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Agroforestry for ecosystem services and environmental benefits: an overview

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Abstract Agroforestry systems are believed to provide a number of ecosystem services; however, until recently evidence in the agroforestry literature supporting these perceived benefits has been lacking. This special issue brings together a series of papers from around the globe to address recent findings on the ecosystem services and environmental benefits provided by agroforestry. As prelude to the special issue, this paper examines four major ecosystem services and environmental benefits of agroforestry: (1) carbon sequestration, (2) biodiversity conservation, (3) soil enrichment and (4) air and water quality. Past and present evidence clearly indicates that agroforestry, as part of a multifunctional working landscape, can be a viable land-use option that, in addition to alleviating poverty, offers a number of ecosystem services and environmental benefits. This realization should help promote agroforestry and its role as an integral part of a multifunctional working landscape the world over.

Keywords Biodiversity conservation · Carbon sequestration · Clean air · Clean water · Multifunctional working landscape · Soil enrichment

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Introduction

The claims of products and services provided by agroforestry practices are many. However, the agroforestry literature lacked evidence for many of these claims until recently. The last decade has seen an increase in scientific data that substantiate some of these claims. Increasingly agroforestry is viewed as providing ecosystem services, environmental benefits, and economic commodities as part of a multifunctional working landscape. The multifunctional role of agro ecosystems has also been emphasized by both the Millennium Ecosystem Assessment (2005) and the International Assessment of Agricultural Science and Technology for Development (2008). There is also a great deal of interest in providing financial benefits to landowners and farmers for land-use practices that maintain environmental services of value to the wider society (FAO State of Food and Agriculture Report 2007).

Attempts have been made to quantify environmental benefits of agroforestry; however, comprehensive reviews or synthesis have been rare. The available reviews have focused mostly on a single ecosystem service. For example, Schroth et al. (2004) put together the first comprehensive synthesis of the role of agroforestry systems in conserving biodiversity in tropical landscapes with examples from many different countries. Schroth and Sinclair (2003) addressed soil fertility enhancement by agroforestry practices. Montagnini (2006) focused on carbon sequestration potential of agroforestry systems using various case studies from around the globe. The objective of this special issue is to bring together a collection of original research articles that deal with a number of ecosystem services and environmental benefits from agroforestry practices the world over.

Major ecosystem services and environmental benefits

The integration of trees, agricultural crops, and/or animals into an agroforestry system has the potential to enhance soil fertility, reduce erosion, improve water quality, enhance biodiversity, increase aesthetics, and sequester carbon (Garrett and McGraw 2000; Garrity 2004; Williams-Guillén et al. 2008; Nair et al. 2009). It has been well recognized that these services and benefits provided by agroforestry practices occur over a range of spatial and temporal scales (Izac 2003; Table 1). Many of these environmental externalities derived at the farm scale or landscape scale are enjoyed by society at larger regional or global scales. Although recent interest in the clean development mechanism (CDM) under the Kyoto Protocol offers promise for economic returns for carbon sequestration benefits of agroforestry systems, society's willingness to pay for other ecosystem services is yet to be fully explored.

I will classify the major ecosystem services of agroforestry into four categories (carbon sequestration, soil enrichment, biodiversity conservation and air and water quality) and briefly discuss each one in the following sections. Overall, the discussion below cuts across the four major categories of ecosystem services (provisioning, regulating, cultural and supporting) identified by the Millennium Ecosystem Assessment (2005).

Agroforestry for carbon sequestration

Carbon sequestration involves the removal and storage of carbon from the atmosphere in carbon sinks (such as oceans, vegetation, or soils) through physical or biological processes. The incorporation of trees or shrubs in agroforestry systems can increase the amount of carbon sequestered compared to a monoculture field of crop plants or pasture (Sharrow and Ismail 2004; Kirby and Potvin 2007). In addition to the significant amount of carbon stored in aboveground biomass, agroforestry systems can also store carbon belowground. Carbon sequestered in agroforestry systems could be sold in carbon credit markets where such opportunities exist. The largest amount and most permanent form of carbon may be sequestered by increasing the rotation age of trees and/or shrubs and by manufacturing durable products from them upon harvesting.

