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SECTION 14

Agroforestry

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14.1 Introduction

Agroforestry is a term which describes systems in which trees, animals and/or crops are grown together in intimate mixtures. The term does not include farm woodlands which do not involve significant biological or environmental interactions between the woodland and agricultural components.

A number of papers in this volume have discussed the possibility of increasing timber production in Cumbria, in response to Britain's present high rate of timber imports and excess agricultural production. Agroforestry could contribute to this increased timber production in a manner which would be attractive to the farming community because land would sustain a significant agricultural income whilst the trees were maturing.

There are several types of agroforestry. *Silvoarable systems* are mixtures of trees and crops, while *silvopastoralism* describes intimate mixtures of trees and animals. *Agrenforestry* is a term used here to emphasize the co-production of bioenergy crops with agricultural and timber crops. Agrenforestry, described later in more detail, could involve strips of energy coppice amongst agricultural crops, or the use of coppice beneath wide-spaced standard trees.

It has been suggested (Lawson 1987) that there are five possible uses for rural land – food, fibre, fuel, pharmaceuticals and fun. This paper moves up the alphabet to discuss five criteria for land use decisions: economics, energy, environment, employment and enjoyment.

14.2 Economics

Agroforestry is an unusual land use in present-day Britain. However, there is a long history of coppicing and pollarding which Satchell has described for Cumbria (see page 6). Multiple use of trees has an even longer history than coppicing, and Satchell has discussed the argument that excessive lopping for fodder caused the extensive decline of elm (*Ulmus* spp.) in pollen diagrams, around 3000 BC. The starch and protein content of leaves from several tree species can exceed that in good grass (Russell 1947). Medieval parkland contained herds of deer, cattle and swine grazing under widely spaced trees. Wooded commons made extensive use of pollarding, and winter grazing within forests remains vital to the survival of deer and sheep in some areas.

However, despite this long-standing experience of agroforestry, it is hard to predict its current profitability, which will be much influenced by factors such as whether:

i. high pruning of conifers can sustain yields

ii. a sufficient premium will develop for veneer-quality timber

iii. intensive fertilization will damage timber quality

iv. bark-stripping can be limited by good grazing management

v. the shelter provided for stock compensates for the grazing loss.

Despite the uncertainties, several economic models of agroforestry have been developed. They are based on rather heroic biological assumptions, but experimental evidence is beginning to verify the predictions.

New Zealand

New Zealand provides an example of agroforestry as it may apply in Britain, and several large-scale experiments have been continuing there for at least 12 years. Agroforestry in New Zealand was a consequence of suggested changes in the management of radiata pine (*Pinus radiata*) on good-quality sites. This 'direct sawlog regime' advocated a low number of crop trees, early thinning to waste instead of productive thinning, and intensive pruning of lower branches (Fenton & Sutton 1968). The possibility of grazing in these widely spaced forests was almost coincidental, but it has engendered considerable interest amongst New Zealand farmers. There are now at least 30 000 ha of agroforestry and 70 000 ha of forests with a grazing component (Percival & Hawke 1985).

The carrying capacity of hill pasture has been examined at different tree densities (Figure 1), and the profitability of agroforestry appears to compare well with conventional agriculture (Table 1). It should be noted that New Zealand now has none of the subsidies for agriculture or forestry which confuse land use comparisons in the European Community (EC). Predictions from all four sites in Table 1 suggest that agroforestry has an internal rate of return on investment in excess of 10%. However, further sensitivity analyses show that agroforestry would be uneconomic with higher stocking rates, infertile sites, poor silvicultural management, long haulage distances, high harvesting and sawmill costs, and a low stemwood price. The optimum spacing was found to be 100

Table 1. Comparison of the profitability of agroforestry at four locations in New Zealand (assuming 100 stems ha^{-1}, 10% discount rate, January 1984 prices, average stocking units ha^{-1}, no premium for quality timber, average site index) (Arthur-Worsop 1985)

