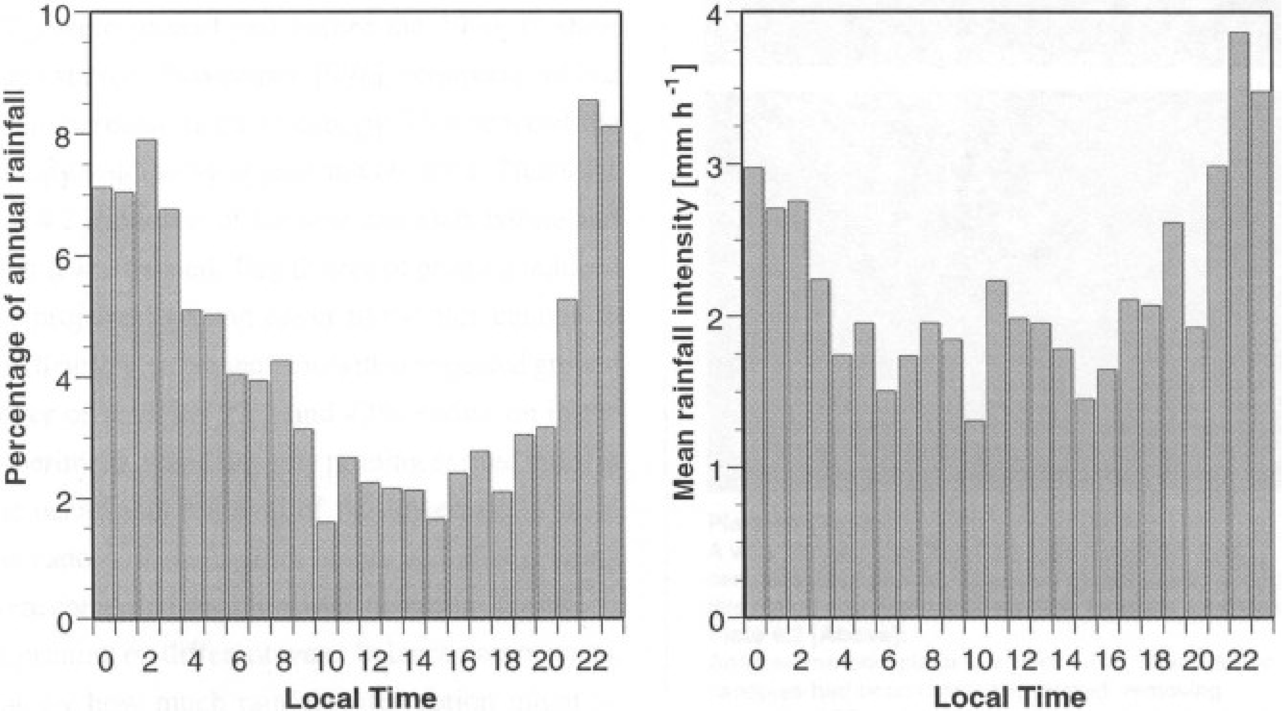


Figure 4.4:
[Above] The percentage of the annual Machakos precipitation falling in any given hour during 24 hours. The mean duration of rainfall = 2.09 +/- 0.07 h. **[Right]** The variation in mean rainfall intensity per hour over 24 hours. Mean rainfall intensity = 2.20 +/- 0.13 mm h^{-1}. Data from 1,511 hours of rainfall between 1/1/92 and 30/6/96

‘short-rains’ precipitation of ~24% *above* average. Even when the annual or seasonal rainfall does match expectations, the rains often start either too early (*i.e.* when the previous season’s crop was still maturing) or too late (*i.e.* not leaving the 90 days of generally sunny weather which the crop needs to mature). In WaNuLCAS, the length of the period between cropping seasons can be altered by adjusting the **Cq_CTimeBareSpec** parameter. The rainfall history observed during the course of the experiment served to highlight the possible contribution to be made by trees in agroforestry systems by scavenging inter-seasonal rainfall.

With the exception of a three week period in early 1994 (when the weather station was relocated) the experiment provided a near-continuous set of meteorological data (see Fig. 4.1) with which to run the WaNuLCAS model, or indeed other agroforestry models. This is particularly important as the variability of the rainfall climate makes it difficult to simulate using rainfall generation sub-models.

4.1.3 Experimental design

By the latter half of the experiment it had become apparent that the *Grevillea robusta* trees were significantly reducing crop growth in the agroforestry treatment, when compared to growth in the maize-only plots. It suggested that the tree component was competing successfully for the available resources, *i.e.* water and/or light. On-farm studies by ICRAF in other parts of Kenya have shown that farmers often prune *Grevillea* drastically, immediately before the crops are sown, and that this strategy results in better crop yields. As one of the intentions of the experiment was to use the model to make recommendations on management strategies, as well as initial agroforestry design, the decision was taken to imitate the local farmers’ pruning regime.

To achieve this, the trees in all the plots (T_d and CT_d) were pruned just before the 1996-97 short rains started [November 1996], removing all but the uppermost metre of canopy. This reduced the canopy volume by approximately 85%. Plates 4.1 and 4.2 show one of the sole tree plots before and after it was pruned. This degree of pruning reduced the projected ground cover of the tree canopy to less than 2%, in comparison with a projected ground cover of between 27% and 43% earlier on in the experiment, when the only pruning carried out was the occasional removal of the lowermost 1 m of the canopy. Results from before and after pruning were compared, enabling us to determine the effects of pruning on different water balance components, *e.g.* by how much rainfall interception might be reduced, or by how much soil evaporation might increase.

Plate 4.1 [Top]:
A view of one of the tree-only plots before the tree canopies were pruned. Projected ground cover during this period was approximately 30% (see text for details).
Plate 4.2 [Above]:
Another tree-only plot a few weeks later after the tree canopies had been drastically pruned, removing upwards of 85% of the canopy, and reducing projected ground cover to less than 2%.

4.2 Water balance components

4.2.3 Canopy/climate interactions

Above- and below-canopy meteorology

Data obtained before the tower and walkway assembly was in place suggested that there was a layer of cooler and wetter air surrounding the tree canopies (Wallace *et al.* 1995). This was not observed later on, using the psychrometers located at various points along a vertical profile in the CT_d and T_d plots (see Plates 3.5 and 3.6), where no significant difference in temperatures or vapour pressure deficits [VPDs] were observed. The point at which the towers were erected coincided with a period of major pruning of the tree canopies (November 1996). The tree canopies started to regrow, but, by the time the experiment finished in June 1997, they had not reached the same degree of canopy closure as they had before pruning was initiated. Consequently, the psychrometers were more exposed than in the previous study and the similarity in temperatures and VPDs (between heights in the profile) can be explained by increased turbulent mixing of air around and below the somewhat reduced tree canopies.

In addition, according to both stem heat balance and porometry data, tree transpiration rates following pruning were very much reduced. Although it is hypothesised that the humid layer of air observed in the previous studies was in part due to soil evaporation, it was assumed that the bulk of the moisture at that height came from tree transpiration. Thus we would not expect to observe similar levels of humidity following pruning. The results from these two studies, *i.e.* with and without an extensive tree canopy, demonstrates that the assumption that trees can substantially modify the below-canopy microclimate is indeed true.

All of the psychrometers used in the experiment, regardless of position or treatment, showed a sharp drop in relative humidities during the daytime, after values close to saturation during the latter half of the night. It is not uncommon for the air to reach dewpoint at least one hour per night, and early morning mists with accompanying dew deposition were regularly observed just after daybreak. It was not possible to quantify what effect the resulting fog or mist would have on the water balance of the system, but other studies have shown that such inputs can be significant. To investigate the hypothesis that the incorporation of trees might increase the water use of the system by modifying the below-canopy microclimate, micro-meteorological data were compared for periods of 25 days before and after the trees were pruned.

Even after ‘conventional’ pruning took place, when the lowermost 1 m of foliage was removed, there were considerable changes in microclimate beneath the tree canopies. Following pruning, the vapour pressure deficit [VPD] measured 0.3 m from the tree decreased by 19% from 1.32 to 1.07 kPa, and decreased by 13% from 1.44 to 1.26 kPa at a distance 2.5 m away (in between the four trees). The net radiation measured at 0.3 m increased by 117% from 3.8 to 8.2 MJ m^{-2} day^{-1}, and increased by 44% from 6.1 to 8.8 MJ m^{-2} day^{-1} at 2.5 m away. The wind speed remained unchanged at both positions, while the potential evaporation [E_{so}] at 0.3 m increased from 2.1 mm day^{-1} (49%) to 3.7 mm day^{-1} (78%), and increased from 3.7 mm day^{-1} (84%) to 4.6 mm day^{-1} (96%) at 2.5 m distance. Percentages shown are of the bare soil value.

When the trees were drastically pruned in November 1996, *i.e.* when all but the uppermost 1 m of canopy was removed, the microclimate beneath the trees was identical to that above bare soil; raising the values of all the above-mentioned variables to levels observed out in the open. The markedly reduced ground cover greatly increased wind speed beneath the trees [u], which trebled, from 0.6 to 1.8 m s^{-1}.

This drastic pruning was a powerful demonstration of the degree to which the tree canopy *does* modify the below-canopy microclimate, as hypothesised. Whether these modifications do indeed lead to an increased water use efficiency requires that individual water balance components be investigated in greater detail.

Rainfall interception

During the course of the experiment there was no significant difference in measured rainfall between the three interception raingauges in the sole crop plot. This was expected, given the relatively homogeneous nature of a crop canopy. However, several differences were observed beneath the more heterogeneous tree canopies, and the effect of the tree canopies in modifying precipitation input and horizontal distribution was examined.

Table 4.1 summarises the amount of water reaching the surface of at distances 0.3, 1.5 and 2.5 m distance from the base of the tree (see Fig. 3.3). Instead of receiving the lowest rainfall input, the soil closest to the tree (0.3 m) received more rainfall than that at 1.5 m away, because of the contribution made to the throughfall ('canopy drip') by stemflow. Stemflow is usually acknowledged to be of little importance when the water balance is calculated on an area average basis. However, stemflow is not evenly distributed over the area beneath a tree canopy, but rather concentrates moderate quantities of water (Prebble & Stirk, 1980) and nutrients (Belsky *et al.*, 1993) into a small area around the base of a tree. In the case of the WaNuLCAS model, stemflow will contribute to the water balance of zones 1 and 4, but not to zones 2 and 3 as rapid infiltration rates meant that stemflow water was absorbed by the soil close to the trees and did not run off.

Table 4.1:
Cumulative rainfall [$\mathbf{P_g}$] and net rainfall [combined throughfall and stemflow: $\mathbf{P_n}$] recorded below the *Grevillea robusta* tree canopy at various distances from the tree. Data are given as mm of water and $\mathbf{P_n}$ as a percentage of $\mathbf{P_g}$.

Period of measurement	Cumulative rainfall (Pg) (Off-plot)	Net rainfall [P_n] at 1.5 m from tree (in row of trees)		Net rainfall [P_n] at 2.5 m from tree (in clearing)		Net rainfall [P_n] at 0.3 m from tree (base of tree)	
	[mm]	[mm]	[% P_g]	[mm]	[% P_g]	[mm]	[% P_g]
1994 Short rains	451	290	64%	419	93%	347	77%
1995 Long rains	373	271	73%	297	80%	311	83%

Data from 48 storms which occurred during the period before the tree canopies were drastically pruned (see section 4.1.3 above) were used to investigate the effect of the tree canopy on spatial redistribution of rainfall. These storms varied significantly both in terms of length and intensity. During the period covered by the storms the cumulative rainfall [$\mathbf{P_g}$] was 829 mm, and the cumulative throughfall [$\mathbf{P_t + P_c}$] recorded by the six raingauges beneath the trees varied between 72 and 86% of $\mathbf{P_g}$. The average seasonal throughfall over the 12 m^2 area between the trees was ~84%. Using the same series of storms, the cumulative stemflow accounted for 1.7% of $\mathbf{P_g}$ when based on an average of 0.083 trees m^{-2}. Combining these two figures, gives an estimate of total rainfall interception of approximately 14% when the tree canopies were at their maximum extent.

After the trees were drastically pruned [November 1996] the interception losses decreased to below 1%. Stemflow also decreased, but was still measurable in almost all cases, implying that the amount of water intercepted by the trunk alone was measurable.

As there is no submodel within WaNuLCAS to calculate rainfall interception as a function of canopy cover, this was obtained using the sparse canopy interception model of Gash *et al.* (1995). The model is based on the capacity of vegetation to store water on the canopy and the average rates of rainfall and evaporation from the wet canopy. Interception can be obtained from the model using simple daily rainfall data and the degree of canopy cover. The model was parameterised using a mean rainfall intensity of 2.3 mm h^{-1}, a canopy storage of 0.8 mm, and a mean evaporation rate during rainfall of 0.2 mm h^{-1}. The model predicted an annual rainfall interception of ~20% with complete cover by the tree canopy, about 10% at 50% cover, and about 3% at 10% cover.

Both the modelled relationship between projected ground cover and rainfall interception, and direct field measurements of interception, were used to specify values for the parameter **Rain_Weight[Zone]**, *i.e.* how incoming rainfall is distributed over the horizontal zones 1-4 in the WaNuLCAS model.

Radiation interception

Figure 4.5 shows an example of shading under the tree canopy in one of the CT_d plots, measured using the mobile solarimeter array before the trees were pruned (*i.e.* projected ground cover of approximately 30%). The fact that the site has a slope of between 18 and 22% means that even when measurements are made at solar noon (as shown here) the shadows cast by the trees are significantly larger than their projected canopy areas (approximate areas shown as circles on figure). In this case, the mean canopy light interception for the 3 m × 4 m spaced trees was ~ 38%. Contrary to expectations, at midday the area

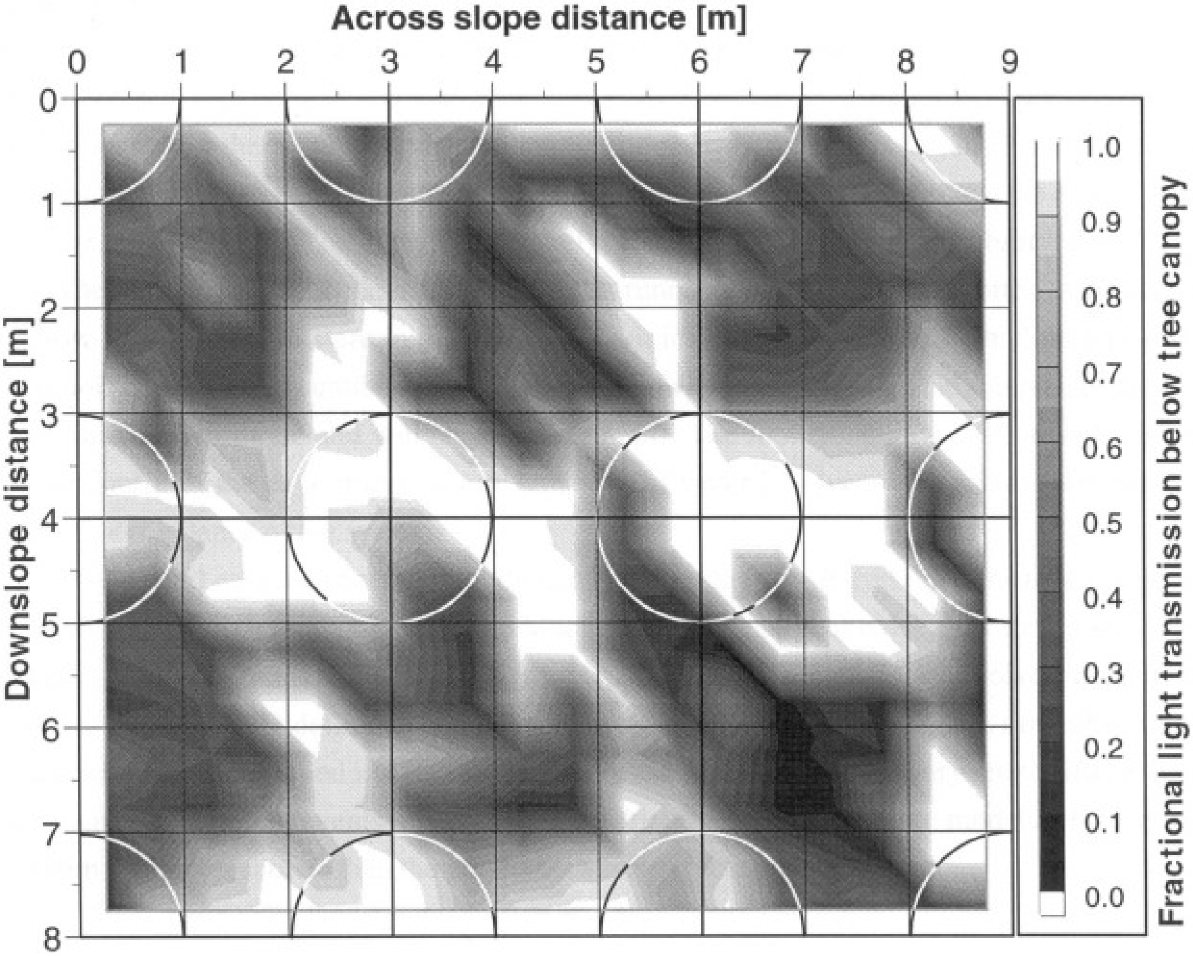


Figure 4.5:
Typical patterns of shade below the *Grevillea robusta* canopy as measured using the mobile 3 m array of solarimeters detailed in section 3.2.1. The circles approximate the projected tree canopy area. The area between four trees is $12m^2$ and each of the small squares is 1 m^2.

of soil directly beneath the trees is in direct sunlight, implying that localised first phase soil evaporation would be high during this period.