Table 1 Spatial scales of various ecosystems services provided by agroforestry systems (modified from Izac 2003 and Kremen 2005)

Ecosystem Services	Spatial Scale		
	Farm/Local	Landscape/Regional	Global
Net Primary Production	■		
Pest Control	■		
Pollination/Seed Dispersal	■		
Soil Enrichment	■		
Soil Stabilization/Erosion Control	■		
Clean Water	■	■	
Flood Mitigation	■	■	
Clean Air	■	■	
Carbon Sequestration	■	■	■
Biodiversity	■	■	■
Aesthetics/Cultural	■	■	■

The potential of agroforestry systems to sequester carbon varies depending upon the type of the system, species composition, age of component species, geographic location, environmental factors, and management practices. A large number of studies have appeared in recent years that report carbon sequestration potential of agroforestry systems from the world over. The inherent variability in the estimates and lack of uniform methodologies have made comparisons difficult. In a recent review, Nair et al. (2009) showed that the carbon sequestration potential of the vegetation component (above and belowground) varied from 0.29 Mg ha^{-1} yr^{-1} in a fodder bank agroforestry system of West African Sahel to 15.21 Mg ha^{-1} yr^{-1} in mixed species stands of Puerto Rico. Soil carbon estimates ranged from 1.25 Mg ha^{-1} in a Canadian alley cropping system to 173 Mg ha^{-1} in an Atlantic Coast silvopastoral system in Costa Rica. These authors concluded that, in general, agroforests on arid, semiarid, and degraded sites had a lower carbon sequestration potential than those on fertile humid sites; and temperate agroforestry systems had relatively lower rates compared to tropical systems.

Attempts have also been made to quantify the global carbon sequestration potential of agroforestry systems. For example, Dixon (1995) estimated a total of 585–1,215 million ha of land in Africa, Asia and the Americas under agroforestry and a global potential to sequester 1.1–2.2 Pg of carbon (vegetation and soil) over 50 years. Nair et al. (2009) estimated a land area of 1,023 million ha under agroforestry worldwide. Using the median carbon sequestration potential used by Dixon (94 Mg ha^{-1}), the land area of 1,023 million ha represents a carbon sequestration potential of 1.9 Pg of carbon over 50 years. Considering the large extent of degraded croplands and pasturelands and the potential to improve them using agroforestry, there is enormous potential to sequester additional carbon in such systems. According to an estimate by IPCC (2000), improving current management practices (e.g. better management of trees on croplands) in existing agroforestry practices could sequester an additional 12,000 Mg C y^{-1} by 2010 and 17,000 Mg C y^{-1} by 2040. Additionally, 630 million ha of unproductive croplands and grasslands could be converted to agroforestry, representing a carbon sequestration potential of 391,000 Mg C y^{-1} by 2010 and 586,000 Mg C y^{-1} by 2040.

There are four papers included in the special issue that address carbon sequestration potential of agroforestry systems. The extent of carbon sequestration, especially in soils, in agroforestry systems of West African Sahel was investigated by Takimoto et al. by comparing two traditional parkland systems, two improved agroforestry systems (live fence and fodder bank), and abandoned land. The authors concluded that improved agroforestry practices such as live fence and fodder bank sequestered more carbon than traditional parklands. Gupta et al. examined soil organic carbon and aggregation under a poplar-based agroforestry system in northwest India. The soil organic carbon concentration and pools were higher in soils under agroforestry and increased with tree age. Kaonga et al. quantified tree and soil carbon stocks and their response to different tree species and soil clay contents in 2, 4, and 10 year old improved fallows in eastern Zambia and concluded that carbon stored in trees and soil of improved fallows could be increased by planting selected tree species on soils with high clay content. Saha et al. examined how tree density and plant-stand characteristics of south Indian homegardens affected soil carbon sequestration. Their results showed that the potential to sequester soil carbon increased with species richness and tree density. All of these case studies further add to the growing body of literature that indicates agroforestry systems have the potential to sequester greater amounts of above and belowground carbon compared to traditional farming systems.

