Renewable Agriculture and Food Systems: 28(1); 80–92 doi:10.1017/S1742170511000585

Reconciling productivity with protection of the environment: Is temperate agroforestry the answer?

Jo Smith*, Bruce D. Pearce, and Martin S. Wolfe

The Organic Research Centre, Elm Farm, Hamstead Marshall, Newbury, Berkshire RG20 0HR, UK
*Corresponding author: jo.s@organicresearchcentre.com

Accepted 1 December 2011; First published online 31 January 2012 **Review Article**

Abstract

Meeting the needs for a growing world population calls for multifunctional land use, which can meet the multiple demands of food and fuel production, environmental and biodiversity protection, and has the capacity for adaptation or resilience to climate change. Agroforestry, a land-use system that integrates trees and shrubs with crops and/or livestock production, has been identified by the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) as a 'win–win' approach that balances the production of commodities (food, feed, fuel, fiber, etc.) with non-commodity outputs such as environmental protection and cultural and landscape amenities. Evidence is now coming to light that supports the promotion of agroforestry in temperate developed countries as a sustainable alternative to the highly industrialized agricultural model with its associated negative environmental externalities. This paper reviews this evidence within the 'ecosystem services' framework to evaluate agroforestry as part of a multi-functional working landscape in temperate regions. Establishing trees on agricultural land can help to mitigate many of the negative impacts of agriculture, for example by regulating soil, water and air quality, supporting biodiversity, reducing inputs by natural regulation of pests and more efficient nutrient cycling, and by modifying local and global climates. The challenge now lies in promoting the adoption of agroforestry as a mainstream land use through research, dissemination of information and policy changes.

Key words: ecosystem services, sustainability, trees, silvoarable, silvopastoral, carbon sequestration

Introduction

The Food and Agriculture Organization (FAO) predicts that food production (net of food used for biofuels) must increase by 70% by 2050 to meet the needs of a growing world population[1]. A major concern is that this will put greater pressure on marginal land and protected habitats, plus intensify existing agricultural practices, with serious implications for the ecological processes that sustain human well-being ('ecosystem services'[2]). This food/fuel/biodiversity conflict calls for multifunctional land use, which can meet the multiple demands of food and fuel production, environmental and biodiversity protection, and has the capacity for adaptation or resilience to climate change.

One approach is to design farming systems that mimic the structure and function of natural ecosystems, based on the hypothesis that natural systems are eco-efficient, with internal cycling of nutrients and energy and protection of the resource base. Agroforestry, a land-use system that integrates trees and shrubs with crops and/or livestock production, builds on this idea of ecological design to optimize beneficial interactions between the woody and other components. A central hypothesis in agroforestry is that productivity is higher in agroforestry systems compared to monocropping systems due to complementarity in resource-capture, i.e., trees acquire resources that the crops alone would not[3].

In addition to increased productivity, agroforestry systems are believed to provide a number of other ecosystem services and environmental benefits, including biodiversity conservation, regulation of soil, air and water quality and carbon sequestration[4]. Agroforestry has been identified by the International Assessment of Agricultural Knowledge, Science and Technology for Development (IAASTD) as a 'win–win' multifunctional land-use approach that balances the production of commodities (food, feed, fuel, fiber, etc.) with non-commodity outputs such as environmental protection and cultural and landscape amenities[5]. While much of the research has focused on agroforestry in tropical systems as a means of addressing both food security and environmental issues in impoverished rural areas, evidence is now coming to light that supports the promotion of agroforestry in temperate developed countries as a sustainable alternative to the highly industrialized agricultural model with its associated negative environmental externalities. In the following review, we examine this evidence in the context of the 'ecosystem services' framework to evaluate agroforestry as part of a multifunctional working landscape in temperate regions.

Definition and classification

While systems integrating trees and agriculture have been practiced for 1000s of years, the term 'agroforestry' was first coined in 1977, in a review of research needs, *Trees, Food and People*, by Bene et al.[6]. In its simplest form, agroforestry can be defined as 'growing trees on farms'[7]. It is generally accepted, however, that agroforestry systems are deliberately designed and managed to maximize positive interactions between tree and non-tree components. A widely accepted definition was formulated by Lundgren in 1982:

> Agroforestry is a collective name for land-use systems in which woody perennials (trees, shrubs, etc.) are grown in association with herbaceous plants (crops, pastures) or livestock, in a spatial arrangement, a rotation, or both; there are usually both ecological and economic interactions between the trees and other components of the system[8].

This represents a concept of integrated land use that combines elements of agriculture and forestry in a sustainable production system. The emphasis here is on managing rather than reducing complexity. Agroforestry uses the natural woodland ecosystem as a model to create 'a dynamic, ecologically-based, natural resources management system'[9]. Agroforestry systems can be classified according to the components present—trees with crops are referred to as silvoarable, trees and animals as silvopastoral, and trees with crops and animals as agrosilvopastoral[10].

Ecosystem Services

Agroforestry is valued as a multifunctional approach that balances productive and protective functions, therefore avoiding the trade-off between provisioning and other ecosystem services that occurs in many modern intensive farming systems.

Provisioning services

Agroforestry supports the production of a wide range of products due to the diversity of planned species within the system (Table 1). Higher productivity from agroforestry systems is based on the ecological theory of niche differentiation; different species obtain resources from

Table 1. Overview of products from agroforestry systems.

Overview of products from agroforestry systems
Food: Depending on the design of the system, food products can include arable crops, vegetables, animal products (meat, eggs, dairy), fruit, mushrooms, oils, nuts and leaves
Fuel: Agroforestry systems can be managed to generate fuel wood as its primary woody product (e.g., willow or hazel coppice, charcoal) or as a by-product of management for other products (e.g., prunings of side branches)
Fodder and forage: Livestock can browse on tree leaves and forage grasses and legumes *in situ* or fodder and hay or silage can be cut, transported and stored
Fiber including wood pulp for paper, cedar pet bedding, pine straw, rubber, cork, bark and woodchip mulch, as well as animal fibers such as hair, fleece, horn and leather and silk from silk moths and herbaceous plant fibers (e.g., cotton, linen and flax)
Timber production for furniture, construction, musical instruments, veneers and shipbuilding
Gums and resins for varnishes (copal, dammars, mastic and sandarac), adhesives, incense and perfume (e.g., frankincense and myrrh)
Thatching and hedging materials, including spars, binders and stakes
Gardening materials including pea sticks, bean poles, fencing and hurdles
Medicinal products including ginseng, goldenseal and witch hazel
Craft products such as natural dyes, wooden carvings, basketry, weaving and sculptures, floral arrangements and decorations, including Christmas trees, holly, mistletoe and ivy
Recreation: fee hunting (for deer, gamebirds, etc.) and agritourism (aesthetic backdrop for horse-riding, fishing, wildlife watching and holiday parks)

different parts of the environment. Tree roots generally extend deeper than crop roots, and so access soil nutrients and water unavailable to crops, as well as absorbing nutrients leached from the crop rhizosphere[11]. These nutrients are then recycled via leaf fall onto the soil surface or fine root turnover. This should lead to greater nutrient capture and higher yields by the integrated tree–crop system compared to tree or crop monocultures. In addition to greater resource capture, increased overall productivity of agroforestry systems also occurs as a result of modification of the microclimate by the presence of trees, which benefits crop growth and livestock production[12]. The establishment of trees on land deemed unsuitable for productive cropping is another way that agroforestry can increase overall productivity from farming systems. Dixon et al.[13] estimated that 140 million ha of marginal or degraded land in North America was available and suitable for agroforestry establishment. In New Zealand, trees have been re-introduced into pasturelands to reduce soil erosion on poor soils; the productive potential of these trees is now being recognized and exploited either for timber production or as a feed resource[14].