It is possible that at some point in the future, when the model is being further refined, the solarimeter data might contribute to determining the following parameters in the model : **Light_*k*T**, **T_CanShape, T_LAIMax** and **T_LAI_MinMaxRatio** . However, these refinements lay outside the remit of the IH work and values for these parameters were either obtained from Nottingham or left at default values.

The solarimeter data was used to scale up processes such as soil evaporation from point measurements (*e.g.* from net radiometers described in section 3.2.1) to an area average basis (see Wallace *et al.*, 1998). Net radiation was greatest over bare soil, with canopy shade reducing net radiation at all times up to when the trees were significantly pruned in November 1996. During this time, net radiation was reduced at the point midway between the four trees in the early morning and late afternoon, as shadows from adjacent trees lengthened and shaded the central area. At the same time, net radiation at the base of the tree was well below the open ‘bare soil’ value for most of the day, with maximum shading occurring just after midday. Variation in potential soil evaporation rates [E_{so}], *i.e.* first phase evaporation, was largely attributed to these differences in net radiation resulting from significant canopy shading from unpruned tree canopies.

4.2.2 Soil surface processes

Surface runoff

In the case of runoff, 5½ years’ data provided little evidence that the presence of a tree canopy significantly reduced runoff levels in comparison with crop-only plots. Previous investigations at the site (Wallace *et al.* 1995) showed that there was a good linear relationship between rainfall and runoff, the slope of which would be equivalent to the **Rain_FracRunoff** parameter, if the equation crossed through the origin. However, there was an offset of 7 mm (*i.e.* threshold rainfall) below which runoff was not observed.

The antecedent soil moisture content affects runoff in two ways. Firstly, often at the start of the season, low surface soil moisture in the Machakos soil leads to soil ‘crusting’ which in turn results in altered runoff characteristics until the crust has broken down. Secondly, when the soil is saturated, clearly no more water can infiltrate and will necessarily run off. The first situation was observed a few times during the course of the experiment, but the amounts of water involved were minute compared to the long-term water balance of the system.

The second case also occurred, particularly during the above-average rains towards the end of 1994. However, the high sand content of the Machakos soil meant that it does not stay at saturation for long, and is relatively freely draining. Therefore again the amounts of water involved were relatively unimportant in terms of modelling the long-term water balance of the system. High rainfall amounts and intensities of the kind observed in 1994 are relatively rare, occurring only every ten to fifteen years. As with all such ‘catastrophic’ events, these cases are difficult to incorporate into models which simulate a system with a lifespan shorter than the period between expected events.

Infiltration

Infiltration rates were measured for soil at various radial distances from the trees using a double ring infiltrometer. No significant differences were observed. However, TDR sensors at positions near to and further away from a tree (Figure 4.6) show different patterns of soil water recharge in the top 0.4 m of soil. Two rainfall events of similar amount, duration and intensity are illustrated, the first when the soil is wetting up after a long dry period and the initial profile water storage was ~18 mm, and the second when the profile is already wet (profile storage ~ 54 mm). In the case of a dry soil profile gradually wetting up, the soil at 2.5 m from the tree wetted up faster than the other two positions, neither of which wetted up completely, even 8 hours after the start of the rainfall. In the second case, the rates of wetting up were much faster at all three positions. This is due to higher hydraulic conductivities, and hence infiltration rates, in wetter soil profiles. In this situation, the soil near the base of the tree wetted up faster than that at 2.5 m, although the final profiles were quite similar.

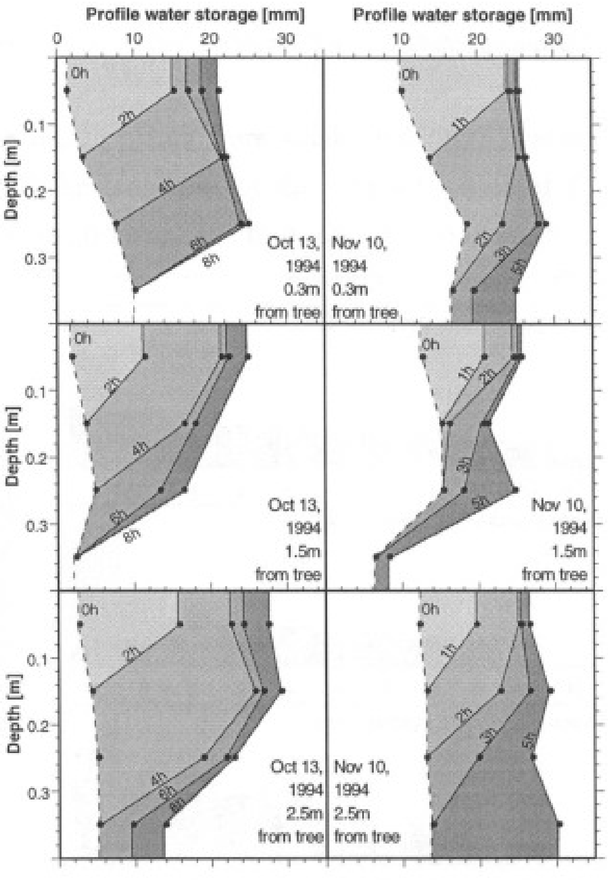


Figure 4.6:
Typical series of surface soil moisture profiles at various distances from the base of a tree in one of the sole tree plots, showing the progression of a wetting front as it infiltrates the soil. Labels on the lines show time, in hours.

Given the similar potential infiltration rates, these differences observed with the TDR technique must be due to rainfall redistribution below the tree canopy and/or abstraction of water by the tree roots. The data agree with the results obtained using interception raingauges (see above) located in equivalent positions. The horizontal similarity in infiltration rates simplified the initial parameterisation of the model, as mentioned in section 3.3.2, as although WaNuLCAS allows for horizontal variation in this respect, it would have meant that more preparation was required before each simulation was initiated. The model should be capable of representing the different patterns of soil water recharge as seen in Fig. 4.6 through a combination of rainfall interception and root abstraction sub-models. Data from the top two TDR sensors at each position were used to determine initial soil water contents for each of the simulation runs, *i.e.* values for **W_ThetaInit*1*[Zone]** (surface water content).

Soil evaporation

The WaNuLCAS parameter **Evap_Pot** specifies the potential evaporation rate of water from bare, *i.e.* unvegetated soil. Values for **Evap_Pot** were determined using the Penman-Monteith formula (equation 4, section 3.2.2) and data obtained from the automatic weather station.

Lysimeters arranged in groups of four (see Fig. 3.6) in the sole tree plots showed no significant difference in evaporation rate [E_s] with regard to position. This suggested that there was no difference in microclimate (*e.g.* radiation, humidity, wind speed *etc.*) between these four positions. On this basis, data from the four lysimeters at each position in the sole tree plots were averaged and reported as values for either the 0.3 m or 2.5 m position accordingly. Lysimeters situated 'on' and 'off' crop rows demonstrates some differences in E_s, depending on the growth stage (and subsequent ground cover) of the crop. Figure 4.7 shows evaporation sequences from lysimeters in bare, unshaded soil, and from lysimeters positioned 'on' and ‘off’ maize rows in the sole crop [Cg] treatment plot at three separate times during the development of the crop.

At 10 days after crop emergence (Fig 4.7$_a$), the maize plants were small, and there was no significant difference between the positions ‘on’ and ‘off’ the crop row, or the bare soil value of E_s. Cumulative bare soil evaporation [Σ_{Es}] over the eleven day period was 19.7 mm. ΣE_s ‘on’ and ‘off’ row over the same period was 19.3 and 19.4 mm respectively. At the crop flowering stage (Fig. 4.7$_b$), bare soil ΣE_s was 21.3 mm, while values ‘on’ and ‘off’ the crop row were 18.4 mm (86%) and 20.3 mm (95%), respectively. Percentages shown are of the bare soil value. At 40 days after emergence (Fig. 4.7$_c$), the maize canopy had completely closed along the row and the leaves of plants in adjacent rows were touching. Bare soil ΣE_s during this period was 27.2 mm, while there was no significant difference between lysimeters ‘on’ and ‘off’ the crop row at 24.4 mm (90% of bare soil value). In general, the differences between on-row and off-row lysimeter positions were not judged to be important, as they did not persist for more than about fifteen days during the development of the crop. Therefore, values from groups of four lysimeters at each position in the plots were averaged and reported as mean values in the same way as for the sole tree plots above.

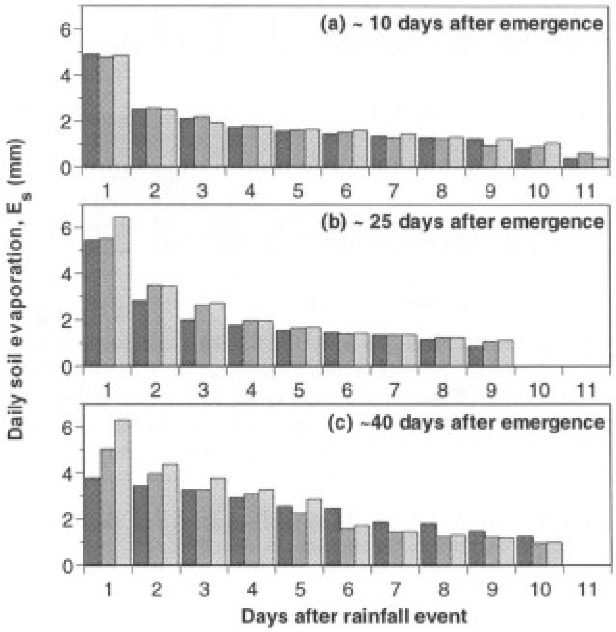


Figure 4.7:
Soil evaporation rates from bare soil □, and under the maize canopy in the sole crop plots from lysimeters ‘on’ ▨ and ‘off’ ■ a crop row at [a] at the thinning stage, [b] just after flowering started, and [c] around maximum canopy cover.

To further investigate the effect of the trees on modifying the below-canopy microclimate, evaporation rates from soil with varying degrees of tree canopy cover were compared. Figure 4.8$_{a\text{-}c}$ shows three evaporation sequences from lysimeters under the *Grevillea* canopy at 0.3 m and 2.5 m distance from a tree in the sole tree plot, and in unshaded, bare soil. Fig 4.8$_a$ shows E_s at a time just before the trees were subjected to ‘conventional’ pruning, where the lowermost metre of the canopy was removed approximately every six to nine months. Bare soil ΣE_s was 14.2 mm, while values of ΣE_s at 0.3 m and 2.5 m from the tree were 10.5 mm (74%) and 11.0 mm (77%), respectively. Percentages shown are of bare soil values. Fig 4.8$_b$ represents the situation shortly after this conventional pruning took place, and bare soil ΣE_s was 17.7 mm, while ΣE_s at 0.3 m and 2.5 m was 14.5 mm (82%) and 16.8 mm (95%), respectively. Fig 4.8$_c$ compares E_s between lysimeters after the trees were drastically pruned in November 1996, removing all but the uppermost metre of canopy. Bare soil ΣE_s was 16.1 mm, while ΣE_s at 0.3 m and 2.5 m from the tree was 15.4 mm and 15.9 mm, respectively. Neither of these amounts differed significantly from the bare soil value.

In previous studies, rates of evaporation were simulated using a modified two stage model of the type first described by Ritchie (1972), and described in detail in Wallace *et al.* (1995). The model used the capacity of the upper (0 - 0.15 m) layer of soil to avoid predicting evaporation when the soil surface is dry. First stage loss rates were calculated using a mean rate of bare soil potential evaporation of 5.4 mm d^{-1}, and a duration of first stage drying (t_1) of 1 day. Second stage evaporation decreased with time according to a factor of $\alpha = 4.4$ mm d$^{-½}$. The model predicted that total bare soil evaporation averaged ~ 55%

of rainfall over three wet seasons between 1994 and 1995. The same soil evaporation model was used to simulate the soil evaporation beneath the tree canopy. Second stage rates were the same as for bare soil, but first stage rates were lower and, under heavy shade, lasted for two days. The model predicted that the presence of even a sparse canopy, such as was present in the 4 I 3 m tree planting, reduced evaporation by 62 mm compared to bare soil rates, and was equivalent to 5% of rainfall. It was intended to investigate how well evaporation was simulated by the relevant submodel within WaNuLCAS, and compare the results with the Ritchie-type model.

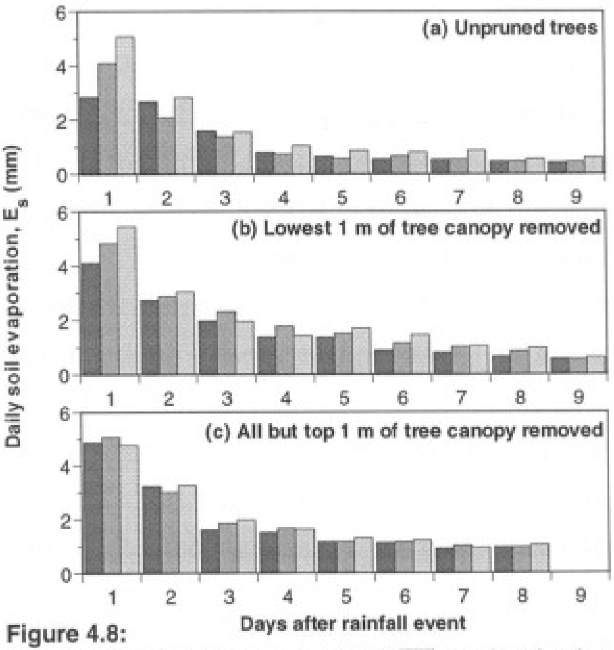


Figure 4.8:
Soil evaporation rates from bare soil ☐, and under the tree canopy in the sole tree plots from lysimeters 2.5 m away ▨ and 0.3 m away from the tree ■, [a] before the tree canopies are pruned, [b] just after moderate pruning, and [c] after sever pruning.

4.2.3 Profile water storage

Soil water content

Due to the heterogeneity of both soil depth and textural composition, comparison of soil water contents from tubes between (and within) plots were complicated. It was decided to standardise the data by converting from soil water contents to soil moisture deficits, effectively expressing the observed soil water status as a function of the maximum (saturated) value of θ_v observed in that particular soil layer. However, even though several of the rainy seasons during the experiment showed above average rainfall for the site, we could not be certain that any given soil layer we had measured had reached saturation under field conditions. Therefore a saturation value [θ_{vsat}] for each soil layer was calculated by taking the value of θ_v which corresponded to a soil matric water potential [Ψ_m] of -50 kPa, as determined from the corresponding water release curve measured by Hill *et al.* (1995). This value of Ψ_m was chosen as representing the situation in the field when all the pore spaces in the soil are filled with water and the layer has started to drain. Soil moisture deficits were obtained by converting both θ_v and θ_{vsat} to water storage values (*i.e.* from $m^3 m^{-3}$ to mm), and subtracting one from the other.

