Water Management with Hedgerow Agroforestry Systems

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1. Introduction

An outline of the methods used to integrate annual crop production with woody perennials, based on the spatial pattern in which trees are grown, is presented by Lal (1989). These methods range from random scattering of trees across a field to alternate strips of trees and annual crops. This latter system has been referred to as alley cropping, avenue cropping, or hedgerow cropping (Lal, 1989). Many of the concepts used to analyze tropical hedgerow systems could be validly applied to parkland and tree-pasture agroforestry (silvopastoral) systems, as well as to hedgerow systems in temperate environments.

Some researchers have proposed that agricultural systems that contain multiple plant species can exploit more resources through temporal or spatial niche differentiation than can monocultural systems. Thus multiple plant systems can potentially complement each other with respect to resource use and therefore be more productive (Berendse, 1979; Anderson and Sinclair, 1993). More recently, Cannell et aI. (1996) have argued that, from a biophysical perspective, the "benefits of growing trees with crops will occur only when the trees are able to acquire resources of water, light and nutrients that the crop would not otherwise acquire."

To address the question of whether and the degree to which agroforestry systems alter water fluxes relative to other agricultural systems, including the amount of water transpired by plants per given area of land per year, the major pathways of water inputs and losses in the soil-plantatmosphere system must be considered. Water is lost from the soil system as evaporation from soil and plant surfaces, as transpiration, as deep percolation, and as surface runoff. Increases in the amount of water used by plants in the system is therefore accompanied by, and in some cases contingent upon, decreases in water lost as evaporation, deep percolation and/or surface runoff. The importance of these various pathways for water loss will vary with climate, soil type and the landscape, as well as with the type and management of the cropping system. In addition, water can enter some plant-soil systems not only as precipitation infiltrating the soil surface, but also through the lateral movement of water beneath the surface. Some cropping systems may be able to access more of this water than others, thus increasing the amount of water available to plants.

2. Surface Runoff/Infiltration

Agroforestry systems have been recommended for decreasing soil erosion caused by surface runoff. Surface runoff can occur when the rate of precipitation exceeds the rate of infiltration of water into the soil surface. It can be reduced by the interception of water by plant canopies and plant litter, which can decrease the amount, the intensity and the spatial distribution of the precipitation reaching the soil surface. Interception of rainfall by plants and litter protects the soil surface from the direct impact of raindrops which can cause breakdown of the soil structure, leading to sealing of the surface and large reductions in surface infiltration rates (Marshall et aI., 1996). However, runoff can also occur when the soil becomes saturated above a shallow, impermeable layer or when groundwater reaches the surface. In such cases, surface infiltration rates would have little impact on runoff.

The infiltration rate of the soil is influenced by factors that contribute to and maintain soil structure, including soil organic matter, roots and soil biota. Mulching the soil surface not only protects it from the direct impact of raindrops, but also provides organic matter that can be consumed by earthworms and other soil fauna. Thus, mulching can indirectly affect soil aggregate formation and stability. Previous studies have demonstrated that crop residue mulches can effectively reduce surface runoff and increase infiltration.

Water that does not immediately infiltrate the soil can move across the soil surface and be collected in depressions or ditches that can serve as temporary storage basins for ponded water. Hedgerows contribute to this process by stabilizing the barriers that create the storage areas (Sheng,1989; Wiersum, 1991; Dano and Siapno, 1992). However, Wiersum (1984; 1991) considers that the main contribution of agroforestry systems to erosion control, and by implication to surface runoff, lies in the the capacity of these systems to establish and maintain a ground cover of litter, rather than in their role in maintaining water storage basins.

2.1 Studies of Surface Runoff

The impact of hedgerow agroforestry systems on soil runoff c~n be affected by variations in management practices such as mulching, tillage and weeding, as well as variations in the amount of time the soil surface is covered by the hedgerow and the effectiveness of trees in maintaining soil conservation structures (Sheng, 1989). Climate, experimental design and *in situ* factors may complicate the interpretation of runoff results. For example, frequency and intensity of precipitation, the slope, and soil type and depth have large effects on surface runoff. Experimental results depend on the time over which measurements are made and plot size.

