Agroforestry: Reconciling Production with Protection of the Environment

A Synopsis of Research Literature

Figure 1. Hardwood and fruit trees are planted in rows between alleys of arable and vegetable crops managed on an organic rotation in a silvoarable system at Wakelyns Agroforestry, Suffolk.

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Synopsis

- Agroforestry is a concept of integrated land use that combines elements of agriculture and forestry in a sustainable production system. An emphasis on managing rather than reducing complexity promotes a functionally biodiverse system that balances productivity with environmental protection.

- Agroforestry systems are 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 *agro-silvopastoral*.

- In the UK, traditional agroforestry systems include wood pastures such as the New Forest, browsing of acorns and beech mast (pannage), parklands, orchard grazing and hedgerows. Modern systems include silvoarable and silvopastoral systems, and woodland chicken and egg production.

- There are both ecological and economic interactions between the trees and crops and livestock. Total productivity of agroforestry systems is usually higher than in monoculture systems due to complementarity in resource-capture i.e. trees acquire resources that the crops alone would not.

- Agroforestry systems support the production of a wide range of products including food, fuel, fodder and forage, fibre, timber, gums and resins, thatching and hedging materials, gardening materials, medicinal products, craft products, recreation, and ecological services.

- Trees modify microclimatic conditions including temperature, water vapour content of air and wind speed, which can have beneficial effects on crop growth and animal welfare.

- By minimising nutrient losses and maximising internal cycling of nutrients, and by enhancing pest and disease control, agroforestry systems reduce the need for agrochemical inputs.

- The role of agroforestry in protecting the environment and providing a number of ecosystem services is a key benefit of integrating trees into farming systems. Other such benefits include regulation of soil, water and air quality, enhancement of biodiversity, pest and disease control, and climate change mitigation and adaptation.

- Integrating trees into the agricultural landscape has the potential to impact the local economy through increasing economic stability, diversification of local products and economies, diversification of rural skills, improved food and fuel security, improvements to the cultural and natural environment, and landscape diversification.

- The potential of agroforestry as a sustainable land-use system that combines production with conservation of natural resources has not yet been fully realised in temperate regions. Three key areas of activity essential for promoting agroforestry into the mainstream are research, dissemination and policy.

Agroforestry: Reconciling Production with Protection of the Environment

1. Introduction

1.1. What is agroforestry?

Although systems integrating trees and agriculture have been practised for thousands of years, the term 'agroforestry' was first coined in 1977 [1]. In its simplest form, agroforestry can be described as *"growing trees on farms"* [2]. It is generally accepted, however, that agroforestry systems are deliberately designed and managed to maximise positive interactions between tree and non-tree components. The following, widely accepted, definition incorporates these various attributes:

"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" [3].

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"* [4]. Key characteristics that distinguish agroforestry systems from agriculture and forestry include greater structural and functional complexity, an emphasis on multipurpose trees, and the production of multiple outputs balanced with protection of the resource base [5].

Agroforestry systems can initially be classified according to the components present – trees with crops are referred to as **silvoarable** (Figs. 1 and 2), trees and animals as **silvopastoral**, and trees with crops and animals as **agro-silvopastoral**. A second level of classification describes the arrangement of the components in space and time. Spatially, the tree and crop and/or animal components may be grown as mixtures, with trees distributed over the whole of the land unit (e.g. shade trees for commercial plantation crops such as tea and coffee, scattered oaks in the Spanish *dehesa* system, or parkland systems in the UK). Alternatively, in spatially zoned systems, the trees may be systematically arranged in rows (such as hedgerow intercropping systems), or as elements such as field boundaries or fodder banks.