Interactions between trees, crops and livestock. Ecological interactions between the tree and crop or animal components in an agroforest occur above ground (microclimate effects) and below ground (root interactions), and involve a number of complex processes related to soil fertility, competition, microclimate, pests and diseases, soil conservation and allelopathy[12,15]. Interactions may be direct (e.g., cattle browsing on leaves) or indirect via changes in the environment (e.g., soil compaction caused by cattle gathering in the tree shade, reducing tree growth)[11] and occur at multiple scales. The strongest interactions are likely to occur in the zone immediately surrounding the tree (the tree–crop interface), while shelter effects are known to extend up to 30 times the height of the tree[16,17]. The influence of trees on soil and hydrological processes may impact watershed/catchment scale systems[18,19], biodiversity benefits may be recorded at the landscape scale, and carbon sequestration effects at a global scale[4].

As agroforestry systems are dynamic, these interactions are likely to change over time, so that there may be complementarity between the components in the early stages, which then shifts into competition for resources as the tree component reaches maturity[12]. The nature of interactions also vary depending on different short- and medium-term ecological factors, such as seasonal and annual variations in rainfall and temperature, so that the balance between the tree and the crop can swing between positive interactions (facilitation) and negative interactions (competition)[20]. The productivity of a system is a net result of these interactions[12].

Measuring productivity. The land equivalent ratio (LER), first proposed by Mead and Willey[21], is a means of comparing productivity of intercropping and monocropping systems. It is calculated as the ratio of the area needed under sole cropping to the area of intercropping at the same management level to obtain a particular yield:

$$\mathrm{LER} = \frac{\text{Tree agroforestry yield}}{\text{Tree monoculture yield}} + \frac{\text{Crop or livestock agroforestry yield}}{\text{Crop or livestock monoculture yield}}.$$

If a rotation includes more than one crop, a weighted ratio for each crop can be used, based on its proportion in the rotation. An LER of 1 indicates that there is no yield advantage of the intercrop compared to the monocrop, while an LER of 1.1 indicates a 10% yield advantage, i.e., under monocultures, 10% more land would be needed to match yields from intercropping[22]. Yields can be expressed in physical units so that the LER refers to the biological efficiency of the mixture, or monetary units where the LER indicates the economical efficiency of the mixture. Biomass yield LER's of agroforestry systems range from 2 in a pear orchard/radish system (Newman, 1986, in[22]) to 1.6 in the early years after establishment of a cherry/fescue system, declining to 1.0 later in the rotation, with an average of 1.2 over the 60-year rotation[22].

Economics. Economic studies of agroforestry systems have shown that financial benefits are a consequence of increasing the diversity and productivity of the systems, influenced by market and price fluctuations of timber, livestock and crops[23–27]. Incorporating trees into an agricultural system produces higher long-term returns (Thorrold et al., 1997, in[28]), while agroforestry practices are able to recoup initial costs more quickly than forestry-only land use due to the income generated from the agricultural component[26]. Fernández-Núnez et al. (2007, in[26]) carried out an assessment of initial investments and establishment costs of forestry, agriculture and agroforestry in the Atlantic area of Spain. They found that establishing agroforestry required higher initial investment than the agricultural and forestry systems due to higher initial inputs, but over a 30-year period, profitability per hectare was higher in the agroforestry system than in the exclusively livestock (17%) or forestry (53%) systems.

Modeling of economic returns from a black walnut alley cropping system in Midwestern USA highlighted the importance of system design and management for maximizing productivity[23]. Systems with widely spaced tree rows (12.2 m between tree rows) were predicted to be more profitable than both closely spaced (8.5 m between tree rows) designs and walnut plantations, while root-pruning increased economic returns by extending the period of profitable crop production within the rotation. All agroforestry systems were modeled as having higher rates of returns than monocropping systems[23].

Regulating services

Air quality regulation. Trees have long been used in urban settings to take advantage of their capacity to ameliorate air pollution from vehicles, buildings and industry. The use of agroforestry in mitigating livestock odor has recently been explored by Tyndall and Colletti[29]. Intensive livestock production units in the American Midwest emit odors that have caused significant social problems with implications for rural and state economies, human health and the quality of rural life. The situation is exacerbated by the highly modified landscapes that lack natural barriers that surround these units, which allow emissions to travel further. Tyndall and Colletti[29] recommend the use of shelterbelts to biophysically mitigate odors, with shelterbelts of modest heights ideal for intercepting the movement of particulates which form the majority of odors.

Climate regulation. Integrating trees into the agricultural landscape can regulate the climate at the local scale through modification of the microclimate and at the global scale through reductions in atmospheric carbon by sequestering, conserving and substituting carbon.

Microclimate modification. As 'ecosystem engineers' (i.e., they directly and indirectly influence ecosystem dynamics by changing the availability of abiotic and biotic resources to other species in an ecosystem[30,31]), trees modify microclimatic conditions, including temperature, humidity and wind speed, which can have beneficial effects on crop growth or animal welfare[12].

Trees provide an important service by reducing wind speed with reductions extending up to 30 times the height of the windbreak on the leeward side, and between two and five times the shelterbelt height on the windward side[16,17]. This can have multiple benefits for crops; increased growth rate and quality, protection from windblown soil, moisture management and soil protection[12,16,28,32–35]. Higher air and soil temperatures in the lee of a shelterbelt can extend the growing season, with earlier germination and more growth at the start of the season[33]. Fruit and vegetable crops are particularly sensitive to wind stress and suffer lower yields and poorer quality at lower wind speeds than agronomic crops[16,33]. Horticultural crops grown in the shelter of a wind break benefit from moderation of temperature extremes, warmer soil and air temperatures, and improved soil water conditions, all of which contribute to increasing total marketable yields and individual fruit weight[33]. Sheltered conditions increase flowering periods and bee activity, leading to increased fruit set and earlier maturity[36].

Shading effects of trees may result in higher levels of soil water content beneath the canopy compared to open cropland or pasture due to tree shade reducing evapotranspiration, especially in semi-arid regions[28]. In Spanish *dehesas*, shade from the cork oaks significantly improved the microclimate of a fodder crop (oats), with a reduction in daily and seasonal variation in soil and air temperatures in the proximity of the trees having implications for understorey phenology and physiology and lengthening the growing season[34].

However, where the tree and crop or livestock components overlap in their use of resources, competition may lead to reduced productivity compared to a monoculture system. Within northern temperate regions, the main limiting resource for plants is usually light, and studies have shown that shading has reduced yields in temperate agroforestry systems[28,37,38]. Competition for water between tree and crop components is likely to limit productivity in semiarid regions such as the Mediterranean, although it is difficult to separate competition for water from that for nutrients[12] and, indeed, reduced evapotranspiration due to tree shade effects on understorey plants may increase soil water content compared to open pastures[39]. The complex relationship between soil water content, rainfall, water uptake by plants and evapotranspiration throughout the seasons makes it extremely difficult to fully understand water dynamics within an agroforestry system. In addition to competing for resources, some species of plants and fungi can have a direct negative impact on others through the production of biochemicals called allelochemicals that influence germination, growth, development, reproduction and distribution of other organisms. These allelochemicals can be released into the rhizosphere as plant residues decompose or via root exudates[12]. For example, walnut and pecan trees produce juglone, a phenolic compound that has been shown to inhibit survival and growth of several herbaceous and woody plants in pot experiments[40].

Shelter for livestock. Modification of the microclimate by trees provides many benefits for livestock; trees provide shelter from rain and wind, shade from the sun, and cover from predators. Cattle are particularly sensitive to heat stress and evaporative cooling is the primary mechanism by which cattle reduce their temperature. By providing shade, trees can reduce the energy needed for regulating body temperatures, and so result in higher feed conversion and weight gain. Research in the southern United States found that cattle that had been provided with shade reached their target weight 20 days before those with no shade[41]. Higher respiration rates and lower activity rates of those cattle without shade were thought to reduce productivity[42]. Cattle are more evenly distributed in the silvopasture compared to open pasture, which has important implications for optimizing forage use and uniform nutrient recycling[42].

