Review

Modifying forestry and agroforestry to increase water productivity in the semi-arid tropics

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Abstract

The need to increase water productivity is a growing global concern as the World Commission on Water has estimated that demand for water will increase by c. 50% over the next 30 years and approximately half of the world’s population will experience conditions of severe water stress by 2025. Three-quarters of African countries are expected to experience unstable water supplies, whereby small decreases in rainfall induce much larger reductions in streamflow. Vital water catchments have been lost or are being degraded, creating concerns about the loss of hydrological functions and increasing competition for scarce water resources between agriculture, urban centres, industry and wildlife. The challenge is to improve water productivity at the landscape or river basin level, especially for the rapidly growing populations in many developing countries. Water productivity is defined as the value or benefit derived from the use of water. In this review, we describe recent findings regarding the hydrology of forests and agroforestry systems and indicate how modifications to tree-based systems may increase water productivity in the semi-arid tropics. Throughout the tropics, reforestation using eucalyptus has been the most significant approach for modifying the water productivity of forestry and agroforestry systems. Fortunately, the ‘eucalyptus dilemma’ of providing local benefit at the expense of decreased streamflow for downstream users has been well articulated in many countries where evidence-based research has changed water policy and discouraged further planting of eucalyptus on water catchments. In East Africa, the most popular replacement for eucalyptus has been another exotic from Australia, Grevillea robusta, which has become the species of choice for farmers in the sub-humid highlands. However, attempts to introduce this species to semi-arid areas have been disappointing due to its evergreen canopy and consequently high demand for water. Current attempts to use deciduous species such as Melia volkensii and Paulownia fortunei in such areas are much more encouraging, although the long-term implications are still unknown. Agroforestry has the potential to improve water productivity in two ways. Trees can increase the quantity of water used on-farm for tree or crop transpiration and may also improve the productivity of the water that is used by increasing the biomass of trees or crops produced per unit of water used. Plot-level evidence shows that improvements in water productivity resulting from modifications to the microclimate experienced by crops may be limited. Instead, evidence from semi-arid areas of India and Kenya has shown that the greater productivity of agroforestry systems is primarily due to the greater quantity of water used. Further research is needed to examine the impact of the increased water use on drainage and base flow at the landscape level. Finally, we describe some of the technical approaches, which may be used to improve water productivity based on differences in tree phenology and the challenges facing smallholders in areas of growing water scarcity.

Keywords: Water productivity, Forestry, Agroforestry, Water use efficiency (WUE), Streamflow
Introduction

The urgent need to increase water productivity is of growing global concern. The World Commission on Water estimates that demand for water will increase by approximately 50% over the next 30 years, and about half of the world’s population will live in conditions of severe water stress by 2025. Water supplies across Africa could be significantly depleted by climate change by the late 21st century. Recent analysis suggests that 75% of African countries will experience unstable water supplies whereby small decreases in rainfall induce disproportionately large reductions in streamflow [1].

Forests are the biggest users of water of all vegetation types in all terrestrial biomes. The tropical forests of Brazil, Congo Democratic Republic, Indonesia, Peru and Venezuela form a large proportion of the closed forests, which are vital for the well-being of the planet; clearing of such forests is therefore strongly opposed. Future increases in food and wood production required in the humid tropics and elsewhere to support rapidly expanding human populations must therefore be achieved from land and water resources already in use. The central challenge is to improve the productivity with which existing land and water resources are used.

Rapid degradation of water catchments and climate change are major factors responsible for decreasing water supplies in many parts of the world. According to Klaus Toeffler, head of the United Nations Environment Programme (UNEP), destruction of East Africa’s forests and climate change are among the main causes of the drought which is currently affecting large parts of the region and threatening to bring misery for millions of people and their livestocks [2]. He emphasized the strong links between drought and on-going environmental damage to forests, grasslands, wetlands and other critical ecosystems, as well as climate change. Many environmentalists and policymakers strongly believe that forests play a vital role in generating rain. In the same article, Christian Lambeth, a member of UNEP’s Early Warning and Assessment group claimed that forests act as natural pumps, releasing moisture to the air and increasing the likelihood of regular rainfall throughout the year. In a detailed study of forest cover in Kenya’s five water catchments, UNEP expressed grave concern that continuation of forest destruction, especially in the Mau Forest, will cause serious further reductions in the flow of the 13 rivers which feed Rift Valley lakes such as Baringo, Nakuru, Turkana and Victoria (Planet and People, 2006).

Debate on the Role of Forests and Water

John Palmer stated that ‘The potential implications of the research summarized in this booklet (From the Mountain to the Tap [3]) are immense, as they contradict some current tree-planting policies and environmental beliefs. Unless there is urgent action now, the looming water crisis will aggravate, and leave the most vulnerable, the rural and urban poor populations, ever more disadvantaged’. In this landmark publication on how land use and deforestation affect water supplies in the tropics, Ian Calder and his co-workers questioned many of the familiar associations between deforestation or forest degradation and environmental disasters such as floods, landslides and sedimentation of reservoirs [3]. They claimed that the motivation for massive tree planting schemes is based on the mistaken belief that forests attract rainfall, which originated in the eighteenth and nineteenth centuries when there was limited understanding of global weather patterns, cycles and variations. This ingrained belief was based on comparisons of paired catchments of entire forests and still shapes the forest policy of many developing countries regarding the benefits of forest protection and rehabilitation in mountainous areas [4].

A major shortcoming of the paired catchment approach is that the findings are often inappropriate for extrapolation to other areas in similar environments, or for situations where land use is changing rapidly. For this reason, physical process-based approaches involving micrometeorological measurements, which are relatively complex and expensive, have been adopted at various sites to gain a full understanding of the sensitivity of forest hydrology to climatic variability and vegetation change [5]. Such process-based approaches are more robust and straightforward to extrapolate to other sites than paired catchment studies. However, after more than a century of forest hydrology, there are still several controversial issues or ‘beliefs’ which hamper rational decision-making regarding land use. Calder summarized these as follows:

1. Forests increase rainfall. This perception is largely myth because the effects of forests are likely to be small, except for extensive cloud forests
2. Forests increase runoff. Evidence suggests that surface runoff from forests is lower than for shorter vegetation such as native grasses because of the greater evaporative losses from trees
3. Forests regulate streamflow and increase dry-season streamflow. These factors are more closely related to the water infiltration properties of the soil than to the presence of forests per se. The strong correlation between vegetation and soils cannot be easily separated, although many studies have shown that the presence of trees reduces streamflow, with the exception of cloud forests. Forested watersheds often exhibit better regulated streamflow, with greater baseflow later in the season
4. Forests reduce erosion. This depends largely on the management methods employed; tree species such as teak may even increase erosion relative to shorter
vegetation such as native grass or pastures which may dramatically reduce erosion

5. Forests reduce floods. There is little scientific evidence to prove a direct relationship between forests and floods, even though trees use more water than grasses. Management activities such as cultivation, road construction and compaction are more important. Some reduction of stream flow by riparian forest may be beneficial

6. Forests improve water quality. Although this is largely true, poor land management is more important. Clear felling of forests and conversion of land to agriculture often reduce water quality, although provision of forest buffers and grass filters may overcome such problems.

The views of Calder and his co-workers have provoked intense debate from other hydrologists, who claimed that such statements are based on relatively dry areas and short-term effects on river flow [6]. They also claim that the publicity surrounding the publication of From the Mountain to the Tap has given reforestation of cleared forests a negative image [7]. What is clear is that this debate has not yet reached policymakers and environmentalists, who are still promoting environmental policies based on the powerful assumption that forests generate rainfall and reduce floods. It is therefore timely that special publications intended to better inform policymakers, development agencies and the media are now appearing. A good example is the recent publication by FAO and CIFOR entitled ‘Forests and Floods – Drowning in Fiction or Thriving on Facts?’ [8]. These publications have cautioned that it is difficult to predict or totally understand complex watershed functions and dangerous to oversimplify generalizations based on few studies. Not only do perceptions vary between researchers and stakeholders with differing backgrounds, but performance also varies between forests in different climatic zones.

Promise of Agroforestry

Agroforestry offers a promising option for productive and sustainable use of land and water. In simple terms, agroforestry involves combining managed trees with productive agricultural activities and provides opportunities to stem the negative impacts that deforestation and intensive cropping systems have brought on the landscape. There are also opportunities to use agroforestry to prevent or reverse land degradation in the humid tropics [9]. Such systems may provide numerous potential benefits ranging from diversification of production to improved exploitation of natural resources. The key benefits in terms of natural resources are:

1. soil conservation in terms of protection against erosion;
2. improvement or maintenance of soil fertility;
3. water conservation and more productive use of water;
4. provision of environmental functions required for sustainability.

