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ECOHYDROLOGY OF AGROFORESTRY SYSTEMS

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28.1 Introduction

Agroforestry is broadly defined as a land use system that deliberately combines trees and/or shrubs (hereafter ‘trees’ for brevity) with crops and/or livestock to produce multiple benefits (1). Agroforestry has been practiced by Indigenous and other traditional cultures over millennia (2, 3) and remains prevalent today, especially in tropical regions. More recently, agroforestry has been promoted globally as a climate smart strategy for sustainable food production that maintains or enhances ecosystem services, including hydrological services (4, 5). Agroforestry can be integrated with ecological restoration to rehabilitate soils and with silvicultural systems to produce timber, thereby providing other products and benefits (6).

Agroforestry systems vary widely in composition, structure, configuration, and management, yet they share several characteristics that set them apart from conventional agriculture, including a higher species diversity and structural complexity, greater resilience to disturbance and climate change, and provisioning of multiple ecosystem services (7, 8). Agroforestry’s hydrological impacts are directly related to the ecohydrological functions of trees, particularly their influence on canopy and soil evaporation, transpiration, and infiltration, which combined affect soil and groundwater recharge, runoff, and water quality (9, 10). Understanding these ecohydrological functions, and how they vary in response to the management of the composition, structure and configuration of the trees, and site conditions, is essential to designing agroforestry systems that meet watershed management goals.

This chapter focuses on eight agroforestry systems (Figure 28.1). While the boundaries between the categories are often diffuse, their ecohydrological functions are primarily determined by the trees’ spatial or temporal arrangement. Thus, we first describe the ecohydrological functions of trees and then review the current knowledge on the ecohydrology of the eight agroforestry systems. Finally, we synthesize the key knowledge gaps and offer recommendations for future research.

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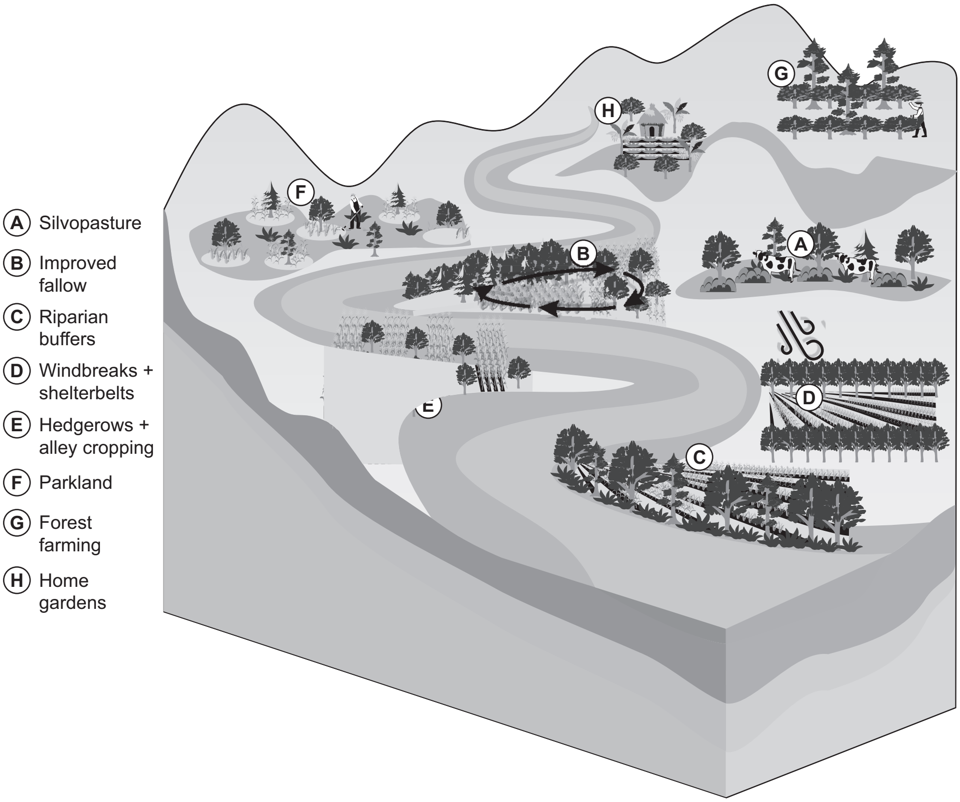

Figure 28.1 A landscape depicting the eight agroforestry systems described in this chapter. (Drawing by D. Aldred).