Figure 2. Potatoes growing in the crop alleys between rows of hazel coppice used for bioenergy, nut and thatching spar production, Wakelyns Agroforestry, Suffolk

1.2. Agroforestry in the UK

Agroforestry systems have traditionally been important elements of temperate regions around the world, evolving from systems of shifting cultivation towards more settled systems involving agriculture, woodland grazing and silvopasture, with fertility transfer from woodlands to cultivated land via manure [6, 7]. The practice of pasturing in woodland by humans is one of the oldest land use practices in our history. Wood-pasture remnants in England, such as the New Forest, feature some of the oldest and widest trees in Europe, providing valuable resources for a wide range of associated biodiversity, as well as having historical and cultural value [8]. Since Roman times, pigs were released into beech and oak woodlands to feed on the acorn and beech mast (pannage), and into fruit orchards to eat fallen fruit. Chickens were also kept in orchards to help control insect pest populations [9]. Parklands were developed in 18th century Britain for aesthetic reasons, but the economic value of their open grown timber for ship building was subsequently recognised [9]. Traditional hedgerows provided many benefits; in addition to the provision of shelter, hedges provided stock-proof barriers, forage and browse for livestock, food and medicinal plants for rural populations. The practice of agroforestry has declined since the end of the Second World War. Seven basic causes have been identified as being responsible for this decline in Europe[6]:

- Increasing mechanisation leading to the removal of scattered trees to facilitate cultivations.
- The post-war demand for increased productivity through monocultures.
- A reduction in the agricultural work force prohibiting labour-intensive systems such as full stature fruit orchards.
- A shift from small fragmented land holdings to larger single farms, with an associated increase in field sizes, the removal of boundary trees and landscape simplification.
- Policy regimes that favoured single crop systems over crop associations.
- Ineligibility of wooded areas for subsidy payments for many years resulted in the removal of trees to maximise subsidy income.
- Stricter quality regulations for dessert fruit leading to intensification of orchard production [6].

Since the introduction of agroforestry as a concept in the late 1970’s, the emphasis has been on the development of new systems designed to fulfil the potential benefits of increased productivity balanced with resource and environmental conservation. Modern agroforestry in the UK is mostly still at the experimental stage, with a number of trial sites established across the UK during the late 1980’s [9]. Perhaps the most commercially successful example of agroforestry in the UK is the production of ‘Woodland Eggs’ through a partnership between Sainsbury’s supermarket and the Woodland Trust. Organic and non-organic free range eggs and chickens are produced from approved farms where chickens have access to woodland.

There are few examples of organic agroforestry systems in the UK; Prof. Martin Wolfe established Wakelyns Agroforestry, an organic silvoarable system, in 1994 on a 22.5 ha site in eastern England, incorporating hazel and willow coppice, and a mixed hardwood and fruit tree system, with cereals, potatoes, field vegetables and leys in rotation within the alleys. Sheepdrove Organic Farm in Berkshire has, until recently, run a silvopoultry system which was integrated into the farm’s organic rotation.

1.3. Agroforestry for sustainable production

The World Agroforestry Centre (ICRAF) identified six ways that agroforestry can contribute to achieving the Millennium Development Goals of combating hunger, poverty, disease, illiteracy, environmental degradation, and discrimination against women [10]:

- Eradicate hunger using agroforestry methods of soil fertility and land regeneration.
- Reduce poverty using market-driven, local tree cultivation systems to generate income and build assets.
- Advance the health and nutrition of the rural poor.
- Conserve biodiversity using agroforestry-based integrated conservation-development solutions.
- Protect watershed services and enable the poor to be rewarded for providing these services.
- Help the rural poor to adapt to climate change and benefit from emerging carbon markets. [10]

While the focus here is primarily on impoverished rural areas in developing countries, many of the points listed above are also relevant to agroforestry systems in temperate, developed countries. In the EU, the CAP reforms of the early 1990's shifted the focus from maximising production to environmentally sound farming, with the introduction of agri-environment schemes to encourage farmers to follow good environmental practices. However, recent shortages in the EU cereals market, coupled with increasing interest in the production of bioenergy crops, concerns about the effects of climate change and questions of sustainability have placed new demands on agriculture. This 'food–fuel–biodiversity' conflict calls for multifunctional land use which can simultaneously meet the various demands of food and fuel production, environmental and biodiversity protection, in addition to providing the capacity for adaptation or resilience to climate change. Identifying and developing agricultural systems that deliver ecosystem services i.e. ecological processes that sustain human well-being, is a high priority among both the research community and policy makers, and agroforestry, with its emphasis on combining productive functions with environmental services, may be able to resolve these conflicts.