	Net present value (NZ$ ha^{-1})			
	Whatawhata (hard hill land)	Tikitere (easy hill land)	Invermay (rolling hills)	Akatore (steep, less fertile)
BENEFITS				
Gross forestry revenue	2524	2842	2343	2412
Forest grazing gross margin (GM)	1335	1646	1519	1406
Total	3859	4488	3862	3818
COSTS				
Forestry costs	1786	1622	1230	1498
Open grazing opportunity costs (GM)	1773	2428	2393	2185
Total	3559	4050	3623	3683
Net effect of agroforestry	+300	+438	+239	+135
Internal rate of return	11.6	11.8	11.0	10.6

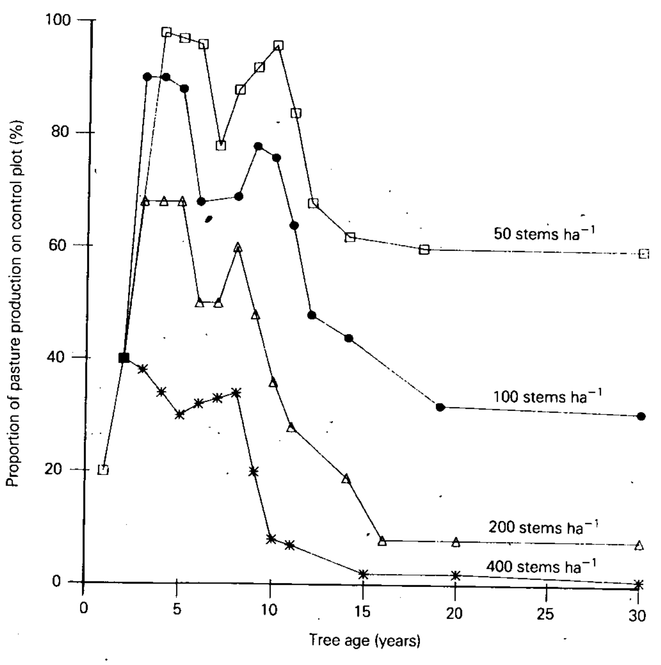

Figure 1. The measured (years 4–11) and predicted (years 12–30) effect of radiata pine on livestock numbers in New Zealand hill pasture (Percival & Hawke 1985)

stems ha^{-1}. As always with comparisons between forestry and agriculture, the assumption of a low discount rate will favour systems with a high revenue from trees at the end of a rotation, rather than agricultural systems with a guaranteed annual return.

Chile

A multidisciplinary group in southern Chile initiated a number of agroforestry experiments in 1977. As in New Zealand, their main interest has been in wide-spaced and pruned radiata pine, but experiments have also been established using southern beech (*Nothofagus* spp.), alder (*Alnus glutinosa*), chestnut (*Castanea sativa*), and Douglas fir (*Pseudotsuga menziesii*) (Penalosa, Herve & Sobarzo 1985). Sheepmeat production within six-year-old pines at 100 stems ha^{-1} has reached 250 kg ha^{-1}, compared to 214 kg ha^{-1} prior to planting. This increase is attributed to the conservation of soil moisture caused by shade from the tree canopy.

Italy

Several fertile valleys in Italy, particularly that of the River Po, demonstrate a system where poplars (*Populus* spp.) compose around 20% of the farming area. The trees are grown at wide spacing (8–10 m) in double or single rows, and are often concentrated at field boundaries or road verges. For the first five years of growth, soil cultivation between rows of poplar increases tree height and girth increment. These benefits remain during the whole rotation (Food and Agriculture Organisation 1980). Farm manure is applied routinely, and appears not to cause the wood quality problems which occur when conifers are heavily fertilized. Forage maize, wheat, pulses and root vegetables are all used in the early years of a plantation (Plate 5), to be followed by the grazing of cattle.