Agroforestry for soil enrichment

The role of agroforestry in enhancing and maintaining long-term soil productivity and sustainability has been well documented. The incorporation of trees and crops that are able to biologically fix nitrogen is fairly common in tropical agroforestry systems. Non N-fixing trees can also enhance soil physical, chemical and biological properties by adding significant amount of above and belowground organic matter and releasing and recycling nutrients in agroforestry systems. A large body of literature, comprised of both original research and synthesis articles, has described the effects of agroforestry on soils in the tropics (e.g. Nair and Latt 1997; Young 1997; Buck et al. 1998; Schroth and Sinclair 2003). Similar accounts are relatively few in the temperate literature; however, the role of woody perennials, both N-fixing and non-fixing, in improving the soil chemical, physical and biological properties has become the subject of investigations in the last decade (Jose et al. 2004). For example, Seiter et al. (1995) demonstrated the use of N-fixing red alder (*Alnus rubra*) in a maize alleycropping system in Oregon. The authors observed, using an ^{15}N injection technique, that 32–58% of the total N in maize was obtained from N fixed by red alder and that nitrogen transfer increased with decreasing distance between the trees and crops. Lee and Jose (2003) demonstrated that alley cropping systems involving pecan and cotton (*Gossypium hirsuitum*) in the southern United States had higher soil organic matter and microbial biomass compared to monoculture cotton. Using high-resolution x-ray computed tomography, Udawatta et al. (2008a) examined the role of agroforestry buffers in improving soil porosity in the Midwest Region of the United States. They observed that average pore paths for grass and agroforestry buffer strip soils were three and five times greater, respectively, than for soils under maize-soybean rotation. In a companion study, Udawatta et al. (2008b) further showed improved soil aggregates stability, soil carbon, soil nitrogen, and soil enzyme activity in soils under agroforestry buffers compared to row crops.

There are four papers in the special issue that deal with soil properties and processes as influenced by agroforestry management practices. Guo et al. examined the effects of crop residues on crop performance and soil N_2O and CO_2 fluxes under monocropping and intercropping systems on a loamy clay soil in subtropical China. While leguminous crop residues and N-fixing hedge rows improved soil quality and crop productivity, they also resulted in increased soil N_2O and CO_2 emissions in the agroforestry systems. The impact of the shade tree *Erythrina poeppigiana* on soil characteristics was evaluated in conventional and organic coffee farms in Costa Rica by Payan et al. They observed higher soil carbon and nitrogen concentrations near the base of trees compared to 2 m away from the base in conventional systems, indicating the importance of shade trees in maintaining and enhancing soil organic matter. However, this trend was not observed in organic coffee systems, perhaps due to the addition of organic amendments uniformly on the soil surface in such systems. Shukla et al. suggested that arbuscular mycorrhizal (AM) inoculation may enhance the growth and phosphorus uptake of intercrops under tree shade in agroforestry systems and made recommendations for tree canopy management to increase the efficiency of AM inoculants. Mendez et al. compared how management approaches affected shade tree diversity, soil properties, and provisioning and carbon sequestration ecosystem services in three shade coffee cooperatives in El Salvador. While higher tree richness generally increased soil pH, CEC, Ca, and Mg, higher tree densities lowered N, K, and organic matter in the shade coffee agroforestry systems. Overall, the distinct management approaches used by the cooperatives differentially affected soil nutrient content and properties. The authors suggested that working with farmer cooperatives, rather than with individual farms, might facilitate improved ecosystem services at the landscape scale. They also emphasized the importance of understanding the complex social and ecological context in which tropical shade coffee agroecosystems exist. An improved understanding of this context would help policy makers and farmers in their efforts to develop shade coffee landscapes and institutional systems that adequately manage and conserve a variety of ecosystem services. This lesson may well apply to agroforestry system management the world over.