2. Productivity benefits of agroforestry

A central hypothesis in agroforestry is that productivity is higher in agroforestry systems compared to monoculture systems due to complementarity in resource-capture i.e. trees acquire resources that the crops alone would not [11]. This is based on the ecological theory of niche differentiation; different species obtain resources from different parts of the environment. Tree roots generally extend deeper than crop roots and are therefore able to access soil nutrients and water unavailable to crops, as well as absorbing nutrients leached from the crop rhizosphere. These nutrients are then recycled via leaf fall onto the soil surface or fine root turnover. This will lead to greater nutrient capture and higher yields by the integrated tree-crop system compared to tree or crop monocultures [12].

2.1. Agroforestry products

Agroforestry systems support the production of a wide range of products:

- Food (arable crops, vegetables, animal products, fruit, mushrooms, oils, nuts, and leaves)
- Fuel (willow or hazel coppice, charcoal, fuelwood)
- Fodder and forage
- Fibre (pulp for paper, rubber, cork, bark and woodchip mulch)
- Timber (construction and furniture making)
- Gums and resins
- Thatching and hedging materials (spars, binders and stakes)
- Gardening materials (pea sticks, bean poles, fencing, hurdles)
- Medicinal products (ginseng, goldenseal, witch hazel [13])
- Craft products (natural dyes, basketry, floral arrangements)
- Recreation (agritourism, sport, hunting)
- Ecological services (discussed in more detail in Section 3)

2.2. Productivity of agroforestry systems

The productivity of an agroforestry system can be compared to monoculture system using the Land Equivalent Ratio (LER) [14]. This is calculated as the ratio of the area needed under monocropping to the area of intercropping (agroforestry) at the same management level to obtain a particular yield. A LER of 1 indicates that there is no yield advantage of the intercrop compared to the monocrop, while a LER of 1.1 indicates a 10% yield advantage i.e. under monocultures, 10% more land would be needed to match yields from intercropping [15]. LER's of agroforestry systems range from 2 in a pear orchard/radish system (Newman [1986, in 15]) 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 [15]. However, the use of a Land Equivalent Ratio does not take into account the 'non-market' products that agroforestry systems support, ecosystem services such as the regulation of air quality, climate, flood control, water quality and management of pests and diseases, and therefore the relative productivity of agroforestry is likely to be higher still.

2.3. Agroforestry interactions

Interactions between the tree and crop/livestock components can be positive, negative or neutral. In the former case complementarity results in increased capture of a limiting resource, and greater total production than if the two components had been grown separately. Conversely, negative interaction, when the two components overlap in their resource use, can lead to competition and hence lower productivity than if the components are grown separately. Where there are no direct interactions between system components, the net effect of combining them is neutral. [16].

2.3.1. Microclimate modification

Trees modify microclimatic conditions including temperature, water vapour content and wind speed, which can have beneficial effects on crop growth and animal welfare [16]. Wind speed reductions can extend to 30 times the height of tree belts on the leeward side [17, 18]. The resultant decline in wind erosion effects can have multiple benefits for crops including increased growth rate and quality, protection from windblown soil, moisture management and soil protection. Furthermore, higher air and soil temperatures in the lee of a shelterbelt can extend the growing season, with earlier germination and improved growth at the start of the season [19].

2.3.2. Animal Welfare

Trees are multifunctional in their provision of resources for animals; they provide shelter from rain and wind, shade from the sun, cover from predators and a diversity of foraging resources. This can be particularly valuable during cooler months and winter storms when protection of new-born lambs, freshly shorn sheep and livestock can lead to significant savings in feed costs, survival and milk production, as reported by producers in Dakota, US [19].

Figure 3. Chickens sheltering in the silvopoultry system on Sheepdrove Organic Farm, Berkshire

Farm animals such as chickens and pigs have forest-dwelling ancestors and therefore prefer to range in tree and thicket cover (Fig. 4). For chickens, trees offer protection from aerial predators in particular, and can provide an escape from aggressive behaviour within the flock as well as reducing visual stimulation that can provoke aggression [20]. The trees can also benefit from the interaction with poultry; higher leaf nitrogen concentrations and increased total height were recorded for 3 year old black walnut trees fertilised with a chicken manure compared to a non-fertiliser control [21]. Behavioural studies of domestic pigs have shown that trees encourage expression of normal behavioural patterns [22].