A recent review by Wallace et al. [10] considered these potential benefits in the humid tropics, while the present review focuses on ways in which forestry and agroforestry systems may be modified to increase water productivity in the semi-arid tropics, where water shortage is already a reality. Here, water productivity is broadly defined as the benefit or value of water at the landscape or river basin level, as described by Molden et al. [11]; however, definitions of water productivity vary depending on the background of the researcher or stakeholder. For example, fast-growing trees such as eucalyptus are highly productive in terms of providing a large quantity of dry biomass per unit of water transpired, i.e. they have a relatively high water use efficiency (WUE). WUE or, more correctly, water use ratio (WUR), is an important means of expressing the productivity of water when the primary focus of the analysis is at the individual farm or plot level. However, eucalyptus is considered a major problem to society at large because of its evergreen nature and high water demand, which reduces streamflow, thereby restricting water supplies for irrigation and the local population.

Despite its poor reputation at the landscape level, there is considerable evidence that the transpiration rate per unit leaf area ($T_L$) of eucalyptus, an important determinant of water use in both forest canopies and trees on farm, is often lower or comparable to more desirable tree species. Myers et al. [12] found that, although the leaf area of Eucalyptus grandis was three times greater than Pinus radiata in southern Australia, the former transpired only 22% more water. Thus the $T_L$ value for E. grandis was much lower than that of P. radiata. By contrast, Meinzer et al. [13] and Hatton et al. [14] found no major differences in $T_L$ between various tree species in tropical rainforest and water-limited forests, respectively. Surprisingly, recent studies of tree rows in western Kenya showed that E. grandis exhibited consistently greater $T_L$ values than other tree species such as Grevillea robusta, which is highly popular for agroforestry systems in the region [15]. The results showed that water use by tree rows was more closely correlated with leaf area and $T_L$ than to micrometeorological factors. The linear relationship between tree water and leaf area over a wide range of leaf areas is specific to row-planting configurations and is quite distinct from forest stands. In tree rows, light interception and canopy conductance increase with leaf area to a much greater extent than would be associated with a similar leaf area in a closed forest canopy (Figure 1). The poor reputation of eucalyptus therefore does not reflect its WUE or $T_L$, but is more closely linked to other characteristics such as its evergreen canopy and reputed deep rooting behaviour, the importance of which will be explored later in this review.
The available resources than equivalent sole stands and/or trees and crops must capture a greater proportion of available light, water and nutrients. To achieve this, the system productivity by increasing exploitation of annual crops. Agroforestry offers substantial scope to improve system productivity by increasing exploitation of available light, water and nutrients, which shallow-rooted crops cannot access. Temporal complementarity occurs when trees and crops make their main demands on available resources at different times, for example, when deep-rooted trees use water and nutrients, which shallow-rooted crops cannot access.

Figure 1. Relation between daily water use and leaf area of tree species [15].

Water Productivity in Agroforestry Systems: Resource Capture Concepts

In rain-fed agricultural systems in the semi-arid tropics, water present in the soil originates primarily from infiltration following rainfall. However, although biomass production is often constrained by limited water availability in annual cropping systems, residual water often remains in the soil after harvest and off-season rainfall goes unused [16, 17]. A significant proportion of the annual rainfall may be lost by evaporation from the soil surface or percolation to horizons beneath the crop rooting zone [18, 19]. In systems where annual crops provide limited ground cover during the early stages of the rainy season and may never achieve complete ground cover, soil evaporation may account for 30–60% of annual rainfall [18, 19]. Rockstrom [20], reported that only 6–16% of the rainfall received on a watershed in Niger was used for transpiration by millet, and that most of the remainder was lost by evaporation (40%) or deep drainage (33–40%). Similarly, sorghum/pigeonpea intercrops in India used only 41% of the annual rainfall, while the remainder was lost as runoff (26%) or soil evaporation and deep drainage (33%); 20% or 152 mm of the annual precipitation was received outside the cropping season [21]. There is therefore considerable scope to develop improved agricultural technologies to exploit these untapped reserves, although in some instances this might limit recharge of wells and aquifers.

Agroforestry has attracted considerable interest because of its potential to maintain or enhance agricultural productivity in areas where high energy input, large-scale agriculture is impractical. Cannell et al. [22] proposed that agroforestry may increase productivity if the trees capture resources that are under-utilized by annual crops. Agroforestry offers substantial scope to improve system productivity by increasing exploitation of available light, water and nutrients. To achieve this, the trees and crops must capture a greater proportion of the available resources than equivalent sole stands and/or use these more efficiently to produce dry matter. It is vital that the trees exhibit complementarity with associated crops rather than being competitive. Complementarity may be either spatial or temporal; the former occurs when trees and crops exploit different resource pools, for example, when deep-rooted trees use water and nutrients, which shallow-rooted crops cannot access.

Figure 1. Relation between daily water use and leaf area of tree species [15].

Significant complementarity of water use may occur naturally if trees with suitable leafing phenology or rooting architecture are used. However, as most tree species promoted for use in agroforestry have root systems whose vertical distribution is similar to agronomic crops [24–26], they often compete with associated crops. Management practices such as root or shoot pruning prior to the cropping season may be used to modify the temporal patterns of resource capture by trees and minimize competition when supplies are limited [27]. Pruning the tree canopy prior to the cropping season may allow annual crops to exploit available water in the surface horizons by reducing demand by the trees; the trees may also be able to exploit deep water reserves as their canopy regrows during the latter stages of the cropping season [28].

There is substantial experimental evidence to support the hypothesis that agroforestry may increase productivity by making better use of available resources. Ong et al. [21] reported that hedgerow plantings of sole leucaena extracted more of the available soil water than sole crops or intercrops of sorghum and pigeonpea at Hyderabad, India. Widely spaced alley crops (4.4 m between hedges) extracted more water than sole leucaena, indicating that the agroforestry system was most effective in exploiting available water. Similarly, Ong et al. [16] observed substantial improvements in productivity resulting from increased utilization of annual rainfall from 40 to 80% in agroforestry systems containing perennial pigeonpea (Cajanus cajan L.) and groundnut (Arachis hypogaea L.). Almost half of the annual water use (416 versus 887 mm) occurred between January and June, when only 211 mm of rainfall, indicating that 205 mm was extracted from soil reserves.

However, the high demand for water imposed by fast growing exotic trees may be problematic for farmers in semi-arid regions. Calder [29] reported that eucalyptus plantations in southern India not only used all of the rainfall, which infiltrated the soil but also extracted a further 100 mm of water for each 1 m depth of soil.
penetrated by the roots. This is a matter for serious concern as the roots of eucalyptus may reach depths of 8 m within three years of planting. In the Sahel, the roots of mature acacia trees may reach water tables located at depths of up to 30 m [30]. In experiments at Machakos, Kenya involving Leucaena leucocephala, Govindarajan et al. [31] found that alley cropping adversely affected crop productivity because increased competition for water outweighed potential soil fertility benefits resulting from applications of green leaf manure (GLM), nitrogen fixation and increased root turnover. Other studies have shown that regular shoot and root pruning of trees in alley cropping systems may encourage proliferation of fine roots in the surface soil horizons, decreasing spatial niche separation between tree and crop roots and hence the potential for complementarity in the use of below-ground resources [22, 32]. It is therefore essential to consider the implications of increased water use in agroforestry systems for medium and long-term water budgets. Particular attention should be paid to the source of water used by trees, the rate of depletion below the crop rooting zone, and the prospects for deep recharge during periods of high rainfall [33]. As noted earlier, it is particularly important to choose trees with appropriate rooting architecture or leafing phenology to ensure spatial complementarity and avoid major crop yield losses.

Although biomass production in water-limited environments clearly depends on the quantity of water available and the proportion used for transpiration, the ‘efficiency’ with which absorbed water is used to produce dry matter is also crucial. The ratio of dry matter production to water transpired is known as the WUR or efficiency (\(e_w\)). Dry matter production (\(W\)) may be expressed as \(W = e_w \Delta E_w\), where \(\Delta E_w\) represents cumulative transpiration. \(W\) is often linearly related to the quantity of water transpired, indicating that \(e_w\) is conservative [34, 35] due to the close linkage between \(CO_2\) and water vapour exchange. Agroforestry systems may enhance productivity by increasing resource capture and/or improving the efficiency with which captured resources are used to produce dry matter.

