13 Water Productivity in Forestry and Agroforestry

C.K. Ong and B.M. Swallow
International Centre for Research in Agroforestry, Nairobi, Kenya

Abstract

Forests are the biggest users of water worldwide and extensive forested areas have been lost or are undergoing conversion to agriculture, creating concerns about loss of hydrological functions and increasing the competition for scarce water between agriculture, urban centres, industries and wildlife. The challenge is to improve the sustainability and productivity of land and water use, especially for the growing populations of many developing countries. In this chapter we review recent findings on the hydrology of forests and agroforestry systems and indicate how modifications in tree-based systems might increase water productivity.

In forestry, the focus of research has moved from the hydrological functions of upland forest reserves that are close to settlements to a greater recognition of the roles played by upland communities in the management of water resources. A major source of conflict over water resources is the contrasting perceptions of 'watershed functions' between forest managers and local people, which are often based more on myths of forest functions than on science – for example, the idea that forests increase rainfall. These myths continue to dominate the views of policy makers and institutions and should be revised. The challenge is to gain a better insight into how farmer-developed land-use mosaics have modified watershed-protection functions. Priority must be given to the perceptions, experiences and strategies of local communities.

Trees on farms have the potential for improving productivity in two ways. Trees can increase the amount of water that is used on farm as tree or crop transpiration. Trees can also increase the productivity of the water that is used by increasing biomass of trees or crops produced per unit of water used. Plot-level evidence shows that improvements in water productivity as a consequence of modifications to the microclimate of the crop are likely to be limited. Instead, evidence from semi-arid India and Kenya showed that the greater productivity of agroforestry systems is primarily due to the higher amount of water used. Almost half of the total water use occurred during the dry season, when cropping was impossible, and the rest was extracted from soil reserves. This implies a high temporal complementarity between the crop and tree components of the landscape mosaic. Research is needed to examine the impact of the increased water use on the drainage and base flow at the landscape level. This chapter also describes some of the technical approaches that can be used to improve land and water management, the role of trees and its relation to hydrology and the challenges for rational land-use decision-making.

Introduction

Forests are the biggest users of water worldwide. The tropical forests in Brazil, the 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 and, therefore, clearing of such forests is strongly opposed. Thus, much of the future increase in food and wood production in the humid tropics and elsewhere will have to be achieved from land and water resources already in use. Therefore, the central challenge is to improve the productivity with which existing land and water resources are used.

Over the past half-century, great progress has been achieved in land- and water-use productivity. In agriculture, the advances are generally referred to as the Green Revolution. In forestry, advances have been brought about through a variety of improvements in forest-management systems, including fast-growing high-yielding plantations, and through genetic improvement. In the early stages of the green revolution, research was directed mainly at plant breeding, fertilizer use and plant protection. However, the pace of advances by these means is slowing. The annual increase in cereal yields in developing countries, which from 1967 to 1982 was 2.9%, has fallen to nearly 1%. As a consequence, more attention has recently been directed at greater productivity in the use of land and water resources – for example, through nutrient recycling and soil and water conservation. A further powerful incentive in this direction has come from considerations of sustainability. Applied to land and water, sustainability means meeting the production needs of present land users while conserving, for future generations, the resources on which that production depends.

Forest Hydrology: Myths and Perceptions

Forest hydrology deals with the hydrological cycle of water from precipitation, interception by the vegetation, infiltration into the soil, drainage to groundwater and runoff. The conventional hydrological approach is to seek at least a 30-year record of stream flows and then it is a straightforward statistical exercise to predict future flows, on the assumption that the data provided are samples from a continuous distribution, unaffected by perturbations. In practice, this assumption is not valid in many developing countries, as entire upland catchment areas are cleared and converted to agriculture within a few years. Nevertheless, such long-term studies of catchments in Europe, America and East Africa gave rise to the widely accepted concept of the benefits of forest protection and rehabilitation in mountainous areas (McCulloch and Robinson, 1993), which still shapes the forest policy of many developing countries.

A major difficulty with the conventional approach is that the findings are rarely appropriate for extrapolation to other areas in similar environments or for situations of rapid changes in land use. For this reason, a physical-process approach with micro-meteorological measurements, which is more complex and expensive, was adopted in a few sites to fully understand the sensitivity to climatic variability and vegetation change (Calder, 1998).

After more than a century of forest hydrology there are still a few controversial issues, or so-called 'myths', which hamper rational land-use decision-making. Calder (1998) summarized these issues as follows:

1. Forests increase rainfall. This is mostly myth because the effects of forests are likely to be small, except for cloud forests.
2. Forests increase runoff. Evidence shows that there is less runoff from forests compared with shorter vegetations, because of higher evaporation losses from trees.
3. Forests regulate flows and increase dry-season flows. This depends more on the water-infiltration properties of soils than the forests *per se*. Many studies show less flow with trees, except for cloud forests.
4. Forests reduce erosion. This depends largely on the management methods employed. Some species of trees, such as teak, may actually cause more erosion than shorter vegetations!