2.3.3. Pest and disease control

Reduced pest problems in agroforestry systems have been recorded due to greater niche diversity and complexity than in monoculture systems [23-28]. This can be attributed to a number of mechanisms [29]:

- Variable distribution of host plants makes it more difficult for pests to find the plants.
- A plant species which is highly attractive to pests can act as a 'trap-crop', protecting nearby economically valuable species from herbivore attack.
- A plant species which is repellent to pest herbivores may also deter them from other, more palatable, species in the vicinity.
- Higher predator and parasitoid densities due to higher plant diversity increases pressure from natural enemies.
- Increased interspecific competition between pest and non-pest species limits the spread of pests.

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 [2, 23]. Trees lead to greater structural and microclimatic diversity, increased temporal stability, greater biomass and surface area, alternate sources of pollen, nectar and prey as well as alternate hosts and stable refuges for beneficials [23]. This is particularly valuable when crop pest populations are reduced following harvest [30, 31].

2.3.4. Negative interactions

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 [32-34]. 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 [16] and, indeed, reduced evapotranspiration due to tree shade effects on understorey plants may increase soil water content compared to open pastures [35]. 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. As well as 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 [16]. 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 [36].

2.4. Reducing inputs

Agroforestry systems are modelled on a natural woodland ecosystem, with the aim of increasing 'eco-efficiency' thereby reducing the need for inputs through minimising losses and maximising internal cycling of nutrients. The 'eco-efficiency' of a land-use system is determined by the efficiency and sustainability of resource-use in farm production. It can be improved by achieving a given level of production using fewer resources, with fewer losses to the environment, while maintaining the productive potential of the land and economic performance [37]. Five keys attributes of eco-efficient farming are [38]:

- Efficient resource-use with maximum inclusion of renewable resources.
- No local pollution and no transfer of pollution elsewhere.
- Predictable output.
- Functional biodiversity conservation to support ecological processes.
- Ability to respond promptly to changes in the social, economic and physical environment.

Successful agroforestry systems have the potential to meet all five of the criteria listed above, and by supporting a broader economic base, should maintain or increase farm profitability compared to monoculture systems. Despite the potential for reducing inputs, agroforestry systems in temperate regions are often managed along conventional lines, however, with inputs of synthetic fertilisers and pesticides. This fails to realise the full potential of agroforestry as a sustainable, low-input system and further research into eco-agroforestry approaches that integrate agroforestry with organic and agro-ecological principles is needed.

2.5. System design and management to maximise productivity

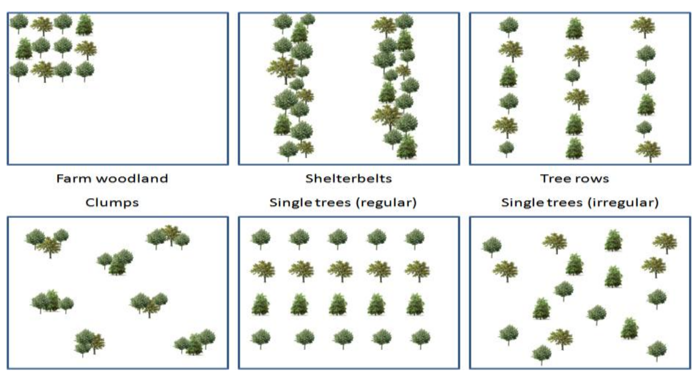

Figure 4. Various spatial arrangements of agroforestry trees

Interactions between woody and non-woody components in agroforestry can be positive, negative or neutral, and the productivity of a system is a net result of these interactions [16]. Agroforestry systems should be designed to optimise resource capture by maximising positive interactions and minimising negative ones. Appropriate selection of the woody and crop or livestock species of the system to meet site and farm business requirements is necessary, as well as careful consideration of the potential interactions between the different species [12]. Ideal tree species for agroforestry systems should maximise niche differentiation between the tree and crop; deep roots are key to access nutrients and water unavailable to the crop and either a crown that is in leaf outside the crop's main growing period or that casts a light even shade. The spatial design of the system will also influence productivity by determining the zone of interactions between the trees and crops, and therefore, the relative potential benefits (Fig. 5). For example, trees distributed evenly will have a larger zone of interaction with the adjacent crop or pasture compared to a clumped distribution [12] and in temperate regions, orientating tree rows in a north-south direction is generally accepted as the most efficient orientation to optimise direct sunlight penetration to the crop/pasture.