During cooler months, windbreaks and shelterbelts provide valuable protection from the wind for livestock, particularly for new-born lambs and freshly shorn sheep. When livestock have been protected from winter storms by windbreaks, significant savings in feed costs, survival and milk production have been reported by producers in Dakota, US (Anderson and Bird, 1993, in[33]).

For livestock species such as pigs and poultry that have evolved from forest-dwelling ancestors, including tree cover within their range can influence ranging behavior and enhance animal welfare. For poultry, trees offer protection from aerial predators in particular, and can provide an escape from aggressive behavior within the flock, as well as reducing visual stimulation that can provoke aggression[27]. Dawkins et al.[43] observed ranging behavior in commercial free-range broiler (table bird) systems and found that the number of birds ranging outside was correlated with the percentage tree cover on the range, with behavioral studies showing that trees and bushes were the preferred habitat[43]. Like chickens, pigs have a forest-dwelling ancestor, the Eurasian wild boar (*Sus scrofa scrofa*), which is found primarily in mixed, predominantly deciduous woodland. Behavioral studies of domestic pigs have shown that trees encourage expression of normal behavioral patterns[44].

The inclusion of a diverse range of woody species within livestock range has potential for enhancing animal health and welfare by providing opportunities for self-medication. For example, willow has been traditionally used as a feed resource for its anti-helminthic properties[45]. However, there has been little recent research exploring the full potential of this approach.

Global climate. There has been an increase in research over the past 20 years investigating the potential of agroforestry as a tool for addressing the issues of climate change through mitigation and adaptation[46–51]. Agroforestry has the potential to reduce atmospheric carbon, by increasing afforestation of agricultural lands (C sequestration), by reducing resource use pressure on existing forests (C conservation) and by producing both durable wood products and renewable energy resources (C substitution). However, agroforestry systems can also be sources of C and other greenhouse gases, where tillage, burning, manuring, chemical fertilization and frequent disturbance can result in emissions of CO_2, CH_4 and N_2O into the atmosphere[52]. Establishing agroforestry systems on previously natural primary or secondary forests will reduce C sequestration potential, whereas planting trees on degraded or treeless agricultural land will increase their C sequestration value[49].

C sequestration. Agroforestry can increase the amount of carbon sequestered compared to monocultures of crops or pasture due to the incorporation of trees and shrubs[4]. The potential for agroforestry systems to sequester carbon depends on a number of factors, including system design, species composition and age, environmental factors such as climate, management and the end product. As a result, estimations for carbon sequestration of agroforestry systems vary from $0.29\,\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ in a fodder bank system in West Africa to $15.21\,\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ in mixed species stands in Puerto Rico[53]. Schroeder[46] estimated average carbon storage by agroforestry systems as 9, 21, 50 and $63\,\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$ in semiarid, sub-humid, humid and temperate regions, respectively, with higher rates in temperate regions reflecting longer rotations and longer-term storage.

Carbon substitution. Biomass energy from short rotation coppice (SRC) is a carbon-neutral source of energy that does not contribute to CO_2 enrichment of the atmosphere. SRC woody crops such as willow produce between 11 and 16 units of useable energy per unit of non-renewable fossil fuel energy used to grow, harvest and deliver SRC[54]. However, there have been concerns that widespread adoption of biomass crops such as *Miscanthus* and SRC willow will compete with food production and impact biodiversity[55,56]. Incorporating SRC into an agroforestry system is one approach to reconciling these conflicting demands. In temperate regions, species with potential as SRC's include poplar (*Populus* spp.), willow (*Salix* spp.) and black locust (*Robinia pseudoacacia*). SRC species such as willow are often suitable for unproductive land such as erodible land or waterlogged sites, thus providing income from marginal land, and as SRC is usually harvested on a 3-year cycle, it provides a more regular income than other forms of agroforestry (e.g., timber).

Greenhouse gas abatement. The role of temperate agroforestry in mitigating greenhouse gases has not yet been investigated fully, although a review of tropical systems highlights the potential of agroforestry for mitigating CO_2 and N_2O and increasing the CH_4 sink strength compared to monoculture systems[57]. In the UK, current work by the Centre for Ecology and Hydrology in Edinburgh is exploring the potential of farm woodlands for ammonia abatement using targeted field measurements and mechanistic and atmospheric emission modeling[58]. In agroforestry systems, there is a reduced need for supplementary nitrogen applications, and recycled nitrogen from leaf litter provides a quantifiable contribution to adjacent crops that can replace inorganic N additions and thus reduce N_2O emissions[59]. A decrease in nitrogen leaching out of the rooting zone will reduce NO_x emissions as a result of denitrification in surface water resources[59]. Models estimate that nitrates leaving a tree-based intercropping system can be reduced by 50% compared to a monoculture control[59].

Water quality and regulation. Research has demonstrated that agroforestry can reduce pollution from crops and grazed pastures[60–64]. Riparian (riverside) buffers in particular, can reduce non-point source water pollution from agricultural land in five general ways[65]:

1. Reducing surface runoff from fields.
2. Filter surface runoff.
3. Filter groundwater runoff.
4. Reduce bank erosion.
5. Filter stream water.

The 'safety net hypothesis' is based on the belief that the deeper-rooting tree component of an agroforestry system will be able to intercept nutrients leached out of the crop-rooting zone, thus reducing pollution and, by recycling nutrients as leaf litter and root decomposition, increasing nutrient use efficiencies[12]. Greater permanence of tree roots means that nutrients are captured before a field crop has been planted and following harvest, when leaching may be greater from bare soil.

Buffer strips can significantly decrease pollution run-off, with reductions of 70–97% reported for suspended solids, 60–98% for phosphorus and 70–95% for nitrogen[62,66]. Agroforestry systems also have the potential to mitigate movement of harmful bacteria such as *Escherichia coli* into water sources[60] and reduce the transport of veterinary antibiotics from manure-treated agroecosystems to surface water resources[67]. Agroforestry has been used to address issues of soil salinization in Australia where a study recorded a lowering of the saline groundwater table by 2.0 m over a 7-year period under a *Eucalyptus*–pasture system, relative to nearby pasture-only sites[68].

A principal cause of non-point source pollution and soil erosion is excessive surface water runoff. Riparian (river bank) buffers and other agroforestry systems can help reduce runoff and increase infiltration[18,19,61]. In Midwestern USA, a multispecies buffer that included woody perennials increased infiltration rates to five times that of cultivated and grazed fields[19]. Agroforestry can reduce soil water content during critical times such as fallow periods and increase water infiltration and water storage. Furthermore, above ground, stems, leaf litter and pruning debris in agroforestry systems can reduce runoff flow rates, thereby enhancing sedimentation within the agroforestry strip and increasing infiltration[19].

The role of agroforestry in rehabilitating polluted soils has been investigated, through exploiting the ability of trees to capture nutrients and pollutants. For example, research has shown that willows can take up heavy metals from soil into their biomass, help break down pollutants to non-toxic compounds and control water dynamics, including contaminated groundwater flow and water penetration into soils via evapotranspiration[54]. Agroforestry systems have been used to recycle urban and agricultural organic waste with the added benefit of increased biomass productivity from the additional nutrients[69,70]. Previously a burden to society, these waste products can be viewed as a valuable resource to maximize biomass production[71].