28.2 Ecohydrological functions of trees and shrubs in agricultural landscapes

Trees directly influence the water balance at the field scale and streamflow at the watershed scale through their effects on key hydrologic processes (Figure 28.2).

Evapotranspiration: canopy interception and transpiration losses are higher for trees than crops due to their larger leaf area, higher aerodynamic roughness, and more extensive root system. However, soil evaporation is reduced beneath and near trees due to shading (11). This effect decreases with distance from the trees and is influenced by the trees' orientation with respect to wind and light (12).

The configuration of the trees (scattered, clumped, linear) affects the canopy's structure and canopy-atmosphere interactions, and therefore evapotranspiration. Scattered individual trees typically have broader crowns with a greater leaf area and exposure to wind and solar radiation, and hence evapotranspiration losses per tree are higher than for trees located within patches. Evapotranspiration losses are often the greatest from trees planted in rows or scattered individuals because of advection at tree-crop edges (13). With increasing tree age, leaf area increases, leading to greater canopy interception and transpiration losses, until canopy closure after which canopy openings and declining leaf area may reduce evapotranspiration (14).

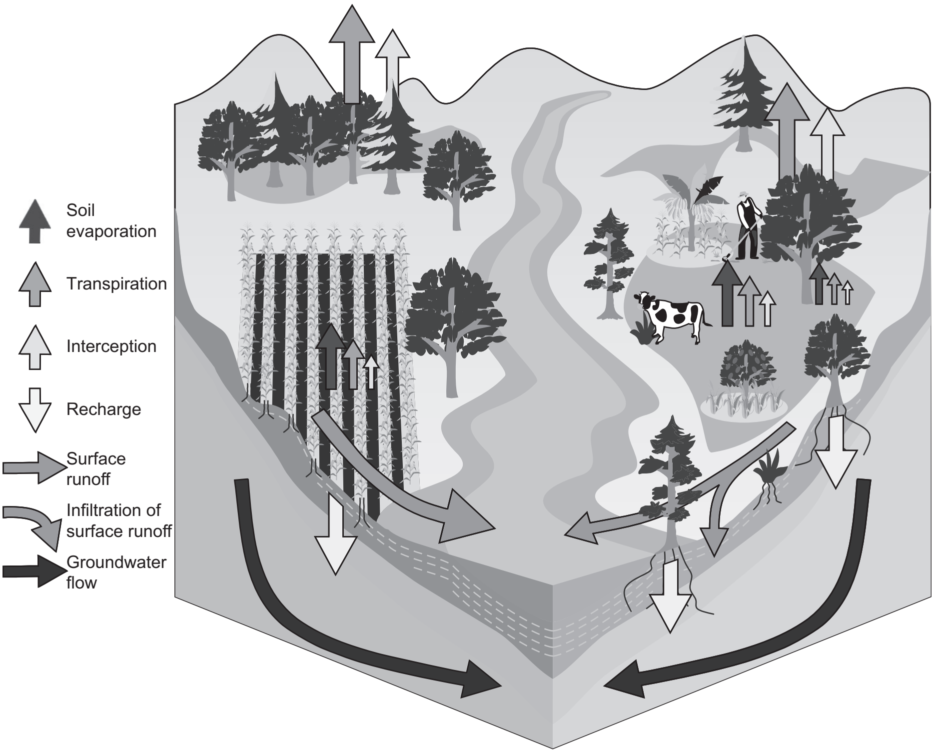

Figure 28.2 A landscape with agroforestry components and the dominant hydrological fluxes (arrows) for the areas with and without trees.

(Drawing by D. Aldred.)

The selection of species with certain functional traits and management practices, such as thinning and pruning, also affect evapotranspiration losses. For example, tree species with deep roots or fast growth rates may use more water than shallow-rooted or slow-growing species (15). Evapotranspiration may also be higher for mixtures of tree species than monocultures due to complementary water use (16).

Evapotranspiration is strongly controlled by the climate, including the seasonal distribution of precipitation and the typical event size, with interception losses being higher for low intensity events (17). Evapotranspiration also depends on soil depth, depth to groundwater, and other biophysical factors that affect plant water availability.