Within agroforestry systems, productivity of each component can be manipulated by management practices including pruning, weed control and protection from animal damage [39, 40]. Controlling the density of the tree canopy through pruning will determine the amount of sunlight reaching the crop or pasture, and is particularly important in hardwood systems to ensure good quality timber. Below-ground pruning of tree roots through management practices such as trenching, knifing, disking or subsoiling aims to minimise belowground competition and so prolong profitable crop production [41]. Weed control is important in the early years after tree planting to reduce competition, and plastic mulching is often used to reduce weed pressure on newly planted trees [42].

3. Environmental benefits of agroforestry

The role of agroforestry in protecting the environment and providing a number of ecosystem services is promoted as a key benefit of integrating trees into farming systems. As traditionally employed, these benefits were intuitive to the farmers and landowners that managed agroforestry systems, although the scientific evidence to support such benefits is only now coming to light [43-45]. The impact of agroforestry on the environment occurs at a range of spatial and temporal scales; from fine-scale impacts on soil structure and quality to impacts on the environment and society at regional or global scales.

3.1. Soil

Soil management is a key feature of agroforestry systems, and in both tropical and temperate climates, agroforestry systems are designed and implemented to counter soil erosion and degradation, and improve soil quality and health.

3.1.1. Erosion

The replacement of natural forest and scrublands by croplands and grasslands devoid of trees on susceptible soils has resulted in increased run-off and accelerated erosion in many agricultural areas. As well as increasing structural stability of the soil, tree roots can enhance water infiltration and improve water storage by increasing the number of soil pores. Macropores rapidly channel surplus surface water flow and allow air and moisture to move into the soil. In this way the risk of soil erosion is reduced; tree roots and trunks also act as physical barriers to reduce surface flow of water and sediment [46, 47].

3.1.2. Remediation

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 breakdown pollutants to non-toxic compounds and control water dynamics including contaminated groundwater flow and water penetration into soils via evapotranspiration [48]. Agroforestry systems have been used to recycle urban and agricultural organic waste with the added benefit of increased biomass productivity from the additional nutrients [49, 50]. Previously a burden to society, these waste products can be viewed as a valuable resource to maximise biomass production [51].

3.1.3.Fertility

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 to 15.0m from the tree row, and nitrogen release from poplar leaf litter was equivalent to 7kg N ha^{-1} yr^{-1} [28]. 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 28] showed that these pathways contributed 10.99 and 15.22 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. 52]. 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 [16]. Significant transfer of fixed nitrogen to crops has been observed in a study which showed that 32 to 58% of the total nitrogen in alley-cropped maize came from nitrogen fixed by the adjacent red alder (*Alnus rubra*) [16].

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 [53]. 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 [53-57].

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 fertiliser input [58-60]. However, while AM fungal diversity tends to be low in conventionally managed agricultural soils, which has been attributed to negative effects of fertilisation, fungicides, soil cultivations and low host diversity, it has been shown that agroforestry systems may enhance AM fungal richness compared to monocropped systems [61] . 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 [61].

Higher levels of soil organic matter in agroforestry systems also positively influence soil invertebrate communities [62, 63]. In a poplar-arable rotation 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 [62].

3.2. Water

The effects of agriculture on water systems are numerous and include changes to water chemistry with eutrophication and food web modifications, pesticide pollution, increased sediment load from soil erosion, changes to hydrological cycles via changes in evapotranspiration rates and run-off, modification of river flow and irrigation impacts, effects of exotic species, and physical modification of the habitat through canalisation, drainage and embankment [64]. Research has demonstrated that agroforestry can reduce pollution from crops and grazed pastures, with tree strips located adjacent to water courses reducing non-point source water pollution from agricultural land in five key ways [65-70]:

- Reducing surface runoff from fields.
- Filtering surface runoff.
- Filtering groundwater runoff.
- Reducing bank erosion.
- Filtering stream water.

3.2.1. Safety net hypothesis

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 [16]. 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.