Erosion regulation. The conversion of natural forest and scrublands to grasslands devoid of trees by European settlers on hill country with steep slopes and erodible soils in New Zealand resulted in increased run-off and accelerated erosion[72,73]. Soil conservation measures involving farm woodlots and wide-spaced tree plantings are needed to support sustainable pastoral and cropping uses on 32% of the North Island and 25% of the South Island (Eyles et al., 1992, in[72]). New Zealand government-subsidized erosion control schemes in the 1960s and 1970s planted over 2 million poplars; during the late 1980s and 1990s there was a shift to planting schemes using radiata pine (*Pinus radiata*), poplar silvopastoral systems and riparian schemes using poplar and willows[72]. Willow and poplar are widely used on unstable hillsides in silvopastoral systems for many reasons: they are easy to propagate and establish; have fast early growth rates; are tolerant of flooding and partially saturated soils; have extensive root systems with fine fibrous root mats that stabilize large soil masses; have high evapotranspiration rates that can help dry out swampy soils; provide shade, shelter and fodder for livestock; and may produce useful timber if managed appropriately (poplar only)[72].

Pest and disease regulation. Reduced pest and disease problems in agroforestry systems are predicted due to greater niche diversity and complexity than in monocropping systems[74]. This can be attributed to a number of mechanisms[75]:

- Intermittent distribution of host plants makes it more difficult for pests to find the plants.
- One plant species acting as a trap-crop, which protects the other crop from herbivore attack.
- One plant species acting as a repellent to the herbivore.
- Higher predator and parasitoid densities due to higher plant diversity.
- Increased interspecific competition between pest and non-pest species.

Trees provide greater structural and microclimate diversity, greater temporal stability, greater biomass and surface area, alternate sources of pollen, nectar and prey, alternate hosts and stable refuges[74,76,77]. Agroforestry systems can be managed to enhance pest regulation, for example by providing sources of adult parasitoid food (e.g., flowers), and sites for mating, oviposition and resting sites[7,74].

Higher insect diversities and natural enemy abundance, and lower abundances of pest species have been recorded in several agroforestry systems[59,78–86]. For example, in an alley cropping system with peas (*Pisum sativa*) and four tree species (*Juglans, Platanus, Fraxinus* and *Prunus*) in Leeds, UK, higher insect diversities and natural enemy abundance and lower abundances of pea and bean weevils (*Sitona* spp.) and pea midge (*Contarinia pisi*) were recorded compared to a monoculture of peas[82]. In this same silvoarable system, grain aphids (*Sitobion avenae*) populations in the winter barley crop were approximately half that of the arable control[81]. This was attributed to an increase in cereal aphid predators, primarily hoverflies (Diptera: Syrphidae), which used the tree-strips as a refuge[83].

While most focus has been on beneficial effects of trees on associated crops and livestock, the tree component may also benefit from pest suppression by livestock. In a study of farmed wild boar in Norway Spruce plantations in Austria, it was observed that mortality rates of the sawfly *Cephalcia abietis*, a defoliant whose larvae pupate in the soil for 21–33 months, increased by an additional 35.2% due to predation and soil disturbance by the boar[87]. Similarly, local domestic breed pigs in South African plantations of *Pinus patula* killed 98% of the soil pupae population of the pest *Nudaurelia cytherea* (pine emperor moth) and 90% of a *Pseudobunaea irius* (poplar emperor moth) infestation (Van Den Berg, 1973, in[24]).

However, some pest groups have been observed in higher numbers in agroforestry systems, and shifts in relative importance of pest groups may present novel management problems and influence crop choice. For example, Griffiths et al.[88] observed increased slug populations and slug damage in agroforestry plots compared to arable controls in a silvoarable experiment in West Yorkshire, UK. This was attributed to the provision of refugia for slugs within the permanent, unploughed vegetated areas under the tree rows and a modified microclimate, which favor slug populations.

Biodiversity regulation. As ecosystem engineers and keystone species, trees provide a range of resources to other flora and fauna, and when integrated into agroecosystems, they can enhance structural heterogeneity and habitat stability of the landscape[89]. Jose[4] identifies five main ways that agroforestry contributes to the preservation of biodiversity:

1. By providing habitat for species that can tolerate a certain level of disturbance.
2. By helping to preserve germplasm of sensitive species.
3. By helping to reduce the rates of conversion of natural habitat and alleviate resource use pressure.
4. By providing connectivity by creating corridors between habitat remnants and the conservation of area-sensitive floral and faunal species.
5. By helping to conserve biological diversity by providing other ecosystem services such as erosion control and water recharge, thus preventing habitat degradation and loss.

There have been a number of studies investigating the role of agroforestry in supporting biodiversity, especially in the tropics[90,91]. These studies demonstrate that agroforestry systems support floral and faunal assemblages that can be as species-rich, abundant and diverse as forests, but often with modified species compositions that include non-forest species[92]. While agroforestry systems are unlikely to provide habitat for specialist forest species that require large tracts of undisturbed forest or woodland, they can support biodiversity in otherwise open landscapes and allow movement of species between habitat remnants, as well as buffer protected areas from the impacts of more intensive systems[90].

Several studies have shown the value of temperate woodland edge habitats such as windbreaks, hedgerows and other agroforestry systems for invertebrate and vertebrate biodiversity, particularly in landscapes otherwise devoid of wooded habitats[93–96]. The impact of agroforestry on biodiversity may extend beyond the landscape-scale; Perfecto et al.[97] consider the correlation between decreasing populations of songbirds in eastern USA and the elimination of shade trees from coffee agroforests in Latin American countries. Those species in decline were migratory species that overwintered in the southern countries, and were found in the forest-like habitats of traditional coffee farms with a diversity of shade tree species.

Natural hazards and extreme events. With the prediction of an increase in extreme events such as flooding and droughts, increasing the number of trees within the landscape can act as buffers to reduce the impact on the farming system and wider environment. By reducing surface runoff and increasing infiltration and soil water holding capacity, the risk of flash flooding following periods of heavy rainfall is reduced in agroforestry systems, with the tree roots and trunks acting as permeable barriers to reduce sediment and debris loading into rivers following floods. In New Zealand, widely spaced poplars reduced pasture production losses due to landslides during a cyclonic storm by 13.8% with, on average, each tree saving 8.4 m^2 from failure (Hawley and Dymond, 1988, in[28]). Mature willow and poplar trees at 12 m spacing can reduce mass movement by 10–20% (Hicks, 1995, in[28]).

Cultural services

Cultural heritage values. Cultural aspects of agroforestry systems, particularly in temperate regions, are often overlooked, despite the long tradition of systems such as woodland and orchard grazing, alpine wooded pastures, pannage, the *dehesa* and parklands[98]. Lifestyles such as nomadism, transhumance and traditional techniques such as pollarding and hedge-laying, are integrated within such systems and the symbolic and cultural perception of these landscapes are shaped by local practices, laws and customs[99].

Societal benefits. A key objective of implementing agroforestry systems in the tropics is improving livelihoods of poor rural smallholders[100]. However, the societal benefits of temperate agroforestry have received less attention, with the focus limited primarily to economics[101]. Integrating trees into the agricultural landscape has the potential to impact the local economy through diversification of local products, diversification of rural skills, improvements to the environment, landscape diversification and economic stability. Wood products such as wood fuel (either as logs or wood chips) need to be produced in close proximity to end-users to reduce transportation costs and make the business economically viable. This creates important links and business relationships between the end-user and local community businesses, so that the money that is paid to obtain these products is spent locally, thus stimulating the local economy[54].

Recreation and ecotourism. Agroforestry systems can provide recreational opportunities that can benefit the general public, as well as the landowner. Activities such as hunting, fishing, mountain biking, equestrianism and rural tourism can diversify income for farmers, while the public can benefit from improved health and enjoyment from agroforestry through sports and wildlife watching[98]. Cultural landscapes such as the *dehesas* of Spain and Portugal, and the wood pastures of the Alps, can create financial opportunities through ecotourism.