Although there is strong evidence that incorporation of trees into farmland may increase seasonal or annual water use, the impact on WUE (\(e_w\)) is less clear. \(e_w\) may be calculated over timescales ranging from instantaneous measurements of the ratio of \(CO_2\) and water vapour fluxes to seasonal estimates based on dry matter accumulation and water use. Long-term estimates are generally much lower than short-term values due to the effects of respiration, which consumes up to 50% of the photosynthate produced [16], and adverse environmental (e.g. drought, nutrient availability) or biological factors (e.g. pests, diseases). Below-ground biomass is rarely included in calculations of \(e_w\), while above-ground biomass often declines as crops approach maturity due to senescence, leading to underestimation of \(e_w\). A further factor is that \(e_w\) should be calculated on the basis of transpired water rather than evapotranspiration, as water evaporated from the soil has no direct role in dry matter production, although it may influence the atmospheric saturation deficit experienced by the crop and hence transpiration rate and \(e_w\). Soil evaporation dominates evapotranspiration during the early part of the growing season for annual crops and may comprise 30–60% of seasonal water use depending on the rate of canopy development and maximum leaf area [18], but may be greatly reduced by the presence of trees in agroforestry systems.

\(e_w\) values for tropical \(C_4\) cereals are often double than those for \(C_3\) species under equivalent conditions; for example, experiments in India provided season-long \(e_w\) values of 3.9–4.6 g/kg for millet compared to 1.5–2.0 g/kg for groundnut [17]. However, \(e_w\) is not always higher in \(C_4\) species as similar values have been reported for drought-tolerant \(C_3\) species such as cowpea and cotton (Gossypium barbadense) and relatively drought-sensitive cultivars of \(C_4\) species such as sorghum and maize. \(e_w\) is affected by factors which influence transpiration such as atmospheric saturation deficit (\(D\)). Squire [36] reported that the seasonal mean \(e_w\) value for groundnut decreased from 5.2 to 1.5 g/kg as mean daytime \(D\) increased from 1 to 2 kPa. Similarly, \(e_w\) for millet decreased from 6.4 to 2.1 g/kg as \(D\) increased from 1.4 to 4.0 kPa [37, 38]. Together with soil water supplies, \(D\), through its effects on \(e_w\), is one of the most important factors limiting productivity in dryland areas as biomass production may be halved as mean seasonal daytime \(D\) values increase from 1 to 4 kPa [36].

The beneficial effect on system productivity of intercropping annual crops may originate from improvements in either seasonal water use or \(e_w\), although the latter often appears to be more important [39]. Intercropping may increase the proportion of available water used for transpiration because the presence of \(C_4\) cereals results in more rapid canopy development and reduces soil evaporation; fast growing \(C_4\) species with inherently high \(e_w\) values may also capture a larger proportion of the available water, increasing overall yield and \(e_w\) for the system. The dominant and subsidiary components of intercrops are often \(C_4\) and \(C_3\) species respectively, with relatively high and low \(e_w\) values. Intercropping may also confer microclimatic benefits by imposing partial shade and thereby reducing transpiration by the shorter component, often a \(C_3\) species with a relatively low photosynthetic light saturation point. In such instances, partial shade has little effect on photosynthetic rate, with the result that \(e_w\) is improved by the associated reduction in transpiration. Such effects are less likely to apply to agroforestry systems, in which the dominant overstorey trees are invariably \(C_3\) species and the understorey species may be \(C_4\) cereals which do not respond favourably to shading [17].

Thus several mechanisms may enable agroforestry systems to use available water more effectively than sole
crops and improve microclimatic conditions for understorey crops [22]. These include reductions in soil evaporation resulting from shading by the tree canopy and reduced air movement through the understorey environment, microclimatic modifications arising from reductions in air temperature, windspeed and saturation deficit which decrease crop water use, and decreases in tissue temperature which benefit the phenology and productivity of understorey crops by minimizing heat stress [22]. The key question is whether these potential benefits are outweighed by the detrimental effects of competition for available resources between trees and crops.

**Productivity and Water Use in the Semi-Arid Tropics**

Long-term studies of overstorey agroforestry systems in semi-arid environments are rare due to the substantial financial, labour and time investments required. ICRAF’s Complementarity In Resource Use on Sloping Land (CIRUS) programme was a multidisciplinary project to examine the changes in tree/crop interactions that occur as trees in semi-arid agroforestry systems establish and mature [22]. CIRUS is one of the most detailed and highly instrumented long-term studies of resource capture, hydrology and microclimate, tree and crop growth and system performance ever carried out within an agroforestry context. Its primary objective was to compile a comprehensive experimental database to improve our mechanistic understanding of tree/crop interactions and support the development and validation of process-based simulation models describing resource capture and tree and crop growth. The experimental site at ICRAF’s Machakos Research Station in semi-arid Kenya had no previous cropping history before being cleared of scrub dominated by *Acacia* species.

*G. robusta* (A. Cunn.; grevillea) trees were grown in a dispersed planting arrangement, either as sole stands or in combination with cowpea (*Vigna unguiculata* L.) or maize (*Zea mays* L.); sole crops were also grown [22]. Crop and system performance were examined over a 4.5 year period (nine growing seasons) commencing in October 1991, although failure of the rains caused the loss of capture of one cropping season. A rotation of cowpea and maize was grown during the first five seasons, but maize was grown during the final four seasons. Sole maize was also grown under spectrally neutral netting which reduced incident radiation by 25, 50 or 75% to establish the relative importance of shade and below-ground competition for water and nutrients in determining the performance of understorey crops. Allometric approaches were used to determine seasonal and annual increases in leaf area and leaf, branch and trunk biomass in grevillea [40]. Crop growth, development and yield were determined, while the spatial distribution of tree and crop roots was established during the latter stages of the experiment. Detailed hydrological studies examined effects on soil water balance and its components (precipitation, interception, runoff and soil moisture status); measurements of spatial and temporal variation in microclimatic conditions examined the mechanistic basis for beneficial or detrimental effects on understorey crops and the influence of proximity to the trees [10].

Tree height, leaf area and trunk and branch biomass were reduced in the agroforestry treatment (CTd) relative to sole grevillea (Td) during the first 600 days after planting (DAP) due to competition with associated crops for above- and below-ground resources [41] (Figure 2). Tree height subsequently increased more rapidly in the agroforestry treatment and regained parity with sole grevillea by 820 DAP. Tree growth continued throughout the dry season, sometimes at rates similar to or greater than during the cropping seasons. However, although seasonal and annual biomass increments were comparable in both treatments once the trees became the dominant component of the agroforestry system, trunk volume and biomass were consistently lower in CTd trees than in sole grevillea, reducing their economic value to subsistence farmers.

Crop biomass and grain yield in the agroforestry system were not significantly affected during the first four seasons, but decreased dramatically as the trees became increasingly dominant. Maize yield reached 50% of the sole crop value only once during the final four seasons, when rainfall was unusually high, and was even more severely affected in the other three seasons [42]. The hypothesis that competition for water was the primary limiting factor for understorey crops once the trees had become established was supported by the performance of maize grown under nets providing shade in the absence of competition for water and nutrients; crop growth was consistently greater than in CTd maize and often comparable to sole maize [42]. This observation shows that shade was not the primary cause of the substantial yield losses exhibited by CTd maize. Performance ratios (ratio of values for the agroforestry system to those for sole stands) for total above-ground and trunk biomass in grevillea were initially low, reflecting the impact of competition with associated crops during tree establishment, but increased to unity within 2.5 years. Performance ratios for grain yield in understorey crops exhibited the reverse trend, initially being close to unity but approaching zero for three of the final four seasons. Performance ratios were never close to unity for both trees and crops during the same season, indicating that there was always competition for available resources irrespective of crop species or tree size.

Land equivalent ratios (LER) for the agroforestry system (sum of performance ratios for trunk biomass and grain yield) were either greater or not significantly different from unity in all except one season when poor rains caused crop failure. This observation indicates that either a larger proportion of the available resources was

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Measurements of stand-level water use by established trees are technically difficult because their deep rooting systems preclude the soil water balance approaches commonly used to determine water use by sole crops or annual intercropping systems, in which the great majority of roots are confined to the upper 50–75 cm of the soil profile. Although sap flow techniques have often been used to determine transpiration by individual trees or crop plants [22], the values obtained must be scaled to obtain community-level estimates of water use. Their complexity and labour-intensive nature also limits the number of treatments that can be examined concurrently. Continuous measurements of water use over extended periods as trees mature are therefore not feasible using sap flow technology alone. Scaling methods to estimate water use during periods when sap flow is not measured should ideally maintain independence of measurements of transpiration by the trees from other components of the water balance [47]. This has been achieved for trees growing in humid environments [47] where water supplies are rarely limiting, enabling scaling procedures to focus on key driving variables for transpiration such as solar energy supply and evaporative demand. However, the impact of soil water availability on water use by trees cannot be ignored in semi-arid environments. Previous studies of the impact of limited water supplies on transpiration [48, 49] have either included parameters captured, or that the captured resources were used more effectively for dry matter production, a situation which occurs when there is niche differentiation between system components or green area duration is extended [43].