5. Forests reduce floods. There is little scientific evidence to prove a direct relationship between forests and floods. Management activities, such as cultivation, road construction and compaction, are more important.
6. Forests improve water quality. This is mostly true, although bad land management is even more significant.

Unfortunately, these myths persist and continue to dominate the views of policy makers and institutions, creating unnecessary conflicts between the government and local communities. For example, development authorities attributed the disastrous floods in Bangladesh and northern India to the deforestation of the Himalayas, even though the frequency or magnitude of flooding has not increased over the last 120 years! Research by Hofer and Messerli (1998) has shown that precipitation and runoff from the Himalayas do not seem to be important causes of floods in Bangladesh. Instead, the main cause appears to be the rainfall patterns in the Meghalaya hills, followed by the Brahmaputra catchment. Curiously, while politicians and engineers perceive floods as the major hazard in Bangladesh, local farmers consider river erosion a much bigger problem than monsoonal floods, which deposit rich organic soil on their fields and increase crop yield! Based on these findings, traditional thinking regarding flood processes, common practices on flood management and even the prioritization of different hazards in Bangladesh must be revised and differentiated. An important lesson from the Bangladesh case is that priority must be given to the perceptions, experiences and strategies of local communities. Furthermore, the underlying causes of conflict probably hold for many other watersheds and are related to the lack of insight into how landscape mosaics influence watershed functions.

Agroforestry

Agroforestry offers one promising option for efficient and sustainable use of land and water. In simplified terms, agroforestry means combining the management of trees with productive agricultural activities. Agroforestry provides opportunities for forest conversion in the true sense of the term – that is, replacement of natural forests with other tree-based land-use systems. There are also opportunities to use agroforestry for the prevention or reversal of land degradation in the humid tropics (Cooper *et al.*, 1996). There are numerous potential benefits that agroforestry systems can achieve, ranging from diversification of production to improved natural-resources utilization. The key benefits in terms of natural-resources use are as follows:

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. Providing environmental functions required for sustainability.

A recent review by Wallace *et al.* (2003) has described the above benefits of agroforestry, while this chapter will focus on the water utilization of agroforestry systems.

Can Trees Increase the Productive Use of Rainfall?

Successful plant mixtures appear to be those that make 'better' use of resources by using more of the resource, using it more efficiently or both. In terms of the water use of an agroforestry system, a central question is, therefore, does intercropping woody and non-woody plants increase total harvestable produce by making more effective use of rainfall? It is possible, at least theoretically, that a mixture of trees and crops may improve the overall rainfall-use efficiency – either directly, by more rain being used as transpiration, or indirectly, by increasing water productivity (WP), i.e. the ratio of biomass or yield over volume of water depleted (Seckler *et al.*, Chapter 3, this volume). Analysis of these two effects requires a systematic study of the water balance of agroforestry systems, such as that carried out by

Ong *et al*. (2000) for an agroforestry system in a subhumid part of Kenya. Wallace *et al.* (2003) describe the complexity of the water balance of an agroforestry system on sloping land at Machakos, Kenya. The interception process in agroforestry systems differs from that of forests in two main ways. First, many agroforestry systems tend to have relatively sparse tree densities and, secondly, additional complexity is introduced by the crop component of the system with its rapidly varying canopy cover. The sparse nature of the tree component of agroforests affects two key factors that influence the interception, i.e. the amount of water stored on the tree canopy and the rate of evaporation from the tree canopy.

In semi-arid agroforestry systems, such as those found in Machakos, Kenya (i.e. 10–50% cover), annual interception loss is between 3 and 10% of rainfall. Higher interception losses have been reported in the much denser multistorey agroforestry systems in Costa Rica, where the rainfall is higher and more intense. High interception losses have also been reported for montane forests in humid tropical regions, e.g. as much as 50% by Schellekens *et al.* (1999). The main reason put forward for these high forest interception losses in humid regions is the advection of energy from nearby oceans.

Significant quantities of water can be lost as evaporation from the soil surface, particularly in tropical regions with frequent rainfall, high radiation and sparse ground cover. In agroforestry systems, the presence of a tree canopy decreases the radiation intensity at the ground, thereby reducing soil evaporation compared with cropping systems. This is because total soil evaporation is determined (at least in part) by the radiant energy reaching the soil surface. Direct measurements of soil evaporation made using minilysimeters show reductions in soil evaporation of up to 30% due to the presence of the tree canopy. The reduction in soil evaporation is smaller with sparser tree canopies, 15% of rainfall when cover is ~0.5% and 6% of rainfall when cover is ~0.2% (Wallace *et al*., 1999).

Clearly, the reductions in soil evaporation produced by tree-canopy shade can help offset the losses of water associated with the tree-canopy interception. The analysis by Wallace *et al*. (1999) indicates that, when annual rainfall is low, the saving in soil evaporation due to canopy shade may be greater than the interception loss. However, once rainfall exceeds ~700 mm per annum, interception losses generally exceed saving in soil evaporation. The exact point at which the two effects completely offset each other will depend mainly on rainfall intensity and soil type.