3.2.2. Reducing pollution

Buffer strips can significantly decrease pollution run-off, with reductions of 70-90% reported for suspended solids, 60-98% for phosphorus and 70-95% for nitrogen [references in 45] A study in central Iowa, US, found that a switch-grass/woody buffer removed 97% of the sediment, 94% of the total N, 85% of the nitrate-N, 91% of the total P and 80% of the phosphate P in the runoff [68]. Agroforestry systems also have the potential to mitigate movement of harmful bacteria such as *Escherichia coli* into water sources [66] and reduce the transport of veterinary antibiotics from manure-treated agroecosystems to surface water resources [71]. Agroforestry has been used to address issues of soil salinisation in Australia where a study recorded a lowering of the saline groundwater table by 2.0m over a 7 year period under a *Eucalyptus*-pasture system, relative to nearby pasture-only sites [72].

3.2.3. Reducing runoff

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 [73, 74]. In Midwestern USA, a multispecies buffer that included woody perennials increased infiltration rates to five times that of cultivated and grazed fields [74]. Agroforestry strips in Missouri, USA, reduced surface water runoff by 9% after just 2 years of establishment, compared with a control watershed [67]. Agroforestry can reduce soil water content during critical times such as fallow periods and increase water infiltration and water storage. Furthermore, aboveground, stems, leaf litter and pruning debris in agroforestry systems can reduce runoff flow rates, thereby enhancing sedimentation within the agroforestry strip and increasing infiltration [74].

3.3. Biodiversity

Agroforestry systems by their very nature are more diverse than monocultures of crops and livestock; this increase in ‘planned’ biodiversity i.e. the components chosen by the farmer, increases the ‘associated’ biodiversity i.e. the wild plants and animals occurring on the farmland. Five main ways that agroforestry contributes to the preservation of biodiversity are [43]:

- By providing habitat for species that can tolerate a certain level of disturbance;
- By helping to preserve germplasm of sensitive species;
- By helping to reduce the rates of conversion of natural habitat and alleviate resource use pressure;
- By providing connectivity through corridors created between habitat remnants and the conservation of area-sensitive floral and faunal species;
- By helping to conserve biological diversity through 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 [25, 26, 63, 75-88]. 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 [89].

3.4. Climate change

There has been an increase in research over the last 20 years investigating the potential of agroforestry as a tool for addressing the issues of climate change through mitigation and adaptation [90-98]. Three groups of activities through which forest management can contribute towards reducing atmospheric carbon are [95]:

- Carbon sequestration through afforestation, reforestation, restoration of degraded lands and improved silvicultural techniques to improve growth rates.
- Carbon conservation through conservation of biomass and soil carbon in existing forests, improved harvesting practices to reduce logging impact, improved efficiency of wood processing, fire protection and more effective use of burning in forests and agricultural systems.
- Carbon substitution through increased conversion of forest biomass into durable wood products to replace energy-intensive materials, increased use of biofuels and enhanced use of harvesting waste as feedstock for biofuel [95].

Agroforestry can increase the amount of carbon sequestered compared to monocultures of crops or pasture due to the incorporation of trees and shrubs [43]. Woody perennials store a significant amount of carbon in above ground biomass and also contribute to belowground carbon sequestration in soils. Average carbon storage by agroforestry systems is estimated at 9, 21, 50 and 63 Mg C ha^{-1} in semiarid, subhumid, humid and temperate regions respectively, with higher rates in temperate regions reflecting longer rotations and longer-term storage [90]. The estimated contribution of agroforestry to global carbon sequestration is 1.9 Pg of carbon over 50 years, based on a worldwide estimate of 1023 million ha of agroforestry [99]. At a global scale, agroforestry systems could be established on 585 to 1274 x 10^6 ha of suitable land, thus storing 12 to 228 Mg C ha^{-1} [100]. Converting unproductive croplands and grasslands to agroforestry, an estimated 630 million ha, could potentially sequester 391,000 Mg C yr^{-1} by 2010 and 586,000 Mg C yr^{-1} by 2040 [101].

Biomass energy from short rotation coppice (SRC) is a carbon-neutral source of energy that doesn't 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 [48, 102]. 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 [103, 104]. 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*). Trees planted around homesteads can also contribute to energy savings in farm buildings; they can reduce the amount of energy needed to heat or cool a house by up to 30% [105].