LER values were consistent with alley cropping studies in India and Kenya [21, 44, 45], in which the tree component dominated resource capture due to the relatively high planting densities used. In their comparison of agroforestry and Savannah systems, Ong and Leakey [32] concluded that agroforestry research has typically focussed on fast growing tree species planted at high densities; as a result the trees captured most of the available resources and potential microclimatic benefits for understory crops that were negated by reductions in soil moisture resulting from increased interception losses and water use by the tree component. Results from other experiments at Machakos revealed an inverse linear correlation between maize yield and the quantity of water used by five tree species, including grevillea, when seasonal rainfall was <250 mm; crop failure occurred when transpiration by the trees exceeded 100 mm.

Proximity to trees significantly affected understory microclimatic conditions and water availability, particularly during the later stages of the experimental period when shading decreased the mean diurnal temperature range and maximum meristem temperature by up to 7 °C relative to sole maize [46]. The non-uniform shade provided by trees induced substantial spatial variation in the rate of thermal time accumulation, creating systematic local variation in the development rate and yield of understory crops. Spatial variation in incident radiation, saturation deficit and soil water availability all contributed to the systematic variation in the performance of understory crops.

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Figure 2. Timecourses for (a) trunk, (b) canopy and (c) total above-ground biomass in the sole (Td, ○) and dispersed agroforestry (CTd, ◆) treatments of grevillea for a 4.5 year period from planting. Arrows denote times of pruning. Solid, stippled and open horizontal bars respectively denote the short (October–February) and long cropping seasons (March–July) and the dry season (August–September). Double standard errors of the mean are shown where larger than the symbols [40].

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accumulated transpiration, rainfall, and the fraction of rainfall of 64–68% 3–4 years after planting. Table 1 shows period was comparable in the sole and agroforestry lative water use by grevillea over the 4.5 year observation cumu-
larative water use by grevillea for all cropping and dry seasons [50]. rainfall during the off-season periods was regarded as being unavailable for crop growth, while the cropping seasons correspond to the periods when crops were present and so differ in duration. Off-season rainfall comprised c. 425 mm or 16% of total rainfall during the four annual cycles examined. Total water use by grevillea in the sole and agroforestry treatments during the dry seasons was 420 and 380 mm respectively, equivalent to 38 and 35% of the annual total water use. This observa-
sion suggests that the trees were highly effective at capturing off-season rainfall, and that this source of water was important for their continued growth. Water use by the trees exceeded rainfall in three of the seven dry seasons examined, suggesting that they were able to exploit residual and/or deep soil moisture reserves. Transpiration was much greater in sole grevillea up to the end of the 1992/93 annual cycle (p < 0.01; Table 1), but was then comparable in both treatments. This equalization of water use occurred after the first pruning at 599 DAP, when the tree canopies were reduced to a similar size in both treatments [41]. Transpiration by the trees accounted for approximately two thirds of the annual rainfall in both treatments after 1992/93, indicating that only one third was available for transpiration by understorey crops, evaporation and runoff. During the 1995 long rains, when 221 mm of rain was received, transpiration by sole maize was <50% of precipitation, compared to c. 85% by the trees in the sole grevillea and agroforestry treatments.

These results clearly support the hypothesis that agroforestry may greatly improve rainfall utilization relative to annual cropping systems by increasing the proportion of annual rainfall captured or utilizing residual or deep soil water reserves which annual crops cannot access. As the trees continued to transpire and grow during the dry seasons, they were able to utilize rainfall that would have been lost from productive use in annual systems as well as exploiting residual soil moisture. However, as its lateral roots may extract substantial quantities of water from the surface soil horizons [50], grevillea is likely not only to compete with crops during the cropping season but also to reduce the moisture content of the surface soil horizons during the dry season preceding the cropping period. Such effects severely affected crop yield once the trees had established [50]. However, the reverse situation applied during the first two annual cycles, when transpiration by grevillea was lower in the agroforestry system than from sole trees, reflecting the adverse effect of crops on tree establish-
ment and initial growth [41]. Thus although grevillea may be highly effective at utilizing scarce water resources in semi-arid environments, careful evaluation of the tradeoffs between losses of crop production and the additional value of tree products is essential. The results from CIRUS suggest that it would be acceptable to incorporate grevillea into relatively densely planted agroforestry sys-
tems in the semi-arid tropics, only if crop yields were little

Figure 3. Cumulative stand-level transpiration by gre-
villa in the sole (Td) and dispersed (CTd) agroforestry treatments during the 4.5 year period from planting. Solid, stippled and open bars respectively denote the short (October–February) and long cropping seasons (March–July) and the dry season (August–September). The tree canopies were pruned at 599, 861 and 1254 DAP by removing the basal branches [41].

describing the soil water deficit, thereby failing to maintain independence of water balance components, or used scaling methods based on biomass production. The latter approach was adopted in CIRUS by regressing sap flow against tree biomass production for periods when sap flow was measured. The correlations obtained were then used in conjunction with regular allometric estimates of tree growth to determine water use during periods when sap flow was not measured [50].

Water use by individual trees and maize plants was determined using heat balance gauges and scaled to provide stand-level estimates of transpiration based on linear relationships between sap flow and leaf area across a range of tree ages and environmental conditions. Water use by grevillea increased as the trees grew larger, was generally greatest during the short cropping season, and was lower in CTd than in Td trees up until the end of the 1993/94 season, reflecting their smaller size and the effect of competition with crops [46, 50] (Figure 3). Depletion of soil moisture reduced transpiration during the dry season except during tree establishment, when their rapidly growing roots exploited deep moisture reserves in the soil profile [51]. Measurements of sap flow through lateral roots showed that grevillea may extract substantial quantities of water over 2 m from the trunk, increasing its competitive impact on associated crops [52]. Maximum stand-level transpiration rates for grevillea ranged from 2.6–4.0 mm/d, consistent with previous studies in similar environments [53, 54].

As stand-level transpiration by grevillea was closely correlated with biomass production, reliable estimates of seasonal transpiration (Figure 3) could be derived from allometric estimates of biomass production [50]. Cumulative water use by grevillea over the 4.5 year observation period was comparable in the sole and agroforestry treatments, reaching a maximum utilization of annual rainfall of 64–68% 3–4 years after planting. Table 1 shows accumulated transpiration, rainfall, and the fraction of rainfall transpired by grevillea for all cropping and dry seasons [50]. Rainfall during the off-season periods was regarded as being unavailable for crop growth, while the cropping seasons correspond to the periods when crops were present and so differ in duration. Off-season rainfall comprised c. 425 mm or 16% of total rainfall during the four annual cycles examined. Total water use by grevillea in the sole and agroforestry treatments during the dry seasons was 420 and 380 mm respectively, equivalent to 38 and 35% of the annual total water use. This observa-
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tems in the semi-arid tropics, only if crop yields were little

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affected and formed the more valuable system component in subsistence or economic terms or, alternatively, the presence of the trees provided an additional valuable economic return.

Mixed Intercropping in Malawi

As noted previously, competition for water and nutrients may be controlled by root and/or shoot pruning. In studies at Makoka Research Station in southern Malawi, the water and nitrogen dynamics of cropping systems containing mixtures of *Gliricidia sepium* (Jacq.) Walp trees with maize (*Z. mays* L.) and/or pigeonpea (*C. cajan* L.) were examined during three consecutive years. During each annual cycle, all tree biomass was removed to a height of 30 cm above ground level 2–4 weeks before planting the crops; the prunings were incorporated into the ridges on which the crops were to be planted. The trees were pruned again when maize reached 60 cm in height and the prunings were incorporated into the soil during normal weeding activities. The hypothesis was that periodic severe pruning of the trees and return of GLM to the cropping area would control competition for soil moisture and enhance crop growth by providing additional nutrients. Neutron probe measurements were used to determine spatial and temporal changes in soil moisture content.