Rao et al. (1991) studied the impact of *Leucaena leucocephala* hedgerows in contrast to mulch on a low-sloping (1-2%), shallow Alfisol in semi-arid India. Un mulched hedgerows were effective in reducing annual runoff by up to 55%, with hedgerows at 3-m spacing appearing to reduce runoff more than hedgerows at *5.4-m* spacing. In contrast, mulches of hedgerow prunings, either applied to the soil surface or incorporated into the soil, reduced runoff by 86% in sole annual crops.

Ong (1995) discusses the results of an experiment conducted on 14% slope at a semi-arid site in Machakos, Kenya, using *Cassia siamea.* Runoff from plots planted with *Cassia* contour hedgerows at 4-m intervals and mulched with prunings was compared to runoff from plots planted to sole cowpea that were either not mulched or mulched with 3 t ha^{-1} of *Cassia* prunings. For one 40-mm rainfall event, runoff from the un mulched sole cowpea was 8 mm, compared to 2 mm from the mulched sole cowpea and less than I mm from the mulched hedgerow-cowpea system.

In a one-year study in Machakos, Kenya, on deep, well-drained Alfisols with 15% slopes, runoff losses from sole maize plots mulched with *Cassia siamea. Gliricidia sepium* and *Grevillea robusta* were 28, 48 and 58% lower, respectively, than from unmulched control plots (Omoro and Nair, 1993). In the unmulched controls, runoff totaled 19.5 mm of water (3.75% of the study period's total rainfall of 519 mm) while losses from treatments mulched at 2.24 and 4.48 t ha^{-1} ranged from 5 to 11 mm. Runoff was significantly less in the long rainy season from the treatment mulched at the higher rate (4.48 t ha^{-1}). Ground covered by the mulch decreased from 80% to less than 20% in 60 days during the long rainy season.

2.2 Infiltration Rates

Direct measurements of surface runoff, even on the small plot-scale level, can be difficult and costly to obtain, as well as difficult to extrapolate to other sites and systems. Researchers have also investigated the impact of agroforestry systems on the infiltration rates of soil. Generally, as ponded water is applied to a dry soil, the infiltration rate will decline quickly as the soil is recharged, approaching an equilibrium value with time that is equivalent to the saturated hydraulic conductivity of the soil. Therefore, some studies report the equilibrium infiltration rate and others report the saturated hydraulic conductivity of the soil in order to assess the effect of agroforestry systems on the soil infiltration rate. For example, Alegre and Rao (1996) found that the saturated hydraulic conductivity after 14 consecutive seasons was 50 cm hr^{-1} in their hedgerow intercrop system vs. 18.5 cm hr^{-1} in their sole crop treatment. These values cannot be used directly to estimate changes in surface runoff, but they can suggest whether decreases in surface runoff might be expected. For example, with infiltration rates as high as 50 cm hr^{-1} any surface runoff that might occur would likely be due to other causes, such as soil saturation above a shallow, impermeable layer. Infiltration values can also be used in conjunction with simulation models to estimate runoff. However, such values may be improved by using additional methods to measure infiltration, such as rainfall simulators, that more realistically mimic soil wetting by rainfall in comparison to the more commonly used infiltrometer methods.

2.3 Biological Activity

The application of mulch can increase soil organic matter and alter soil temperature and water regimes. These changes in turn provoke changes in biotic populations and root density. The activities of biota and roots may enhance or maintain surface infiltration rates by promoting the formation of biochannels and improving soil structure (Lal, 1989).

2.4 Negative Impacts

Phytotoxicity or increased pest and disease risks may offset the advantage of decreased runoff associated with mulching. Tian and Kang (1994) investigated possible phytotoxic effects of Gliricidia sepiu11l prunings. In the laboratory, maize seedling growth was significantly reduced by leachate from the prunings. In the field, leaf chlorosis was observed in maize and cowpea seedlings mulched with Gliricidia prunings.

Fodder is often a higher priority use for leaf and stem prunings than is mulch (Ong et aI., 1991). In an analysis of economic returns from a number of hedgerow agroforestry treatments, Rao et al. (1991) reported negative returns on mulched plots in semi-arid India because mulching did not improve crop yields, fodder value was lost and mulching required additional labor. However, Alegre and Rao (1996) argue that in the humid tropics hedgerow agroforestry systems, which provide on-site mulch in the form of hedge prunings, are more viable than mulching systems that require off-site production and transportation.