Plate 5. Casale Monferato, Italy. Two-year-old rooted cuttings of poplar (*Populus × euramericana*) underplanted with arable crops. (Photograph G J Lawson)

Plate 6. Bruton, Somerset. New parkland dominated by 80-year-old oak (*Quercus* spp.). Agricultural grants and firewood revenues covered the cost of conversion from neglected scrub. (Photograph G J Lawson)

Prevosto *et al.* (reported in Food and Agriculture Organization 1980) conducted extensive trials on the reduction in yield of different crops caused by wide-spaced rows of poplar. These yield reductions, together with the higher costs of cultivation, have been incorporated in an economic assessment of the implications of gradually introducing poplars on to a typical farm of the Po Valley. Prior to poplar planting, the farm yielded \$429 ha^{-1} (1975 prices), while at the end of a ten-year rotation the revenues per hectare had reached \$509, \$589 and \$669 for 10%, 20% and 30% poplar respectively at a 10% discount rate. Poplars may have an even greater advantage in areas where crop yields are reduced by wind exposure, or where the prunings are used for animal fodder. However, in recent years, increasing agricultural subsidies and a depressed market for timber in Italy have significantly reduced the prevalence of agroforestry on fertile farmland.

Britain

The Hill Farming Research Organisation and Forestry Commission have jointly considered the economics of a combined conifer and sheep silvopastoral system (Maxwell 1986; Sibbald *et al.* 1987). Data from a number of species are used to predict conifer growth, shading effect and timber yield at a range of planting densities, and under two sheep production systems (Table 2). Under the given assumptions, the model indicates that silvopastoralism may be the most profitable land use on upland farms, and predicts that a density of 100 stems ha^{-1} is preferable to 400 stems ha^{-1}.

Another modelling exercise was performed jointly by the Animal and Grassland Research Institute and the Forestry Commission, this time for lowland grassland and broadleaved trees. Simple competition models for light, moisture and nutrients were used to predict the yield of grass beneath ash (*Fraxinus excelsior*) trees at spacings of up to 200 ha^{-1}, receiving different levels of nitrogen fertilizer. High-quality timber production was predicted to be much more profitable than early felling for firewood, and 100 stems ha^{-1} was considered the optimum spacing. Again, the discount rate selected considerably influences profitability. At a 5% rate, and particularly with fertilizer levels less than 150 kg ha^{-1}, the model suggests significant advantages for hardwood silvopastoral systems in the lowlands (Doyle, Evans & Rossiter 1987).

Crop interaction economics

In agroforestry one can distinguish between *symbiotic, independent* and *competitive* relationships.

In a *symbiotic* relationship, the crops have positive influences on the growth of each other. There are many possible examples in UK agroforests: shelter may increase pasture yields by raising ground temperature in spring and relieving moisture stress in summer (Marshall 1967); cultivating the soil between rows of poplar during the early years of a rotation can increase the growth rate of the trees (de Damas 1978); nitrogen-fixing understories will enhance the growth of trees on poor soils (O'Carroll 1982).

An *independent* relationship exists if the two crops have no influence on each other, for example if they use labour at different times of year, or if the trees and herbaceous crops are using different pool of nutrients or moisture.

Competitive relationships exist when the two crops compete for resources of light, moisture, nutrients, labour, land or capital.

Table 2. Net present value of various silvopastoral options compared with conventional agriculture or forestry (£ ha^{-1}, 5% discount rate, assumed planting densities 100 and 400 stems ha^{-1}, Douglas fir, yield class 20, individual protection assumed for trees – allowing grazing from the first year, upland sheep = 10 greyface ewes ha^{-1}, hillsheep = 2.5 blackface ewes ha^{-1}, premium of 7% assumed for high timber quality, 4 prunings assumed) (Maxwell 1986)

		Hill			Upland		
	All forest	All agri-culture	Agro-forestry (100 ha^{-1})	Agro-forestry (400 ha^{-1})	All agri-culture	Agro-forestry (100 ha^{-1})	Agro-forestry (400 ha^{-1})
Forestry	1129	—	268	638	—	268	638
Agriculture	—	555	525	433	4234	4005	3304
Total	1129	555	793	1071	4234	4273	3942