Figure 4.9 shows the variation in soil moisture deficit [SMD] in soil profiles in each of the treatments over the course of three seasons, including the short rains of 1994-95 during which the seasonal rainfall was well above average. The treatment with the highest water depletion was the intercropped *Grevillea*/maize [CT_d], followed by the tree-only plots [T_d]. The lowest depletion was in the C_g treatment. After the above average 1994 short rains, the C_g profile maintained a significantly lower soil moisture deficit during the following growing season (1995 long rains).

Further investigations determined that the difference between the soil moisture depletion in the T_d and CT_d plots was more pronounced with depth, *i.e.* there was little difference in the top 0.8 m, with both treatments showing similar patterns of recharge and depletion. In contrast, depletion was much more marked in the 0.8 - 1.2 m zone in the CT_d plots than the T_d plots. This suggests that the trees in the CT_d plots were using water from a greater depth than those grown without crops [T_d], and that this may be because competition from the crop roots in upper soil layers forced the trees to utilise water beyond the reach of the crops. In the case of both T_d and CT_d plots, the soil layers below 0.4 m showed little if any response to rainfall in terms of recharge during either the 1994 or 1995 short rainy seasons. This suggests that the extensive rooting system of the *Grevillea* trees observed to be present in the top 0.4 m (Smith *et al*. (1998) utilised much if not all of the incoming rainfall during these seasons, and prevented the lower soil layers from recharging.

It appears that with trees of this size, the profiles will recharge at depth only during large and intense rainfall events, such as those observed during the 1994 short rains. Even then, the effects are short lived, and the soil moisture deficit rapidly increases again after the rain stops, often within just two weeks. Values of θ_v were used to determine the initial soil water contents for vertical layers 2 ...4 in the WaNuLCAS model, *i.e.* setting initial values of the **W_ThetaInit*i*[zone]** parameter for layers below 15 cm.

As pruning the tree canopies had already been considered as a means of controlling above-ground and soil-surface processes, it was necessary to investigate how pruning might affect the recharge of the soil profile. Figure 4.10 demonstrates the effect that pruning the tree canopy had on the competition for available soil water between the tree and crop components. Three series of neutron probe data are shown for each of the sole crop, sole tree and combined tree + crop treatments.

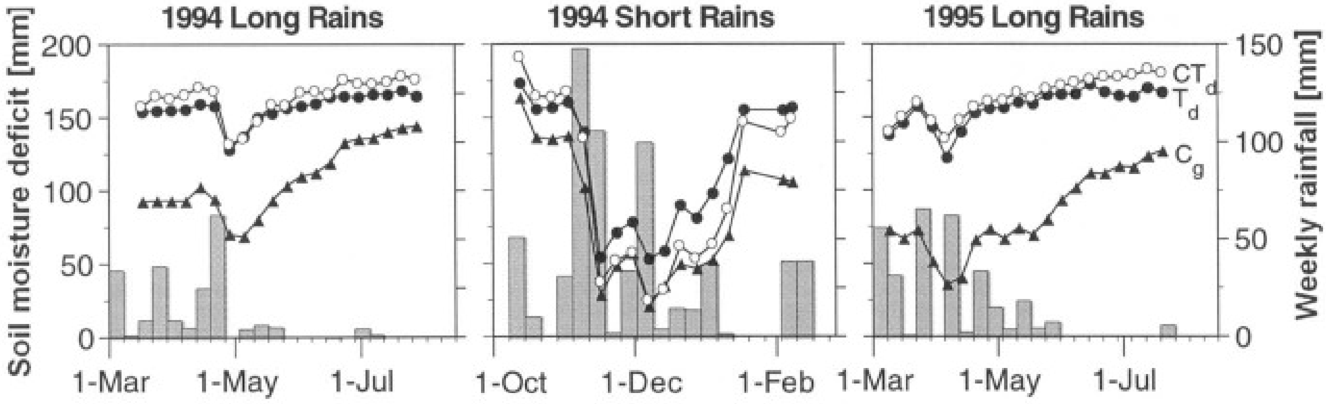


Figure 4.9:
Changes in the soil water deficits in response to rainfall, over the 1.7 m soil profiles in the three treatments: sole crop [▲], sole tree [●], and tree+crop plots[○]. Data are from three rainy seasons between 1994 and 1995, and weekly rainfall is shown on each graph.

The first (left-hand) series was recorded during the 1993 short rains, when the trees were about two years old and were not yet large enough to significantly out-compete the crop component. The data show that at this stage of the experiment, both increases and subsequent decreases in soil water content of the soil profile were smaller in the presence of a maize crop, either grown solely (+67 mm;-38 mm) or with trees (+70 mm;-46 mm). Under the same conditions, the soil water content of the sole tree treatment which was still essentially bare ground with a few small trees, increased by +79 mm and then decreased by -52 mm. The net recharge to the profile over the period was similar for all three treatments, varying between +24 mm and +29 mm. From the graphs it is clear that drainage to below 1.7 m occurred in all treatments as the profiles did not coincide at the deepest available neutron probe measurement (1.6 m).

The second (middle) series was recorded during the long rains in 1996. By this time the trees had reached a height of approximately 8 m and had exhibited the maximum canopy size, beyond which pruning would be used to reduce the water demand of the tree component and hence reduce competition with the crop. The response of the sole crop soil water content following rainfall was to wet up the entire profile in a fashion similar to that observed in 1993. The observed increase in soil water content in the sole tree plot was reduced to about 50% of the sole crop value, presumably due to a combination of decreased rainfall input (through increased canopy interception) and rapid abstraction of water by the larger trees. The increase in soil water content following rainfall in the combined tree+crop treatment was even less than in the sole tree treatment (~29% of the sole crop value).

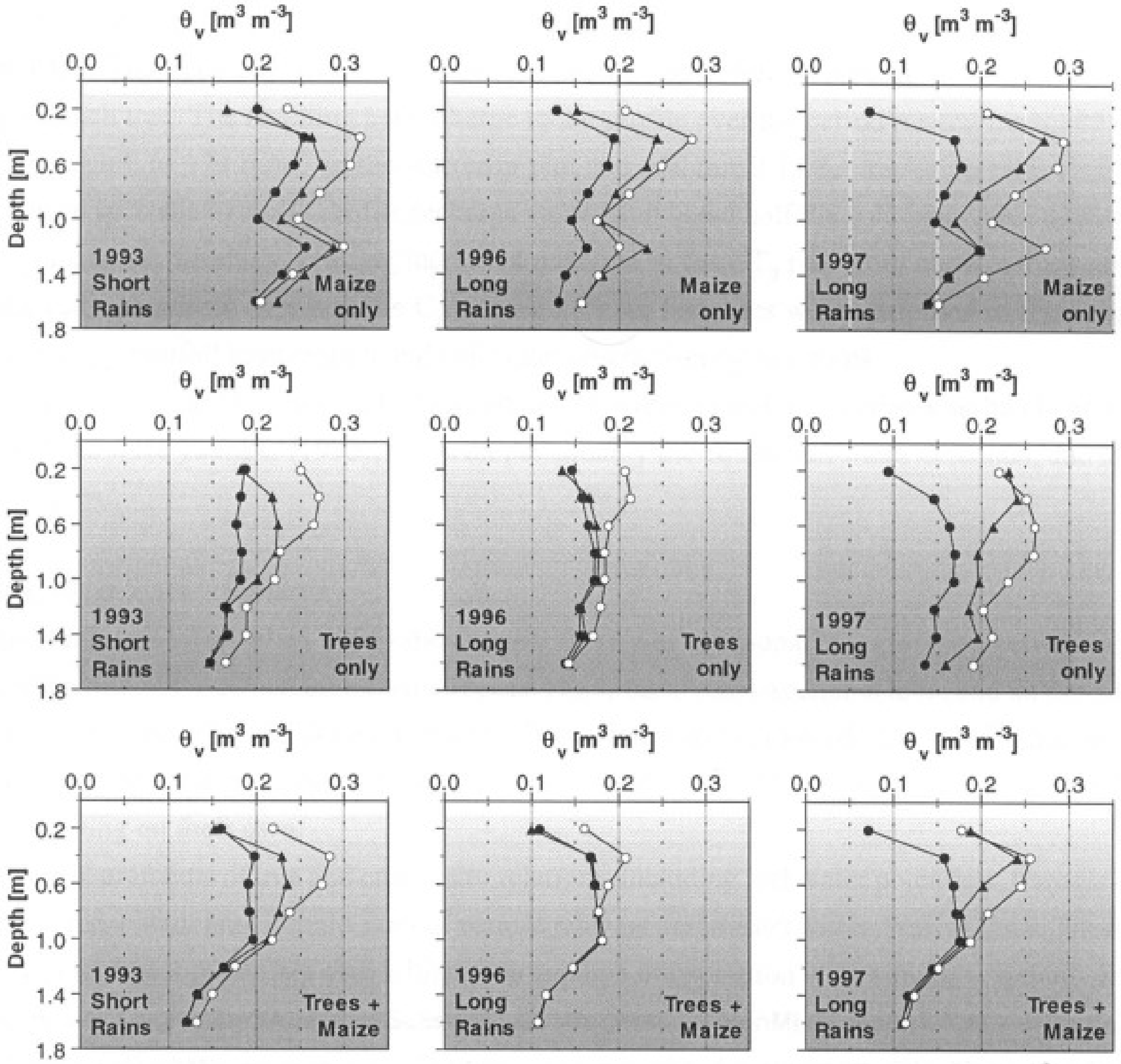


Figure 4.10:
Changes in the volumetric water content [θ$_v$] of the soil profile of the three treatments, at three periods during the experiment, when the trees exerted different water demands (see text for details). In each case, the data show water content measurements a week before rain [●], one or two weeks after rain [○], and four to five weeks after rain [▲].

Furthermore, little or no soil water recharge (or subsequent depletion) occurred below 0.6 m in the CT$_d$ plot. This reflects the severe competition for water between the tree and crop roots in the surface soil layers, which substantially reduced crop yields in this treatment. The net recharge to the profile over the period ranged from +64 mm in the sole crop plot, to only +5 mm in the sole tree plot. There was a net depletion of -2 mm over the same period in the intercropped treatment. From the graphs it is clear that drainage to below 1.7 m still occurred in the C$_g$ plot, but has all but ceased in both the plots with trees as the profiles overlapped at 1.6 m.

The final (right-hand) series of neutron probe data was recorded a year later during the long rains in 1997. The trees had been heavily pruned six months before, removing upwards of 85% of the canopy on each tree. The resulting net recharge to the profile over the period ranged from +89 mm in the sole tree plot, to +73 mm in the sole crop plot and +50 mm in the tree+crop plot. Tree pruning resulted in an increase in the T$_d$ profile recharge value from about half the sole crop value to about equal to the C$_g$ recharge. Similarly, pruning increased recharge in the CT$_d$ plot from about a third of the sole crop plot value to a little over half the C$_g$ recharge. These increases were attributed to the reduction in both the canopy rainfall interception and soil water abstraction by tree roots.

In general, pruning re-established patterns of recharge and abstraction that had been observed when the trees were younger (1993), and with presumably the equivalent water demands, due to similar sized canopies.

Tree and crop water demand

Previous studies (Wallace *et al.* 1995) showed that there was a reasonable correlation between the mean transpiration rate of the *Grevillea robusta* trees and their basal cross-sectional area, and an estimated tree transpiration rate per plot of 1.9 mm d^{-1} for the T_d treatment and 1.4 mm d^{-1} for the CT_d treatment. This result implies that the trees grown with an intercrop transpire about 35% less water than trees at the same spacing growing on their own.

Measurements of tree and crop water relations, including leaf water potentials, transpiration *etc.* were compared with default initial values of various relevant parameters within WaNuLCAS. The observed ranges of plant water potentials over which crop and tree transpiration were similar to default values for the parameters **Cq_PotSuctAlphMax[Season]** and **Cq_PotSuctAlphMin[Season]**, **TW_PotSuctAlphMax**, and **TW_PotSuctAlphMin** respectively. The two other associated parameters, **CW_Alpha** and **TW_Alpha**, were left at their default values of 0.01. Data from ICRAF and Nottingham University experiments were used to obtain the transpiration (water use) efficiency for the crop, **Cq_TranspRatioSpec[Season]** . As this report went to press, data necessary to determine the tree transpiration efficiency, **T_TranspRatio**, had not been analysed. The lack of a tree WUE value will be addressed later in the report.

Data from the Institute of Hydrology root modelling project (Smith *et al*., 1998) were used to determine values for the below-ground water relations parameters required, **CW_L**, **TW_L**, **CW_PotSuctBuff** and **TW_PotSuctBuff**, as well as the root length densities in each zone and soil layer, **RT_TLrvData*i*[Season]** and **RT_CLrvmSn*i*[Season]**.

Percolation and deep drainage

The excavation of a soil pit around one of the *Grevillea robusta* trees (Plate 4.3) showed that the soil/rock interface consisted of a layer approximately 0.10 - 0.15 m deep, of weathered bedrock. Roots were observed to grow down though the weathered material, following small channels filled with soil, but upon encountering the hard gneiss underneath the roots turned and grew laterally along the boundary rather than penetrating the hard gneiss layer. Over the 12 m^2 area we exposed, only three major roots were observed to penetrate the rock to below 2 m and these were judged to represent a small fraction of the whole root system. The data from the double-ring infiltrometer showed that water infiltrated into the rock at a rate of approximately 2 mm d^{-1}.

The instantaneous profile studies showed that the soil at the Machakos site was relatively free draining, as suggested by some of the infiltration data from the TDR sensors. Figure 4.11 shows the changes in total soil water potential [Ψ_t] as the irrigation wetting front progresses down the soil profile. A substantial amount of water was used to irrigate

Plate 4.3:
An area of 12 m^2 excavated to a depth of ~ 2 m around one of the *Grevillea robusta* trees in a tree-only plot. The tree was supported during excavation, and was successfully replanted after the investigation. The exposed bedrock was studied for fissures and infiltration rates.