When rainfall reaches the soil surface, some of it will normally infiltrate into the soil. If the rainfall rate is greater than the infiltration rate, the excess water starts to collect at the surface and, when the surface storage is exceeded, runoff will occur. Infiltration is, therefore, a dynamic process that changes during the course of a rainstorm depending on the soil characteristics, the slope of the land and the rainfall intensity. Where the intercropping of woody and non-woody plants alters any of these factors, then infiltration and runoff may be affected (Kiepe, 1995a). Soil characteristics that affect infiltration are surface crusting, surface storage, saturated hydraulic conductivity and the presence or absence of plant residues. Vegetation cover generally increases infiltration and reduces runoff by altering one or more of these factors. It is well known that conversion from forestry to agriculture can dramatically reduce infiltration within 2–3 years, but restoration of infiltration by reforestation might take several years on severely degraded watersheds. This hysteresis effect is rarely acknowledged and more research is needed to determine how to speed up the restoration of infiltration in conjunction with water-harvesting structures.

There are a number of agroforestry practices that are designed to conserve water and reduce runoff by their direct effect on soil slope. Planting of trees or hedgerows on the contours of sloping land can have the effect of forming natural terraces, as water and soil are collected on the up-slope side of the hedgerow. The barrier effect of the hedgerow not only reduces soil loss but also runoff, commonly to about one-third of its value without hedges. Measurements by drip infiltrometer at Machakos, Kenya, showed that, on a Lixisol (Alfisol) soil with a 14% slope, rates of infiltration were 69 mm h^{-1} under hedgerows and 11 mm h^{-1} under the cropped alleys (Kiepe, 1995a,b). This increased infiltration rate also reduced runoff in these contour-hedgerow systems. Drainage is the component of the water balance that is most difficult to measure directly. At Machakos, it was concluded that drainage from the tree/crop mixture was much less than from the sole crop.

Another way in which trees can affect soil moisture is via the possibility of 'hydraulic lift', in which water taken up by plant roots from moist zones of soil is transported through the root system and released into drier soil (Dawson, 1993). Rainfall captured through stem flow, especially by a woody canopy, can be stored deep in the soil for later use when it is returned to the topsoil beneath the canopy by hydraulic lift. Recently, the opposite of hydraulic lift has been reported in Machakos and elsewhere, i.e. water is taken from the topsoil and transported by roots into the subsoil (Burgess *et al.*, 1998; Smith *et al.*, 1999). This mechanism, termed 'downward siphoning' by Smith *et al.* (1999), would lead to the opposite effect of hydraulic lift and would enhance the competitiveness of deep-rooted trees and shrubs.

The likely effect on each of the water-balance components of the combination of trees with a crop compared with growing the crop alone is summarized in Table 13.1.

Interception losses are around 10% in semi-arid areas but they can be between 10 and 50% in humid tropical climates, depending on whether the location is continental, montane or coastal. This loss will be completely compensated for by a decrease in soil evaporation in a semi-arid climate, but only partially in a humid tropical climate. Runoff, soil moisture and drainage are all likely to decrease in an agroforest in either climatic regime, with the amount varying according to soil type, slope and species. The extra canopy and the ability of tree roots to exploit water at depth in the soil will lead to a general increase in transpiration in the agroforestry system.

Water Productivity in Tree/Crop Mixtures

The WP, or water-use ratio, of any crop or tree/crop mixture is inversely proportional to the mean saturation deficit (expressed in kPa) of the atmosphere, d (Monteith, 1986):

$$\mathrm{WP} = k/d \tag{13.1}$$

where k is a physiological characteristic specific to a given species. WP can be expressed as kg m^{-3}. The total dry-matter production or grain yield is simply the product of WP and the amount of water used by the vegetation. Theoretical considerations and experimental studies have shown that (at least, under fairly idealized conditions) the product of WP and d is quite conservative among species groups (Ong *et al.*, 1996). Therefore,

Table 13.1. Differences in water-balance components between an agroforestry system with 50% tree cover and a monocrop (from Wallace *et al.*, 2003).

Water-balance component	Difference between agroforestry and a monocrop (% of rainfall), semi-arid climate	Difference between agroforestry and a monocrop (% of rainfall), humid tropical climate
Interception loss	+10%	+10–50%
Runoff	Decrease	Decrease
Soil moisture	Decrease	Decrease
Soil evaporation	−10%	−5%
Transpiration	Increase	Increase
Drainage	Decrease	Decrease

the net effect of atmospheric humidity on any given species is one of the most important factors affecting productivity, since dry-matter production per unit of water transpired decreases by a factor of two as saturation deficit increases from ~2 kPa in moist temperate climates to ~4 kPa in semi-arid areas. For example, experiments in India under similar mean saturation deficits (2.0–2.5 kPa) provided season-long values of 3.9 and 4.6 kg m^{-3} for millet, compared with 1.5–2.0 kg m^{-3} for groundnut. WP for grain yield is usually about half of the values indicated above. However, WP is not always higher in C_4 species, since similar values have been reported for drought-tolerant C_3 species, such as cowpea and cotton, and relatively drought-sensitive cultivars of the C_4 species, sorghum and maize.