These three types of interaction are expressed in Figure 2 at different points on the revenue curve between pure agriculture (A) and pure forestry (E). The line, A to E, represents increasing tree density. At very low tree stocking rates (A–B), the sheltering effect of trees may benefit agricultural production or control erosion. Timber revenue rises rapidly as density increases because there is little inter-tree competition. This is, therefore, a period of symbiotic interaction. The interaction becomes competitive as the tree density is further increased and agricultural production declines (B–D). Further increases in density reduce the net discounted revenue from forestry because of thinning costs or early harvesting, and agricultural revenue soon reaches zero (D–E). At points B and D, there is an independent relationship because a marginal increase in one crop makes no difference to revenue from the other. The optimum density is at point C, where a marginal decrease in forestry revenue is matched by an equal increase in agricultural revenue.

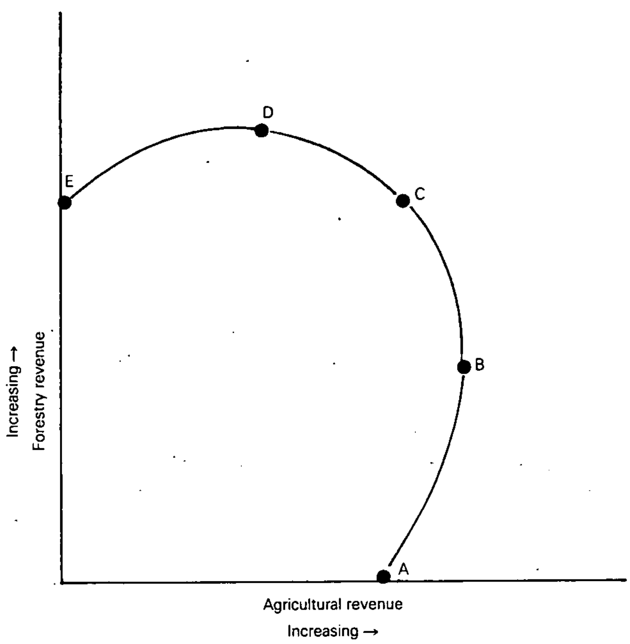

Figure 2. Revenue interactions for different mixtures of agriculture and forestry (adapted from Filius 1982, see text for discussion)

Note that a convex shape for this 'crop interaction curve' favours agroforestry. A concave curve would indicate that agroforestry was not economic, and would occur if the two crops were competitive throughout the rotation, or if significant economies of scale exist in the monocultures.

Given enough biological information, Figure 2 is a useful economic nomograph to decide on the balance between two competing uses of a resource. When applied to the allocation of land between agriculture and forestry, it shows that the points of maximum agricultural revenue (B) and forestry revenue (D) need not maximize the use of the land resource. A useful extension of the method would be to apply shadow pricing to reflect the true value of each product to government and to account for the energetic (section 14.3), environmental (section 14.4) and social (section 14.5) implications.

Non-accountable factors

The economic models described above are overly simplistic, and this fact is emphasized by their authors. Interactions between trees and understorey vegetation or animals are very diverse (Appendix I), and demand much more research.

Wide-spaced 'silvopastoral shelter strips' in the uplands would have several economic advantages, some of which are rather difficult to quantify.

i. Shelter would be provided within the strip as well as outside it.

ii. Shelter extends further downwind from a sparse shelterbelt than from a dense one (Figure 3).

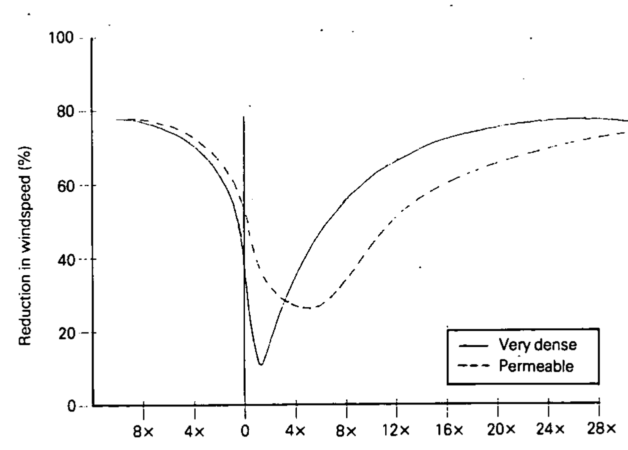

Figure 3. Differences in pattern of windspeed reduction between a permeable and a very dense shelterbelt (after Caborn 1965)

iii. For small areas, individual tree shelters are significantly cheaper than fencing. Wide-spaced planting will therefore be economic in smaller units, which will suit a varied topography.