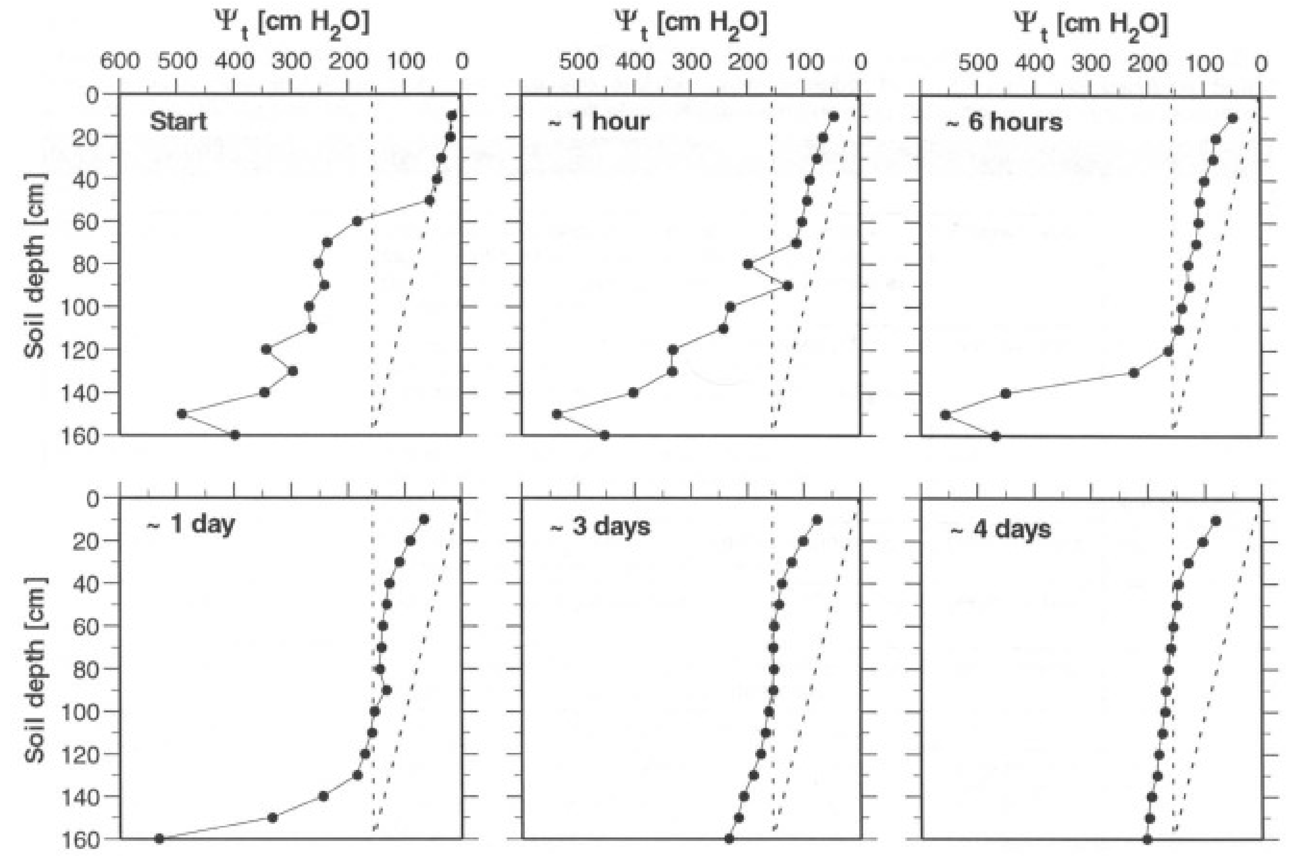


Figure 4.11:
The progression of the wetting front in the instantaneous profile experiment over the course of four days following irrigation. The diagonal dashed is a 1:1 line representing the situation where the matric component of the total soil water potential [Ψ_t] at each depth equals zero, and the subsequent potential results from the gravitational potential water alone.

the soil blocks, in the order of 50 -60 mm. However, within an hour after irrigation had stopped, the surface 0.5 m of soil had drained away from saturation — the data no longer coincide with the dashed diagonal line representing $\Psi_t = 0$.

As mentioned in section 3.3.2, the vertical layers in the WaNuLCAS soil submodel need to be parameterised with regard to water content/potential relationships. The water release curves relating matric potential [Ψ_m] to water content [θ_v] provided data of good enough quality to parameterise **W_PhiTheta*i*[zone]** for each soil layer (layers identical between horizontal zones). However, the range of soil water contents over which the instantaneous profile experiment was conducted was insufficient to determine other necessary parameters such as the saturated conductivity. It was decided that as a compromise, data from the soil textural analyses, and the water release curves (figs 4.2 and 4.3) would be used in conjunction with the **Wanulcas.xls** spreadsheet functions to generate values for the missing parameters.

The relevant clay and silt fractions and bulk density values were input into the spreadsheet. The 'predicted' water release curve was compared graphically with the measured curve (fig. 4.3), and the remaining 'factors' such as organic content and median sand particle size were adjusted slightly until the curves matched. The resulting lookup tables generated by the model for **W_PhiTheta*i*[zone]**, and for the remaining parameters; **W_PTheta*i*[zone]**, **W_ThetaP*i*[zone]**, **W_ThetaPMax[zone]**, **W_ThetaInacc*i*[zone]**, **W_CPhiP*i*[zone]** and **W_TPhiP*i*[zone]**, were copied to the relevant input section in the revised model.

Table 4.1
Input parameters required for running WaNuLCAS. This table defines the size and slope of the agroforestry system being modelled, the rainfall and evaporation climate, and the light interception by the tree and crop canopies. Some parameters in this and tables 4.2 - 4.5 are the result of modifications made after the initial model runs were made.

Group/Parameter	Description	Dimension	Value
Rainfall			
Rain_AType	Options 0, 1 or 2 determine how rainfall is input. (0 = daily rainfall generated from tabulated monthly data, 1 = daily rainfall from random generator, 2 = daily rainfall as data from external file)	dimensionless	2
Rain_CoefVar	Coefficient variation of rainfall in mm. Necessary if rainfall is generated randomly (Rain_AType = 1), or if generated from tabulated monthly rainfall (Rain_AType = 0)	dimensionless	n/a
Rain_Data	Actual daily rainfall data. Read from external spreadsheet file WaNuLCAS.xls Necessary if Rain_AType = 2	mm	Spreadsheet files : SR94/95 and SR95/96
Rain_DayP	Probability of raining each day. Value input as monthly probability. Necessary if Rain_AType = 0 or 1	dimensionless	n/a
Rain_DOYStart	Day of year when the simulation begins (*i.e.* 1st January = 1, 1st February = 32, etc.)	dimensionless	1
Rain_RunoffFrac	Fraction of rainfall ending up as runoff. Negative values indicates 'run on' — *i.e.* 'input' to another zone.	dimensionless	0
Rain_RunoffLimit	Threshold rainfall below which runoff does not occur	mm	0
Rain_GenSeed	Seed Random Generator. Needed if Rain_AType=0 or 1	dimensionless	n/a
Rain_Heavy	Average precipitation rate on a heavy rain day; for Rain_AType = 1	mm day^{-1}	n/a
Rain_HeavyP	Probability of heavy rain; for Rain_AType =1	dimensionless	n/a
Rain_Light	Average precipitation rate on a light rain day; necessary if Rain_AType = 1	mm day^{-1}	n/a
Rain_MonthTot	Tabulated data of monthly rainfall; for Rain_AType = 0	mm month^{-1}	n/a
Rain_Weight[Zone]*	Fraction of rainfall that is not intercepted by tree/crop canopies above each zone relative to other zones (*e.g.* no interception from any of 4 zones — 1:1:1:1)	dimensionless	Depends on canopy — see Table 4.6
Evaporation and Light Interception			
Evap_Pot_Type	Parameter determining how potential soil evaporation is calculated. (0 = constant daily value, 1 = daily values generated from monthly average data, 2 = daily data which is read from an external spreadsheet file).	dimensionless	1
Evap_Pot_MonthAvg	Potential amount of water evaporating from top soil in absence of plant cover.	mm day^{-1}	SR94/95 and SR95/96 data
Evap_Pot_DailyData	Potential amount of water evaporating from top soil in absence of plant cover.	mm day^{-1}	SR94/95 and SR95/96 data
Evap_Pot_Cons	Potential amount of water evaporating from top soil in absence of plant cover.	mm day^{-1}	3.96
Cq_*k*LightSpec[Season]	Current crop extinction light coefficient — the efficiency of crop foliage in absorbing light	dimensionless	0.65
T_*k*LightSpec	Tree extinction light coefficient — the efficiency of tree foliage in absorbing light	dimensionless	0.7
Agroforestry Zones			
AF_Zone[Zone]	Width of each zone. Width of zone 4 is the remainder when AF_Zones[1-3] are subtracted from AF-ZoneTot	m	0.5 for zones 1,…,3
AF_ZoneTot	Total width of agroforestry field simulated	m	2
AF_CanSym	Parameter determining type of agroforestry system: 1 = contour trees on sloping land system, 0 = other systems	dimensionless	0
AF_Circ	Parameter to decide circular versus linear symmetry. 1 = linear systems, 0 = other systems	dimensionless	0
AF_SlopeInit	Initial slope angle	%	22
AF_SlopeCurr	Current slope angle	%	22
AF_TopSoilDepthInit	Initial thickness of top soil (perpendicular to soil surface)	metre	0.15
AF_Crop?[Zone]	Parameter determining if crop present in each zone. 1 = yes, 0 = no	dimensionless	1:1:1:1

* In original model Rain_Weight[Zone] was a weighting factor that determined *redistribution* rather than *interception* of rainfall.

Table 4.2 Input parameters required for running WaNuLCAS cont.

Group/Parameter	**I el I I I tI ol**	**I I mel I I ol I**	**I al ue**
Soil layers			
AF_DepthF1[Zone]	Soil depth in layer 1 of each zone (function of AF_SlopeInit, AF_SlopeCurr, AF_TopSoilDepthInit, AF_Zone[Zone] *etc.* if AF_CanSym = 1, or input if = 0).	metre	0.15
AF_Depth*i* [Zone]	Soil depth in *i*-th layer of each zone for layers 2 … 4. Soil depth in layer 1 is a function of slope and depth F1 *etc.*	metre	0.60, 0.70, 0.20 for *i* = 2,…,4
Soil water			
W_CPhiP*i*[Zone]	Graphs of relationship between pressure head in layer *i* of each zone at the crop root surface and matrix flux potential. Data is entered in file WaNuLCAS.xls.	graph	WaNuLCAS spreadsheet
W_TPhiP*i*[Zone]	Graphs showing relationship between pressure head in *i*-th soil layer of each zone at tree root surface and matrix flux potential. Data is entered in file WaNuLCAS.xls.	graph	WaNuLCAS spreadsheet
W_Hyd	Parameter determining if 'hydraulic lift' is to be applied to model. 1 = yes; 0 = no.	dimensionless	0
W_PhiTheta*i*[Zone]	Matrix flux potential at a given theta/soil water content in layer *i* of each zone. Data is entered in file WaNuLCAS.xls.	graph	WaNuLCAS spreadsheet
W_Ptheta*i*[Zone]	Graphs of relationship between volumetric soil water content and pressure head in *i*-th soil layer of each zone. Data is entered in file WaNuLCAS.xls.	graph	WaNuLCAS spreadsheet
W_ThetaInacc*i*[Zone]	Amount of water in *i*-th soil layer of each zone not available for plant. Data is entered in file WaNuLCAS.xls.	l m^{-2} day^{-1}	WaNuLCAS spreadsheet
W_ThetaInit*i*[Zone]	Initial soil water content in *i*-th soil layer of each zone	cm^3 cm^{-3}	Seasonal — see Table 4.6
W_ThetaP*i*[Zone]	Graphs of relationship between pressure head in *i*-th soil layer of each zone and volumetric soil water content Data is entered in file WaNuLCAS.xls.	graph	WaNuLCAS spreadsheet
W_ThetaPMax[Zone]	Volumetric soil water content at a given maximum soil potential at top layer. Data is entered in file WaNuLCAS.xls.	cm	WaNuLCAS spreadsheet
Soil nutrients/organic matter			
Mc_Carbon	Proportion of total carbon in plant litter and residue	g m^{-2}	0.42
Mc_Clay	Proportion of clay in top soil	dimensionless	0.31
Mc_InitMetab[Zone]	Initial amount of C in metabolic pool of each zone	g m^{-2}	0
Mc_TempLim	Rate of decomposition as function of soil temperature	graph	n/a
Mn_CN_Act_Target	C:N ratio of active pool	dimensionless	8
Mn_CN_Pass	C:N ratio of passive pool	dimensionless	11
Mn_CN_Slw_Target	C:N ratio of slow pool	dimensionless	11
Mn_CN_Struc	C:N ratio of structural pool	dimensionless	150
Mn_InitAct[Zone]	Initial amount of N in active pool of each zone	g m^{-2}	1.5
Mn_InitMetab[Zone]	Initial amount of N in metabolic pool of each zone	g m^{-2}	0
Mn_InitPass[Zone]	Initial amount of N in passive pool of each zone	g m^{-2}	15
Mn_InitSlw[Zone]	Initial amount of N in slow pool of each zone	g m^{-2}	7.5
Mn_InitStruc[Zone]	Initial amount of N in structural pool of each zone	g m^{-2}	0
N_Init*i*[Zone]	Initial amount of nitrogen in soil layer *i* of each zone. Actual amount of nitrogen in *i*-th soil layer of each zone available for tree per day; based on tree root density	mg cm^{-3}	0.15, 0.10, 0.05, 0.05, for *i* = 1,…,4
Soil temperature			
Temp_AType	Parameter determining type of soil temperature data used in (0 = constant daily value, 1 = daily values generated from monthly average data, 2 = daily data which is read from an external spreadsheet file).	dimensionless	1
Temp_Cons	Constant soil temperature throughout the simulation period; necessary if Temp_AType = 0	°C	n/a
Temp_MonthAvg	Monthly average of soil temperature, necessary if Temp_AType = 1	°C	graph
Temp_DailyData	Actual daily data of soil temperature; necessary if Temp_AType = 2	°C	n/a

Table 4.3 Input parameters required for running WaNuLCAS cont.

Group/Parameter	**Description**	**Dimension**	**Value**
Tree Growth			
T_CanBiomInit	Initial amount of biomass accounted for by tree canopy, (leaves and small stems)	kg m^{-2}	Seasonal — see Table 4.6
T_CanHMax	Maximum height of tree canopy	metre	Seasonal — see Table 4.6
T_CanShape	Factor determining which part of the tree LAI is concentrated in the T_frac_area: a value of 1 gives an even spread of tree leaves over the alley, a higher value (*e.g.* 2) concentrates leaves above the trees	dimensionless	1.5
T_CanWidthMax	Maximum width of tree canopy	metre	1.5
T_GroMax	Maximum growth rate of trees at full canopy closure	kg m^{-2}	Seasonal — see Table 4.6
T_GroResFrac	Fraction of tree carbohydrate reserves converted to biomass during regrowth stage after pruning	dimensionless	0.15
T_LAI_MinMaxRatio	Parameter describing canopy thickness/density. Value 1 is the maximum thickness	dimensionless	0.8
T_LAIMax	Critical value of LAI at which tree would capture all the light needed for transpiration	dimensionless	4
T_LWR	Leaf Weight Ratio — leaf dry weight per unit shoot dry weight.	dimensionless	0.5
T_SLA	Specific leaf area of tree — tree leaf surface area per unit leaf dry weight	m^2 kg^{-1}	11.52
T_StemBiomInit	Initial amount of biomass in tree stem/trunk	kg m^{-2}	Seasonal — see Table 4.6
T_StemHInit	Initial value of tree bare stem height (tree height excluding canopy)	metre	Seasonal — see Table 4.6
T_TimeRecov	Time needed for tree to recover after pruning	days	21
T_TranspRatio	Amount of water needed per unit dry matter production of tree	l kg^{-1}	60[†]
Tree Water and Nitrogen			
TN_Dfa	Fraction of N tree demand met by atmospheric N_2 fixation per day	g m^{-2}	0
TN_CanBiomInit	Initial amount N in canopy biomass	g m^{-2}	2
TW_Alpha	A small value (*e.g.* 0.01) used in calculating reducing factor for potential demand	m^{-2}	0.01
TW_L	Hydraulic conductivity of tree roots; related to physiological entry resistance to water per unit length	cm day^{-1}	1.62×10^{-5}
TW_PotSuctAlphMax	Plant potential where transpiration is (1 - Alpha) × potential transpiration, where Alpha is a small value (*e.g.* 0.01)	cm	-5000
TW_PotSuctAlphMin	Plant potential where transpiration is Alpha × potential transpiration, where Alpha is a small value (*e.g.* 0.01)	cm	-15000
Cropping Cycle			
Cq_AType[Season]	Parameter determining the type of crop planted in each season. WaNuLCAS can accommodate a maximum of 4 crop seasons per year, with a different crop each season if required. Values can be 1-6, where 1-5 are default values (1 = cassava, 2 = maize, 3 = rice, 4 = groundnut, 5 = cowpea). Option 6 = another type of crop or if you have your own data for crop LWR, Harvest Index, SLA and relative light use efficiency.	dimensionless	2
Cq_CTimeBareSn[Season]	Number of days field is left bare between successive cropping seasons.	days	not used*
Cq_CTimeGenSn[Season]	Length of generative stage for each crop species	days	45
Cq_CTimeVegSn[Season]	Length of vegetative stage for each crop species	days	60

* In the simulations the model was run for one season at a time only.

[†] Initial assumed value of tree WUE. This parameter was varied later on during sensitivity analysis.