Equation 13.1 shows that there are two ways that overall production could be increased. The first is by increasing *k*, the physiological characteristic, which depends on the biochemistry controlling the photosynthetic processes in plant cells. This may be achieved by plant selection (e.g. C_3 or C_4 species) or by breeding or genetically engineering crops with a higher value of *k*. The second way to increase WP is to reduce *d*, either by manipulating the microclimate or by growing plants in a more suitable macroclimate. This means that agroforests growing in humid tropical regions, where the air is more humid (i.e. low *d*), will have higher WP.

In theory, the potential of agroforestry to improve WP is limited compared with intercropping, as the understorey crops are usually C_4 species and the overstorey trees are invariably C_3 species. Improvement in WP is most likely if the understorey crop is a C_3 species, which is usually light-saturated in the open so partial shade may have little effect on its assimilation. However, the shade will reduce transpiration, with the result that WP increases. Evidence from both semi-arid India and subhumid Kenya indicates that WP is about 10% higher in agroforestry systems with a C_3 understorey compared with those with a C_4 understorey (Ong *et al.*, 1996). This may explain why cotton yield in the Sahel is not reduced by the heavy shading of karite (*Vitellaria paradoxa*) and nere (*Parkia biglobosa*) in parklands, while yields of millet and sorghum are reduced by 60% under the same trees (Kater *et al.*, 1992). The same process may explain the observation that in the South and Central American savannahs C_3 grasses are found only under trees and never grow in open grasslands dominated by C_4 grasses.

There is also the potential for microclimate modification in agroforestry systems, due to the presence of an elevated tree canopy. This may alter not only the radiation, but also the humidity and temperature around an understorey crop. Some evidence for this has been found where crops have been grown using trees as shelter-belts, and decreases in *d* have been reported for several crops (Brenner, 1996). Data from an agroforestry trial in Kenya also show that the air around a maize crop growing beneath a *Grevillea robusta* stand is more humid than the free atmosphere above the trees (Ong *et al.*, 2000).

Evidence from a series of shade-cloth trials on maize and bean at Machakos shows small but beneficial effects of shading on crop temperature and crop production when rainfall is inadequate for crop production (Ong *et al.*, 2000), but, unlike the savannah situations, the crops failed because below-ground competition consistently outweighed the benefits of shade. In contrast, Rhoades (1997) reported increased soil water (4–53% greater than in the open) in the crop root zone beneath *Faidherbia albida* canopies in Malawi. In theory, trees can increase soil water content underneath their canopies if the water 'saved' by reduced soil evaporation and funnelling of intercepted rainfall as stem flow exceeds that removed by the root systems beneath tree canopies (Ong and Leakey, 1999). At high tree densities, the proportion of rainfall 'lost' as interception by tree canopies and used for tree transpiration would exceed that 'saved' by shading and stem flow, resulting in drier soil below the tree canopy. Van Noordwijk and Ong (1999) expressed this as the amount of water used per unit of shade. This may be one of the most important factors for the observed difference between savannah and alley-cropping systems and between cloud-forest vegetation and fast-growing tree plantations. Below is a list of the situations in which agroforestry can increase water productivity.

1. Understorey vegetation comprises C_3 plants, e.g. cotton and C_3 grasses.
2. Tree shade increases humidity of understorey vegetation in semi-arid climates, e.g. parkland systems and wind-breaks.
3. Planting of trees as contour hedgerows on hill slopes increases infiltration and reduces runoff.
4. Presence of deep water beyond the reach of crop rooting systems.
5. Trees can use rains that fall outside the cropping season.
6. Trees have canopy architecture that intercepts high amounts of water per unit shade.

Can Agroforestry Mimic the Ecological Functions of Natural Ecosystems?

It is often assumed that appropriate agroforestry systems can provide the environmental functions needed to ensure sustainability and maintain microclimatic and other favourable influences, and that such benefits may outweigh the disadvantages of a more complicated management (Sanchez, 1995). Secondly, it is also assumed that agroforestry might be a practical way to mimic the structure and function of natural ecosystems, since components of the latter result from natural selection towards sustainability and the ability to adjust to perturbations (Van Noordwijk and Ong, 1999). Recent reviews of agroforestry findings, however, have highlighted several unexpected but substantial differences between intensive agroforestry systems and their natural counterparts that would limit their adoption for solving some of the critical land-use problems in the tropics (Rhoades, 1997; Ong and Leakey, 1999; Van Noordwijk and Ong, 1999). The most intractable problems for agroforestry appear to be in the semi-arid tropics. In this section, we describe recent insights into the physiological mechanisms between trees and crops in agroforestry systems and how they might be employed to reduce the trade-offs between environmental functions and crop productivity, i.e. retain the positive effects of trees observed in natural ecosystems.

Resource Capture: Complementarity or Competition?