Infiltration and surface runoff: trees improve soil structure and macroporosity by increasing soil organic matter through roots and litter inputs and associated macropore-promoting soil fauna (18). This increases infiltration rates and reduces surface runoff for areas where rainfall intensities exceed the infiltrability (19). Trees planted on degraded soils are more likely to increase infiltrability and reduce surface runoff compared to trees planted on non-degraded soils with favorable hydraulic properties (20). The positive effects of trees on water quality are largely due to their effect on reducing surface runoff and related transport of pollutants and sediment to streams. Management practices resulting in the build-up of organic matter (i.e., green manure or mulching) typically increase soil infiltrability, while frequent removal of litter or pruning of trees may negate the positive effects of trees on infiltration (21). Furthermore, certain species (i.e., eucalypts, pines) and fires may increase soil water repellency and cause a reduction in infiltration (22).

Soil moisture: the effects of trees on soil moisture depend on the trade-off between the increased evapotranspiration losses and increased infiltration (by reducing surface runoff due to the improved soil hydraulic properties under trees) (23, 24). Trees can also impact soil water through hydraulic redistribution, a process by which water moves passively from wetter to drier zones in the soil profile (25).

Streamflow: increasing tree cover within a watershed tends to lead to higher evapotranspiration losses and lower streamflow (26). However, dry season flows may increase (even if annual yields decrease) due to greater soil and groundwater recharge (as a result of the increase in infiltration and reduction in surface runoff) and a greater soil storage capacity (due to the positive effects of trees on soil hydraulic properties) (27). However, a minimum tree cover may be needed for a significantly positive effect on recharge and hydrologic regulation (28, 29).

The ecohydrological effects of trees on streamflow are mediated by their location and spatial configuration within the watershed. Trees located near streams typically maintain higher transpiration rates during dry periods than those planted on the midslopes and are also more likely to intercept surface runoff before it reaches the stream (30). Trees growing along contour lines are more effective at capturing surface runoff than scattered or clumped trees (31).

28.3 Ecohydrology of different agroforestry systems

28.3.1 Scattered multipurpose trees on agricultural land

Scattered trees are an integral feature of a large proportion of agricultural lands worldwide (32). Agroforestry parklands, for example, constitute the predominant farming system in the African Sahel (33). Farmers deliberately retain certain trees after clearing for cultivation and introduce valuable tree species in cultivated fields through planting or farmer-managed natural regeneration (34).

Most research on the ecohydrological impacts of scattered trees has focused on their role in reducing soil evaporation (35), reducing wind speeds and ameliorating microclimate (36), enhancing infiltration, reducing surface runoff, and changing soil and groundwater recharge (24). Enhanced soil organic carbon, soil fauna, and root activity near trees improve soil structure and porosity (37), which increase the infiltrability, preferential flow, and deep soil and groundwater recharge (38). Data collected across different land use systems in sub-Saharan Africa showed that woody cover had a positive effect on the infiltrability (39). However, trees also increase evapotranspiration losses (40), which may explain the lower deep soil moisture content observed next to trees in an agroforestry parkland (24), and may lead to reduced crop yields due to competition for limited resources.

Improvements in soil infiltrability affect surface runoff and erosion, and in turn, streamflow and sediment dynamics at the watershed scale. A meta-analysis reported a five-to-ten-fold reduction in erosion and surface runoff from agroforestry compared to non-agroforestry systems, in sub-Saharan Africa, regardless of climate (41). Erosion control was more effective for trees planted along contour lines compared to scattered trees (42).

28.3.2 Silvopasture

Silvopasture systems integrate trees and livestock within the same land area, with varying tree cover and spatial configuration and management intensity (43, 44). Trees in pasturelands can positively impact soil hydrologic functions by increasing soil infiltrability and preferential flow and reducing soil evaporation and surface runoff (45). Moreover, trees in pastures intercept rainfall, redistributing it as throughfall and stemflow, reducing the erosive powers of rain drops and mitigating soil erosion losses (46). While trees may compete with pastures for water (47), the deep root systems of trees may also redistribute groundwater to the upper soil layers, benefiting shallow-rooted pastures (48). Shade from silvopasture trees can reduce cattle heat stress, which benefits milk and beef production (49).