Table 4.4 Input parameters required for running WaNuLCAS cont.

Group/Parameter	**I el I I I tl ol**	**I I mel I I ol I**	**I al ue**
Crop Growth			
Cq_GroMaxSpec[Season]	Maximum growth of each crop species at 100% light intensity	kg m^{-2}	0.2
Cq_GSeedSpec[Season]	Seed weight as initial amount of crop biomass	kg m^{-2}	0.004
Cq_HBiomConv[Season]	Conversion factor between crop biomass increment and crop height increment	dimensionless	7
Cq_TranspRatioSpec[Season]	Amount of water used per unit dry crop matter produced	l kg^{-1}	30
Cq_CHarvAllocSpec[Cr]	Harvest index — proportion of crop that can be harvested. This parameter depends on the choice of Cq_AType. It uses the default value if Cq_AType is between 1-5. If Cq_AType = 6, values must be entered via the file WANULCAS.xls.	dimensionless	based on Cq_AType = 2
Cq_CLWRSpec[Cr]	Crop leaf weight ratio — gram of leaf per gram of shoot , for each crop species. This parameter depends on the choice of Cq_AType.	g m^{-2}	based on Cq_AType = 2
Cq_CRelLUESpec[Cr]	Relative light use efficiency for each type of crop grown. This parameter depends on the choice of Cq_AType.	dimensionless	based on Cq_AType = 2
Cq_CSLASpec[Cr]	Crop specific leaf area — leaf area per dry weight leaf, for each crop species. This parameter depends on the choice of Cq_AType.	m^2 g^{-1}	based on Cq_AType = 2
Crop Water and Nitrogen			
Cq_NDfa[Season]	Fraction of N crop demand met by atmospheric N_2 fixation per day	dimensionless	0
Cq_PotSuctAlphMax[Season]	Plant potential where transpiration is (1 - Alpha) × potential transpiration, Alpha is a small value (*e.g.* 0.01).	cm	-5000
Cq_PotSuctAlphMin[Season]	Plant potential where transpiration is Alpha × potential transpiration, Alpha is a small value (*e.g.* 0.01).	cm	-15000
CW_Alpha	A small value (*e.g.* 0.01) used in calculating reducing factor for potential demand	m^{-2}	0.01
CW_L	Hydraulic conductivity of crop roots; related to physiological entry resistance to water per unit length	cm day^{-1}	1.05×10^{-5}
Crop and Tree Roots			
Rt_ACType	Parameter governing type of crop root density data. 0 = Lrv data available, otherwise 1 = Lrv calculated using an exponential decrease model	dimensionless	0
Rt_ATType	Parameter governing type of tree root density data. 0 = Lrv data available, otherwise 1 = Lrv calculated using an exponential decrease model	dimensionless	0
Rt_LrvmCmSn*i*[Season]	Crop root length density in *i*-th soil layer; necessary if Rt_ACType = 0	cm cm^{-3}	Seasonal — see Table 4.6
Rt_TLrv-Data*i*[Zone]	Tree root density in soil layer *i* in each zone; necessary if Rt_ATType = 0	cm cm^{-3}	Seasonal — see Table 4.6
Rt_CDiam	Crop root diameter. Used in calculating water and nutrient uptake.	mm	0.1
Rt_Tdiam	Tree root diameter. Used in calculating water and nutrient uptake.	mm	0.1
Rt_CLraX0Spec	Total crop root length per unit area at X (distance to tree) = 0 (tree stem). necessary if Rt_ACType = 1	cm cm^{-2}	n/a
Rt_TLraX0	Total root length per unit area at X (distance to tree) = 0 (tree stem). for Rt_ATType=1	cm cm^{-2}	n/a
Rt_CDecDepthSpec[Season]	Parameter determining the rate of decrease in crop roots with depth; necessary if Rt_ACType = 1	m^{-1}	n/a
Rt_TDecDepth	Parameter governing decrease of tree root with depth; for Rt_ATType = 1	m^{-1}	n/a
Rt_TDistShape	Tree root distribution shape. Necessary if Rt_ATType =1	dimensionless	n/a

Table 4.5 Input parameters required for running WaNuLCAS cont.

Group/Parameter	**Description**	**Dimension**	**Value**
System management: Pruning and mulching			
T_PrunDayInput [*n* = 1,…,10]	Day number when pruning number [*n*] started.	days	0 and sowing
T_PrunLimit	Threshold amount of tree biomass at which time the trees will automatically be pruned	kg m^{-2}	n/a
T_PrunTime	Required labour time to prune trees each pruning time	days	25
T_PrunWeight[Zone]	Weighting factor determining the amount of tree pruning going into each zone as mulch relative to other zones (*e.g.* equal distribution in all 4 zones — 1:1:1:1)	dimensionless	1:1:1:1
T_LifallWeight[Zone]	Weighting factor determining the amount of tree litterfall going into each zone as mulch relative to other zones (*e.g.* equal distribution in all 4 zones — 1:1:1:1)	dimensionless	1:1:1:1
Cr_ResidWeight[Zone]	Weighting factor determining the amount of crop residue going into each zone relative to other zones (*e.g.* equal distribution in all 4 zones — 1:1:1:1)	dimensionless	1:1:1:1
Cr_LignResid	Lignin concentration of crop residue (*e.g.* 20% = 0.2)	dimensionless	0.2
T_LignPrun	Lignin concentration in tree pruning	dimensionless	0.2
System Management: Nutrients			
Cq_FertAmountSn[Season]	Amount of each N fertilizer input applied	g m^{-2}	0 for each season
Cq_FertDateSn[Season]	Date [DOY] when each N fertilizer input is given	day	0 for each season
Cq_FertWeight[Zone]	Weighting factor determining the amount of inorganic fertilizer going into each zone relative to other zones (*e.g.* equal distribution in all 4 zones on area basis — 1:1:1:1)	dimensionless	1:1:1:1

4.3 Modelling

4.3.4 WaNuLCAS

Significant advances have been made in the field of modular systems modelling in the time this project has existed. This has allowed groups all over the world to work on different aspects of large, often complex, systems modelling. In the case of the ICRAF generic model, WaNuLCAS, while staff at ICRAF-Indonesia have been refining the broader structure of the model and working on tree and crop growth and yield sub-models, IH has been examining the water balance submodel, and both Wye College (UK) and Reading University (UK) have been investigating the nutrient balance sub-models.

4.3.1 Input requirements

Initial parameterisation of the model

Input parameters for running WaNuLCAS with Machakos data are listed in Tables 4.1 to 4.5. Most of the meteorological and soil water parameters were determined from IH measurements in the field. Other required parameters were obtained from either UNott and ICRAF staff working on CIRUS, from the simultaneous IH root study project or else, in the case of standard crop parameters, from crop 'lookup' tables supplied with the model.

The planting arrangement of the trees in the Machakos agroforestry system required that a linear rather than circular symmetry (**AF_Circ** = 0) was chosen. The four horizontal zones therefore lay within the area between four trees (see Fig. 4.12). Field observations confirmed that the tree canopies tended to overlap along the 3 m between trees along a 'row'. In this sense, we could consider the system to be composed of lines of trees, following the contours of the hillside. As can be seen in Fig. 4.12, the horizontal zones were 0.5 m in width, stretching from the base of the trees to a midpoint between tree lines.

As the two crop rows lay along the boundary between zones, the symmetry of the system meant that modelling was simplified.

Considering the system as essentially a question of two dimensions (*i.e*. horizontal distance away from the tree line, and soil depth) was judged the best choice of the agroforestry system options currently available within WaNuLCAS. At the planting density employed (0.08 tree m^{-2}), the trees would be far too close together to consider them individually, as a semi-savannah like system. However, almost all of the experimental data had been collected before the choice of model had been made. Consequently, the initial requirement was to interpolate from grid point-based measurements to come up with data expressed on the basis of a horizontal 'zone' and a variable-depth soil 'layer'.

Even though WaNuLCAS allows for the possibility of 'similar-depth' soil layers behaving differently depending on their proximity to the tree (*i.e.* in different horizontal 'zones' defined in WaNuLCAS), observations made in the field confirmed that this was unnecessary in the case of the Machakos site; the infiltration rates did not vary laterally to any great degree. Therefore soil water parameters were determined for 'layers' 1 to 4, and used in each of the four horizontal zones between the trees.

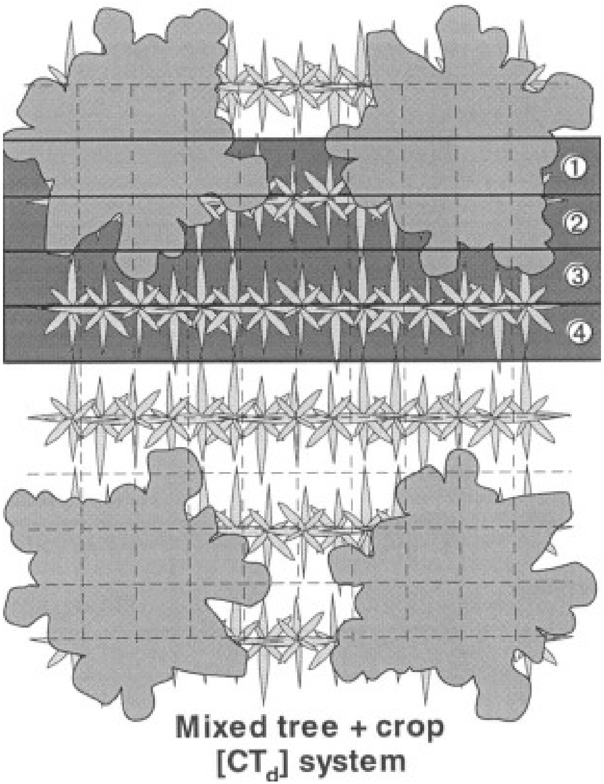


Figure 4.12:
Stylistic representation of the four horizontal 'zones' used when the WaNuLCAS model was applied to the Machakos situation. Each of the zones is 0.5 m wide and effectively infinite in length.

4.3.2 Validation

It was intended to run the simulation over two seasons, using rainfall data from the short rains in 1994-95 (above-average rainfall) and 1995-96 (below-average) input using the **Wanulcas.xls** spreadsheet. As the short rainy season runs over the end of the year [Oct - Feb], this complicates the running of the model which uses a 'day of the year' [DOY] basis. The rainfall and evaporation data were all arranged on the linked spreadsheet as if Jun 1 was DOY 1, instead of DOY 151. Values for other parameters that varied seasonally are given in Table 4.6.

The simulations were run for a little over six months, which included the dry season [June - Oct] when only the trees were growing, followed by the 90 - 100 day crop growing season. The timestep was set at one day, and the model output section was modified slightly to tabulate the data as it accrued [which could then easily be transferred out of the program to be used for graphical comparisons]. It was not the intention of the IH part of the agroforestry experiment to simulate crop and tree growth, as we were interested primarily in how well the model manages to estimate the components of the water balance. In this regard, the first simulation was disappointing. The amounts of rainfall reaching the ground below the tree and crop canopies were generally much higher than field measurements of canopy interception would suggest. In addition, predicted cumulative water losses through runoff were higher than measured, and the model predicted runoff to occur even after storms with low rainfall duration and/or intensities. In the model, soil evaporation is

Table 4.6
Input parameters required for running WaNuLCAS cont. These parameters vary between the seasons used in the simulations, depending on climate, pruning regime *etc.* [*Initial values or values assumed to remain ‘constant’ throughout growth season]. Initial/constant values used as input parameters.

			Short rains 1994-95		**Short rains 1995-96**	
			66o66 a66ra66 s6asona6 rain6a66		**666o6 a66ra66 s6asona6 rain6a66**	
			6nitia6 6a6666	**6ina6 6a666**	**6nitia6 6a666**	**6ina6 6a666**
6ara66t6r6	**66s6ri6tion6**	**6nits6**	**15616694**	**1566695**	**64616695**	**966696**
Rain_Weight[Zn1]	Rainfall	Dimensionless	0.749		0.754	
Rain_Weight[Zn2]	redistribution	Dimensionless	0.798		0.804	
Rain_Weight[Zn3]	by tree+crop	Dimensionless	0.889		0.903	
Rain_Weight[Zn4]	canopies	Dimensionless	0.942		0.947	
W_ThetaInit*1*[Zn1]	Initial & final	$m^{3} m^{-3}$	0.062	0.187	0.071	0.114
W_ThetaInit*1*[Zn2]	soil water	$m^{3} m^{-3}$	0.063	0.189	0.059	0.121
W_ThetaInit*1*[Zn3]	content/zone	$m^{3} m^{-3}$	0.059	0.190	0.063	0.121
W_ThetaInit*1*[Zn4]	in soil layer 1	$m^{3} m^{-3}$	0.064	0.189	0.069	0.117
W_ThetaInit*2*[Zn1]	Initial & final	$m^{3} m^{-3}$	0.145	0.176	0.145	0.156
W_ThetaInit*2*[Zn2]	soil water	$m^{3} m^{-3}$	0.144	0.177	0.144	0.154
W_ThetaInit*2*[Zn3]	content/zone	$m^{3} m^{-3}$	0.148	0.178	0.149	0.156
W_ThetaInit*2*[Zn4]	in soil layer 2	$m^{3} m^{-3}$	0.154	0.179	0.159	0.160
W_ThetaInit*3*[Zn1]	Initial & final	$m^{3} m^{-3}$	0.155	0.190	0.157	0.157
W_ThetaInit*3*[Zn2]	soil water	$m^{3} m^{-3}$	0.151	0.183	0.151	0.156
W_ThetaInit*3*[Zn3]	content/zone	$m^{3} m^{-3}$	0.153	0.182	0.153	0.158
W_ThetaInit*3*[Zn4]	in soil layer 3	$m^{3} m^{-3}$	0.163	0.185	0.164	0.162
W_ThetaInit*4*[Zn1]	Initial & final	$m^{3} m^{-3}$	0.106	0.137	0.112	0.112
W_ThetaInit*4*[Zn2]	soil water	$m^{3} m^{-3}$	0.114	0.157	0.131	0.133
W_ThetaInit*4*[Zn3]	content/zone	$m^{3} m^{-3}$	0.156	0.180	0.159	0.153
W_ThetaInit*4*[Zn4]	in soil layer 4	$m^{3} m^{-3}$	0.182	0.205	0.196	0.171
T_CanBiomInit	Initial canopy/	kg m^{-2}	0.32	0.61	0.61	0.67
T_StemBiomInit	stem biomass	kg m^{-2}	0.39	0.60	0.60	0.83
T_StemHInit	and height	m	2.25	2.31	3.23	3.31
T_CanHMax	Canopy height	m	5.80	6.72	4.10	4.20
T_GroMax	& growth rate	Dimensionless	33.2		19.3	
Rt_LrvmCmSn*1*	Crop root	cm cm^{-3}	0.941		0.309	
Rt_LrvmCmSn*2*	length density	cm cm^{-3}	0.150		0.006	
Rt_LrvmCmSn*3*	in layer 1 … 4	cm cm^{-3}	0.003		0.000	
Rt_LrvmCmSn*4*	(no variation betweeen zones)	cm cm^{-3}	0.000		0.000	
Rt_TLrv-Data*1*	Tree root	cm cm^{-3}	1.835		1.835	
Rt_TLrv-Data*2*	length density	cm cm^{-3}	0.664		0.664	
Rt_TLrv-Data*3*	in layer 1 … 4	cm cm^{-3}	0.096		0.096	
Rt_TLrv-Data*4*	(no variation betweeen zones)	cm cm^{-3}	0.045		0.045	

determined, at least in part, by a value of the average potential bare soil evaporation [$\mathbf{E_{so}}$] over the duration of the simulation run. As it was intended that the simulation runs would also incorporate the dry seasons during which only the trees were growing, the 'constant' value of $\mathbf{E_{so}}$ used in the initial runs (3.96 mm d^{-1}) was the average value over the wet and dry seasons from 1994 through 1996. The suitability of using such long-term average values such as this when $\mathbf{E_{so}}$ can vary substantially on a month to month (or even daily) basis, was investigated later in the project.