The principles of resource capture have been used to examine the influence of agroforestry on ecosystem function, i.e. the capture of light, water and nutrients (Ong and Black, 1994), and to better understand the ecological basis of sustainability of tropical forests. For example, Cannell *et al*. (1996) proposed that successful agroforestry systems depend on trees capturing resources that crops cannot. The capture of growth resources by trees and crops can be grouped into three broad categories to show competitive, neutral or complementary interactions. In the neutral or trade-off category, trees and crops exploit the same pool of resources, so that increases in capture by one species result in proportional decreases in capture by the associated species. If trees were able to tap resources unavailable to crops, then the overall capture would be increased, as shown by the convex curve, i.e. complementary use of resources. In the third category, negative interactions between the associated species could result in serious reduction in the ability of one or both species to capture growth resources. It is important to bear in mind that tree–crop interactions may change from one category to another depending on the age, size and population of the dominant species, as well as the supply and accessibility of the limiting growth resources.

Such ideas on capture of deep water and nutrients, coupled with recent innovations in instrumentation (minirhizotrons, sap-flow gauges), have stimulated a new interest in root research (Van Noordwijk and Purnomosidhi, 1995; Khan and Ong, 1996) and increased attention on spatial complementarity in rooting distribution and the potential beneficial effects of deep rooting. Agroforestry is also considered as critical for maintaining ecosystem functioning in parts of Australia where deep-rooted perennial vegetation has been removed and replaced by annual crops and pastures, leading to a profound change in the pattern of energy capture by vegetation, rising water tables and associated salinity (Lefroy and Stirzaker, 1999). The Australian example showed that, compared with the natural ecosystem it replaced, the agricultural system is 'leaky' in terms of resource capture, which gives rise to salinity because of the salts accumulated over millions of years in the Australian continent. Recent investigations in West Africa suggest that a similar magnitude of 'leakiness' is possible when native bush vegetation or woodland, which provides little runoff or groundwater recharge, is converted into millet fields. In West Africa, there is no likelihood of salinity associated with the greater recharge but nutrients are leached to lower depths. The expectation is that agroforestry systems will be able to improve nutrient cycling because of their extensive tree-root systems. Earlier research on South African savannahs has shown that tree roots extend into the open grassland, providing a 'safety net' for recycling water and nutrients and accounting for 60% of the total below-ground biomass (Huntley and Walker, 1982).

Manipulation of Water Use and Root Function

Early studies of spatial complementarity in agroforestry began by examining the rooting architecture of trees and crops grown as pure stands. For example, Jonsson *et al*. (1988) described the vertical distribution of five tree species at Morogoro, Tanzania, and concluded that the root distribution of trees and maize were similar except for *Eucalyptus camaldulensis*, which had a uniform distribution of 1 m. Thus, they concluded that there is little prospect of spatial complementarity if these trees and crops were grown in combination. Recent reviews of the rooting systems of agroforestry systems by Gregory (1996) and Ong *et al*. (1999) essentially supported the earlier conclusion of Jonsson *et al*. (1988).

What is the extent of spatial complementarity in water use when there is such a considerable overlap of the two rooting systems? Results at Machakos, Kenya, consistently showed that there was no advantage in water uptake when there was little water recharge below the crop root zone (Jackson *et al*., 2000). However, when recharge occurred following heavy rainfall, tree roots were still able to exploit more moisture below the rooting zone of the crops, even when there was a complete overlap of the root systems of trees and crops.

Where groundwater is accessible to tree roots, there is clear evidence for spatial complementarity. For instance, measurements of stable isotopes of oxygen in plant sap, groundwater and water in the soil profile of wind-breaks in the Majjia valley in Niger showed that neem trees, *Azadirachta indica*, obtained a large portion of their water from the surface layers of the soil when rain was abundant, but during the dry season tree roots extracted groundwater (6 m depth) or deep reserves of soil water. In contrast, at a site near Niamey, West Africa, where groundwater was at a depth of 35 m, they found that both the trees and millet obtained water from the same 2–3 m of the soil throughout the year (Smith *et al*., 1997).

Recently, it has been shown that it is worthwhile to manage below-ground competition by root pruning. For example, Singh *et al*. (1989) demonstrated that root barriers to 50 cm depth are extremely effective in reducing competition between 4-year-old *Leucaena leucocephala* hedgerows and associated crops in semi-arid India. However, the beneficial effects lasted only one season because tree roots reinvaded the crop rooting zone from beneath the root barriers. In contrast, studies in Bangladesh (Hocking, 1998; Hocking and Islam, 1998) revealed that below-ground competition from a wide range of tree species (mainly fruit trees) was virtually eliminated by pruning the lateral roots off the trees. Likewise, studies in Uganda show that competition by *Maesopsis emini*, the fastest growing of 12 tree species compared, was completely eliminated by root pruning (Ong *et al*., 2002). Results with all species showed that overall tree transpiration was not reduced after root pruning because unsevered roots that were located deeper increased their rates of sap flow to satisfy transpirational demand from the atmosphere. More importantly, root pruning dramatically improved crop growth.