Aesthetic values. Public attitudes to agroforestry reflect society's view of non-market benefits connected with amenity, habitat, landscape and animal welfare. The visual impact of monocultures of crops or trees is unappealing for many people; integrating trees into agricultural landscapes can increase the diversity and attractiveness of the landscape[98].

Supporting services

Soil formation and nutrient cycling. By promoting a closed system with internal recycling of nutrients, whereby nutrients are accessed from lower soil horizons by tree roots and returned to the soil through leaf fall, agroforestry systems enhance soil nutrient pools and turnover and reduce reliance on external inputs. For example, leaf fall from 6-year-old poplars resulted in mean soil nitrate production rates in the adjacent crop–alley up to double that compared to soils 8.0–15.0 m from the tree row, and nitrogen release from poplar leaf litter was equivalent to $7\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$[59]. Trees can also significantly influence nutrient additions to adjacent alley crops through intercepting rainfall, via throughfall (rainwater falling through tree canopies) and stemflow (rainwater falling down branches and stems). Zhang (1999, in[59]) showed that these pathways contributed 10.99 and $15.22\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ in hybrid poplar and silver maple systems, respectively.

There have been many studies assessing the value of green mulch from leguminous trees to enhance soil fertility for adjacent crops in tropical agroforestry systems (e.g.,[102]). However, relatively few of the 650 woody species that are able to fix atmospheric nitrogen occur in temperate regions; of these black locust (*Robinia*), mesquites (*Prosopis*), alder (*Alnus*) and oleaster (*Eleagnus*) have been investigated for their nitrogen-fixing potential[12]. Significant transfer of fixed nitrogen to crops has been observed in a study, which showed that 32–58% of the total nitrogen in alley-cropped maize came from nitrogen fixed by the adjacent red alder (*Alnus rubra*)[12].

As many soil biological processes are performed by soil microorganisms, the presence of an abundant and diverse soil microbial community is essential to sustain productivity of an agroecosystem. In agroforestry systems, differences in litter quality between the tree and crop components promote spatial diversity in enzyme activities and microbial functioning and this spatial variation is enhanced by tree effects on microclimate[103]. Several studies have recorded higher microbial diversity, increased enzyme activity and greater stability in agroforestry alley cropping systems, attributable to differences in litter quality and quantity and root exudates[103–107].

Arbuscular mycorrhizal (AM) fungi enhance plant nutrient uptake and growth, soil stability and soil aggregation, litter decomposition rates, and could potentially enhance crop yields while reducing the need for chemical fertilizer input[108–110]. However, while AM fungal diversity tends to be low in conventionally managed agricultural soils, which has been attributed to negative effects of fertilization, fungicides, soil cultivations and low host diversity, it has been shown that agroforestry systems may enhance AM fungal richness compared to monocropped systems[111]. The role of AM symbioses in temperate regions have so far only been studied in intensive, high-input agroforestry; the potential of AM fungi to enhance plant growth in low-input and organic systems still needs quantifying[111].

Higher levels of soil organic matter in agroforestry systems also positively influence soil invertebrate communities[112,113]. In a poplar–arable silvoarable system, soil organic matter, soil arthropod abundance and cumulative body mass were higher in samples taken close to the trees, with lower levels in the crop alleys attributed to frequent cultivations, lower litter inputs and a reduction in tree root densities[112].

Valuing ecosystem services in agroforestry

Recently, there has been considerable interest in placing a monetary value on the delivery of ecosystem services or public goods, such as soil protection and carbon sequestration. Porter et al.[114] calculated the values of market and non-market ecosystem services of a novel combined food and energy agroforestry system in Taastrup, Denmark. Belts of fast-growing trees (hazel, willow and alder) for bioenergy production are planted at right angles to fields of cereal and pasture crops, and the system is managed organically with no inputs of pesticides or inorganic N. Field-based estimates of ecosystem services, including pest control, nitrogen regulation, soil formation, food and forage production, biomass production, soil carbon accumulation, hydrological flow into ground water reserves, landscape aesthetics and pollination by wild pollinators produced a total value of US\$1074 $\mathrm{ha^{-1}}$ of which 46% is from market ecosystem services (production of food, forage and biomass crops) and the rest from non-market ecosystem services. Porter et al.[114] then extrapolated these values to the European scale and calculated that the value of non-market ecosystem services from this novel system exceeds current European farm subsidy payments. Obviously there are many challenges involved with using an ecosystem services or public goods approach to developing a support scheme for sustainable agricultural practices, but there has been much progress in the field of ecological economics recently and increased awareness at policy level of the potential of this approach[115].

Carbon credits. One particular area of environmental services where there has been more progress is the potential of an agroforestry approach to conserve and sequester C while maintaining land for food production and reducing deforestation and degradation of remaining natural forests. The 1997 Kyoto Protocol provides a mechanism by which countries that emit carbon in excess of agreed limits can purchase carbon credits from countries that manage carbon sinks. Leading the way with establishing tradable securities of carbon sinks to offset emissions, Costa Rica invested US\$14 million in 1997 for the Payment for Environmental Services (PES), with 80% of funding coming from a tax on fossil fuels and 20% from international trading of carbon from public protected areas. This scheme led to the reforestation of 6500 ha, the sustainable management of 10,000 ha of natural forests and the preservation of 79,000 ha of private natural forests[49]. In 2003, the scheme was expanded to include agroforestry systems, and the Costa Rican government budgeted US\$400,000 for the integration of agroforestry management into the C trading schemes with payments depending on the number of trees present on the farm[116]. Introducing carbon payments to landowners and managers of agroforestry systems in temperate regions opens the way to obtaining additional income from these systems and may increase the attractiveness of establishing an agroforestry system, as well as adding value to established systems such as riparian buffers, shelterbelts, silvopastoral and silvoarable systems.

Conclusions

This review demonstrates that temperate agroforestry can provide an alternative approach to land management that, through the re-integration of trees and agriculture, can balance productivity with protection of the environment. With careful design and management, agroforestry systems can be more productive, and by producing a wide range of products, including food, fuel, fodder and timber, avoid the food or fuel conflict for land. Establishing trees on agricultural land can help to mitigate many of the negative impacts of agriculture, for example by regulating soil, water and air quality, supporting biodiversity, reducing inputs by natural regulation of pests and more efficient nutrient cycling, and by modifying local and global climates. The challenge now lies in promoting the adoption of agroforestry as a mainstream land use through research, dissemination of information and policy changes. In a second paper on temperate agroforestry, we discuss further how to develop modern systems that integrate ecological farming and agroecological advances to achieve sustainable intensification. We also discuss the existing barriers to wider adoption of agroforestry, and identify how these barriers can be overcome to promote agroforestry as a mainstream land-use system[117].

Acknowledgements. We gratefully acknowledge the support of the Ashden Trust which allowed us to carry out this literature review. Thanks also to Helen Pearce and Louisa Winkler for their valuable comments on an earlier draft.