Agroforestry for biodiversity conservation

Ecosystems and species important in sustaining human life and the health of our planet are disappearing at an alarming rate. Consequently, the need for immediate action to design effective strategies to conserve biodiversity is receiving considerable attention worldwide. Scientists and policy makers are becoming increasingly aware of the role agroforestry plays in conserving biological diversity in both tropical and temperate regions of the world. The mechanisms by which agroforestry systems contribute to biodiversity have been examined by various authors (e.g. Schroth et al. 2004; McNeely 2004; Harvey et al. 2006). In general, agroforestry plays five major roles in conserving biodiversity: (1) agroforestry provides habitat for species that can tolerate a certain level of disturbance; (2) agroforestry helps preserve germplasm of sensitive species; (3) agroforestry helps reduce the rates of conversion of natural habitat by providing a more productive, sustainable alternative to traditional agricultural systems that may involve clearing natural habitats; (4) agroforestry provides connectivity by creating corridors between habitat remnants which may support the integrity of these remnants and the conservation of area-sensitive floral and faunal species; and (5) agroforestry helps conserve biological diversity by providing other ecosystem services such as erosion control and water recharge, thereby preventing the degradation and loss of surrounding habitat. Designing and managing an agroforestry system with conservation goals would require working within the overall landscape context and adopting less intensive cultural practices to achieve the maximum benefits (Table 2).

The important role that agroforestry plays in the battle to conserve global biodiversity has been illustrated by various studies in the recent past. Shade coffee is an agroforestry system that shows great promise to enhance biodiversity compared to traditional agricultural practices (Perfecto et al. 1996; Moguel and Toledo 1999). Similarly, multistrata cacao (*Theobroma cacao*) agroforestry systems that include timber, fruit, and native forest species also contribute to biodiversity conservation by providing habitat for avian, mammalian, and other species, enhancing landscape connectivity, and reducing edge effects between forest and agricultural land (see a special issue of Biodiversity and Conservation, Volume 16 Number 8 published in 2007 for a series of papers on the topic). For example, Harvey and González Villalobos (2007) characterized bat and bird assemblages occurring in forests, two types of agroforestry systems (cacao and banana) and plantain monocultures in the indigenous reserves of Talamanca, Costa Rica. Agroforestry systems had bat assemblages that were as (or more) species-rich, abundant, and diverse as forests, contained the same basic suite of dominant species, but also contained more nectarivorous bats than forests. Agroforestry systems also harbored bird assemblages that were as abundant, species-rich, and diverse as forests. However, the species composition of these assemblages was highly modified with fewer forest-dependent species, more non-forest species and different dominant species. These authors concluded that the diverse cacao and banana agroforestry systems

Table 2 Desirable characteristics of agroforestry systems for biodiversity conservation (after Harvey et al. 2007)

Type of activity	Variable	Desirable characteristics
Design of agroforestry system	Species composition	Diverse species composition, mixture of early, mid and late successional species, preferably native species
	Tree/Shrub density	Higher tree/shrub density (and greater areas) leads to greater biodiversity
	Type of agroforestry system	Any system as long as it is floristically and structurally diverse
	Duration of agroforestry system	Long rotation is desirable to provide stability
Management of agroforestry system	Management regime	Minimal management is preferable
		Management strategies should maximize habitat heterogeneity and availability of diverse resources for wildlife
	Soil management	Minimal
	Harvesting of products	Minimal harvesting or harvesting that emulates natural disturbance regimes
	Fire management	Fire regimes should follow natural fire regimes to the extent possible
	Management of snags and coarse woody debris	Maintain snags and coarse woody debris as habitat for certain species
Spatial configuration	Location within broader landscape	Position the agroforestry practices strategically to enhance landscape connectivity, by functionally linking habitat fragments
		Position adjacent to protected areas, riparian corridors and remnant native habitat, to buffer these areas from agricultural impacts
	Types of land	Degraded sites, where revegetation through agroforestry will have a beneficial impact on biodiversity

contributed to conservation efforts by serving as habitats to large numbers of bird and bat species, including species of known conservation concern.