The impacts of trees in silvopastures are complex and moderated by the type of livestock and vegetation, grazing intensity, climate, and soil texture (50). A high grazing intensity may outweigh the positive effect of trees on soil infiltrability (51). Management of grazing densities, animal behavior and movement, as well as fire intensity and frequency all influence a silvopasture's effects on infiltrability (52). Rotational grazing systems may be more effective at maintaining critical ecohydrological functions (53).

High grazing intensities typically result in soil compaction due to livestock trampling and reduced soil organic carbon, which in turn deteriorates the soil structure, decreases infiltrability and increases soil erosion (54). These impacts are affected by the type of livestock, vegetation, grazing intensity, climate, and soil texture (50). A high grazing intensity may outweigh the positive effect of trees on soil infiltrability (51). Management of grazing densities, animal behavior and movement, and fire regime all influence a silvopasture's effects on infiltrability (52). Rotational grazing systems may more effectively maintain critical ecohydrological functions (53).

At the watershed scale, silvopastures with high canopy cover may reduce annual water yields due to high evapotranspiration losses (55), while intermediate tree covers may maximize groundwater recharge (24). Silvopastures can improve water quality by stabilizing soils and reducing soil erosion and nutrient leaching (56), provided that livestock is kept out of the waterways.

28.3.3 Alley cropping and hedgerows

Alley cropping and hedgerows are an agricultural system in which crops are grown in alleys between widely spaced rows of trees or shrubs (5), with the trees providing multiple ecosystem services (57). Almost all ecohydrological studies on alley cropping and hedgerows have been conducted at the scale of a single tree row or hedgerow and single-species systems. These studies generally have shown a higher macroporosity and infiltrability under tree rows than in the crop alleys (58, 59). As a result, surface runoff from the alleys may infiltrate in the tree or hedgerow, which has positive impacts on runoff and water quality (60). Direct uptake of nitrogen may further improve water quality in hedgerow systems (61).

Evapotranspiration rates are higher for the trees than the crops due to the higher canopy interception and transpiration losses (13). Soil moisture is typically lower under tree rows compared to crop alleys (62). Groundwater levels under hedgerows in Australia were lower than in adjacent cropland due to the increased evapotranspiration losses but the observed variation was only partly explained by factors, such as tree-belt and alley width, or vegetation density, underscoring the complex effects of tree configuration on evapotranspiration (63).

The effects of hedgerows at the catchment scale depends on the density and configuration of the hedgerow network and are often the greatest in the driest years (64). For a catchment in Brittany (France), hedgerows reduced surface runoff and improved groundwater recharge and nutrient cycling (65).

28.3.4 Windbreaks

Windbreaks (or shelterbelts) incorporate linear plantings of trees or shrubs in agricultural landscapes, typically at right angles to the prevailing wind direction (66). Windbreaks reduce wind speeds on the leeward side, reducing turbulence and modifying the microclimate (12), which can increase water use efficiency (12, 67), reduce soil erosion (68), and benefit crop yields and livestock. The reduction in wind speed depends on the optical porosity, height, shape, and width of the trees (68), with recorded reductions reaching distances as far as 30 times the height of the trees (69). Windbreaks can increase temperature and humidity in sheltered areas over a distance of approximately ten times the windbreak's height (70). Windbreaks also redistribute the precipitation through canopy interception and disruptions to the wind field, resulting in up to 15% greater precipitation input on the leeward side (71). However, windbreaks also use more water than cultivated fields, resulting in a deeper groundwater table and lower soil moisture within a distance of 1-20 times the windbreak's height (72).

At the watershed scale, windbreaks can improve infiltration, lower antecedent soil moisture, and mitigate flood peaks (73). Conversely, studies warn that over-planting of trees could exacerbate soil water scarcity in semiarid regions (74), underscoring the importance of site-specific understanding of the net effects of windbreaks on watershed hydrology.

28.3.5 Riparian buffers

Riparian buffers are located adjacent to water bodies and serve as boundaries between the aquatic environment and the surrounding uplands (30). Riparian buffers provide essential functions, such as filtering and retaining sediment, reducing the transport of agro-chemicals, reducing floods, providing habitat connectivity and refugia for wildlife, and cooling (75).