Long-term studies of the effects of root pruning are needed because such information is crucial for promotion of the technology to farmers. While many farmers appreciate the benefits of reduced tree–crop competition following crown pruning, ideas of below-ground competition are completely new to most of them. The experience in Bangladesh indicated that root pruning is feasible when land is relatively scarce (average of 0.8 ha per household), crop yields and earnings are quite low and there is a need to grow more trees for household needs and income generation (Hocking, 1998). While crown pruning yields immediate products (firewood and fodder) and offers longer-term gains in crop yield, benefits from root pruning are delayed and thus farmers need convincing that the effort is worthwhile. In Africa, many farmers consider root pruning too difficult and impractical to execute. Fortunately, the techniques themselves can be quickly and easily demonstrated in the field and experience has shown that farmers can readily change their minds regarding the practicality of incorporating root pruning into their cultivation cycles. However, long-term studies of root-pruned trees are needed to address the following questions:

1. Does forcing tree roots to extract most of their water from beneath the crop-rooting zone influence soil-water recharge at depth, and what are the implications for the long-term water balance?
2. Is the growth of the tree and its stability in the wind significantly influenced by root pruning?
3. Does the loss of fine roots and mycorrhizas diminish the capacity of the tree roots to intercept and recycle plant nutrients that leach from near the soil surface?
4. What are the implications of severing surface roots on N_2 fixation and mycorrhizal activity?

Progress and Challenges Ahead

This review has shown that considerable progress has been made in terms of the hydrology of protected forest catchments and agroforestry plots. Much of this process information has been incorporated into various models in order to extrapolate the findings to other environments (Lawson *et al.*, 1995; Van Noordwijk and Lusiana, 1999). A major challenge is how to look beyond the plot and farm level in order to deal with interactions between the plots that comprise a land-use mosaic at the landscape, watershed and regional scales. The conventional approach is to sum across areas of similar hydroecological conditions, assuming that the factors involved in scaling up are proportional to the area occupied by each zone. However, this approach might overstate the beneficial effects of water saved at the plot level, since water that is used in one plot is not available to down-slope plots. This approach also misses a potentially more important effect: the effect of land use on the quality of water available to down-slope users. Swallow *et al.* (2002) discuss how filters and channels affect lateral flows. A contour hedgerow, for example, may occupy a very small part of the landscape but have disproportionately large effects on reducing surface runoff. A boundary planting of trees running down the slope, on the other hand, will have very little beneficial effect on surface runoff.

These lateral-flow effects need to be taken into account in an assessment of water productivity at the catchment or river-basin scale. Computer-based simulation models can be useful tools for predicting the effects of different land- and water-use regimes on catchment hydrology. Catchment experiments in different sizes and shapes of catchment are needed to fully appreciate the cross-temporal and cross-spatial effects of different configurations of agroforestry, forests, agriculture and other land uses on catchment hydrology. Catchment experiments need to be fully participatory throughout the planning and implementation stages, with research, development and monitoring activities very well integrated (Johnson *et al.*, 2002).

The importance of obtaining more information using a catchment-wide approach is underlined by pointing out that current understanding of resource capture by agroforestry systems is based on well-managed small plots, often in research stations, in which about 30–45% of the rainfall is used for transpiration. Such a level of rainfall utilization is rarely achieved in subsistence agriculture or on a watershed scale and there are still ample opportunities for increasing water use by incorporating trees in the landscape. For example, Rockström (1997) reported that only 6–16% of the total rainfall in a watershed in Niger was utilized by pearl millet for transpiration and the remainder was lost by soil evaporation (40%) or deep drainage (33–40%). Thus, future opportunities for simultaneous agroforestry systems should be explored within the landscape as well as on underutilized niches within and around the farms, such as boundary plantings. Increases in productivity may also be achieved by combining agroforestry with small water-harvesting structures (Rockström *et al.*, Chapter 9, this volume).

Another important challenge is resolving the contrasting perceptions of 'forest functions' by various stakeholders. Existing institutions and policies are largely based on a forest–agricultural land-use dichotomy and this may lead to an unnecessary sense of conflict. For example, Verbist *et al.* (2003) proposed that some farmer-developed agroforestry mosaics in Sumatra are as effective in watershed protection functions as the original forest cover! If this is true, then conflicts between state officials and local communities can be resolved to mutual benefit. Experience from the floods of Bangladesh illustrates the importance of understanding the perceptions of local people and the impacts of land-use mosaics and climate.

In tropical countries where forested catchments are located on submontane and montane elevations, there is a growing concern that deforestation is associated with the decline in river flows, although there is no hard evidence to show that link between deforestation, rainfall and river flow. Nevertheless, evidence from elsewhere showed that montane or 'cloud' forests play a vital role in intercepting moist air and maintaining low flow, which cannot be reproduced by planting fast-growing trees, such as pines and eucalptyus (Schellekens *et al.*, 1999). More research is clearly needed to determine ways to restore the hydrological functions of such vital catchments.

Although there appears to be limited scope for spatial differentiation in rooting between trees and crops, i.e. spatial complementarity in water-limited environments, it is worthwhile to manage below-ground competition by shoot and root pruning. Pruning of lateral roots could redirect root function and be a powerful tool for improving spatial complementarity, provided that there are adequate resources at depth (Ong *et al.*, 2002). Research is needed to examine how the downward displacement of functional tree roots following root pruning affect their role in intercepting nutrients leaching from the zone of crop rooting and the long-term hydrological implications.