References

1 FAO. 2009. How to feed the world in 2050. Food and Agriculture Organisation. Available at Web site http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf (accessed January 16, 2012).
2 Millenium Ecosystem Assessment. 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington.
3 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.
4 Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: An overview. Agroforestry Systems 76:1–10.
5 IAASTD. 2008. Executive summary of the synthesis report. International Assessment of Agricultural Knowledge, Science and Technology for Development. Available at Web site http://www.agassessment.org/docs/IAASTD_EXEC_SUMMARY_JAN_2008.pdf (accessed January 16, 2012).
6 Bene, J.G., Beall, H.W., and Côté, A. 1977. Trees, Food and People – Land Management in the Tropics. IDRC, Ottawa.
7 Young, A. 1997. Agroforestry for Soil Management. 2nd ed. CAB International, Wallingford.
8 Lundgren, B. 1982. Introduction (Editorial). Agroforestry Systems 1:3–6.
9 Leakey, R.R.B. 1996. Definition of agroforestry revisited. Agroforestry Today (ICRAF) 8(1):5–7.
10 Nair, P.K.R. 1985. Classification of agroforestry systems. Agroforestry Systems 3:97–128.
11 Sinclair, F.L., Eason, W.R., and Hooker, J. 2000. Understanding and management of interactions. In A.M. Hislop and J. Claridge (eds). Bulletin 122. Agroforestry in the UK. Forestry Commission, Edinburgh.
12 Jose, S., Gillespie, A.R., and Pallardy, S.G. 2004. Interspecific interactions in temperate agroforestry. Agroforestry Systems 61:237–255.
13 Dixon, R.K., Winjum, J.K., Andrasko, K.J., Lee, J.J., and Schroeder, P. 1994. Integrated land-use systems: Assessment of promising agroforest and alternative land-use practices to enhance carbon conservation and sequestration. Climate Change 27:71–92.
14 Mead, D.J. 1995. The role of agroforestry in industrialised nations: The southern hemisphere perspective with special emphasis on Australia and New Zealand. Agroforestry Systems 31:143–156.
15 Young, A. 1997. Agroforestry, soil management a and sustainability. In A. Young (ed.). Agroforestry for Soil Management. CAB International, Wallingford. p. 1–22.
16 Tamang, B., Andreu, M.G., and Rockwood, D.L. 2010. Microclimate patterns on the leeside of single-row tree windbreaks during different weather conditions in Florida farms: Implications for improved crop production. Agroforestry Systems 79(1):111–122.
17 Williams, P.A., Gordon, A.M., Garrett, H.E., and Buck, L. 1997. Agroforestry in North America and its role in farming systems. In A.M. Gordon and S.M. Newman (eds). Temperate Agroforestry Systems. CAB International, Wallingford. p. 9–84.
18 Bharati, L., Lee, K.H., Isenhart, T.M., and Schultz, R.C. 2002. Soil–water infiltration under crops, pasture and established riparian buffer in Midwest USA. Agroforestry Systems 56:249–257.
19 Seobi, T., Udawatta, R.P., Anderson, S.H., and Gantzer C.J. 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an albaqualf. Soil Science Society of America Journal 69:893–901.
20 Gea-Izquierdo, G., Montero, G., and Canellas, I. 2009. Changes in limiting resources determine spatio-temporal variability in tree–grass interactions. Agroforestry Systems 76:375–387.
21 Mead, D.J. and Willey, R.W. 1980. The concept of a 'land equivalent ratio' and advantages in yields from intercropping. Experimental Agriculture 16:217–228.
22 Dupraz, C. and Newman, S.M. 1997. Temperate Agroforestry: The European Way. In A.M. Gordon and S.M. Newman (eds). Temperate Agroforestry Systems. CAB International, Wallingford. p. 181–236.

23 Benjamin, T.J., Hoover, W.L., Seifert, J.R., and Gillespie, A.R. 2000. Defining competition vectors in a temperate alley cropping system in the midwestern USA 4. The economic return of ecological knowledge. Agroforestry Systems 48:79–93.

24 Brownlow, M.J.C. 1994. The Characteristics and Viability of Land-Use Systems Which Integrate Pig or Poultry Production with Forestry in the UK. Department of Agriculture. University of Reading, Reading, MA.

25 Brownlow, M.J.C., Dorward, P.T., and Carruthers, S.P. 2005. Integrating natural woodland with pig production in the United Kingdom: An investigation of potential performance and interactions. Agroforestry Systems 64:251–263.

26 Rigueiro-Rodríguez, A., Fernández-Núnez, E., Gonzalez-Hernandez, M.P., McAdam, J., and Mosquera-Losada, M.R. 2008. Agroforestry Systems in Europe: Productive, Ecological and Social Perspectives. In A. Rigueiro-Rodríguez et al. (eds). Agroforestry in Europe: Current Status and Future Prospects. Springer, Belfast. p. 43–65.

27 Yates, C., Dorward, P., Hemery, G., and Cook, P. 2007. The economic viability and potential of a novel poultry agroforestry system. Agroforestry Systems 69:13–28.

28 Benavides, R., Douglas, G.B., and Osoro, K. 2009. Silvopastoralism in New Zealand: Review of effects of evergreen and deciduous trees on pasture dynamics. Agroforestry Systems 76:327–350.

29 Tyndall, J. and Colletti, J. 2007. Mitigating swine odour with strategically designed shelterbelt systems: A review. Agroforestry Systems 69:45–65.

30 Jones, C., Lawton, J.H., and Shachak, M. 1994. Organisms as ecosystem engineers. Oikos 69:373–386.

31 Jones, C., Lawton, J.H., and Shachak, M. 1997. Positive and negative effects of organisms as physical ecosystem engineers. Ecology 78(7):1946–1957.

32 Bird, P.R. 1998. Tree windbreaks and shelter benefits to pasture in temperate grazing systems. Agroforestry Systems 41:35–54.

33 Brandle, J.R., Hodges, L., and Zhou, X.H. 2004. Windbreaks in North American agricultural systems. Agroforestry Systems 61:65–78.

34 Moreno, G., Obrador, J.J., Garcia, E., Cubera, E., Montero, M.J., Pulido, F., and Dupraz, C. 2007. Driving competitive and facilitative interactions in oak dehesas through management practices. Agroforestry Systems 70:25–40.

35 Wang, Q. and Shogren, J.F. 1992. Characteristics of the crop–Pawlonia system in China. Agriculture, Ecosystems and Environment 39:145–152.

36 Norton, R.L. 1988. Windbreaks: Benefits to orchards and vineyard crops. Agriculture, Ecosystems and Environment 22:205–213.

37 Chirko, C.P., Gold, M.A., Nguyen, P.V., and Jiang, J.P. 1996. Influence of direction and distance from trees on wheat yield and photosynthetic photon flux density (Qp) in a Paulownia and wheat intercropping system. Forest Ecology and Management 83:171–180.

38 Reynolds, P.E., Simpson, J.A., Thevathasan, N.V., and Gordon, A.M. 2007. Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada. Ecological Engineering 29:362–371.

39 Joffre, R. and Rambal, S. 1993. How tree cover influences the water balance of Mediterranean rangelands. Ecology 74 (2):570–582.

40 Jose, S. and Gillespie, A.R. 1998. Allelopathy in black walnut (*Juglans nigra* L.) alley cropping. II. Effects of juglone on hydroponically grown corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) growth and physiology. Plant and Soil 203:199–205.

41 Mitlohner, F.M., Morrow, J.L., Dailey, J.W., Wilson, S.C., Galyean, M.L., Miller, M.F., and McGlone, J.J. 2001. Shade and water misting effects on behaviour, physiology, performance and carcass traits of heat-stressed feedlot cattle. Journal of Animal Science 79:2327–2335.

42 Karki, U. and Goodman, M.S. 2009. Cattle distribution and behaviour in southern-pine silvopasture versus open-pasture. Agroforestry Systems 78(2):159–168.

43 Dawkins, M.S., Cook, P.A., Whittingham, M.J., Mansell, K.A., and Harper, A.E. 2003. What makes free-range broiler chickens range? *In situ* measurement of habitat preferences. Animal Behaviour 66:151–160.

44 Stolba, A. and Woodgush, D.G.M. 1989. The behaviour of pigs in a semi-natural environment. Animal Production 48 (2):419–425.

45 Waller, P.J., Bernes, G., Thamsborg, S.M., Sukura, A., Richter, S.H., Ingebrigsten, K., and Höglund, J. 2001. Plants as de-worming agents of livestock in the Nordic countries: Historical perspective, popular beliefs and prospects for the future. Acta Veterinaria Scandinavica 42:31–44.

46 Schroeder, P. 1994. Carbon storage benefits of agroforestry systems. Agroforestry Systems 27:89–97.

47 Albrecht, A. and Kandji, S.T. 2003. Carbon sequestration in tropical agroforestry. Agriculture, Ecosystems and Environment 99(1–3):15–27.