The type of vegetation in riparian buffers is important, as composition, structure, and function depend on river type, climate, and topography. Riparian buffers >30 m are recommended to ensure reduction of runoff from adjacent fields (30) but narrower riparian buffers (<10 m) were also found to significantly improve water quality (75).

Riparian buffers can have positive impacts on hydrologic regulation due to the combined effects of increased evapotranspiration and the interception and infiltration of surface runoff. These impacts are especially pronounced with deeply rooted trees (76) and along field-buffer edges subject to advective energy (77). Overall, riparian buffers have been shown to be cost-effective in increasing sediment and nutrient retention, reducing peak flows, and enhancing flood control at the watershed scale (78–80).

28.3.6 Homegardens

Homegardens (a.k.a., multi-strata polycultures, food-forests, forest gardens, urban agroforests) are mixtures of woody and nonwoody crops forming a complex multi-strata structure similar to native forest ecosystems (81, 82). Although they are typically small (often <1 ha), homegardens may comprise a large proportion of the landscape (83), augmenting their cumulative watershed scale impact. The ecohydrology of homegardens resembles that of forest ecosystems. For example, canopy interception was similar for a multi-strata palm-cacao-Brazil nut-kudzu polyculture and an unmanaged native forest (84). Excavations in Thai homegardens indicated that the diversity of plants leads to vertical root stratification, which maximizes the use of water and nutrients (85).

Homegardens can ameliorate the microclimate and reduce soil erosion relative to the surrounding agricultural or urban environments (2, 85, 86). Homegardens in China created a cooling effect of 2.7°C, which was positively correlated with tree cover, species, and biomass per unit area (87). Erosion rates for homegardens in Sri Lanka were comparable to those in forests and less than 1% of those for annual croplands (88, 89).

At the watershed scale, a synthesis of 37 river rehabilitation initiatives in urban environments, including food forests, reported a positive impact of food forests on water quality, river hydromorphology, and riparian habitat (90). In the wet tropics, homegardens frequently contain ponds used for aquaculture and were shown to regulate water flow in Sri Lanka (89).

28.3.7 Forest farming

Forest farming refers to the cultivation of plants (often of commercial value) beneath the canopy of a native mature forest (91). Some of the most notable products are coffee, tea, cacao, spices, and medicinals. Shade trees provide significant microclimatic buffering for plants underneath them, regulating temperature, humidity, and radiation (92) and help maintain plant water use (93, 94). Forest farming systems typically rely on tree litter to maintain fertility, while extensive and deep tree root systems increase porosity, soil aeration, water-holding capacity, infiltrability (95), and nutrient recycling (96).

By retaining much of the overstory canopy in forest farming systems, the ecohydrological processes are often similar to those in native forests. In the Peruvian Andes, evapotranspiration, surface runoff, and groundwater recharge were similar for coffee agroforestry and forest ecosystems (97). In Costa Rica, interception and transpiration losses were higher in a coffee agroforestry system than a coffee monoculture, and infiltration was enhanced, reducing runoff and recharge (98). In Mexican shade-coffee agroforestry systems, complementary interactions occurred whereby shade tree species obtained water from deeper soil layers, reducing competition with coffee plants (99).

At the watershed scale, forest and coffee agroforestry exhibited much larger preferential pathways and more extensive root networks, which greatly enhanced infiltration and the water storage capacity compared to pasture and sugarcane (100). In Costa Rica, 87% of streamflow from coffee agroforestry originated from baseflow, while only 6% came from surface runoff (101), highlighting its potential to enhance aquifer recharge.

28.3.8 Improved fallows and taungya

Improved fallows and taungya are technical improvements made to traditional swidden agricultural systems, which are still widely practiced worldwide (102). In improved fallows, the regrowth during the successional cycle is purposefully planted, often with nitrogen-fixing species, to accelerate recovery (103). At the end of the improved fallow period (one to five years), the woody plants are harvested, and the prunings are applied as green manure to enhance soil fertility (104). Taungya, also a successional agroforestry system, involves growing crops during the early stages of the establishment of timber plantations until the canopy closes (105).