The contrasting rainfall patterns in the three annual cycles examined allowed treatment effects on available soil moisture, water and nitrogen use and biomass production to be established under a range of water supply conditions. As expected, the agroforestry systems were most productive and produced substantial quantities of GLM (2.4–9.0 t/ha/y), a primary objective of the land use systems examined here [55] (Table 2). Significant improvements in maize yield were obtained in the agroforestry systems within three years following regular applications of GLM, with c. 3.0 t/ha of grain being produced. No beneficial influence of pigeonpea was apparent either in the presence or absence of gliricidia. Competition for water was not a critical limiting factor for tree and crop growth as rainfall exceeded potential evaporation during the maize-cropping season in all years. However, available soil moisture was generally lower at the beginning of the cropping period in the agroforestry systems, suggesting that the trees continued to deplete soil moisture during the dry season. Available soil water at the peak of the recharge phase was generally greatest in the system containing a mixture of gliricidia, maize and pigeonpea, perhaps due to a combination of increased infiltration resulting from improvements in soil structure and reductions in soil evaporation associated with increased ground cover, as fractional light interception was 0.6–0.7 in the tree-based systems compared to 0.1–0.4 in sole maize and the maize/pigeonpea intercrop [56].

Table 1  Number of days in the season, rainfall, stand-level transpiration for grevillea in the sole (Td) and agroforestry (CTd) treatments, and percentage of rainfall transpired by grevillea for each season and annual cycle. S, L and D respectively denote short and long cropping seasons and the dry season. Seasons are identified by the year in which they occurred, i.e. S91/92 denotes the 1991–1992 short growing season. A and B denote the dry seasons between short and long, and long and short cropping seasons [41].

<table>
<thead>
<tr>
<th>Season</th>
<th>Days</th>
<th>Rainfall (mm)</th>
<th>Transpiration (mm)</th>
<th>Fraction of rainfall used (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Td</td>
<td>CTd</td>
</tr>
<tr>
<td>S91/92</td>
<td>102</td>
<td>357.0</td>
<td>1.7</td>
<td>0.4</td>
</tr>
<tr>
<td>D92A</td>
<td>49</td>
<td>5.0</td>
<td>0.9</td>
<td>0.2</td>
</tr>
<tr>
<td>L92</td>
<td>136</td>
<td>256.0</td>
<td>14.3</td>
<td>4.4</td>
</tr>
<tr>
<td>D92B</td>
<td>72</td>
<td>1.0</td>
<td>13.2</td>
<td>2.7</td>
</tr>
<tr>
<td>1991/92</td>
<td>619.0</td>
<td>30.1</td>
<td>7.7</td>
<td>4.9</td>
</tr>
<tr>
<td>S92/93</td>
<td>100</td>
<td>606.0</td>
<td>30.2</td>
<td>11.8</td>
</tr>
<tr>
<td>D93A</td>
<td>47</td>
<td>99.2</td>
<td>185.5</td>
<td>137.3</td>
</tr>
<tr>
<td>L93+D93B</td>
<td>214</td>
<td>Rains failed; entire period included in D93A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1992/93</td>
<td></td>
<td>705.2</td>
<td>215.7</td>
<td>149.1</td>
</tr>
<tr>
<td>S93/94</td>
<td>96</td>
<td>165.4</td>
<td>119.3</td>
<td>118.6</td>
</tr>
<tr>
<td>D94A</td>
<td>44</td>
<td>132.6</td>
<td>56.3</td>
<td>62.0</td>
</tr>
<tr>
<td>L94</td>
<td>123</td>
<td>157.2</td>
<td>102.4</td>
<td>115.2</td>
</tr>
<tr>
<td>D94B</td>
<td>84</td>
<td>59.2</td>
<td>52.0</td>
<td>54.8</td>
</tr>
<tr>
<td>1993/94</td>
<td>514.4</td>
<td>330.0</td>
<td>350.6</td>
<td>64.1</td>
</tr>
<tr>
<td>S94/95</td>
<td>123</td>
<td>546.8</td>
<td>244.6</td>
<td>262.6</td>
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<tr>
<td>D95A</td>
<td>20</td>
<td>105.0</td>
<td>43.3</td>
<td>55.7</td>
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<tr>
<td>L95</td>
<td>112</td>
<td>221.0</td>
<td>182.2</td>
<td>191.3</td>
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<tr>
<td>D95B</td>
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</tr>
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<td>1994/95</td>
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<td>574.9</td>
<td>60.3</td>
</tr>
<tr>
<td>S95/96</td>
<td>108</td>
<td>238.1</td>
<td>150.5</td>
<td>139.4</td>
</tr>
</tbody>
</table>
Table 2: Total biomass, water use and WUE in the sole maize (SM), sole gliricidia (SG), sole pigeonpea (SP), maize+pigeonpea (MP), gliricidia+maize (GM) and gliricidia+maize+pigeonpea (GMP) treatments during the 1999/98, 1998/99 and 1999/00 cropping seasons at Makoka Research Station, southern Malawi [55].

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>1997/98 Above-ground biomass (kg/ha)</th>
<th>1998/99 Above-ground biomass (kg/ha)</th>
<th>1999/00 Above-ground biomass (kg/ha)</th>
<th>Water use (mm) 1997/98</th>
<th>Water use (mm) 1998/99</th>
<th>Water use (mm) 1999/00</th>
<th>WUE (g/kg) 1997/98</th>
<th>WUE (g/kg) 1998/99</th>
<th>WUE (g/kg) 1999/00</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM</td>
<td>4470</td>
<td>1300</td>
<td>3320</td>
<td>863.5</td>
<td>881.8</td>
<td>612.5</td>
<td>0.52</td>
<td>0.15</td>
<td>0.54</td>
</tr>
<tr>
<td>MP</td>
<td>10610</td>
<td>5160</td>
<td>5290</td>
<td>866.9</td>
<td>886.0</td>
<td>606.6</td>
<td>1.23</td>
<td>0.62</td>
<td>0.87</td>
</tr>
<tr>
<td>GM</td>
<td>7520</td>
<td>19600</td>
<td>11220</td>
<td>901.1</td>
<td>917.8</td>
<td>596.0</td>
<td>1.43</td>
<td>1.97</td>
<td>1.88</td>
</tr>
<tr>
<td>GMP</td>
<td>9100</td>
<td>17240</td>
<td>14890</td>
<td>855.4</td>
<td>914.8</td>
<td>617.8</td>
<td>1.82</td>
<td>1.76</td>
<td>2.41</td>
</tr>
<tr>
<td>SP</td>
<td>N/A</td>
<td>N/A</td>
<td>2100</td>
<td>N/A</td>
<td>N/A</td>
<td>601.1</td>
<td>N/A</td>
<td>N/A</td>
<td>0.35</td>
</tr>
<tr>
<td>SG</td>
<td>N/A</td>
<td>N/A</td>
<td>30040</td>
<td>N/A</td>
<td>N/A</td>
<td>619.7</td>
<td>N/A</td>
<td>N/A</td>
<td>4.86</td>
</tr>
</tbody>
</table>

Table 2. Above-ground biomass (kg/ha) Water use (mm) WUE (g/kg)

<table>
<thead>
<tr>
<th>Cropping system</th>
<th>1997/98 Above-ground biomass (kg/ha)</th>
<th>1998/99 Above-ground biomass (kg/ha)</th>
<th>1999/00 Above-ground biomass (kg/ha)</th>
<th>Water use (mm) 1997/98</th>
<th>Water use (mm) 1998/99</th>
<th>Water use (mm) 1999/00</th>
<th>WUE (g/kg) 1997/98</th>
<th>WUE (g/kg) 1998/99</th>
<th>WUE (g/kg) 1999/00</th>
</tr>
</thead>
<tbody>
<tr>
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<td>3320</td>
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<td>2.41</td>
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<tr>
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<td>N/A</td>
<td>2100</td>
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<td>N/A</td>
<td>601.1</td>
<td>N/A</td>
<td>N/A</td>
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</tr>
<tr>
<td>SG</td>
<td>N/A</td>
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<td>30040</td>
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<td>N/A</td>
<td>619.7</td>
<td>N/A</td>
<td>N/A</td>
<td>4.86</td>
</tr>
</tbody>
</table>

Jackson et al. [57] reported that the initial recharge of the soil profile following heavy rain was greater in agroforestry treatments than in sole maize or sole tree treatments at Machakos in Kenya, possibly because percolation of water down through the soil profile was facilitated by channels created by tree roots which had died and decomposed [27, 55]. Jackson et al. [57] noted that soil moisture in the 1.2–1.6 m horizon of the agroforestry treatments was rapidly depleted following rainfall, perhaps because competition with associated crops in the surface horizons forced the trees to abstract water from deeper horizons. No equivalent rapid depletion of water in the deeper horizons was apparent at Makoka as soil moisture in the 1.2–1.5 m horizon of treatments containing trees reached field capacity in March and April in all seasons [56].