iv. Grazing remains possible in silvopastoral strips (Figure 1), thereby reducing the cash flow problems incurred in plantations of conventional spacing.

v. Trees planted at wide spacing tend to develop spreading root systems, and will suffer less from windblow after thinning.

vi. Control of deer and foxes will be easier than in dense forest.

vii. Prunings from lower branches may be a useful food supplement for cattle and sheep.

There are also some disadvantages of agroforestry which are difficult to quantify. These include the effect of heavy fertilizer applications on timber quality, and the damage to trees caused by soil compaction or bark-stripping.

Agroforestry, therefore, can have implications for farmers which are not amenable to economic accounting. Farmers interested in forestry may plant tree cover for game birds, shelter for livestock or as a use for areas of their farm which are unsuitable for agriculture. Several mutual benefits were described by Mutch and Hutchinson (1980), where case studies of 13 upland farms indicated that afforestation of approximately 25% of the land was accompanied by an increase in livestock production of 33%, and an increase in employment of more than 50%.

Macro-economic factors

The micro-economic models also fail to account for the differences in subsidies given to farming and forestry. They are notoriously difficult to disentangle, but the following statistics emphasize that the balance of official support is highly likely to move towards woody crops, and away from intensive agriculture.

i. Obvious subsidies given to UK agriculture in 1985 were £2.21 billion, compared with a net farming income of only £1.15 billion (Ministry of Agriculture, Fisheries and Food 1986).

ii. Some estimates suggest that up to 2.4 Mha in the UK will be producing food surpluses by the year 2000 (Brown 1988). Even the Ministry of Agriculture, Fisheries and Food (MAFF) has accepted that land producing surpluses may exceed one Mha by the year 2000 (Anderson 1987). Comparable figures for the EC range up to 15 Mha.

iii. Of the timber used in the EC, 60% is imported. As long ago as 1959, the Mansholt Plan envisaged the need to transfer 5 Mha from farming to forestry. Imports of timber and timber products into the UK amount to £4.5 billion annually. The Forest Action Plan, currently under discussion in the EC, suggests many measures which would support the development of both agroforestry and plantation forestry, and would introduce support for wood marketing associations and wood utilization industries (Commission of European Communities 1986).

iv. In the EC, 45% of the fuel used is imported, and pressures are developing to subsidize the production of alcohols, or other biofuels, from energy plantations.

14.3 Bioenergy

In their summary of the potential for wood as fuel in the UK, the Department of Energy (Price & Mitchell 1985) predicts that 0.65 million tonnes coal equivalent (Mtce) could be raised from existing wood residues by the end of the century. If supplemented by wood energy plantations, this contribution could rise to 1.0 Mtce for industrial markets and 2.8 Mtce for the domestic sector. A doubling of energy prices would increase the availability of fuelwood three- to four-fold. The maximum predicted contribution at these increased prices would be around 13 Mtce, and this figure represents around 4% of total energy consumption in the UK, or 12% of the current consumption of coal. A study has been made of the land in Great Britain which could be available for energy forestry (Department of Energy 1987). This study suggested that up to 4.6 Mha could (at 1977 prices) be used profitably for energy coppicing, or for the enhanced used of residues from a modified form of single-stem forestry.

The major impediment to increased utilization of wood fuel is not the cost of production, but the fact that the bulk of wood residues is produced too far away from the heavily populated areas which sustain the best prices. There is considerable need for an economic comparison of the profitability of biomass plantations with conventional forestry and agriculture, where the conventional land uses have been stripped of the complex structure of planting grants, price support and tax relief.