It was necessary to inspect some of the sub-models that affect how rainfall is distributed through the agroforestry system. The first of these was the redistribution of incident rainfall by the tree and crop canopies. In the original model the parameter **Rain_Weight[Zone]** acted as a weighting factor, determining how much rainfall reached the soil in any one zone relative to the other zones (*e.g.* equal rainfall in each zone on area basis means 1:1:1:1). This allows for substantial *redistribution* of rainfall between zones below the canopy, but does not introduce any concept of *interception* loss of rainfall by the canopy. In areas with more generous rainfall climates, the fraction of rainfall lost through interception may be insignificant, but this is not the case in semi-arid agroforestry systems such as that at Machakos, where observations confirmed that interception could account for anything up to 20% of all rainfall.

Also part of the rainfall sector or submodel, the parameter **Rain_FracRunoff** is a weighting factor that determines a certain fraction of *all* rainfall that is lost through runoff. This approach implies a constant relationship between rainfall and runoff - *e.g.* 20% lost through runoff regardless of whether the rainfall event was 6 mm or 60 mm, and is unrealistic. Additionally, it does not allow for the concept of a threshold - *i.e.* a rainfall amount below which runoff does not occur. It was relatively simple to adjust the model to incorporate the variable relationship and threshold rainfall value reported in section 4.2.2.

Figure 4.13 shows part of the rainfall sector within the WaNuLCAS model (see Fig. 3.8 for complete sector structure) with and without modifications made. As the **Rain_Weight** parameter was changed to become a fraction of rainfall permitted to pass through the canopy (*throughfall*), the **Rain_WeightTot** parameter was no longer required. **Rain_Weight** acted on **Rain** to produce a new (intermediate) parameter **Rain_Throughfall**, representing the process of canopy rainfall interception. **Rain_Throughfall** was then acted on by the runoff submodel parameters (**Rain_Slope**, **Rain_RunoffOffset** and **Rain_RunoffLimit**) to produce **Rain_In**, the rainfall input to each of the horizontal zones. Values for the modified **Rain_Weight** parameter were obtained from measurements of rainfall interception made beneath the tree and crop canopies over the 1994-95 and 1995-96 short rains. Again, point measurements were converted to values for the 0.5 m horizontal zones.

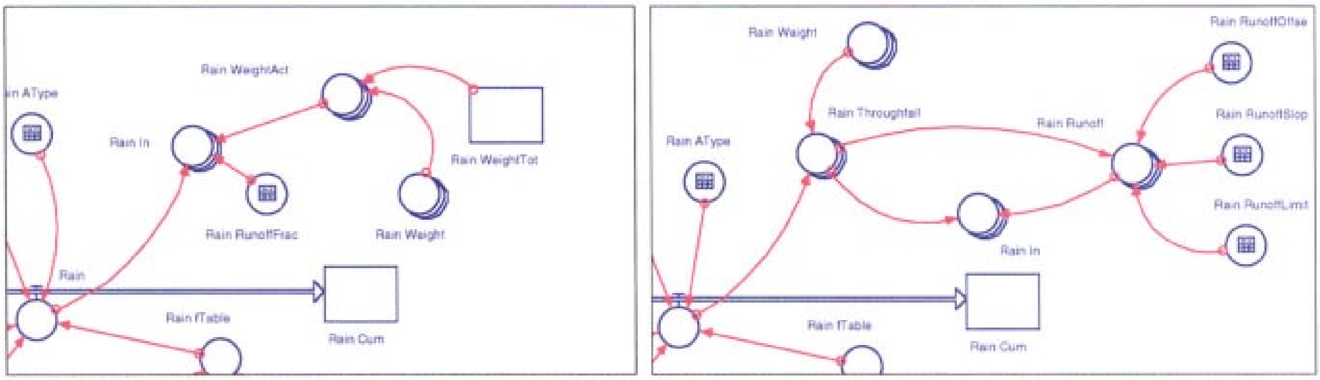


Figure 4.13:
Part of the rainfall sector (submodel) from the original, unmodified WaNuLCAS model (**left**) and the modified version (**right**), which incorporates canopy rainfall interception as well as redistribution, and also a variable rainfall-runoff relationship with a threshold rainfall limit.

To test the effect of these modifications, the original and modified models were run with the same data sets from both 1994-95 and 1995-96 short rainy seasons.

Firstly, in order to compare values of throughfall (where this parameter did not exist explicitly in the original model), the unmodified model was run with the fractional values for **Rain_Weight[Zone]** given in Table 4.6, with **Rain_RunoffFrac** set to zero.

Secondly, the effect of a variable versus constant rainfall-runoff relationship was compared. For the 1994-95 short rains shown in Fig. 4.14 the constant value [**Rain_RunoffFrac**] was set to 0.12 (the cumulative fraction of runoff determined from field observations), and the variable relationship was parameterised as follows. The original equation of Wallace *et al.* (1996) related runoff to *gross* precipitation. However, due to the structure of the model (see Fig. 4.13) the equation had to be recalculated, expressing runoff as a function of *throughfall*. The value of the parameters **Rain_Slope**, **Rain_RunoffOffset** and **Rain_RunoffLimit** were defined as 0.2988, -1.835 and 7, respectively. The graphical comparisons of results from the 1994-95 short rains are shown in Figure 4.14.

The first thing to note is the way that the original **Rain_Weight** parameter redistributes the rainfall around the mean of 610 mm (dark line, top graph). The redistributed rainfall ranges from between 530 mm in zone 1 (closest to the tree line) through to 672 mm in zone 4. It is possible that redistribution of rainfall might occur to such an extent that some zones might receive 'throughfall' [P_t and P_c from Fig. 3.4] that is greater than the incident rainfall [P_g], given a substantial canopy, with branches than hang down away from the trunk. However, such a phenomenon was never observed at Machakos, where throughfall was always lower than P_g. When the modifications to the model were introduced, throughfall ranged between 457 mm in zone 1 through to 579 mm in zone 4 in between the tree lines.

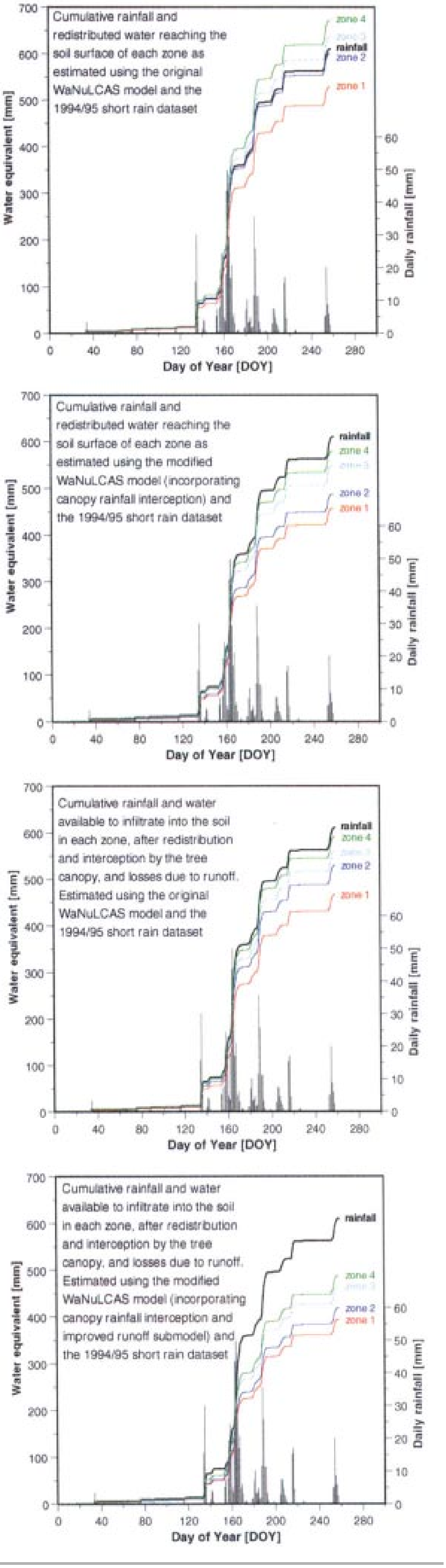


Figure 4.14 (opposite):
Comparisons of redistributed rainfall (or *throughfall*) estimated using original and modified versions of the WaNuLCAS model, and the 1994-95 short rains data set. See text and graphs for details.

When runoff is included in the model [lower two graphs in Fig. 4.14], the effect of the constant value of **Rain_RunoffFrac** is to reduce the resultant water input to the soil in all four horizontal zones to below P_g. However, the net input of water to the soil midway between the lines of trees [zone 4] was only reduced by 3%. This is substantially less than was predicted using the variable runoff relationship [19%] or was observed in the field [17%]. The original model estimated that rainfall was redistributed and reduced by 23% in zone 1, as compared to 35% in the modified model, and between 25 and 40% from field measurements.

These differences highlight one of the potential problems associated with oversimplification of basic processes within agroforestry systems, and also the fact that the necessary level of complexity in modelling may be dependent on the sort of climate that the model is required to simulate. The Machakos site has an almost temperate rainfall climate in the sense that a large percentage of the rainfall comes in small, evenly spaced rainfall events. If no threshold exists below which runoff cannot occur, then a large [cumulative] overestimation of runoff may result. Similarly, small, frequent rainstorms will leave a substantial fraction of the rain on the tree canopy, which will subsequently be lost through evaporation rather than reaching the soil surface.

After the modifications had been added to the model, the agreement between the simulated and observed infiltration of rainfall into the soil was much better than with earlier model runs. There were, however, still some instances where estimated and measured soil water contents did not agree. Figure 4.15 shows the modelled vs. measured water storage [mm] in the uppermost soil layer [layer 1 : 0.15 m] over the course of the 1994-95 short rains. Given that the graph is comparing daily values [modelled results] with hourly measurements obtained from the two TDR sensors closest to the surface, the agreement between the two traces is good. However there are at least two cases [~DOY 138 and 182] where the model significantly overestimates water infiltration into the surface layer. The first, and far greater of these overestimations is likely to have been the result of a massive runoff event occurring at the start of the rainy season. At this point the soil had been dry for a number of months, and had developed a crust [typical of these soils] that inhibited infiltration. On the basis of rainfall and preceding surface soil water content, the model predicted greater infiltration than was observed to occur. Fig. 4.4 showed the daily variation in rainfall amount and intensity and this can cause disparaties between measured and modelled data of up to 24 hours as rainfall occurring late in the evening (common) will be input as to the model as that day's daily rainfall, although the TDR or other measurement techniques may not detect a change in soil moisture status until the following day.

Wallace *et al*. (1995) found that when soil evaporation was modelled on a daily timestep basis, the day-to-day agreement was not always very good, but when looked at over the longer scale of weeks or months, the cumulative results agreed very closely. This appears to be the case with modelling the surface soil water infiltration, *i.e*. certain events are over- or underestimated, but the overall simulation is good. This is an important point to make, as although the model calculates all the parameters on a daily basis, the results that are of general interest are expressed on a seasonal, yearly or even longer basis.

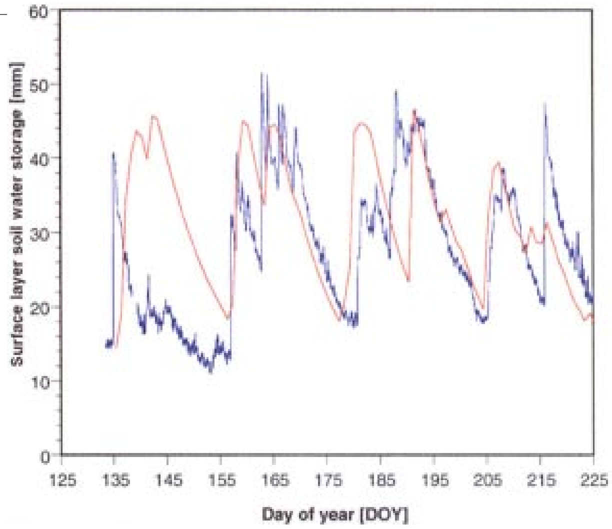


Figure 4.15:
Modelled [thin line] and measured [thick line] surface soil water storage [mm] over the 1994-95 short rains. Measured values come from the uppermost two TDR sensors, while simulated values come from the modified WaNuLCAS model.

The problem of matching data with different timesteps is also apparent in Figure 4.16, which shows gradual wetting up of the next layer down [layer 2 : 0.15 to 0.75 m] over the same time period as in Fig. 4.15. The neutron probe measurements, made weekly, were generally in good agreement with the modelled data.

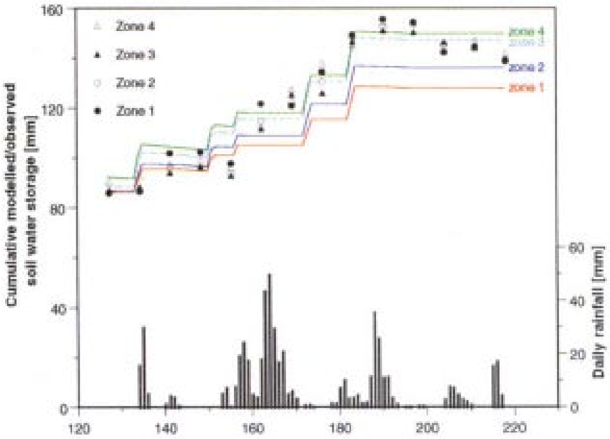


Figure 4.16:
Modelled [thin lines] and measured [symbols] soil water storage [mm] in layer 2 [0.15 - 0.75 m] over the 1994-95 short rains. Measured values come from weekly neutron probe measurements, while simulated values come from the modified WaNuLCAS model. Daily rainfall for the period is also shown.

However there were occasional disagreements, when rainfall occurred soon after neutron probe measurements had ended. Also, the measured data peaks around DOY 195 and then starts to gradually decrease as water is lost through drainage and/or abstraction by tree and crop roots. This decrease is not exhibited by the modelled data where the soil layer fills up gradually over the season until maximum capacity is reached. After that point, drainage commences to the layer below [layer 3], following the bucket-type approach of the water balance model. As mentioned earlier, tree water use efficiency values were unavailable at the time when modelling was undertaken, and consequently the tree water uptake was uncertain. This problem will be dealt with more specifically later on, but it is clear that while the measurements suggested that this season demonstrated a significant recharge in the soil water storage, and that significant abstraction was going on toward the end of the season, the model, using standard tree WUE values, did not give the same result. Further indications that there was a problem was apparent in the diverging pattern between modelled water storage values [grey lines] in the different horizontal zones as compared to relatively stable and small differences apparent in the equivalent measured values [symbols].

Losses of water through soil evaporation were expected to be high at Machakos, given the tropical location and the rainfall characteristics. We were interested in possible variations in modelled soil evaporation output that might result from using seasonal rather than monthly, or even daily, bare soil potential evaporation rates [E_{so}]. In the original run, the user was required to input a value of E_{so} that would remain constant throughout the entire simulation. The model was modified so as to give the user a choice of inputs. Where monthly (or even daily) E_{so} data were available, they could be input via the **WaNuLCAS.xls** spreadsheet in a similar fashion to rainfall data. Figure 4.17 shows the daily and cumulative soil evaporation in each of the four horizontal zones over the course of the 1995-96 short rains, using the constant value of E_{so} from the original model, and the variable monthly value of E_{so} from the modified version.