These differing patterns of water abstraction may reflect differences in tree management as the trees were pruned infrequently and pruning was confined to the upper canopy at Machakos, but were pruned to 30 cm above ground-level before and during each cropping season at Makoka. Ong and Leaky [32] reported that trees subjected to repeated shoot pruning may develop greater rooting densities in the surface soil horizons and may therefore compete for water with associated crops at different times due to the altered pattern of activity induced by pruning. At Makoka, gliricidia was coppiced to remove all foliage before and during the cropping season with the intention of minimizing transpiration, shading and other competitive tree/crop interactions. Water abstraction from the 0–30 cm horizon was nevertheless greater than from deeper horizons in all treatments and seasons [55], suggesting that tree and crop roots both absorbed water from this soil layer.

The similarity of soil moisture profiles in all cropping systems at Makoka [59] suggests that there was little spatial complementarity in water abstraction between tree and crop roots, despite the prevailing deep soil profile, supporting previous findings that the rooting density of gliricidia is greatest in the surface horizons [26]. However, other studies in Malawi indicate that, the roots of unpruned gliricidia may reach depths exceeding 4 m during the dry season [60]. These findings suggest that gliricidia invests a substantial proportion of its below-ground resources in root growth in the surface horizons when water is readily available, but may root to much greater depth under water-limited conditions. Indeed, Chirwa et al. [55] found that unpruned sole gliricidia abstracted residual water to a depth of 150 cm to support continued growth during the dry season; they concluded that, under the relatively high rainfall conditions typical of southern Malawi, the soil profile contains enough stored water during the dry season to sustain the growth of gliricidia and pigeonpea, thereby demonstrating temporal complementarity resulting from the use of residual water following the maize harvest. However, it should be noted that the ability of potentially deep rooting species to achieve spatial complementarity may be confounded by factors such as limited soil depth above impenetrable bedrock, as in the Machakos study referred to previously, perched water tables or persistent anaerobiosis at depth.

The absence of detectable treatment effects on available soil water in all years at Makoka suggests that similar quantities of water were used in the various cropping systems examined, a view supported by estimates of seasonal water use [59]. Droppelmann et al. [28] reported similar findings for a system involving *Acacia saligna* and *S. bicolor* in Northern Kenya. However, this conclusion may not be valid for the Makoka study in view of the substantial differences in productivity between the tree-based and sole cropping systems; for example, above-ground biomass production by sole gliricidia was almost 10-fold greater than in sole maize in 1999/00 (Table 2). A possible explanation is that the water table may remain close to or within the rooting zone for much of the cropping season in areas of relatively high rainfall or poor drainage. Under such circumstances, genuine treatment differences in water use may be masked if significant quantities of water are extracted from the water table by deep rooting species as measurements of water abstraction from horizons above the water table, as at Makoka, cannot provide reliable estimates of total water use. This difficulty may be avoided by using sapflow gauges to determine water...
uptake by individual system components [50]; this approach provides direct, non-destructive measurements of the quantity of water used during the production of dry matter and provides unequivocal estimates of WUE for each system component.

Soil evaporation may have contributed to the apparently high water use in the sole maize and maize + pigeonpea treatments as evaporative losses may be large in annual cropping systems in the semi-arid tropics [18, 19, 61]. Ground cover was limited at the beginning of the cropping season in all treatments except sole gliricidia because the trees in the mixed cropping systems had been pruned and the maize and pigeonpea were still small. Transpiration would therefore have been low at this time, with the result that a substantial proportion of water, which infiltrated into the soil profile, may subsequently have been lost by evaporation. In support of this view, Droppelmann et al. [28] reported that a large proportion of the available water was lost by evaporation from bare soil in alleys between pruned sole trees in Northern Kenya during periods when ground cover was negligible following pruning. This situation is analogous to the present study, in which gliricidia was pruned to 30 cm above ground-level before and during each cropping season. However, the pruned gliricidia had established root systems, which were able to extract a proportion of the water which infiltrated into the soil profile during the regrowth periods and ensuing dry season. This component of the soil water balance represents the fraction used to produce the dry matter which provided GLM at subsequent prunings.

Ong [16] concluded that, although total water use may not differ greatly between sole and intercropping systems, the latter often use water more efficiently. This conclusion is supported by the Makoka study, which suggests that \( e_w \) was much greater in tree-based systems than in sole maize or sole pigeonpea (Table 2). However, the \( e_w \) values presented here should be treated with caution as soil evaporation and abstraction from the water table were not quantified. If these were taken into account, \( e_w \) values might be higher than shown in Table 2 for the sole crop treatments but lower for sole gliricidia. This view is substantiated by reports that season-long \( e_w \) values range between 2.1–5.2 g/kg in C₄ species such as millet and 1.5–6.4 g/kg in C₃ species such as groundnut depending on the prevailing atmospheric conditions [17]. Lower values have been reported for castor beans grown under semi-arid conditions (0.88–1.31 g/kg) [61]. The \( e_w \) values obtained for sole millet and sole pigeonpea were substantially lower in the Makoka study (Table 2), but appear more realistic for treatments containing gliricidia. The values for the gliricidia + maize and gliricidia + maize + pigeonpea treatments increased between 1997/98 and subsequent years as the trees became increasingly established and their biomass production increased. The high \( e_w \) value obtained for sole gliricidia in 1999/00 reflects the intense shade provided by its dense canopy, as fractional light interception reached 96% [56]; the associated microclimatic changes would have greatly reduced soil evaporation, ensuring that evapotranspiration losses were dominated by transpiration. By contrast, the canopy of sole pigeonpea did not close at any stage of the season and maximum light interception was c. 10%, with the result that evaporation would have approached potential evaporation whenever the soil surface was wet.

As noted previously, soil moisture content in the deeper soil horizons increased sharply between December 1997 and January 1998 and January and February in 1999 and 2000; the deepest horizons reached or exceeded field capacity in the tree-based systems in all years. These results clearly show that substantial percolation of water from the soil surface to deeper horizons occurred during the early stages of the cropping season. This process has potentially important implications for soluble nutrients such as NO₃–N and NH₄–N released by the mineralization of GLM added prior to the cropping season, as these are highly susceptible to being leached to deeper horizons, particularly in acid (5.1–5.6) sandy loam soils with a relatively low cation exchange capacities (6.2–10 cmol/kg) such as that examined at Makoka. Chirwa et al. [59] reported that soil mineral N concentration was invariably high at the start of the cropping season but declined rapidly due to leaching during periods of high rainfall. They concluded that leaching of mineral N from the surface horizons was particularly severe in sole maize and maize + pigeonpea due to their small size and limited nutrient requirements during the early stages of the cropping season. Leaching of mineral N from the surface horizons is common in Savannah areas where the onset of the rains promotes its rapid production [62, 65]. N leached from the surface horizons of agroforestry systems may be captured in deeper horizons by tree roots and recycled to the soil surface through litter fall or applications of GLM.

Despite the likelihood that some of the mineral-N released during decomposition of the gliricidia GLM applied in the tree-based cropping systems was leached from the surface horizons during the early stages of the cropping season, the marked improvement in maize yield in these systems [56] suggests that the crops captured a significant proportion of the N released. The observation that foliar nitrogen concentration and N accumulation in the haulm and grain of maize was greatly increased in the tree-based systems [55, 56] suggests that the GLM applied in these treatments provided a major source of N to meet the needs of maize during its vegetative and reproductive growth.

**Tree Phenology**

One of the great challenges of agroforestry is to select tree species, which optimize the capture and utilization efficiency of environmental resources in a sustainable way,
while fulfilling farmers’ objectives [16]. However, few tree species with consistently limited competitive or beneficial effects on associated crops have been identified to date [66]. Successful incorporation of trees on farms in semi-arid areas requires identification of species that use limited water supplies efficiently, impose minimal competition on associated crops and meet farmers’ needs. A key factor determining species choice is leafing phenology, as this influences the pattern and rate of soil water abstraction, and hence the extent of effects on associated crops [67–69].