Even without subsidies, energy coppices of fast-growing hardwoods like willow (*Salix* spp.) and poplar can be a profitable use of marginal agricultural land, provided that secure markets have been established (Scott *et al.* 1986). The best UK study of energy coppice comes from Northern Ireland, in conjunction with the Long Ashton Research Station (McElroy & Dawson 1986). Annual yields of 12–15 t ha^{-1} have been achieved over a nine-year rotation using a particular clone of willow (*Salix* 'Aquatica gigantea'). The experiments were conducted on surface mineral gley soils, which are marginal for agriculture. Three points are of particular note:

i. the costs of fertilizer additions were incompletely met by revenue from the resulting small increases in yield (up to 20%);

ii. the annual energy output from coppiced willow was 136 GJ ha^{-1}, compared with a net energy output from grass on comparable beef-producing land of 40 GJ ha^{-1};

iii. this variety of willow has recently been severely damaged by a rust fungus, illustrating the danger of an over-reliance on individual clones.

The Forestry Commission has also established energy coppice trials in different parts of the country ranging from the Cambridgeshire Fens to a gleyed site at 250 m OD in Scotland. Poplar and willow are confirmed as the most reliable producers, whilst establishment problems have been experienced with alder, and frost or disease problems are apparent for southern beech and *Eucalyptus* (Booth 1988).

Aberdeen University has established 11 trial single-stem plantations at 1 m × 1 m spacing in different parts of the country. Ten tree species have been planted, and the economic harvesting period should be around 20–30 years. Aberdeen University is also engaged in two large-scale (2 ha) coppice trials, with the intention of establishing 'production level' yields and management costs (Mitchell 1987).

Whilst very dense plantations offer the shortest rotations, they also maximize planting costs. Recent opinion, therefore, favours planting at lesser densities (3000–4000 stems ha^{-1}) for short-rotation forestry (Zsuffa & Barkley 1985). Others argue that, rather than establishing dedicated energy plantations, we should use more plantations at conventional spacing, and harvest the residues for energy. Prevosto (1979) compared the economics of conventional and close-spaced poplar, and concluded that spacings of 5–6 m were clearly more profitable because of the higher proportions of sawn wood and veneer wood which they contain, despite the fact that they produce less wood in total and at longer rotations. This conclusion seems likely to pertain also in lowland Britain.

Where conditions are suitable for productive energy coppice, it is likely that greater profits would be made using suitable timber trees. Hardwoods such as southern beech, poplar, *Eucalyptus*, red alder (*Alnus rubra*), ash, cherry (*Prunus* spp.) and sycamore can grow extremely rapidly in suitable habitats. Many conifers, such as Douglas fir, will also perform well in lowland soils, and the economics of using good land to produce wood for burning must be questioned.

Fortunately, it is possible to combine energy and timber cropping on the same unit of land. Like most good ideas it is not new, and involves a rediscovery of the coppice-with-standards system. Selected specimens of light-demanding and open-canopied trees, like ash, southern beech or poplar, would be established at wide spacing and underplanted with shade-bearing trees like hazel (*Corylus avellana*) or shrubs like *Rhododendron* (Lawson 1987). These would be coppiced regularly, and lower branches from the timber trees would be high-pruned at the same time. Whilst the species mentioned and the intensity of management will not replace the environmental diversity of old coppice, many of the disadvantages of monocultures discussed in the next section will be avoided.

14.4 Environment

Species diversity

Agroforests are likely to be more diverse in structure and species than monocultures (Callaghan *et al.* 1986). This is true in the case of animals and plants, and it also applies to the less obvious microflora and microfauna. However, tree monocultures can have biologically rich phases, and young forest plantations, which are protected from grazing, will support a larger population of small mammals and predatory birds than will silvopastoral mixtures of Sitka spruce (*Picea sitchensis*) and rye-grass (*Lolium perenne*).