Using the constant value for E_{so} reduced the cumulative evaporation over the period from ~141 mm (49% of rainfall) to 118 mm (41%). This is due largely to the fact that potential evaporation rates are low in the dry season when the climate is particularly cloudy and dry. Despite the fact that the trees are still growing during this cloudy, often cold, season, rainfall events are extremely small and widely dispersed. Monthly average values of E_{so} over the period varied between 2.66 and 5.37 mm d^{-1}, with the higher values occurring during the months with the highest rainfall. Previous attempts to model the soil evaporation at Machakos, using a modified Ritchie-type evaporation model (Wallace *et al*. 1996). Soil evaporation estimates were made using simulated evaporation values for shaded and unshaded areas, and scaling these proportionally according to the total fraction of shaded/unshaded soil surface. The area-average soil evaporation over an 18 month period from Jan 1, 1994 to Jul 1, 1995 as 613 mm, approximately 50% of the rainfall during the period. The WaNuLCAS simulation over a

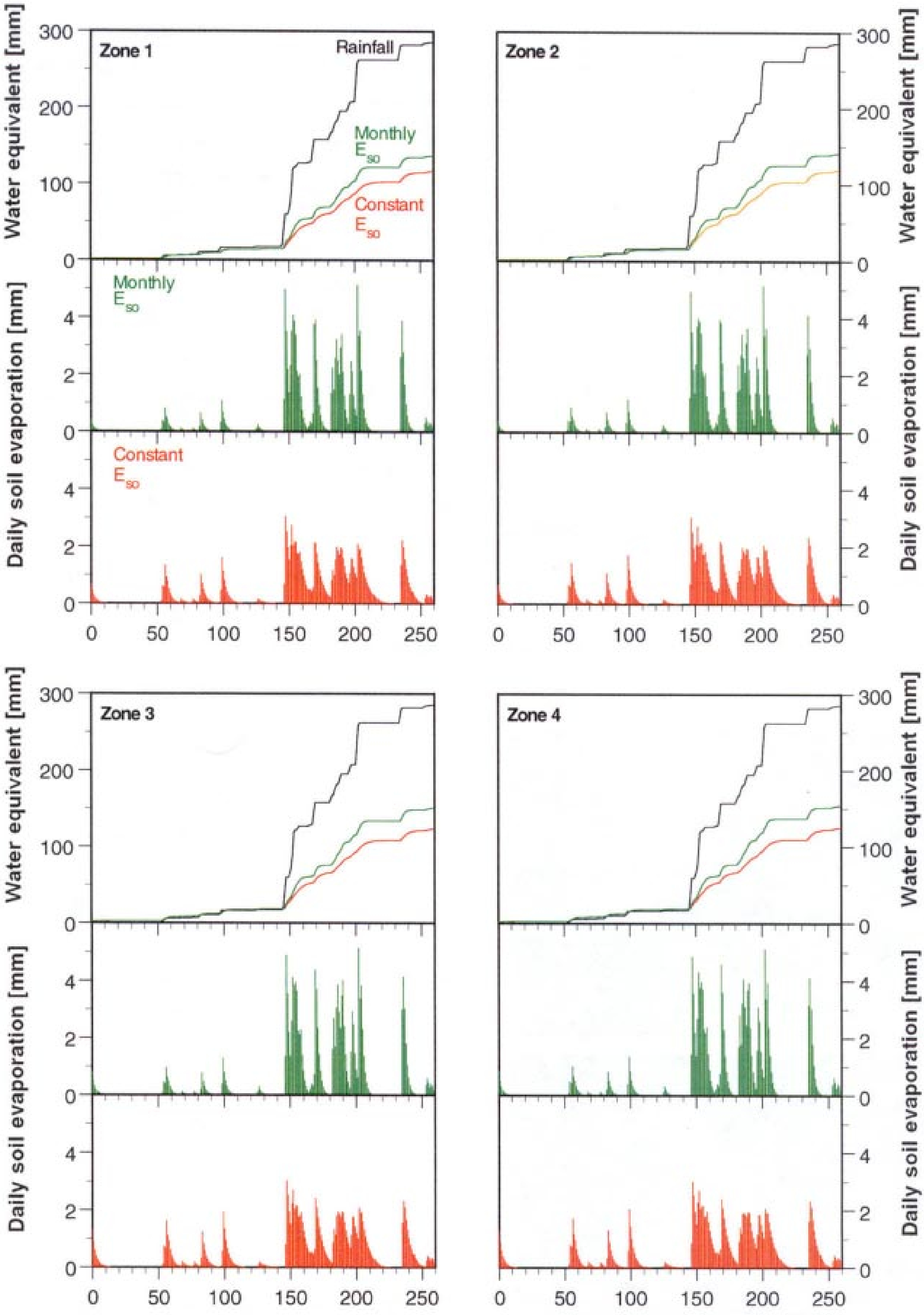


Figure 4.17:
Simulated evaporation from the soil surface in the four horizontal zones, estimated using the modified WaNuLCAS model, and either the constant (**Evap_Pot_Type** = 0) or monthly average (**Evap_Pot_Type** = 1) values for bare soil potential soil evaporation rate [$\mathbf{E_{so}}$]. Daily values of soil evaporation are shown as well as cumulative evaporation and rainfall.

different, shorter period, using the monthly average value of soil evaporation was very close to this at 49% of rainfall. Using the daily data set of $\mathbf{E}_{so}$ values (**Evap_Pot_Type** = 2) gave a cumulative evaporation of 47% of rainfall; a difference that did not seem to warrant the extra complexity in data collection.

On investigation, the biomass output graphs from the model (Figure 4.18) predicted that although crop growth was greater (in zones 2 ... 4) during the above-average rainfall season of 1994-95, no crop growth occurred in zone 1 (closest to the tree) in either season, despite evidence to the contrary observed during both seasons (Plates 4.4 and 4.5). It was not within the IH remit to investigate this aspect of the agroforestry system, but there are clearly some areas on the initial parameterisation that are currently incomplete. As mentioned earlier, values for the water use efficiency of the *Grevillea robusta* were unavailable at the time when modelling was undertaken, and values for the crop were taken from the crop lookup table for maize supplied with the model. It is worth noting that the variety of maize used in the experiment (*Katumani* composite) was specifically bred to mature within a 90 - 100 day period, and therefore some of the typical maize parameters may not necessarily be appropriate.

The model suggests that tree canopy biomass seems to recover quickly after pruning at the start of both the dry and rainy seasons. However, it suggests that in both dry seasons the canopy expansion was limited, presumably by available soil moisture. Measurements of canopy expansion were not made during the dry season, and therefore the model prediction cannot be accurately confirmed nor refuted.

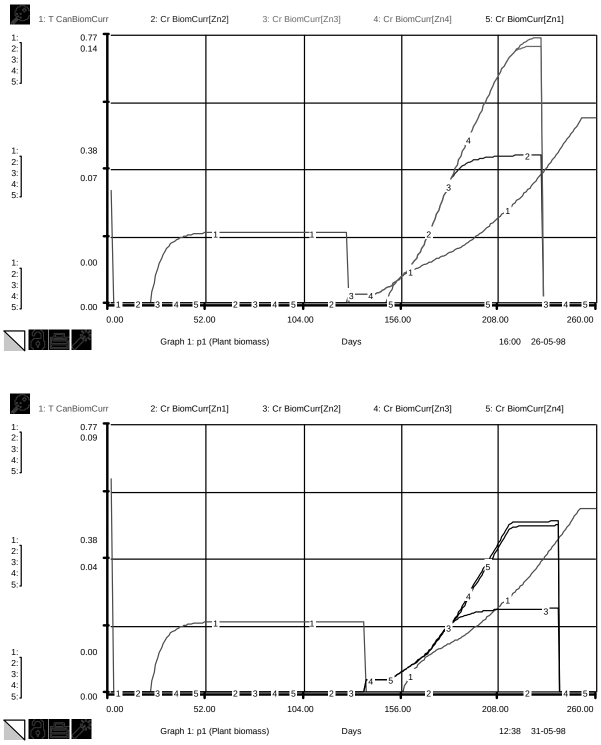


Figure 4.18:
Output graphs from the modified version of the WaNuLCAS model showing the tree canopy biomass (variable 1 in both graphs), and the crop biomass in zones 1 ... 4 (see graphs for variable numbers). The seasons simulated are the 1994-95 short rains (**top**) and the 1995-96 short rains (**above**).

Plates 4.4 and 4.5:
Photographs from the midpoint of the 1994-95 short rains (**top**) and towards the end of the 1995-96 short rains (**above**), demonstrating that the maize crop produced some biomass (if little harvestible yield) even in zone 1 (closest to the tree line).

4.3.3 Sensitivity analysis

By conducting analyses of the various sectors associated with the water balance portion of WaNuLCAS it may be possible to enhance the model in terms of how input parameters are used, and help to identify particular parameters that are key to determining the water balance and hence should take priority in terms of field measurements required for validation. In terms of a semi-arid hillslope agroforestry system such as that at Machakos, prior investigations suggested that these 'key' factors would be interception, runoff and soil evaporation.

Both observed and model results presented in this report suggest that canopy rainfall interception is of major importance in semi-arid agroforestry systems. The modifications made to the model were incomplete in the sense that static interception values had to be assigned to the model for each simulation run, rather than allowing interception to be a dynamic property of canopy cover *etc*. as in the Gash model of sparse canopy interception. In the longer term, it is hoped that the Gash model or some other simulation will be able to be incorporated as a user-option, linked to the growth part of WaNuLCAS so that as the canopy expands (or contracts following pruning) the rainfall interception parameters would be altered.

Runoff has previously been considered to be of limited significance in the context of Machakos, as severe runoff events are few and far between - often occurring with a frequency (years) of less than the average lifespan of the *Grevillea* before they are harvested. However, it is still important to predict runoff accurately, particularly because major runoff events often occur (as mentioned earlier) towards the start of the crop growth season when the soil is very dry and has developed a crust. If runoff at this point is significantly underestimated, infiltration will, necessarily be overestimated and premature crop emergence and growth will be the modelled result.

The importance of including a runoff threshold limit has already been demonstrated, but an additional number of simulations were made when the limit was varied upwards from 7 mm to 28 mm. The results are shown in Figure 4.19. Increasing the runoff limit from 7 to 14 mm reduced predicted runoff by 13% in the 94-95 rains, and by 18% in the 95-96 rains. Further increasing the runoff limit to 21 mm reduced predicted runoff by 45% in 94-95, and by 66% in 95-96. With a threshold limit of 28 mm, the model predicted no runoff would occur during the average-rainfall 1995-96 short rains, while predicted runoff during the above-average 1994-95 rains was reduced by more than 64%.

This analysis confirmed that the model was working well, and attributing the majority of runoff to major rainfall events, with smaller events causing little or no runoff. Changing the slope and offset of the variable rainfall/runoff relationship had a greater effect on the runoff, but this serves to demonstrate the limitations of adopting an empirical approach to a parameter within what was intended to be a generic agroforestry model. It would, however, be possible to

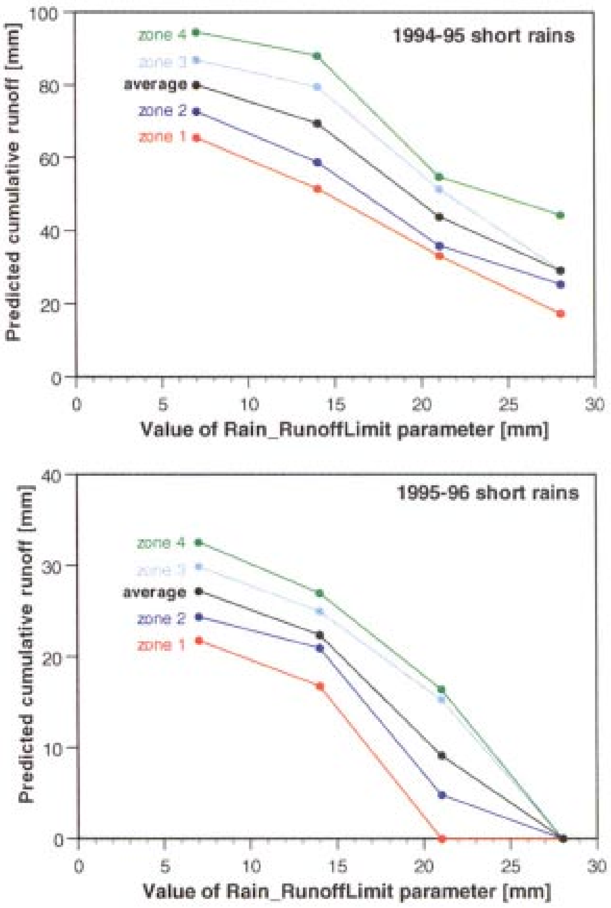


Figure 4.19:
The effect of changing the **Rain_RunoffLimit** parameter (the threshold limit below which runoff does not occur) on the estimated cumulative runoff from the four horizontal zones in the short rains of 1994-95 (above average rainfall) and the short rains of 1995-96 (average rainfall).

incorporate some form of feedback approach to runoff generation linking antecedent soil moisture conditions (already simulated) to crusting or saturated soil water contents, either of which would lead to runoff generation.

As in the case of tree canopy growth, it was impossible to accurately assess the model's capability to simulate water uptake by the trees in the various vertical soil layers as the water demand (or requirement) was uncertain as the tree water use efficiency parameter (**T_TranspRatio**) was unknown. This parameter was identified as one of the key factors mentioned above, and the dependence of water uptake from the four vertical soil layers was examined as a function of the value of **T_TranspRatio**. Figure 4.20 shows how the uptake in all of the four layers increases with **T_TranspRatio**). This is particularly evident in layers 2 and 3 (at 1.35 m, the bulk of the soil profile) when an increase in **T_TranspRatio** from 60 to 150 l kg^{-1} more than doubles uptake from the profile from 35 to 72 mm. Various other parameters such as the tree light extinction coefficient (**T_*k*LightSpec**) were investigated to see if, through increased canopy growth, they would increase tree water uptake. None seemed to be as important in determining tree water demand as the water use efficiency.

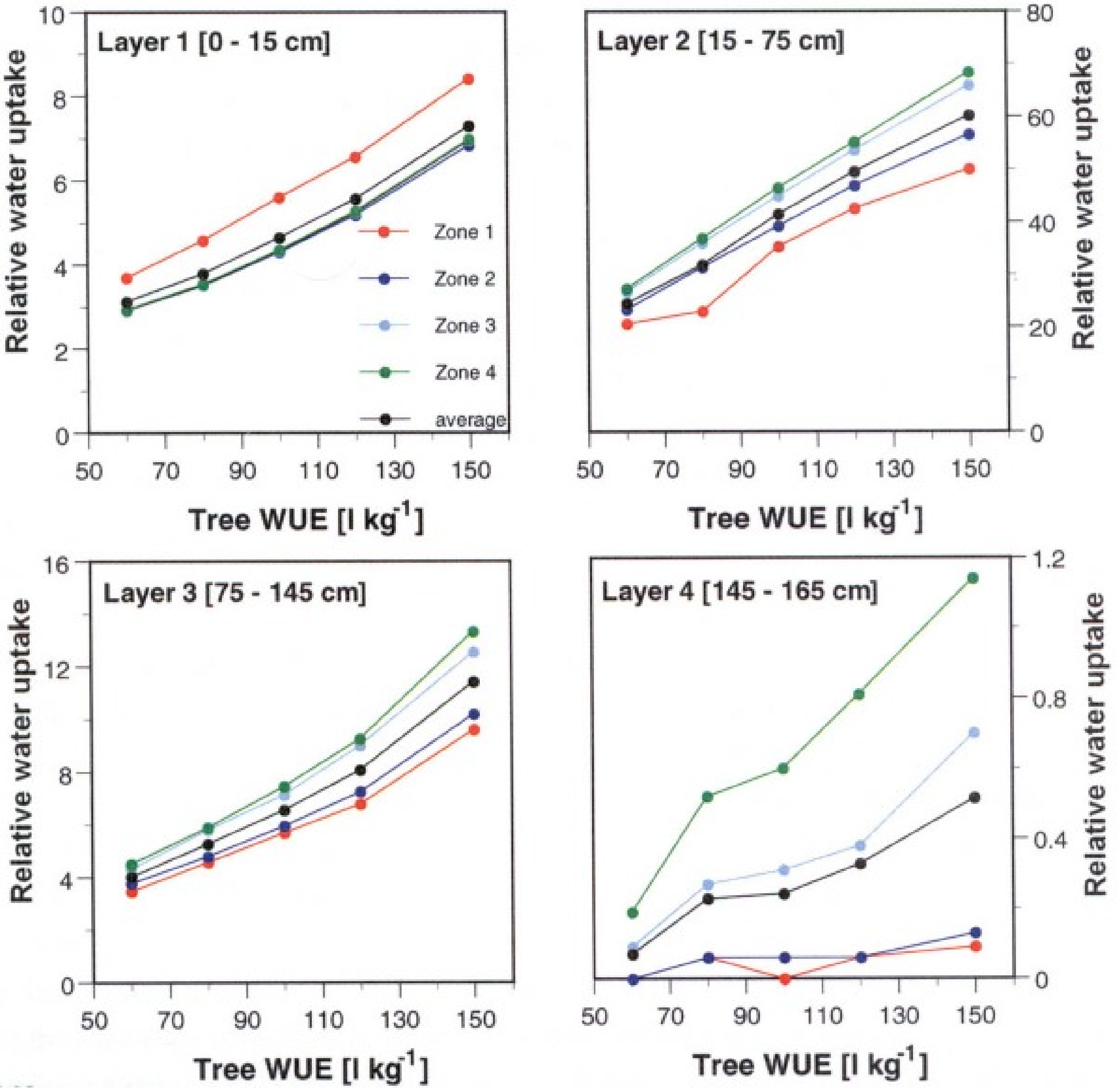


Figure 4.20:
Sensitivity analysis of the modified WaNuLCAS model investigating the effect of increasing tree water use efficiency (**Tree_TranspRatio** parameter) on relative water uptake [mm] from each vertical soil layer in each horizontal soil zone during the 1995-96 short rains. **Tree_TranspRatio** was varied between realistic values of 60 to 150 l kg^{-1}.