The ecohydrological impacts of improved fallows and taungya systems are primarily linked to the recovery of soil health. In Zambia, soil water storage and deep drainage increased under improved fallows compared with conventionally tilled non-fertilized maize, leading to improved maize yields in rotation (106). The differences were attributed to increased root and soil faunal activity and organic matter content (107, 108). Improved fallows also significantly increased the infiltrability compared to natural fallows (109) and continuous cropping (110). However, the effect may be temporary. In Zimbabwe, the positive effects of improved fallows on infiltrability decreased markedly after the first year of maize cropping (112).

28.4 Synthesis and key knowledge gaps

Trees in agricultural landscapes provide important water-related regulating services (Section 28.2). However, relatively few studies have quantified the ecohydrological functions of agroforestry systems at the watershed scale, as most studies focused on the plot (field) scale and a single hydrological process (Section 28.3). The lack of research on the ecohydrological effects of agroforestry systems at the watershed scale severely limits their management for optimizing water resources.

Drawing on existing knowledge of the ecohydrological functions of trees, we can make inferences about agroforestry systems' effects on watershed hydrology (Figure 28.3a). Increasing tree cover across agroforestry systems will generally result in greater evapotranspiration and lower annual streamflow compared to agroforestry systems with lower tree cover (Figure 28.3c and d). Tree cover can increase infiltration and reduce surface runoff due to improved soil structure, but outcomes depend on prevailing rainfall intensities and soil properties (Figure 28.3b). In some cases, such as well-conserved grasslands, all water already infiltrates into the soil so that the effect of increasing tree cover on the total amount of water that infiltrates is negligible. In other cases, especially in water-limited environments, total infiltration may even decrease because the higher canopy interception losses result in less water reaching the soil surface (Figure 28.3b). Although peak flows tend to diminish with increasing tree cover in agroforestry systems due to the effects on soil infiltration and water storage, the uncertainty and variability are high (Figure 28.3e). The effects of agroforestry on low flows are particularly uncertain and will largely depend on the infiltration-evapotranspiration trade-off (Figure 28.3f). Agroforestry systems with intermediate densities of tree cover (e.g., alley cropping, silvopasture, parklands, shelterbelts at 40–60% cover) established on degraded soils would likely have the greatest potential for increasing low flows (Figure 28.3f).

Given the high degree of variability in expected watershed scale outcomes for different agroforestry systems (Figure 28.3), more research is needed to refine these predictions across a range of site conditions and watershed locations. Understanding where in the watershed to prioritize the establishment of different agroforestry systems to maximize desired ecohydrological functions and watershed services is another important knowledge gap.

Models have been used to understand the watershed scale effects of agroforestry relative to alternative land use systems. Mwangi et al. (111) assessed the impact of agroforestry (classified as 'woodlots') on the hydrology of the Mara River Basin in East Africa and found that agroforestry generally reduced surface runoff due to enhanced infiltration but also increased evapotranspiration and consequently reduced baseflow and annual streamflow. Another modeling study, which classified agroforestry as '50% cropland-woodland, 30% irrigated cropland and pastures, and 20% mixed forest', showed that agroforestry could have a positive effect on the water supply for the city of Santa Cruz, Bolivia (86). A modeling study by Kamamia et al. (112) showed that establishing agroforestry in the upper watershed regions in Kenya would greatly improve environmental sustainability, including a 78% reduction in sediment loads, 14% increase in low flows, and only slightly decreased (<4%) crop yields.

Combined, these modeling studies highlight the challenges of parameterizing agroforestry systems and underscore the valuable insights gained by using an integrated modeling approach to understand the ecohydrological functions of agroforestry at the watershed scale. Such an approach could guide watershed managers by quantifying the potential hydrological trade-offs associated with different agroforestry systems compared to other land use systems. Models could also be used to determine the effect of the trees' location, spatial configuration, and species composition on streamflow, and how these effects depend on the soil properties, climate, topography, and management.