3.4.1. 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 [106]. 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 modelling [107]. 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 [28]. A decrease in nitrogen leaching out of the rooting zone will reduce NO_x emissions as a result of denitrification in surface water resources [28]. Models estimate that nitrates leaving a tree-based intercropping system can be reduced by 50% compared to a monoculture control [28].

3.4.2. Adaptation

Trees help to buffer against environmental extremes by modifying temperatures, providing shade and shelter and by acting as alternative feed resources during periods of drought, as discussed in previous sections. Easterling *et al.* [108] used a crop modelling approach to look at the effect of climate change on shelterbelt function and found that under several climate change scenarios, tree belts could help maintain crop production, with sheltered crops performing better than unsheltered crops. They conclude that windbreaks will have an important role in helping agricultural producers to adapt to changing climates.

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 8.4m^2 from failure [Hawley and Dymond, 1988, in 32]. Mature willow and poplar trees at 12m spacing can reduce mass movement by 10-20% [Hicks, 1995, in 32].

The value of agroforestry systems in semi-arid regions such as the Mediterranean and parts of Australia where water availability limits agricultural sustainability demonstrates the potential role of agroforestry in temperate regions with a changing climate. In semi-arid climates, soil water content under tree canopies can be higher than in open pasture due to reduced evapotranspiration in the tree shade out-weighing water uptake by plants [32, 35].

For farmland biodiversity, scattered trees within agricultural landscapes act as 'keystone species' that facilitate the movement of wildlife through a landscape that may otherwise be too hostile [109]. This role of agroforestry in providing corridors that allow movement of species through landscapes will increase in importance under predicted climate change scenarios by allowing species to adapt their distributions in response to the shifting climate.

4. Socio-economic benefits of agroforestry

A key objective of implementing agroforestry systems in the tropics is improving livelihoods of poor rural small holders [10]. However, the societal benefits of temperate agroforestry have received less attention with the focus limited primarily to economics and there is a pressing need for more socio-economic research in temperate systems [110]. Integrating trees into the agricultural landscape has the potential to impact the local economy through increasing economic stability, diversification of local products and economies, diversification of rural skills, improved food and fuel security, improvements to the environment (both cultural and biological), and landscape diversification.

4.1. Economics

Economic studies of agroforestry systems have shown that financial benefits are a consequence of increasing the diversity and productivity of the systems which are influenced by market and price fluctuations of timber, livestock and crops. In addition to higher yield potentials of agroforestry, product diversification increases the potential for economic profits by providing annual and periodic revenues from multiple outputs throughout the rotation and reducing the risks associated with farming single commodities [41]. Compared with exclusive forestry land use, agroforestry practices are able to recoup initial costs more quickly due to the income generated from the agricultural component [111, 112], while studies have shown increased profitability of silvoarable [20, 41] and silvopastoral [32, 113] systems compared to agricultural monoculture systems.

Recently, there has been considerable interest in placing a monetary value on the delivery of ecosystem services 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. 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 ha^{-1} of which 46% came from market ecosystem services (production of food, forage and biomass crops) and the rest from non-market ecosystem services. Extrapolated to the European scale, the value of nonmarket ecosystem services from this novel system exceeded current European farm subsidy payments [114].

4.2. Diversification of local products and economies

Diversifying the range of products produced locally benefits the local community in a number of ways. Within the UK, agricultural and food products alone account for 28% of goods on the roads, at a cost of £2.35bn yr^{-1} [115]. Producing and using goods locally through agroforestry should reduce transportation costs. For some products, e.g. wood fuel (either as logs or wood chips) there is a need for production to be in close proximity to end-users to 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 [48]. Tree products can also be used on the farm (e.g. for fence posts, fodder or bioenergy) and this should reduce inputs and increase the 'eco-efficiency' of the farming system as discussed earlier.

4.3. Rural skills and employment

Economic tropical agroforestry systems show that management of intercropped systems is often intensive with high manual labour input required [116, 117]. Within the UK and across parts of Northern Europe, there has been a decline in opportunities for manual employment in rural areas over the last 20 years, and tree management skills such as coppicing and hedge laying appear to have been lost from the rural workforce. Establishment of agroforestry systems requires a wider skill base, but estimating the impact of agroforestry on rural employment is restricted by the complexity of the system and a lack of formal studies. In addition to diversifying the skills base of the local labour force, there are likely to be positive implications for local industries supplying inputs and processing outputs from both the agricultural and forestry components of the system [118]. More research is needed to investigate such interactions.