In the humid tropics, agroforestry systems offer opportunities for conversion of forested land to productive use, while retaining many of the beneficial effects of watershed functions. Multistrata systems (forest gardens, agroforests) and perennial-crop combinations appear to be the most appropriate agroforestry systems for sustainable land use in the humid tropics, including on sloping land; these systems are commonly found acceptable by farmers. Research is needed to examine their impacts on the quantity and quality of water of the stream flow.

In semi-arid environments, it may be more worthwhile to focus attention on the selection of trees that provide more direct and immediate benefits to farmers (rather than the selection for soil enrichment), with minimum loss of crop productivity. It is perhaps not surprising that farmers are already beginning to experiment with such systems. For example, in the drylands of eastern Kenya, farmers have recently developed an intensive parkland system, using a fast-growing indigenous species, *Melia volkensii* (*Meliaceae*), which provides high-value timber in 5–8 years and fodder during the dry season without apparent loss in crop productivity (Ong *et al.*, 2002).

Finally, although there is clearly great potential for agroforestry systems to conserve and improve resource use, it is by no means suggested that agroforestry automatically brings about all of the above benefits. In order to do so, an agroforestry system must be appropriate for the environment (climate, soil, etc.), practicable (within the local and on-farm constraints), economically viable and acceptable to the farmer. Finally, as with any system of agriculture or forestry, to achieve the potential benefits an agroforestry system needs to be well managed. If these conditions are fulfilled, there is considerable potential for agroforestry to combine production with sustainable land use.

Acknowledgements

This chapter is largely drawn from a review presented by J.S. Wallace, A. Young and C.K. Ong at the United Nations Educational, Scientific and Cultural Organization (UNESCO) Meeting on Water, People and Forest, Kuala Lumpur, August 2001, Malaysia.

References

Brenner, A.J. (1996) Microclimate modifications in agroforestry. In: Ong, C.K. and Huxley, P.A. (eds) *Tree–Crop Interactions. A Physiological Approach*. CAB International, Wallingford, pp. 156–186.

Burgess, S.S.O., Adams, M.A., Turner, N.C. and Ong, C.K. (1998) Redistribution of water within plant root systems. *Oceologia* 115, 306–311.

Calder, I.R. (1998) *Water-resource and Land-use Issues*. SWIM Paper 2, International Water Management Institute, Colombo, Sri Lanka.

Cannell, M.G.R., Van Noordwijk, M. and Ong, C.K. (1996) The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. *Agroforestry Systems* 34, 27–31.

Cooper, P.J.M., Leakey, R.R.B., Rao, M.R. and Reynolds, L. (1996) Agroforestry and the mitigation of land degradation in the humid and sub-humid tropics of Africa. *Experimental Agriculture* 32, 235–290.

Dawson, T.E. (1993) Hydraulic lift and water use by plants: implications for water balance, performance and plant–plant interactions. *Oceologia* 95, 565–574.

Gregory, P.J. (1996) Approaches to modelling the uptake of water and nutrients in agroforestry systems. *Agroforestry Systems* 34, 51–65.

Hocking, D. (1998) Trees in wetland rice fields: a successful tree management technology developed through participatory action–research in Bangladesh. *Agroforestry Today* 10, 4–6.

Hocking, D. and Islam, K. (1998) Trees on farms in Bangladesh. 5. Growth of top and root-pruned trees in wetland rice fields and yield of understorey crops. *Agroforestry Systems* 39, 101–115.

Hofer, T. and Messerli, B. (1998) *Floods in Bangladesh. Process Understanding and Development Strategies*. United Nations University Press, 32 pp.

Huntley, B.J. and Walker, B.H. (eds) (1982) *Ecology of Tropical Savannas*. Springer Verlag, Berlin, 669 pp.

Jackson, N.A., Wallace. J.S. and Ong, C.K. (2000) Tree pruning as a means of controlling water use in an agroforestry system in Kenya. *Forest Ecology and Management* 126(2), 133–148.

Johnson, N., Ravnborg, H.M., Westermann, O. and Probst, K. (2002) User participation in watershed management and research. *Water Policy* 6(3), 507–520.

Jonsson, K., Fidjeland, L., Maghembe, J.A. and Hogberg, P. (1988) The vertical distribution of fine roots of five tree species and maize in Morogoro, Tanzania. *Agroforestry Systems* 6, 63–69.

Kater, L.J.M., Kante, S. and Budelman, A. (1992) Karite (*Vitellaria paradoxa*) and nere (*Parkia biglobosa*) associated with crops in South Mali. *Agroforestry Systems* 18, 89–118.

Khan, A.A.H. and Ong, C.K. (1996) A low cost heat pulse method for measuring tree root water uptake. *Agroforestry Today* 7(2), 19–22.

Kiepe, P. (1995a) *No Runoff, No Soil Loss: Soil and Water Conservation in Hedgerow Barrier Systems*. Tropical Resource Management Papers 10, Agricultural University, Wageningen, The Netherlands.

Kiepe, P. (1995b) Effect of *Cassia siamea* hedgerow barriers on soil physical properties. *Geoderma* 66, 113–120.