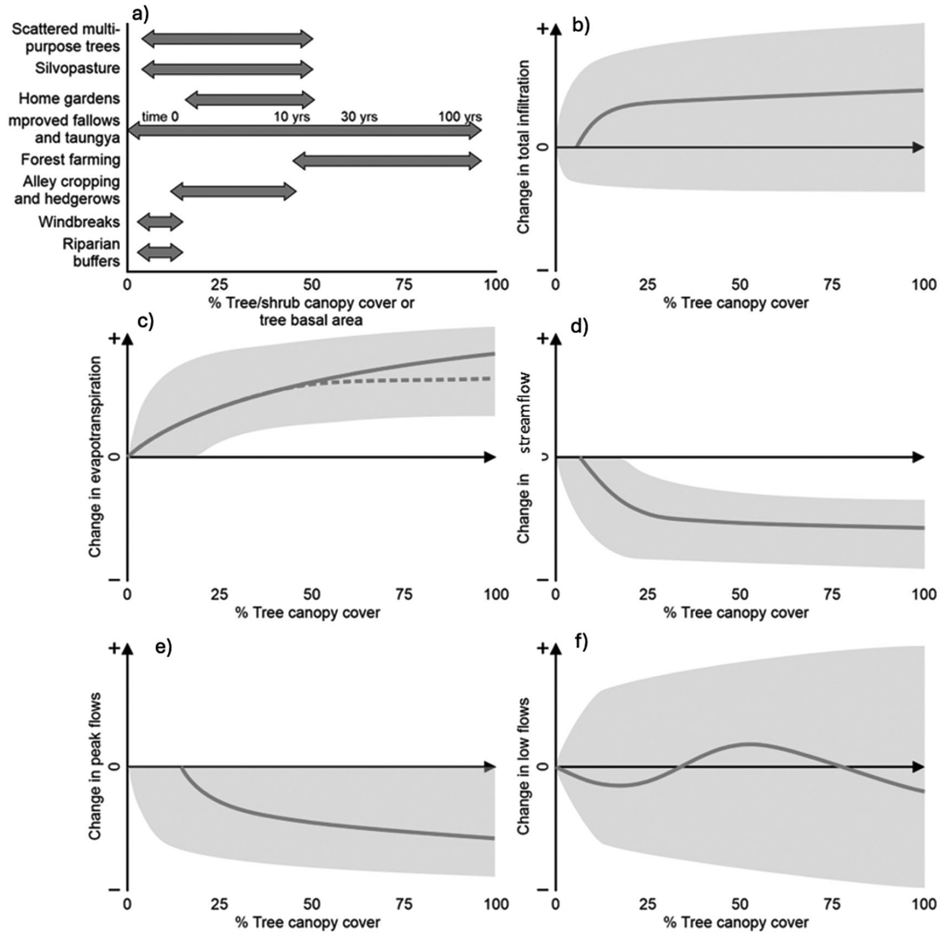

Figure 28.3 Range in tree cover for the different agroforestry systems and the hypothesized range of the effects of increasing tree cover on the change in hydrological fluxes at the watershed scale compared to a treeless situation: total infiltration(b), annual evapotranspiration (c), annual streamflow (d), peak flows (e), and low flows (f) (green area). The black line represents one of many potential outcomes. The dashed line for evapotranspiration indicates one of the many trajectories in a water limited system. The y-axis scale represents the relative difference (percent change) between the minimum and maximum possible change for each individual component.

A limitation of the above studies is that they relied on default land cover types for parameterizing agroforestry within the model. Ideally, models would incorporate empirical field data on ecohydrological processes from different agroforestry systems to improve the realism of the model and accuracy of the predictions. A study conducted by Birkel et al. (113) illustrates this approach. They developed an ecohydrological model for a shade coffee agroforestry system that uses field-based measurements (e.g., sap flux-derived transpiration, Eddy Covariance-derived actual evapotranspiration, and measured soil water contents) for model calibration. This approach allows for upscaling plot-level measurements to the hillslope and catchment scales to better understand the effects of agroforestry on hydrological services.

28.5 Concluding words

Integrating trees with crops and/or livestock through agroforestry has the potential to transform agricultural landscapes by boosting the provision of hydrologic and other ecosystem services. Studies have examined how field-scale ecohydrological processes are affected by agroforestry systems but information on the effects at the watershed scale are lacking. The ecohydrological functions of trees in agroforestry settings are likely location-specific and the range of potential outcomes is broad. Integration of field studies with watershed modeling could improve our knowledge and inform the design of agroforestry systems to meet water management objectives.

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