Other agroforestry systems have also been studied for their conservation values, especially in the tropics. Homegarden agroforests, both from the neo tropics and old-world tropics, are well known for their high floristic diversity. Many ecologists consider such systems structurally and functionally the closest mimics of natural forests (e.g. Ewel 1999). In a review, Kumar and Nair (2004) reported species richness of tropical homegardens varying from 27 (Sri Lanka) to 602 (West Java). In various parts of the world where land clearing for agriculture has decimated forest cover, homegardens and similar agroforestry systems serve as refugia of species diversity. For example, in Bangladesh where natural forest cover is less than 10% of the total geographic area, homegardens, which are maintained by at least 20 millions households, represent one possible strategy for biodiversity conservation (Kabir and Webb 2009). In an extensive survey of floristic and structural diversity of 402 homegardens from six regions across southwestern Bangladesh, Kabir and Webb (2009) reported 419 species (59% native), including six species of conservation concern.

Variations in tree–crop combinations and spatial arrangements in agroforestry have been shown to affect insect population density and species diversity. Studies with pecan (*Carya illinoensis*) in the United States, for example, have looked at the influence of ground cover types on arthropod densities in agroforestry systems (Bugg et al. 1991; Smith et al. 1996; Stamps and Linit 1997). Bugg et al. (1991) observed that cover crops (e.g. annual legumes and grasses) sustained lady beetles (Coleoptera: Coccinellidae) and other arthropods. Brandle et al. (2004) reported greater density and diversity of insect populations in windbreaks. They attributed this to the heterogeneity of the edges that provided varied microhabitats for life-cycle activities and a variety of hosts, prey, pollen, and nectar sources.

Agroforestry practices also provide improved wildlife habitat by increasing structural and compositional plant diversity on the landscape. Windbreak and riparian buffers offer the only woody habitat for wildlife in many agriculture dominated landscapes (Johnson and Beck 1988). In a comparison of maize (*Zea mays*) monoculture to riparian buffer plantings of clover (*Trifolium repens*) and orchardgrass with three different tree species in Indiana, Gillespie et al. (1995) observed that the riparian strips had higher bird density and diversity than maize monoculture. In Sweden, Söderström et al. (2001) reported that increasing the proportion of pasture area covered by shrubs and trees had a positive effect on the species richness of birds. This was partially attributed to an increase in the abundance and diversity of insects and other invertebrates.

The literature on the role of agroforestry in conserving biodiversity is growing rapidly. There are eight papers included in this special issue that cover a wide variety of topics related to biodiversity conservation. Moco et al. compared the distribution of meso and macrofaunal communities in soil and litter under cacao agroforestry systems and in a natural forest in the southern Bahia state of Brazil. Higher plant diversity in agroforestry and forest systems provided diverse microhabitats and heterogeneous litter, contributing to greater biological diversity in the soil. These authors concluded that these agroforestry systems had beneficial effects on the soil and litter faunal communities, and such cacao agroforestry could be considered as a conservation strategy for soil fauna. The trade-off between increased biodiversity of shade coffee systems and increased fungal diseases of coffee plants in Jamaica was the subject of investigation by Johnson et al. According to their findings, vegetation complexity might attract beneficial insect-eating birds that could reduce insect damage, but complexity was also associated with greater prevalence of fungal leaf symptoms. Diaz–Forestier et al. investigated the nectar volume and secretion dynamics in the soapbark tree (*Quillaja saponaria*) and the entomofauna associated with its flowers, as a tool for the implementation of sustainable apicultural management plans. They reported 42 different species of insects visiting the flowers during the study. The main insect orders represented were: Hymenoptera and Coleoptera (34%), Diptera and Lepidoptera (12%) and Hemiptera (5%). Hoehn et al. examined population dynamics of the wasp, *Rhynchium haemorrhoidale*, and its natural enemies in relation to season, climate and varying shade tree composition in cacao agroforestry systems in Indonesia. High wasp densities in the wet season were associated with high diversity of the parasitoid species. Wasp densities also increased with decreased shading due to more favorable climatic conditions and higher densities of their major prey, the cacao pest *Agathodes caliginosalis*. These authors further discussed about the possibility of managing for wasp populations as a biological control of the cacao pest.