4.4. Reduced reliance on fossil fuels

In a time of mounting concerns about long-term availability of oil, agroforestry systems have the potential to reduce reliance on fossil fuel consumption in a number of ways. The production of renewable energy, through coppice systems or as a by-product of timber production can reduce the use of fossil fuels for heating and cooking. Furthermore, internal cycling of nutrients, and enhanced pest and disease control, can reduce the need for oil-based agrochemicals and localised production of multiple outputs can avoid the need for long-distance transportation of goods and therefore reduce fuel use.

4.5. Aesthetics

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 [119]. Traditional agroforestry systems such as grazed orchards, parkland and wood pastures are valued for their visual appeal. However, establishing modern agroforestry systems which tend to be more artificial, geometric and rigid in appearance than traditional systems, causes aesthetic changes at a landscape scale, and such changes must be carefully considered in the design and location of such systems [120].

4.6. Culture

Cultural aspects of traditional agroforestry systems, particularly in temperate regions, are often overlooked, despite the long history of woodland and orchard grazing, alpine wooded pastures, pannage, the *dehesa* and parklands [119]. Lifestyles such as nomadism, transhumance (seasonal movement of people with their livestock) 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 [121]. While only remnants of these traditional landscapes exist today, the significance and value of these cultural landscapes have been recognised at the international level by UNESCO and at the European level by the European Landscape Convention. Within the UK, National Park status was awarded in 2005 to the New Forest, to protect one of the largest remaining areas of wood-pasture in temperate Europe.

4.7. Recreation

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 [119]. Furthermore, cultural landscapes such as the New Forest in England, the cork oak systems of Spain and Portugal, and the wood pastures of the Alps, can create financial opportunities through eco-tourism.

5. The Future of Agroforestry

This synopsis highlights the multiple benefits of integrating trees and agriculture, and demonstrates the potential for agroforestry to reconcile the need for increased productivity with protection of the environment and delivery of ecosystem services including soil, water and air quality regulation, biodiversity support and cultural services. However, this potential has not yet been fully realised in temperate regions. Three key areas of activity essential for promoting agroforestry into the mainstream are research, dissemination of information and policy.

Scientific research on agroforestry systems started in the late 1970's, and focused on tropical systems; studies on temperate systems only starting to appear in the literature from the early 1990's [122, 123]. The long time scale needed for such research is a limiting factor, with very few examples yet available of complete cycles of the systems through to tree harvest. Research needs range from studies at the fine-scale (species interactions), the farm-scale (economic as well as environmental benefits) right up to the landscape-scale (e.g. watershed impacts on nitrate leaching, biodiversity enhancement), national-scale (e.g. home-grown timber and fuel to reduce imports and increase renewable energy production) and global-scale (climate change mitigation and adaptation).

Another primary barrier to wider adoption of agroforestry is limited awareness among farmers and landowners of agroforestry practices [124]. For agroforestry to be adopted on a wider scale, economic viability and practical management skills need to be demonstrated to farmers and landowners. This relies crucially on effective dissemination and therefore outreach support and extension projects are essential [125].

Supportive policies are seen as instrumental in providing incentives and removing constraints to wider adoption of agroforestry [125]. Agroforestry systems often fail to qualify for subsidies under either agricultural or forestry policies, although there have been a number of recent developments in policy reforms (e.g. in France) that adopted options for payments to establish new agroforestry systems. Raising awareness of the potential of agroforestry among policy makers is essential for promoting agroforestry as a mainstream land-use system.

In temperate systems, the general belief seems to be that the high cost of manual labour in Europe necessitates a greater reliance on agrochemical input and intensive management, particularly in the industrialised northern countries. Many temperate agroforestry systems are only one step up from conventional, intensive monocultures; while these systems benefit in a number of ways from integrating trees with crops or livestock, the full potential of agroforestry as a low-input, biodiverse approach to sustainable production and ecosystem service delivery is yet to be realised. At the Organic Research Centre, we are promoting the adoption of an 'eco-agroforestry' approach whereby agroforestry is integrated with organic and agro-ecological principles in order to take full advantage of the multiple benefits of this land-use system.

6. References

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