Species of open-ground birds will certainly be discouraged by any extensive tree planting. Golden plover (*Pluvialis apricaria*), red grouse (*Lagopus lagopus scoticus*), dunlin (*Calidris alpina*), snipe (*Gallinago gallinago*), curlew (*Numenius arquata*), meadow-pipit (*Anthus pratensis*), ringed plover (*Charadrius hiaticula*), lapwing (*Vanellus vanellus*), wheatear (*Oenanthe oenanthe*), stone curlew (*Burhinus oedicnemus*) and skylark

(*Alauda arvensis*) are likely to be in this category (Reed 1982). A larger list of birds benefit from pre-thicket stage plantations: these include the willow warbler (*Phylloscopus trochilis*), grasshopper warbler (*Locustella naevia*), chaffinch (*Fringilla coelebs*), whinchat (*Saxicola rubetra*), stonechat (*Saxicola torquata*), woodlark (*Lullula arborea*), tree pipit (*Anthus trivialis*), whitethroat (*Sylvia communis*) and black grouse (*Lyrurus tetrix*). Mammals also benefit considerably from the diversity within an open woodland (Staines 1986). It is unlikely that heavily grazed silvopastoral systems will provide great benefit to some of these species. Nevertheless, the open structure of an agroforest will duplicate many of the advantages of an immature woodland. For example, the nesting and brooding sites for many bird species are likely to be brought closer together. Certainly, the inhospitable conditions of a thicket-stage plantation will be avoided, and it is thought that silvopastoralism will be of net benefit to a wide variety of wildlife. The benefit of silvoarable systems is clearer, because not only will the two main crops be juxtaposed, but the uncultivated ground within rows of trees will provide an additional habitat.

In the absence of any experimental evidence about the wildlife implication of agroforestry, we must draw parallels from existing evidence in agriculture and forestry. Using bird populations as an indicator of habitat 'richness', it is clear that a greater diversity of agricultural crops increases wildlife interest (Figure 4a), and more diverse woodland structures cause similar increases in numbers of species (Figure 4b). Agroforestry should, therefore, aim towards diverse mixtures of crop types and structures.

Pests and pathogens

Species diversity will often lead to a greater resistance to disease and predation. The western spruce budworm (*Christoneura fumiferana*) causes severe damage to monocultures of balsam fir (*Abies balsamifera*) and Douglas fir, but has much less effect on mixtures (Fauss & Pierce 1969). Similarly, pine looper moth (*Bupalis piniaris*) has been reported to cause much less damage in mixed stands of oak (*Quercus* spp.) and Scots pine (*Pinus sylvestris*), than it does in pure pine stands. The pure stands are thought to have fewer parasites and other checks on the looper moth (Niemeyer 1986).

However, tree mixtures are not always healthier than monocultures. The spruce gall aphid (*Adelges cooleyi*)

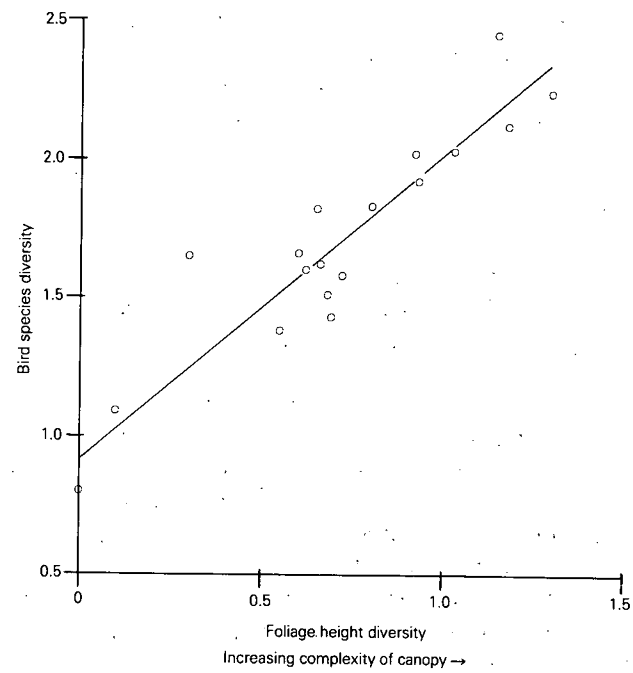

Figure 4a. Relationship between bird species diversity and foliage height diversity when examining a variety of mature woods with broadleaved or coniferous species or mixtures (Newton & Moss 1981)