3. Soil Evaporation

When the soil surface is wet and plant cover is absent, water can evaporate from the soil at rates greater than 5 mm d^{-1}, depending primarily on climatic conditions. This is called the first stage of drying. In a freely draining soil, as the soil surface continues to dry, the evaporation rate will decrease rapidly until a very low rate of evaporation is established. Some of the improvements in water use efficiency of annual cropping systems have resulted from increasing the rate of crop canopy closure, which in turn decreases the amount of water that is lost as soil evaporation. Increases in the rate of crop canopy closure have been obtained by utilizing crop species with rapid canopy growth and/or by increasing plant density.

Continuous perennial covers (such as pastures, orchards, and forests) are land management systems that minimize soil evaporation. Hedgerow agroforestry systems can provide perennial cover, but only over a limited area (ICRAF, 1995). Mulching the soil surface provides additional cover and encourages surface rooting; both the cover and the surface rooting act to lower soil evaporation (Loomis and Connor, 1992). Decaying or dead roots and other macropores, such as those created by rodents, termites and earthworms, minimize soil evaporation by providing channels for rapid subsurface infiltration of water.

3.1 Canopy Closure

In regions with seasonal rainfall, water is frequently lost to soil evaporation at the onset of the rainy season, before crop canopies are well established. Hedgerows are generally severely pruned immediately before this time in order to decrease competition with annual crops, which reduces their potential to decrease soil evaporation.

If crops reach physiological maturity before the end of the rainy season, hedgerows may take up some superficial soil water that might otherwise be lost to soil evaporation at the end of the annual cropping season. Additionally, hedgerows may utilize water from intermittent rains during the dry season that might otherwise be lost to soil evaporation. The importance of hedgerows in utilizing such water is highly dependent on the annual distribution of rainfall. Moreover, in many agronomic systems, weeds use precipitation occurring between cropping seasons.

3.2 Mulching

Mulches can reduce soil evaporation by reducing the amount of radiation absorbed by the soil and by decreasing air turbulence at the soil surface. Budelman (1989) evaluated the impact of Leucaena leucocephala, Gliricidia sepium and Flemingia macrophylla mulches on surface soil temperature reduction (5-cm depth at 15.00 h) and moisture conservation (percent weight at 0 to 5-cm depth) near Abidjan, Ivory Coast, on a soil that was 85% sand. Leaves of all species were applied at a rate of 5 t ha-^{I} during a 60-day dry period, when rainfall averaged 59.5 mm and the average maximum air temperature was 31°C. The mulches were held in place by light bamboo frames or tree branches. Budelman described the effect of the mulches using two parameters: the initial impact (as measured 10 days after the mulches were applied) and the effective lifetime of the mulches. The initial impact ranged from a reduction in soil temperature of 5.6°C for Leucaena to 9.8OC for Flemingia and an increase in soil moisture from 4.0% for Leucaena to 5.6% for Flemingia. The effective lifetime was the time at which the impact was no greater than the least significant difference between the mulched and unmulched treatments. For moisture, this ranged from 44 days for Leucaena to more than 90 days for Flemingia.

In sandy soils in semi-arid environments, there is evidence that the first stage of drying may last for less than a day; i.e., that the soil surface dries rapidly and evaporation begins to decline in a few hours after rainfall (Pilbeam et a\., 1995). Under these conditions, the soils are said to be "self-mulching" and mulches and shading would be expected to have little effect on soil evaporation (Affolder, 1995; Pilbeam et a\., 1995). Mulches are thus more likely to reduce soil evaporation when rainfall events are frequent and on finer textured soils.

3.3 Water Funneling/Deep Infiltration

Hedgerows may tend to funnel intercepted precipitation to their base. This preferential channeling may result in an uneven distribution over the surface and thus to deeper penetration of water into the soil underneath the hedgerow (Lal, 1989; Monteith et al., 1991; Huxley et al., 1994). Huxley et al. (1994) suggested increased maize yields in rows on the windward side of Grevillea robusta hedgerows may have been due to increased infiltration of precipitation on this side of the hedgerow, as well as to a wind shelter effect.

3.4 Surface Rooting

Studies which compare the root system of several tree species grown at the same site give an indication of genetic differences, though these differences may vary in expression at other dissimilar sites. Comparisons of the same species from studies conducted at dissimilar sites ideally should be indicative of the response of the species to different physical environments, but it is often difficult to account for, or control the influence of, seasonal dynamics, management practices and biological factors (e.g., weeds and mycorrhizae). Also, root systems can be measured in different ways, such as weight per volume of soil, root length per volume of soil, or root count per area of soil, and the relationship among these different measures can vary with species and environmental factors. Of these root indices, root length per unit volume of soil is probably most useful in estimating water uptake.