48 Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304:1623–1627.

49 Montagnini, F. and Nair, P.K.R. 2004. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. Agroforestry Systems 61:281–295.

50 Peichl, M., Thevathasan, N.V., Gordon, A.M., Huss, J., and Abohassan, R.A. 2006. Carbon sequestration potentials in temperate tree-based intercropping systems, southern Ontario, Canada Agroforestry Systems. 66:243–257.

51 Schoeneberger, M.M. 2009. Agroforestry: Working trees for sequestering carbon on agricultural lands. Agroforestry Systems 75:27–37.

52 Dixon, R.K. 1995. Agroforestry systems: Sources or sinks of greenhouse gases? Agroforestry Systems 31:99–116.

53 Nair, P.K.R., Kumar, B.M., and Nair, V.D. 2009. Agroforestry as a strategy for carbon sequestration. Journal of Plant Nutrition and Soil Science 172 (1):10–23.

54 Volk, T.A., Abrahamson, L.P., Nowak, C.A., Smart, L.B., Tharakan, P.J., and White, E.H. 2006. The development of short-rotation willow in the northeastern United States for bioenergy and bioproducts, agroforestry and phytoremediation. Biomass and Bioenergy 30:715–727.

55 Hall, D.O. and House, J.I. 1994. Trees and biomass energy: Carbon storage and/or fossil fuel substitution. Biomass and Bioenergy 6(1/2):11–30.
56 Rowe, R.L., Street, N.R., and Taylor, G. 2009. Identifying potential environmental impacts of large-scale deployments of dedicated bioenergy crops in the UK. Renewable and Sustainable Energy Reviews 13(1):271–290.
57 Mutuo, P., Cadisch, G., Albrecht, A., Palm, C.A., and Verchot, L. 2005. Potential of agroforestry for carbon sequestration and mitigation of greenhouse gas emissions from soils in the tropics. Nutrient Cycling in Agroecosystems 71:43–54.
58 Braban, C., Famulari, D., Twigg, M., Robertson, A., Quinn, A., Theobold, M., Nemitz, E., Dragosits, U., Bealey, W., Dore, T., and Sutton, M. 2009. Potential for ammonia abatement using agroforestry. In New Futures for Farm Woodlands. Farm Woodland Forum Annual Meeting 2009: National Forest Youth Hostel, Derbyshire. p. 2–3.
59 Thevathasan, N.V. and Gordon, A.M. 2004. Ecology of tree intercropping systems in the North temperate region: Experiences from southern Ontario, Canada. Agroforestry Systems 61:257–268.
60 Dougherty, M.C., Thevathasan, N.V., Gordon, A.M., Lee, H., and Kort, J. 2009. Nitrate and *Escherichia coli* NAR analysis in tile drain effluent from a mixed tree intercrop and monocrop system. Agriculture, Ecosystems and Environment 131:77–84.
61 Udawatta, R.P., Krstansky, J.J., Henderson, G.S., and Garrett, H.E. 2002. Agroforestry practices, runoff, and nutrient loss: A paired watershed comparison. Journal of Environmental Quality 31:1214–1225.
62 Lee, K.H., Isenhart, T.M., and Schultz, R.C. 2003. Sediment and nutrient removal in an established multispecies riparian buffer. Journal of Soil and Water Conservation 58:1–8.
63 Anderson, S.H., Udawatta, R.P., Seobi, T., and Garrett H. E. 2009. Soil water content and infiltration in agroforestry buffer strips. Agroforestry Systems 75:5–16.
64 Udawatta, R.P., Garrett, H.E., and Kallenbach, R.L. 2010. Agroforestry and grass buffer effects on water quality in grazed pastures. Agroforestry Systems 79(1):81–87.
65 Dosskey, M.G. 2001. Toward quantifying water pollution abatement in response to installing buffers on crop land. Environmental Management 28(5):577–598.
66 Borin, M., Passoni, M., Thiene, M., and Tempesta, T. 2009. Multiple benefits of buffer strips in farming areas. European Journal of Agronomy.
67 Chu, B., Goyne, K.W., Anderson, S.H., Lin, C.-H., and Udawatta, R.P. 2010. Veterinary antibiotic sorption to agroforestry buffer, grass buffer and cropland soils. Agroforestry Systems 79(1):67–80.
68 Bari, M.A. and Schofield, N.J. 1991. Effects of agroforestry-pasture associations on groundwater level and salinity. Agroforestry Systems 16:13–31.
69 Aronsson, P. and Perttu, K. 2001. Willow vegetation filters for wastewater treatment and soil remediation combined with biomass production. Forest Chronicle 77:293–299.
70 Rockwood, D.L., Naidu, C.V., Carter, D.R., Rahmani, M., Spriggs, T.A., Lin, C., Alker, G.R., Isebrands, J.G., and Segrest, S.A. 2004. Short-rotation woody crops and phytoremediation: Opportunities for agroforestry? Agroforestry Systems 61:51–63.
71 Mirck, J., Isebrands, J.G., Verwijst, T., and Ledin, S. 2005. Development of short-rotation willow coppice systems for environmental purposes in Sweden. Biomass and Bioenergy 28(2):219–228.
72 Wilkinson, A.G. 1999. Poplars and willows for soil erosion control in New Zealand. Biomass and Bioenergy 16: 263–274.
73 Blaschke, P.M., Trustrum, N.A., and DeRose, R.C. 1992. Ecosystem processes and sustainable land use in New Zealand steeplands. Agriculture, Ecosystems and Environment 41:153–178.
74 Stamps, W.T. and Linit, M.J. 1998. Plant diversity and arthropod communities: Implications for temperate agroforestry. Agroforestry Systems 39:73–89.
75 Vandermeer, J. 1989. The Ecology of Intercropping. Cambridge University Press, Cambridge.
76 Schmidt, M. and Tscharntke, T. 2005. The role of perennial habitats for Central European farmland spiders. Agriculture, Ecosystems and Environment 105(1–2): 235–242.
77 Dix, M.E., Johnson, R.J., Harrell, M.O., Case, R.M., Wright, R.J., Hodges, L., Brandle, J.R., Schoeneberger, M.M., Sunderman, N.J., Fitzmaurice, R.L., Young, L.J., and Hubbard, K.G. 1995. Influences of trees on abundance of natural enemies of insect pests: A review. Agroforestry Systems 29:303–311.
78 Best, L.B., Whitmore, R.C., and Booth, G.M. 1990. Use of cornfields by birds during the breeding season: The importance of edge habitat. American Midland Naturalist 123:84–99.
79 Peacock, L. and Herrick, S. 2000. Responses of the willow beetle *Phratora vulgatissima* to genetically and spatially diverse *Salix* spp. plantations. Journal of Applied Ecology 37:821–831.
80 Williams, P.A., Koblents, H., and Gordon, A.M. 1995. Bird use of an intercropped maize and old fields in southern Ontario. In Proceedings of the Fourth North American Agroforestry Conference 1995, Boise, ID, USA. p. 158–162.
81 Naeem, M., Compton, S.G., Phillips, D.S., and Incoll, L.D. 1994. Factors influencing aphids and their parasitoids in a silvoarable agroforestry system. Agroforestry Forum 5 (2):20–23.
82 Peng, R.K., Incoll, L.D., Sutton, S.L., Wright, C., and Chadwick, A. 1993. Diversity of airborne arthropods in a silvoarable agroforestry system. Journal of Applied Ecology 30:551–562.
83 Phillips, D.S., Griffiths, J., Naeem, M., Compton, S.G., and Incoll, L.D. 1994. Responses of crop pests and their natural enemies to an agroforestry envronment. Agroforestry Forum 5(2):14–20.
84 Stamps, W.T., McGraw, R.L., Godsey, L., and Woods, T.L. 2009. The ecology and economics of insect pest management in nut tree alley cropping systems in the Midwestern United States. Agriculture, Ecosystems and Environment 131:4–8.
85 Corbett, A. and Rosenheim, J.A. 1996. Impact of a natural enemy overwintering refuge and its interaction with the surrounding landscape. Ecological Entomology 21(2): 155–164.