Lawson, G.J., Crout, N.M.J., Levy, P.E., Mobbs, D.C., Wallace, J.S., Cannell, M.G.R. and Bradley, R.G. (1995) The tree crop interface: representation by coupling forest and crop process-models. *Agroforestry Systems* 30, 199–221.

Lefroy, E.C. and Stirzaker, R.J. (1999) Agroforestry for water management in southern Australia. *Agroforestry Systems* 45, 277–302.

McCulloch, J.S.G. and Robinson, M. (1993) History of forest hydrology. *Journal of Hydrology* 150, 189–216.

Monteith, J.L. (1986) How do crops manipulate water supply and demand? *Philosophical Transactions of the Royal Society, London, B* 316, 245–259.

Ong, C.K. and Black, C.R. (1994) Complementarity in resource use in intercropping and agroforestry systems. In: Monteith, J.L., Scott, R.K. and Unsworth, M.H. (eds) *Resource Capture by Crops*. Nottingham University Press, Loughborough, UK, pp. 255–278.

Ong, C.K. and Leakey, R.R.B. (1999) Why tree–crop interactions in agroforestry appear at odds with tree–grass interactions in tropical savannahs. *Agroforestry Systems* 45, 109–129.

Ong, C.K., Black, C.R., Marshall, F.M. and Corlett, J.E. (1996) Principles of resources capture and utilisation of light and water. In: Ong, C.K. and Huxley, P.A. (eds) *Tree–Crop Interactions – a Physiological Approach*. CAB International, Wallingford, UK, pp. 73–158.

Ong, C.K., Deans, J.D., Wilson, J., Mutua, J., Khan, A.A.H. and Lawson, E.M. (1999) Exploring below ground complementarity in agroforestry using sap flow and root fractal techniques. *Agroforestry Systems* 44, 87–103.

Ong, C.K., Black, C.R., Wallace, J.S., Khan, A.A.H., Lott, J.E., Jackson, N.A., Howard, S.B. and Smith, D.M. (2000) Productivity, microclimate and water use in *Grevillea robusta* based agroforestry systems on hillslopes in semi-arid Kenya. *Agriculture, Ecosystems and Environment* 80, 121–141.

Ong, C.K., Wilson, J., Deans, J.D., Mulatya, J., Raussen, T. and Wajja-Musukwe, N. (2002) Tree–crop interactions: manipulation of water use and root function. *Agricultural Water Management* 53, 171–186.

Rhoades, C.C. (1997) Single-tree influences on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. *Agroforestry Systems* 35, 71–94.

Rockström, J. (1997) On-farm agrohydrological analysis of the Sahelian yield crisis: rainfall partitioning, soil nutrients and water use efficiency of pearl millet. PhD dissertation, University of Stockholm.

Sanchez, P. (1995) Science in agroforestry. *Agroforestry Systems* 30, 5–55.

Schellekens, J., Scatena, F.N., Bruijnzeel, L.A. and Wickel, A.J. (1999) Modelling rainfall interception by a lowland tropical rain forest in northeastern Puerto Rico. *Journal of Hydrology* 225, 168–184.

Singh, R.P., Ong, C.K. and Saharan, N. (1989) Above- and below-ground interactions in alley cropping in semiarid India. *Agroforestry Systems* 9, 259–274.

Smith, D.M., Jarvis, P.G. and Odongo, J.C.W. (1997) Sources of water used by trees and millet in Sahelian windbreak systems. *Journal of Hydrology* 198, 140–153.

Smith, D.M., Jackson, N.A., Roberts, J.M. and Ong, C.K. (1999) Reverse flow in tree roots and downward siphoning of water by *Grevillea robusta*. *Functional Ecology* 13(2), 256–264.

Swallow, B.M., Van Noordwijk, M. and Garrity, D.P. (2002) The effects of scales, flows and filters on property rights and collective action in watershed management. *Water Policy* 6(3), 457–474.

Van Noordwijk, M. and Lusiana, B. (1999) Wanulcas, a model of water, nutrient and light capture in agroforestry systems. *Agroforestry Systems* 43, 217–242.

Van Noordwijk, M. and Ong, C.K. (1999) Can the ecosystem mimic hypotheses be applied to farms in African savannahs? *Agroforestry Systems* 45, 131–158.

Van Noordwijk, M. and Purnomosidhi, P. (1995) Root architecture in relation to tree–soil–crop interactions and shoot pruning in agroforestry. *Agroforestry Systems* 30, 161–173.

Verbist, B.J.P., Van Noordwijk, M., Tameling, A.C., Schmitz, K.C.L. and Ranier, S.B.L. (2003) A negotiation support tool for assessment of land use change impacts on erosion in a previously forested watershed in Lampung, Sumatra, Indonesia (in press).

Wallace, J.S., Jackson, N.A. and Ong, C.K. (1999) Modelling soil evaporation in an agroforestry system in Kenya. *Agricultural and Forest Meteorology* 94, 189–202.

Wallace, J.S., Young, A. and Ong, C.K. (2003) The potential of agroforestry for sustainable land and water management. *Journal of Hydrology* (in press).