Many agroforestry species appear to have their highest root densities in the surface 0 to I5 cm or I5 to 30 cm of soil. Of the 12 species studied by Toky and Bisht (1992), eight had their greatest percent of total root biomass in the 0 to 15-cm layer and three species had their greatest percent of total root biomass in the 15 to 30-cm layer. The percent of total number of roots of all diameters, as well as the percent of total number of roots in the 0 to 2-mm size class, was greatest in the 0 to 15-cm depth for six species and in the 15 to 30-cm depth for five species. In a study conducted in Tanzania comparing fine root distribution of five two-year-old agroforestry species growing on a sandy loam soil, all but one of the species had the greatest fine root biomass in the 0 to 20-cm soil layer (Jonsson et al., 1988).

Several agroforestry studies with *Leucaena leucocephala* report higher root densities at soil depths below IS cm. Root length density during the dry season of *Leucaena lel/cocephala* in a hedgerow experiment conducted on an Alfisol in Hyderabad, India, was approximately 0.1 cm cm^{-3} in the surface 15 cm; this was less than *Leucaena* root length density from 15 to 30 cm (Ong eta!., 1991

4. Deep Percolation

There has been considerable interest in the use of agroforestry systems to recover water and nutrients that are lost as deep percolation in other cropping systems. There are several aspects of deep percolation (water moving below the cropping system root zone) that deserve further discussion. Taking up more water at depth in the soil profile is often identified with decreasing water lost to deep percolation, but this is not always the case. In the absence of runoff and water uptake from ground water or laterally transferred water beneath the soil surface, deep percolation can be viewed as the difference between precipitation and evapotranspiration. Under a given rainfall regime, reducing deep percolation requires increasing evapotranspiration. Where the actual rate of evapotranspiration is at the maximum rate (potential evapotranspiration), deep percolation cannot be significantly reduced and thus some soil water will inevitably be lost to drainage. Potential evapotranspiration is controlled primarily by the climate. However, vegetation has some influence on potential evapotranspiration rates. Potential evapotranspiration rates from surfaces covered with agronomic crops or pasture may differ from surfaces covered with trees (Oke, 1987). Evapotranspiration from tree surfaces may be greater than from crop surfaces when the canopy is frequently wetted by small storms and the surface area of the tree canopy is greater than that of the crop canopy. In this case, evaporation of water intercepted by plant canopies can be a significant component of the water budget. In contrast, when canopies are dry, but transpiration is not limited by soil water availability, transpiration from crop surfaces may be greater than from tree surfaces due to higher leaf temperatures and, possibly, lower canopy resistance to vapor transfer.

4.1 Humid Environments

In humid climates, monthly precipitation generally equals or exceeds potential evapotranspiraton. This means that soil water is not often depleted below the frequently recharged surface horizons. Opportunities to decrease deep percolation will most likely be found in minimizing the time that it takes annual crops to attain a closed canopy and utilizing cropping systems that maintain a constantly transpiring cover. For these climates, increasing rooting depth per se will likely have little impact on deep percolation.

4.2 Semi-Arid Environments

In semi arid climates, long periods occur in which potential evapotranspiration rates exceed precipitation rates. At first glance, it would seem that cropping systems that can access water deep in the soil profile would be able to transpire more water in these climates than shallow-rooted cropping systems. However, the manner in which water moves deep into the soil must be considered. Significant downward movement of water in soil generally occurs only when the overlying soil is above field capacity. For example, for water to move below a depth of 1.5 m in a deep soil profile, the soil must be recharged so that the water content of the soil profile above 1.5 m exceeds field capacity. If 200 mm of water is required to recharge a soil depleted of plant-available soil water to field capacity to a depth of l.5 m, it would seem at first glance that even in semi-arid regions, with annual rainfall of 500 mm or more, movement below 1.5 m could occur. However, on warm, sunny days, evaporation from the soil surface combined with transpiration can remove greater than 5 mm of water per day. This means that the opportunities for recharge to occur at depth are limited to times when rainfall events are of high intensity and/or long duration or when potential evapotranspiration rates are low. Such a model of soil water movement predicts that, under the same climatic regime, soils with low water holding capacities, such as sands, will recharge to greater depths than soils with large water holding capacities. However, this model does not account for water movement in some highly structured soils, in which ponded water may enter cracks or root channels and move rapidly through the pore, thus bypassing the surface soil (Scanlon and Goldsmith 1997). Also, in semi-arid regions recharge at depth may occur locally where water collects after a rainstorm (Scanlon and Goldsmith, 1997).