Woody species fall into four phenological categories, evergreen, brevi-deciduous, semi-deciduous and deciduous [64]. Evergreen species retain a full canopy throughout the year and leaf turnover is continuous. Brevi-deciduous species exhibit brief reductions in canopy size, although these never exceed 50% and do not occur every year. Semi-deciduous species show reductions in canopy density of 50% or more each year, while deciduous trees are leafless for at least one month every year [70]. Deciduousness may be regarded as a seasonal response to environmental factors and an adaptation to areas subject to periods of water stress or adverse temperature conditions [71]. Differing patterns of tree leaf cover are likely to influence the temporal patterns of tree–crop interactions in agroforestry systems.

Studies at Machakos, Kenya using four tree species providing a range of leafing phenologies examined the hypothesis that temporal complementarity may be used to reduce competition for water between trees and crops during the cropping period and improve utilization of annual rainfall [68, 69]. The species examined were Melia volkensii, which sheds its leaves twice a year, Senna spectabilis and Gliricidia sepium, which shed their leaves during the long dry season, and the evergreen Croton megalocarpus. The main differences in leafing phenology were between indigenous and exotic tree species. Thus the Central American species, S. spectabilis and G. sepium, shed their leaves during the dry season preceding the short rains, while the native species, M. volkensii and C. megalocarpus, showed reduced leaf cover during both dry seasons. C. megalocarpus maintained leaf cover throughout the annual cycle. M. volkensii and S. spectabilis lost almost all leaves during the long dry season (July–October) and flushed prior to the ensuing rains (Figure 4). S. spectabilis showed limited leaf fall during the short dry season, while M. volkensii shed a greater proportion of its foliage before flushing before the long rains (March–July). Although evergreen, leaf cover in C. megalocarpus decreased during the dry season and increased rapidly during periods of high rainfall. G. sepium exhibited a period of low leaf cover during the long dry season and did not regain full leaf

Figure 4. (a) Seasonal timecourses of leaf cover for C. megalocarpus, M. volkensii, S. spectabilis and G. sepium between March 1996 and February 1998 at Machakos, Kenya. Leaf cover was scored on an arbitrary scale where 0 indicates that no leaves were present and 1, 2 and 3 denote low, intermediate and full leaf cover; double standard errors of the mean are shown. (b) daily rainfall (histograms), maximum and minimum air temperatures and maximum saturation deficit (D). Seasonal total rainfall is shown for each cropping season. Shaded areas indicate the duration of the cropping seasons [68].
cover until mid-way through the short rains. These patterns resemble those reported for 38 indigenous and introduced woody perennials in bimodal humid areas of Uganda, where two flushing periods occur [71]; the more intense of these coincided with the onset of the short rains, while less intense flushing occurred at the start of the long rains. The absence of significant variation in daylength (10 min between solstices at Machakos) demonstrates the absence of a link between tree phenology and photoperiod.

The cessation of flushing during dry periods and occurrence of leaf fall during unusually wet periods imply that leafing phenology was predominantly under exogenous control. Broadhead et al. [67, 68] suggested that increased soil moisture content following the onset of the rains was the most likely trigger for leaf flushing in C. megalocarpus, a view supported by measurements of trunk water content during the dry season. This was lowest in C. megalocarpus (39% of trunk fresh weight [72]), suggesting that increase in the quantity of stored water within the trees may have promoted flushing. Huxley and van Eck [71] also reported a lack of correlation between leaf fall and flushing in various species and climatic conditions in Costa Rica, while Reich and Borchert [73] and Borchert [74] proposed that flushing during dry periods may result from rehydration of trees following reductions in transpiration caused by leaf fall. Borchert [74] suggested that trees with a greater water storage capacity are more likely to remain active during drought periods. This hypothesis provides an attractive explanation for the leafing phenology of M. volkensii, S. spectabilis and Gl. sepium observed at Machakos, as flushing invariably followed periods of maximum leaf fall and minimum leaf cover. The relatively high trunk water contents of M. volkensii (58%), S. spectabilis (48%) and Gl. sepium (57% [67, 68]) are comparable with the values reported for deciduous softwood species in a Costa Rican Savannah, in which flushing or flowering occurred during periods of drought following stem rehydration [74]. The absence of a similar pattern in Gl. sepium suggests that the proximity of flushing to the onset of the rains may have resulted from an undetected environmental cue [67, 68].

These results suggest that classification of tree species according to their geographic origin is unlikely to reflect specific functional differences relevant to agroforestry. Instead, the eco-climatic zone of origin and functional tree type are more likely to provide pertinent information regarding the phenological behaviour of individual species [74]. Thus full leaf cover in C. megalocarpus developed only following rainfall and after the crops were sown. Where crop growth is limited by water availability, this pattern is likely to limit abstraction of water by trees during the early stages of crop growth, so decreasing competition. By contrast, the leafing phenologies exhibited by M. volkensii and S. spectabilis are likely to increase water abstraction and interception of rainfall by the tree canopy, promoting competition. Any improvement in water availability during the later stages of crop growth resulting from decreases in the leaf cover in these species is unlikely to improve crop yield significantly. Conversely, flushing during the dry season provides a degree of temporal complementarity, which may increase tree growth without exacerbating competition for water with adjacent crops. The absence of full leaf cover in Gl. sepium during the short rains at Machakos may have decreased competition for water, but is also likely to have decreased tree growth. Whether this would be beneficial or disadvantageous within specific agroforestry systems will depend on the relative economic value of the tree and crop components in the system under consideration.

Further studies at Thika and Naro Moru in Kenya of deciduous (Paulownia fortunei), semi-deciduous (Alnus acuminata) and evergreen tree species (G. robusta) support these conclusions [75, 76]. Pa. fortunei remained leafless for approximately three months during the annual cycle, partly during the cropping season, providing potential benefits for associated crops. A. acuminata shed only some of its leaves during the dry season, although it is fully deciduous elsewhere [78], while G. robusta was evergreen. The leaf fall pattern in Pa. fortunei was comparable to that observed for exotic tree species (S. spectabilis and Gl. sepium) at Machakos [67, 68], although leaf fall occurred earlier in Pa. fortunei, at the end of the long rains. The observation that the leafing phenology of Pa. fortunei differs from the indigenous species examined by Broadhead et al. [68] supports the view that the main contrast in leafing phenology is between indigenous and exotic tree species. The onset of flushing in Pa. fortunei prior to the end of the dry season at a time when soil moisture content was low (c. 15%) further substantiates the view that continued water uptake following leaf fall increases the quantity of stored water available within the tree to support flushing. By contrast, flushing of the other species examined, A. acuminata and G. robusta, at the start of the rainy season suggests that this was triggered by increased soil moisture content [76].

Effects on the growth and yield of associated crops varied between tree species and sites [77]. Thus a positive interaction between A. acuminata and maize was found at Thika, whereas growth was suppressed in the first two crop rows at Naro Moru. G. robusta reduced maize yield by 36% adjacent to the trees at Thika, whereas yield losses were negligible adjacent to Pa. fortunei. These observations suggest that there was complementarity of resource use between A. acuminata and maize at Thika but neutral or competitive interactions were apparent in all other treatments. The enhanced crop growth adjacent to A. acuminata at Thika is analogous to that reported in Uganda [78, 79]. Although G. robusta is popular with farmers in semi-arid and sub-humid areas of Kenya, and has been reported to increase crop yield [80], the results from the Thika and Naro Moru sites clearly indicate otherwise, as has been found in other studies [40, 81, 82].
The tree species examined exploited available soil moisture in different ways [76]. At Thika, G. robusta generally extracted more water than the other tree species and some competition between trees and crops for limited water supplies was apparent, suggesting that the performance of maize was water-limited. Measurements of soil moisture at two distances from the trees were sufficient to explain species differences in water abstraction for the relatively young trees examined. However, as trees grow larger, measurements of soil moisture at greater distances are likely to be needed to provide a full understanding of the partitioning of water between trees and crops and their WUE ($e_w$). $e_w$ was slightly lower in G. robusta than in the other tree species examined, contributing to its more rapid depletion of available soil moisture [76].

In view of the increasing demand for water for non-agricultural uses, and to deploy available water resources most effectively for crop production, it is essential to optimize the use of water [81]. Agricultural research therefore has the key responsibility of developing and implementing techniques and practices which improve the WUE and productivity of cropping systems [82]. Leaf shedding during periods of low soil moisture content provides an important tool for reducing the transpiring area and hence the depletion of residual soil moisture [83, 84]. This emphasizes the potential benefit of adopting trees, which shed their leaves at appropriate times of year, as these are likely to be much less competitive with crops than species, which maintain a full canopy throughout the year in water-limited environments.