Incorporation of native species in agroforestry systems often depends on the indigenous knowledge of local landowners and communities. Langenberger et al. evaluated the utilization of plant resources by Philippine lowland farmers in order to identify native species suitable for integration into agroforestry systems. The farmers reported using 122 plant species for 77 purposes; however, only a few species could be recommended for adoption due to the lack of well-developed markets for most species. Brodt et al. examined why landowners and farmers in California were not adopting biodiversity enhancing farm edge features like hedgerows and windbreaks, despite their perceived benefits. These authors identified several social, economic, and agronomic incentives as well as constraints in their study. Constraints included high costs, fear of harboring weeds and rodents, and lack of certainty about ecosystems benefits. Government cost-share programs and more scientific information on ecosystem benefits could help increase adoption of hedgerows and windbreaks by farmers. The opportunity for hunting along in-field shelterbelts and on adjacent lands in Iowa was the focus of the paper by Grala et al. Using focus groups of landowners, these authors concluded that the vast majority of respondents (95%) allowed some hunting on their lands. However, only 55% of respondents indicated that the potential existed for developing a fee hunting market associated with in-field shelterbelts. Intangible features of hunting, such as recreation and better land stewardship, were ranked higher than tangible benefits such as additional income. Although reforestation with native species is often the key to restoring biodiversity, conservation professionals find it difficult to encourage landowners to use native species in restoration projects. The study by Garen et al. evaluated the experiences of farmers participating in a native species reforestation initiative in rural Panama to identify lessons learned that can guide on-going or future tree planting efforts. They concluded that farmers' interests and perceptions when planning, implementing, and evaluating reforestation initiatives were critical to ensuring the success of such projects. As suggested by McNeely (2004) and McNeely and Schroth (2006), the interrelationship between forest ecosystems, agroforestry and biodiversity can be made more dynamic through adaptive management strategies that incorporate results from research and monitoring in order to feed information back into the management system. Active participation by local landowners and communities is also critical in this context.

Agroforestry for improved air and water quality

Agroforestry practices such as windbreaks and shelterbelts are touted as having numerous benefits. These benefits include effectively protecting buildings and roadways from drifting snow, savings in livestock production—by reducing wind chills, protecting crops, providing wildlife habitat, removing atmospheric carbon dioxide and producing oxygen, reducing wind velocity and thereby limiting wind erosion and particulate matter in the air, reducing noise pollution, and mitigating odor from concentrated livestock operations, among others. In recent years, interest in using shelterbelts as a potential approach to dealing with livestock odor has received considerable attention (Tyndall and Colletti 2007). The majority of odor-causing chemicals and compounds are carried on aerosols (particulates). Vegetative buffers can filter airstreams of particulates by removing dust, gas, and microbial constituents. In their detailed review on this topic with particular reference to swine odor, Tyndall and Colletti (2007) suggested that when planted in strategic designs, shelterbelts could effectively mitigate odor in a socio-economically responsible way.