4.3.4 Conclusions and recommendations

The work presented in this report concentrated on the water balance of the CIRUS agroforestry experiment and generally ignored aspects of tree and crop growth and yield as this was being separately modelled by University of Nottingham and ICRAF staff. For this reason, we are able to make recommendations on how the hydrological aspects of the WaNuLCAS model might be improved, rather than the model as a whole. The main conclusions are summarised below.

Identification of 'key' parameters within model

As Lott *et al*. (1997) demonstrated with the HyPAR agroforestry model, some parameters can drastically affect the accuracy with which a model can simulate natural processes. In our limited experience with the WaNuLCAS model, we identified two such parameters : one from the original, unmodified model (tree water use efficiency - **T_TranspRatio**), the other as part of a modification we ourselves made to the model (runoff threshold - **Rain_RunoffLimit**). No doubt other such '*key*' input parameters exist and we recommend that the model be closely examined to identify them. Once this is achieved, a '*checklist*' can be assembled of parameters that need to be independently validated if the model is to be applied to other regions with different climate, soil type or tree/crop mixtures. It is worth noting, however, as suggested by Lott *et al*. (1997), that this could undermine the express reason for developing generic agroforestry models; *i.e*. the ability to simulate system behaviour in new environments or over extended periods of time during which interseasonal variation is expected to occur.

Rainfall interception by the tree and crop canopies

As mentioned earlier, losses of rainfall due to the interception by plant canopies can be severe in semi-arid climates. It is therefore crucial to have a submodel that can simulate this accurately - an element missing from the original version of WaNuLCAS we were working with. The **Rain_Weight** parameter which acts to redistribute rainfall across the four horizontal zones ignores interception and, as a minimum, we recommend the adoption of the modifications made by us and presented earlier in the report, as it is difficult to imagine a situation where absolutely no canopy rainfall interception occurs at any point during the year. In the longer term it would obviously be preferable to develop some dynamic feedback interaction between the expansion (or reduction) in tree and crop canopies and the consequent rainfall interception. As can be seen from some of the data collected at Machakos, the process of stemflow can be an important part of the interception process. This is not simulated by either the original or modified versions of the model, but might be a welcome '*user option*' to incorporate into future releases of the model.

Runoff as a function rather than fraction of rainfall

The importance of determining a functional relationship (slope and offset) between rainfall and runoff was demonstrated. In the case of rainfall climates with a small average size of rainfall event the application of a constant-fraction approach to runoff may not correctly simulate the process. Even if the model makes an accurate estimation of seasonal cumulative runoff using this approach, individual runoff events will be over- or underestimated, with a knock-on effect on water available for other processes such as infiltration and soil evaporation.

Our recommendation is to offer the user a choice to replace **Rain_RunoffFrac** with the combination of **Rain_RunoffSlope**, **Rain_RunoffOffset** and **Rain_RunoffLimit** where a dynamic relationship between rainfall and runoff can either be measured or inferred. In any case, runoff should be a function (or at least a fraction) of the *throughfall* [$\mathbf{P_c}$ and $\mathbf{P_t}$] and not of the gross precipitation [$\mathbf{P_g}$]. Runoff type could be then be selected (as is rainfall type in the original model, or evaporation type in the modified version) on the basis of what data is available for the region in question.

Long term (multi-season) average values of potential soil evaporation rates

As in the section above, it is suggested that the user should be offered the choice of how they wish the **Evap_Pot** parameter should be defined. Clearly in some cases such as Machakos, where there is considerable variation in $\mathbf{E_{so}}$ between the wet and dry seasons, long-term average values can overestimate soil evaporation when rain is infrequent, and underestimate evaporation when the soil is wet. Modifications to the model such as those we have introduced would allow the user to input monthly or even daily $\mathbf{E_{so}}$ data where present, and to choose a constant value if that is warranted or indeed the only available data.

Flexibility in pruning/managing tree canopy dynamics

It is commendable that WaNuLCAS incorporates pruning, as if it did not then its addition would be one of our major recommendations. Lott *et al*. (1997) has recommended the addition of pruning to the HyPAR model for the same reasons as we have identified, namely that agroforestry systems with closely planted trees will only ever succeed if the tree canopies are regularly pruned to minimise their competitive impact on understorey crops. However, when pruning was introduced to the WaNuLCAS simulations, canopy biomass was reduced far more (~ 100%) than was commonly the case in the field, where normally only the lowermost metre of the canopy (~ 15%) was removed. We recommend that there needs to be some way in which *partial* pruning can be selected. The farmers in Kenya do occasionally remove all the canopy during pruning, but this is not always the case and can be deleterious in the case of many species.

Soil physical characteristics

There will be further development in producing pedotransfer functions describing water movement through *tropical* soils and it recommended that these be incorporated as soon as possible into the associated **Wanulcas.xls** spreadsheet. At present it is likely that the functions developed by Wösten *et al*. (1995) do not adequately reflect the typically high sand/clay and low silt soils common to many areas of the tropics. Indeed just such research is currently being undertaken at the Institute of Hydrology and it is intended that any resulting functions should be added as a user option to later releases of the WaNuLCAS model.

In the meantime it is recommended that water movement through tropical that is simulated using temperate-based pedotransfer functions should be treated with caution until proven correct. That said, these functions did an adequate job of simulating the recharge in the Machakos soil profile, even if uncertainty concerning soil water depletion rates meant that simulated drainage rates from each soil layer could not be accurately compared with observed rates.

Additional climatic variables as possible input parameters

Given that most meteorological data files that one would intend to use with WaNuLCAS contain variables such as solar radiation, air temperature and relative humidity, wind speed *etc*. it is surprising that more of these are not used as input parameters in the model. For instance, an estimate of bare soil evaporation, even if it is a yearly average, might be weighted to give more appropriate monthly values by the utilisation of generally ubiquitous daily class A pan evaporation values. These kinds of data normally accompany rainfall data and their utilisation might add to the power of the model.

Agroforestry systems other than rain-fed systems

At present, WaNuLCAS only simulates agroforestry systems that are entirely rain-fed. However, systems are relatively common where some (often a large part) of the water demand is met by alternative sources. These include situations where a water table is accessible by the tree (and sometimes also the crop) component, or a hillside system where substantial amount of water (and sometimes nutrients) are brought into the system through runoff from less vegetated areas higher up the slope. Less common, but still interesting, are systems where measurable amount of water input are derived from fog and mist interception in tropical regions.

At present, none of these situations can be modelled using WaNuLCAS and our recommendation is that at least the possibility of an accessible water-table should be included in the model, particularly if (as in the most recent release of the model) the phenomenon of hydraulic lift is supported. This is one way in which agroforestry systems might be made to work - *i.e*. if water from depth can be redistributed vertically by the tree roots, some of which then becomes available to the crop roots.

5 Outputs vs. Objectives

Project R6364 was designed to address the question of how to increase the contribution of trees to the productivity of tree/crop based systems. To achieve this, it was intended that through a combination of field data collection and model development and validation, knowledge of above- and below-ground tree/crop interactions would be improved, and this knowledge would be incorporated into management strategies.

5.1 Defining both total and component water use of a 4 to 5 year old *Grevillea robusta*/ crop agroforestry system

The main objective of this part of the project was to quantify the water use of crops and trees in a well-established agroforestry system containing mature trees. The various water balance components of the system were measured over the course of several seasons, during which time both the water available to trees and crops varied enormously due to above- and below-average rainfall, and the water demand of the trees was affected by different pruning practices.

The field data showed that evaporation and rainfall interception were strongly dependent on tree canopy size, and together accounted for between 40 and 65% of the seasonal rainfall. Runoff accounted for between 5 and 13% of rainfall, and was affected by the extent of the tree canopy. Occasional extreme runoff events occur that can have drastic results in terms of water and soil lost from the system. However, these are difficult to predict, and may never actually occur within the 5 - 8 years it takes for the tree component to mature and the agroforestry cycle to be repeated.

Soil water content measurements showed that, with the exception of seasons where rainfall was considerably greater than the seasonal average, profile water recharge did not occur below about 0.9 m. Given the free-draining nature of the sandy-loam soil and the high density planting of trees and crops, the lack of recharge below 0.9 m was attributed to high rates of abstraction of soil water by tree and crop roots near the soil surface. Data from the parallel tree/crop root experiment (Smith *et al.*, 1998) demonstrated that the distribution of both tree and crop roots was greatest in the uppermost soil layers. In semi-arid agroforestry systems that are entirely rain-fed, it appears almost inevitable that competition will arise between the trees and crops for available soil water, unless enough rainfall occurs to recharge to soil below the crop rooting zone. Apart from the occasional season (such as the 1994-95 short rains) with rainfall significantly greater than average, such deep-profile recharge is unlikely to occur in the semi-arid regions (McIntyre *et al*., 1997).

In semi-arid, rain-fed agroforestry systems where the tree component is allowed to grow to a large size, management strategies to curb the tree water demand must be employed, at least during the crop growth season. These will include initial decisions on tree planting density and distribution (contour/ grid/boundary planting), canopy pruning (regularity and extent), and in severe cases root pruning through trenching. Caution should be exercised in the choice of tree, bearing in mind that species such as *Grevillea*, that are observed to draw large amounts of water from depth in their natural environment (north Australian rainforest, surrounded by other woody perennial species), will almost certainly behave differently when grown in drier climates, shallower soils and able to dominate the root zone in the absence of perennial competitors.

5.2 Modelling the water balance of the system, describing competition for water and seasonal water uptake of both trees and crops.

The modelling aspect of the project was completed after data from enough situations where variations in the rainfall climate, the age and size of the trees, and their resource demand, were accumulated to accurately validate the model. The accumulated dataset covers a 5½ period from when the tree plots were established and should greatly benefit future model development and improvement.

The modelling work consisted of using ICRAF's generic agroforestry model, WaNuLCAS, to simulate the water balance of the Machakos agroforestry system. Although further validation is required, the simulated values of most water balance components was similar to field observations. The principal conclusions following the modelling exercise were highlighted in the previous section. The improvements to the model included more correctly simulating above-ground processes such as canopy rainfall interception and runoff, and enabling more discrete climatic data to be used as input parameters. They are aimed at assisting end-users who may have access to similar sorts of climatic data. Users of the model will be able to simulate situations in which agroforestry systems may or may not succeed on the basis of complementary or competitive tree/crop interactions.

6 Contribution of outputs

6.1 Outputs, dissemination and agreed evaluation criteria

The planned outputs, proposed dissemination pathways and agreed criteria by which project R6364 would be monitored and evaluated were as follows:

Outputs

- The compilation of a comprehensive database on all aspects of the water balance of a tree/crop agroforestry system, comprising data from seasons with varying rainfall amounts, and at various ages and sizes of the tree component.
- Quantifying abstraction of water at different depths in the soil, thus providing information on the complementary or competitive nature of tree/crop interactions.
- Agroforestry system water balance models
- Reports to the DFID Forestry Research Programme
- Publications in refereed journals, conference proceedings and DFID reports.

Dissemination

The results obtained from the project will be disseminated through published papers in refereed journal and reports, presentations at conferences and workshops, and through requests from scientists and extension workers involved with agroforestry.

Agreed evaluation criteria

- Completion of field experiments within the specified timescale; compilation of water balance component database.
- Validation and improvement of agroforestry system model (water balance submodel) using data from the database
- Completion of final report to DFID Forestry Research Programme and publication of results in refereed journals
- Dissemination of results through ICRAF agroforestry extension networks (AFRENA).

The first three **outputs** have all been successfully completed and the results presented in this report. This work constitutes output 4, the final report to the DFID Forestry Research Programme. Other results from the project have been published or are at various stages of publication at present (see section 6.2 below).

Dissemination has already started, with requests for data having been received from other members of the FRP Agroforestry Modelling Project, and it is intended that both the data and modelling results will be disseminated through the AFRENA and CGIAR extension networks.

6.2 Published articles and commissioned reports

Allen, SJ, Roberts, JM, Smith, DM, Jackson, NA and Lawson, GJ. (1997) Simulating the interaction between tree cover and crop temperature in integrated agroforestry models. *Agroforestry Forum* **8**(2): 20-23.

Jackson, NA and Wallace, JS. Rapid changes in surface soil water content measured with high spatial resolution using time domain reflectometry. Submitted to *European Journal of Soil Science*

Jackson, NA, Wallace, JS and Ong, CK. Tree pruning as a means of controlling water use in an agroforestry system in Kenya. Submitted to *Forest Ecology and Management*

Jackson, NA. A detailed calibration of the neutron probe technique for soil moisture measurement in highly heterogeneous tropical soils. Submitted to *Journal of Hydrology*

Jackson, NA and Wallace, JS. Soil evaporation in a *Grevillea robusta* agroforestry system. I. Use of microlysimeters to measure soil evaporation. Submitted to *Agricultural and Forest Meteorology*

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Wallace, JS, Jackson, NA and Ong, CK. Soil evaporation in a *Grevillea robusta* agroforestry system. II. Modelling the effects of a tree canopy. Submitted to *Agricultural and Forest Meteorology*

Wallace, JS. (1997). Evaporation and radiation interception by neighbouring plants. *Quarterly Journal of the Royal Meteorological Society* **123**: 1885-1905.

6.3 Dissemination as part of other reports

International Centre for Research in Agroforestry (1994). Annual report 1993, pp. 67 - 73. ICRAF, Nairobi, Kenya.

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Smith, DM, Jackson, NA and Roberts, JM (1998). Root quantity, activity and below-ground competition in *Grevillea robusta* agroforestry systems. Final Report to the Forestry Research Programme, DFID.

6.4 Seminars, lectures and conference presentations

Jackson, NA. (1995). Water balance of Kenyan hillslope agroforestry systems. Presentation to ODA Agroforestry Modelling Workshop. ITE Edinburgh, January 1995.

Jackson, NA. (1995-97). Water balance of hillslope agroforestry systems. Presentation to International Youth Science Forum. London, Summer 1995 - 1997.

Jackson, NA, Smith, DM, Roberts, JM, Wallace, JS and Ong, CK. (1997). Water balance of agroforestry systems on hillslopes. Presentation at CIRAD/INRA workshop : l'Agroforesterie pour un développment rural durable. Montpellier, France. June 1997.

Roberts, JM. (1997). Agroforestry: making plants work together. Exhibit at the Royal Society New Frontiers in Science Exhibition. June 18-19, 1997, London.

6.5 Training

- Several agroforestry training courses for scientists, farmers and other participants were run at Machakos over the course of the 5½ years and the IH staff were involved in training in almost all cases, using the CIRUS experiment as an example of semi-arid agroforestry.
- A series of short training course in soil water measurement techniques were given, accompanied by illustrated guides to be used by ICRAF for future training purposes throughout the AFRENA networks.

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