**Modelling with WaNuLCAS**

Simulations with the Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) model [84] were used to explore the influence of land use changes (agroforestry versus monoculture) in Central Kenya on water balance and biomass production [84]. Water shortage is particularly acute in the Naro Moru area to the west of Mount Kenya, where immigration has led to rapid changes in land use and increased demand for water resources. Having originated from high potential areas where water is not limiting, immigrant farmers lack knowledge of water conservation techniques. Small-scale mixed farming is the predominant form of land use, with 70% of the plots being between 0.25 and 1.6 ha; in such dry environments, the plots are too small to support a family at a sustainable level. Furthermore, maize production in the area is water-limited [86], resulting in frequent crop failure. Another potential concern is the introduction of tree species in the agroforestry systems, which have been adopted in the area. For example, G. robusta (silky oak) is spreading rapidly after being introduced by migrant small-scale farmers as a boundary marker. Boundary plantings increase tree cover and fuel wood supplies and provide protection against strong winds [82], as well as reducing runoff and increasing infiltration. However, the increase in tree cover has also generated competition for water between trees and crops in marginal areas where water resources are inadequate to meet the needs for livestock and human consumption [82]. Irrigated and rain-fed crop production is rapidly expanding in the area, with most of the irrigation supplies being obtained by illegal abstraction from rivers, leading to a serious decline in streamflow [86].

It was therefore anticipated that introduction of deciduous or semi-deciduous tree species into the cropping systems might reduce demand for the limited water supplies. Three agroforestry species, G. robusta (grevillea), A. acuminata (alnus) and Pa. fortunei (paulownia), respectively representing evergreen, semi-deciduous and deciduous leafing phenologies, were intercropped with maize within WaNuLCAS to test the hypothesis that the use of deciduous tree species would reduce demand limited water supplies. Model simulations showed that altering leafing phenology from evergreen through semi-deciduous to deciduous decreased tree water uptake and interception losses, but increased crop water uptake, drainage and soil evaporation rate for all tree species. These observations suggested that water use would be lower for paulownia than grevillea, perhaps increasing streamflow. The simulations suggested that leafing phenology is one of the most important tree attributes affecting water use.

Figure 5 shows the water balance components (soil evaporation, rainfall interception, drainage, runoff and water uptake by trees and crops) obtained from simulations using different tree leafing phenologies. These suggest that a substantial fraction of the total water balance was accounted for water uptake by the crop, soil evaporation and drainage, whereas the proportions attributable to interception losses, uptake by trees and runoff were substantially smaller. Altering leafing phenology from evergreen, through semi-deciduous to deciduous generally decreased water uptake and interception losses for all tree species, whereas crop water uptake, drainage, evaporation and runoff all increased when a deciduous scenario was adopted with the exception of alnus, in which runoff decreased when leafing phenology was changed from semi-deciduous to deciduous.

The changes in water balance components induced by altering leafing phenology were greatest in paulownia and smallest in alnus, for which the differences between the deciduous and semi-deciduous phenologies were small. Simulated total water uptake was nevertheless greater for all agroforestry systems than for sole maize, although estimated water uptake by the crop component of the agroforestry systems was close to that for sole maize, especially when the deciduous leafing phenology was adopted. Simulated uptake by sole maize was 1090 mm. In the agroforestry treatments, the lowest and highest simulated crop water uptake values were obtained for the
paulownia system using the evergreen and deciduous leafing phenology scenarios respectively. Conversely, the highest and lowest simulated tree water use values were obtained for the same treatments.

Simulated biomass production was generally lower for all tree species when the leafing phenology option was activated. The greatest change in water balance was observed for paulownia, which showed a dramatic reduction in water uptake at both sites as leafing phenology was altered from semi-deciduous to deciduous (Figure 5). Although total water uptake was greater in the agroforestry systems than in sole maize, the quantity of water captured by sole maize differed little from that apportioned to the crop under the deciduous and semi-deciduous scenarios, suggesting that the absence of trees does not necessarily increase water uptake by the crop. An increased proportion of the available water was attributed to soil evaporation in the sole maize system, for which the simulated value was 1747 mm compared to 1537 mm in the alnus treatment using the deciduous phenology scenario.

Similar estimates were obtained for runoff and drainage for all tree species under all leafing phenology scenarios, with the highest values being obtained for sole maize and

Figure 5. Simulated values for the water balance components in sole maize (SM) and agroforestry systems containing G. robusta, Alnus acuminata or Pa. fortunei in a five year simulation involving evergreen (E), semi-deciduous (SD) or deciduous (D) leafing phenology scenarios at Thika, Kenya [85].
the lowest values under the evergreen leafing phenology scenario. This complies with observations that agroforestry may improve WUE by reducing the unproductive components of water balance i.e. run-off, soil evaporation and drainage [16, 75]. However, increases in the drainage component were apparently beneficial in the present study by facilitating recharge of the water table and replenishment of groundwater reserves, which may in turn increase streamflow. Therefore, although agroforestry offers considerable potential for exploiting residual water supplies within the soil profile and deep reserves beyond the maximum rooting depth of annual crops [17, 50, 69, 87, 88], it is essential to achieve a satisfactory balance between recharge and exploitation of groundwater. The simulations suggest that trees with deciduous or semi-deciduous leafing phenologies may offer a good compromise between the evergreen and sole maize systems because their water requirements are intermediate between these two extremes. This view is supported by observations that leafing phenology may influence the partitioning of water, as species exhibiting the smallest seasonal variation in leaf area have been shown to tap increasingly deep sources of soil water as the dry season progresses [89]. Furthermore, competition for limited soil water during the dry season is reported to be influenced by species-dependent differences in leafing phenology [13].

Conclusions

We began this review by stating that the common belief of environmentalists and policymakers that trees create rainfall is not supported by current evidence or scientific explanations. Most hydrologists now accept that there should be a serious effort to produce clear, rigorous and well-articulated policy briefs aimed at key stakeholders, the ultimate end-users of this information. The recent publication of the books From the Mountain to the Tap, Forests and Floods, and Forests, Water and Livelihoods are an important step in this direction. The belief that forests create rainfall is so ingrained in government policy and text books that it will take decades to rectify this erroneous view.

Throughout the tropics, reforestation using eucalyptus has been the most significant approach for modifying the water productivity of forestry and agroforestry systems for many years. Fortunately, the ‘eucalyptus dilemma’ of providing local benefit at the expense of decreased streamflow for downstream users has been well articulated in many countries where evidence-based research has changed water policy and eliminated or penalized the planting of eucalyptus. The most dramatic and successful example is in South Africa, where good science and dialogue with policymakers has created substantial improvements in water governance [90]. Other countries with extensive eucalyptus plantations, such as China and India, are now re-examining their reforestation efforts [3]. Lessons from these countries have stimulated similar re-examination of the role of eucalyptus in water catchments and turned attention to local alternatives [91].

The search for better alternatives to eucalyptus for water catchments and agroforestry systems has led to many blind alleys. The biggest mistake has been the choice of fast-growing, highly competitive leguminous species such as Leucaena leucocephala and Gl. sepium over the last two decades [16], as these have proved to be highly competitive as they exploit the same soil horizons as crops [31]. It is only recently that scientists have developed severe coppicing techniques, such as the mixed intercropping system in Malawi referred to earlier, which reduced competition to an acceptable level as well as providing valuable GLM [55, 56]. In East Africa, the most popular replacement for eucalyptus has been another exotic from Australia, G. robusta, which became the species of choice for farmers in the sub-humid highlands where it is most compatible with crops [92, 93]. However, attempts to extend this species to semi-arid areas have been disappointing due to its evergreen canopy [22, 77]. Current attempts to use deciduous species such as M. volkensii and Pa. fortunei in such areas are much more encouraging, although the long-term effects implications are still unknown [57, 77].

Our review has demonstrated that substantial scientific progress has been made at the plot level in terms of improving complementarity and resource capture in the semi-arid tropics. However, it remains to be seen whether this will be sufficient to address the challenge posed by the increasingly variable climatic conditions and more frequent and severe droughts predicted for much of the African continent [1]. The famous Chagga homegardens which comprise a key element of the ecosystems around Kilimanjaro have faced a formidable decline in rainfall during the past 100 years which is leading to the drying of formerly permanent streams and environmental degradation [94]. What can be done to improve the water productivity of the Chagga ecosystem? Would the introduction of deciduous trees provide worthwhile improvements in the resilience of the Chagga homegardens? These are some of the challenges facing current efforts to adapt forestry and agroforestry to cope with declining rainfall in Sub-Saharan Africa.

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