5. Groundwater / Drainage Water

In many parts of the world, destruction of native forests, overgrazing of pasture land and introduction of irrigation systems have resulted in large areas of land being subjected to rising groundwater, which is frequently saline (Greenwood, 1986; Bell et aI., 1990; Bari and Schofield, 1991; Bodia et aI., 1994; O'Leary and Glenn, 1994). Researchers have identified two biological methods to reduce groundwater levels. The first method involves the removal of superficial water by plants whose roots do not reach the water table (non-phreatophytes). As discussed in Section 4.3, silvopastoral systems can be quite effective at reducing or halting deep drainage through the uptake of superficial water. In the second method, plants whose roots grow freely into a water table (phreatophytes) take up water directly from the saturated zone (Greenwood. 1986). Researchers in Western Australia (Bari and Schofield, 1991) evaluated silvopastoral systems of mixed pine species (*Pinus radiata and P. pinaster*), pure *Eucalyptus camaldulensis* and mixed eucalyptus species (*Eucalyptus sargentii, E. wandoo, E. camaldulensis and E. calophylla*) at densities that covered about 58% of the ground area. In comparison to nearby pasture, the water table declined over a 10-year period by 1-m and salinity declined 9% in the mixed pine and *E. camaldulensis* site and over an 8-year period the water table declined 2 m and salinity decreased 6% in the mixed eucalypt site. In a study of the hydrological effect of *Casuarina glauca* established on a salt pan in central Queensland, Australia (Walsh et aI., 1995), the water table adjacent to the tree was depressed 130 mm relative to the water Table 10m from the tree. The authors concluded that the rate of water use by the trees was sufficient to inhibit the flow of water to the soil surface and thus halt the concentration of salts by evaporation at the soil surface. This decline in salinity and increase in surface soil moisture would also presumably promote the establishment of grasses between the trees.

Agroforestry systems have also been irrigated with poor quality, subsurface drainage water (Jorgensen et aI., 1992; Tanji and Karajeh, 1993; Miyamoto et aI., 1994) in order to reduce the volume of such water. The long term management and viability of these systems, however, remain unclear (Tanji and Karajeh, 1993).

6. Conclusions

There has been considerable interest in increasing the total water uptake in agroforestry systems compared to annual cropping systems through selecting trees that will root deeply and access water at depth in the soil profile - water that otherwise would not be used by annual crops. Whether enhanced utilization of water at depth in the soil profile may occur in agroforestry systems will depend on several factors. Many important agroforestry tree species do not appear to be especially deep rooted when contrasted to annual crops. Furthermore, the management of these tree species (wide spacing, frequent pruning and interplanting with crops) may promote proliferation of roots near the surface. This suggests that the trees are more likely to compete with crops for water being recharged at the surface than to take water up at depth. In some cases, more complete and vigorous crop or pasture canopies could decrease the amount of water moving below the soil surface horizons, thus limiting the amount of water available for uptake at depth. Frequent, large rain events will enhance the movement of water below the soil surface horizons, especially in soils with low water holding capacity (coarse textured soils and Oxisols) and with poorly developed crop canopies (low fertility soils). If these conditions occur in regions with a sustained dry season, deeply rooted plants may then access water at depth in the soil that has been recharged during the rainy season. Research aimed at increasing water uptake at depth should focus on these areas and on identifying trees that will root deeply in agroforestry systems.

When uptake of water by trees from water tables is considered, the image that frequently comes to mind is deep rooted trees accessing water tables at great depths in the soil. Since some tree species have the ability to grow roots into a water table and/or survive under conditions of fluctuating water tables, they can increase system water uptake by utilizing water in shallow water tables that would not be used by many annual crops and pastures. This can have a positive environmental effect of lowering water tables that are close to the soil surface and might otherwise contribute to soil salinization. In areas where soil and water salinization has already occurred, agroforestry systems might also prove valuable, as some trees are tolerant of saline conditions. Design and testing of agroforestry systems for these conditions has been limited and should be further pursued.

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