Agroforestry practices are also a proven strategy to provide clean water. In conventional agricultural systems, less than half of the applied N and phosphorous fertilizer is taken up by crops. Consequently, excess fertilizer is washed away from agricultural fields via surface runoff or leached into the subsurface water supply, thereby contaminating water sources and decreasing water quality (Cassman 1999). For example, agricultural surface runoff can result in excess sediment, nutrient, and pesticide delivery to receiving water bodies and is a major contributor to eutrophication in the Gulf of Mexico. Agroforestry systems such as riparian buffers have been proposed as a means to combat non-point source pollution from agricultural fields. Riparian buffers help clean runoff water by reducing the velocity of runoff, thereby promoting infiltration, sediment deposition, and nutrient retention. Buffers also reduce nutrient movement into ground water by taking up the excess nutrients. Several studies have shown that agroforestry vegetative buffers reduce nonpoint source pollution from row crop agriculture (e.g. Udawatta et al. 2002; Lee et al. 2003; Anderson et al. 2009). For example, Lee et al. (2003) documented increased nutrient removal efficiency when trees were incorporated into a riparian buffer strip placed on the border of agronomic field plots in Iowa. The authors reported that a switchgrass (*Panicum virgatum*) and woody stem buffer removed 20% more nutrients compared to a switchgrass only buffer.

Trees with deep rooting systems in agroforestry systems can also improve ground water quality by serving as a "safety net" whereby excess nutrients that have been leached below the rooting zone of agronomic crops are taken up by tree roots. These nutrients are then recycled back into the system through root turnover and litterfall, increasing the nutrient use efficiency of the system (van Noordwijk et al. 1996; Allen et al. 2004). Trees also have a longer growing season than most agronomic crops, which increases nutrient use and use efficiency in an agroforestry system by capturing nutrients before and after the cropping season. A few studies have reported the safety net role of tree roots in both the tropical (van Noordwijk et al. 1996) and temperate regions (Allen et al. 2004; Nair and Graetz 2004; Nair et al. 2007). For example, in a pecan–cotton alley cropping system in northwest Florida, Allen et al. (2004) reported a 72% reduction in nitrate-N at a depth of 0.9 m compared to a monoculture cotton. In a silvopastoral system in Florida, USA, Nair et al. (2007) monitored soil phosphorus concentrations in pastures with and without 20 year-old slash (*Pinus elliottii*) pine trees and concluded that silvopastoral associations enhanced soil nutrient retention and reduced nutrient transport in surface and subsurface water. Overall, the current evidence suggests that agroforestry systems could play a substantial role in mitigating water quality issues arising from intensive agricultural practices.

One of the papers in the special issue by Tyndall et al. addresses the swine odor mitigation potential of shelterbelts mentioned in the earlier discussion. In this study, the authors conducted a farm-level financial feasibility analysis to examine the use of shelterbelts as a swine odor mitigation technology. They concluded that both with and without cost share programs such as the environmental quality incentive program (EQIP), total costs were below expenditures for other known odor management strategies. In the last paper, McIvor et al. examined the coarse root growth patterns of poplar trees (*Populus deltoides* × *nigra*) on erodible silvopastoral hill slopes in New Zealand. Mechanical reinforcement by poplar root systems is important in stabilizing the slopes, particularly when the roots are anchored into the fragipan or underlying rock. Despite their beneficial effects, the authors observed that shallower soil depth and the consequent reduced availability of soil water were likely limiting root development and growth of the poplar trees.

Conclusions

There has been a recent accumulation of evidence that supports the ecosystem services and environmental benefits claims of agroforestry systems and practices in both the tropical and temperate regions. In the past, the paucity of hard evidence has hindered the progress of agroforestry and its acceptance by practitioners, farmers and policy makers. However, the solid scientific foundation that has been laid, over the past decade in particular, cannot be overlooked. In an era of environmental consciousness and ecological sustainability, the role of agroforestry as an environmentally benign and ecologically sustainable alternative to traditional farming that also offers a number of ecosystem services needs to be fully explored. In addition to poverty alleviation, agroforestry also offers proven strategies for carbon sequestration, soil enrichment, biodiversity conservation, and air and water quality improvement for not only the landowners or farmers, but for society at large. This realization should help promote agroforestry and its role as an integral part of multifunctional working landscapes the world over.

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