86 Murphy, B.C., Rosenheim, J.A., and Granett, J. 1996. Habitat diversification for improving biological control: Abundance of *Anagrus epos* (Hymenoptera: Myrmaridae) in grape vineyards. Environmental Entomology 25(2): 495–504.
87 Fürher, E. and Fischer, P. 1991. Towards integrated control of *Cephalcia abietis*, a defoliator of Norway Spruce in central Europe. Forest Ecology and Management 39:87–95.
88 Griffiths, J., Phillips, D.S., Compton, S.G., Wright, C., and Incoll, L.D. 1998. Responses of slug numbers and slug damage to crops in a silvoarable agroforestry landscape. Journal of Applied Ecology 35:252–260.
89 Manning, A.D., Gibbons, P., and Lindenmayer, D.B. 2009. Scattered trees: A complementary strategy for facilitating adaptive responses to climate change in modified landscapes? Journal of Applied Ecology 46:915–919.
90 Bhagwat, S.A., Willis, K.J., Birks, H.J.B., and Whittaker, R.J. 2008. Agroforestry: A refuge for tropical biodiversity? Trends in Ecology and Evolution 23(5): 261–267.
91 McNeely, J.A. and Schroth, G. 2006. Agroforestry and biodiversity conservation—traditional practices, present dynamics, and lessons for the future. Biodiversity and Conservation 15:549–554.
92 Harvey, C.A. and Gonzalez-Villalobos, J.A. 2007. Agroforestry systems conserve species-rich but modified assemblages of tropical birds and bats. Biodiversity and Conservation 16:2257–2292.
93 Bernier-Leduc, M., Vanasse, A., Olivier, A., Bussières, D., and Maisonneuve, C. 2009. Avian fauna in windbreaks integrating shrubs that produce non-timber forest products. Agriculture, Ecosystems and Environment 131:16–24.
94 Puckett, H.L., Brandle, J.R., Johnson, R.J., and Blankenship, E.E. 2009. Avian foraging patterns in crop field edges adjacent to woody habitat. Agriculture, Ecosystems and Environment 131:9–15.
95 Berges, S.A., Moore, L.A.S., Isenhart, T.M., and Schultz, R.C. 2010. Bird species diversity in riparian buffers, row crop fields, and grazed pastures within agriculturally dominated watersheds. Agroforestry Systems 79(1):97–110.
96 Gelling, M., Macdonald, D.W., and Mathews, F. 2007. Are hedgerows the route to increased farmland small mammal density? Use of hedgerows in British pastoral habitats. Landscape Ecology 22:1019–1032.
97 Perfecto, I., Vandermeer, J., and Wright, A. 2009. Nature's Matrix: Linking Agriculture, Conservation and Food Sovereignty. Earthscan, London.
98 McAdam, J., Burgess, P.J., Graves, A.R., Rigueiro-Rodríguez, A., and Mosquera-Losada, M.R. 2008. Classifications and functions of agroforestry systems in Europe. In A. Rigueiro-Rodríguez et al. (eds). Agroforestry in Europe: Current Status and Future Prospects. Springer, Belfast. p. 21–42.
99 Ispikoudis, I. and Sioliou, K.M. 2005. Cultural aspects of silvopastoral systems, In M.R. Mosquera-Losada, J. McAdam, and A. Rigueiro-Rodríguez (eds). Silvopastoralism and Sustainable Land Management: Proceedings of an International Congress on Silvopastoralism and Sustainable Management held in Lugo, Spain 2004. CABI Publishing, Wallingford. p. 319–323.
100 Garrity, D.P. 2004. Agroforestry and the achievement of the Millenium Development Goals. Agroforestry Systems 61:5–17.
101 Mercer, D.E. and Miller, R.P. 1998. Socioeconomic research in agroforestry: Progress, prospects, priorities. Agroforestry Systems 38:177–193.
102 Yobterik, A.C., Timmer, V.R., and Gordon, A.M. 1994. Screening agroforestry tree mulches for corn growth: A combined soil test, pot trial and plant analysis approach. Agroforestry Systems 25:153–166.
103 Mungai, N.W., Motavalli, P.P., Kremer, R.J., and Nelson, K.A. 2005. Spatial variation of soil enzyme activities and microbial functional diversity in temperate alley cropping systems. Biology and Fertility of Soils 42:129–136.
104 Udawatta, R.P., Kremer, R.J., Adamson, B.W., and Anderson, S.H. 2008. Variations in soil aggregate stability and enzyme activities in a temperate agroforestry practice. Applied Soil Ecology 39:153–160.
105 Lacombe, S., Bradley, R.L., Hamel, C., and Beaulieu, C. 2009. Do tree-based intercropping systems increase the diversity and stability of soil microbial communities? Agriculture, Ecosystems and Environment 131:25–31.
106 Seiter, S., Ingham, E.R., and William, R.D. 1999. Dynamics of soil fungal and bacterial biomass in a temperate climate alley cropping system. Applied Soil Ecology 12(2):139–147.
107 Lee, K.H. and Jose, S. 2003. Soil respiration and microbial biomass in a pecan-cotton alley cropping system in Southern USA. Agroforestry Systems 58:45–54.
108 Hijri, I., Sykorova, Z., Oehl, F., Ineichen, K., Mader, P., Wiemken, A., and Redecker, D. 2006. Communities of arbuscular mycorrhizal fungi in arable soils are not necessarily low in diversity. Molecular Ecology 15: 2277–2289.
109 Rillig, M.C., Wright, S.F., and Eviner, V.T. 2002. The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: Comparing effects of five plant species. Plant and Soil 238:325–333.
110 Schädler, M., Brandl, R., and Kempel, A. 2010. 'Afterlife' effects of mycorrhisation on the decomposition of plant residues. Soil Biology and Biochemistry 42:521–523.
111 Chifflot, V., Rivest, D., Olivier, A., Cogliastro, A., and Khasa, D. 2009. Molecular analysis of arbuscular mycorrhizal community structure and spores distribution in tree-based intercropping and forest systems. Agriculture, Ecosystems and Environment 131:32–39.
112 Park, J., Newman, S.M., and Cousins, S.H. 1994. The effects of poplar (*P. trichocarpa* × *deltoides*) on soil biological properties in a silvoarable system. Agroforestry Systems 25:111–118.
113 Price, G.W. and Gordon, A.M. 1999. Spatial and temporal distribution of earthworms in a temperate intercropping system in southern Ontario, Canada. Agroforestry Systems 44:141–149.
114 Porter, J., Costanza, R., Sandhu, H., Sigsgaard, L., and Wratten, S. 2009. The value of producing food, energy and ecosystem services within an agro-ecosystem. Ambio 38 (4):186–193.
115 Cooper, T., Hart, K., and Baldock, D. 2009. The provision of Public Goods through Agriculture in the

European Union. Report prepared for DG Agriculture and Rural Development Contract no. 30-CE-0233091/00-28. Institute for European Environmental Policy, London.

116 Oelbermann, M., Voroney, R.P., and Gordon, A.M. 2004. Carbon sequestration in tropical and temperate agroforestry systems: A review with examples from Costa Rica and southern Canada. Agriculture, Ecosystems and Environment 104:359–377.

117 Smith, J., Pearce, B., and Wolfe, M.S. 2012. A European perspective for developing modern multifunctional agroforestry systems for sustainable intensification. Renewable Agriculture and Food Systems, in press.