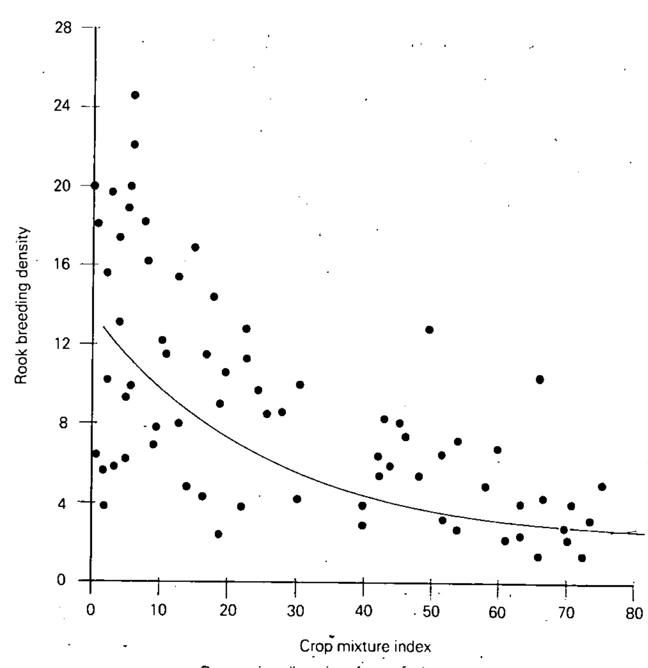

Figure 4b. Relationship between rook breeding density and an index of crop diversity (lower index values have higher diversity – Brenchley 1984)

alternates its life cycle between Douglas fir and spruce. The presence of both species can lead to significant damage to the spruce. Similarly, the rust fungus *Melampsora pinitorqua* alternates its life cycle between pine and aspen (*Populus tremula*), and causes significant damage to pines in mixed stands (Savill & Evans 1986).

The presence of lines of trees will make crop spraying more difficult. However, row spacings can be selected to match existing farm machinery; for example, a 14 m spacing permits conventional 12 m booms and 4 m combine harvesters to be used. Useful research is proceeding in MAFF's Boxworth project, and elsewhere, to quantify the environmental effects and costs of different levels of pesticide application (Hardy 1986). Less intensive management of cereals may be justified by the possibility that pesticides may cause further infestations by reducing the population of predatory bugs and mites (Chaboussou 1986). Hedgerows and field boundaries are the overwintering sites for these predatory insects, and similar habitats are available in agroforests. Seed-eating birds will thrive in close mixtures of trees and crops, but it is likely that cereals will be grown only during the first four to five years of a silvoarable rotation. Insectivorous birds will also benefit from the proximity of trees.

In summary, therefore, the difficulties of applying herbicides and pesticides will certainly reduce the profitability of arable farming, but increases in the populations of insectivorous birds and predatory insects may counteract some of the losses. Silvoarable systems are a natural accompaniment to organic farming, and there is ample opportunity for research on the effects of different agricultural practices on wildlife and on the growth of trees.

Conservation of nutrients

In both silvopastoral and silvoarable systems, the tree component is unlikely to experience a shortage of nutrients. Indeed, it is possible that the high levels of nitrogen applied routinely to reseeded grassland may induce over-rapid growth in some tree species, and lead to a loss of timber strength. Loss of form caused the abandonment of early trials of widely spaced and heavily fertilized trees in Northern Ireland (J H McAdam pers. comm.). The nature and timing of fertilizer applications in agroforests are, therefore, an important topic for research.

Given normal agricultural levels of fertilizer application, and accepting that good agroforest species of tree will root more deeply than the herbaceous intercrops, it appears unlikely that competition for nutrients will be as serious as initial competition for moisture and developing competition for light.

It is possible that some trees may increase the fertility of extensively managed grassland because the roots of most tree species will penetrate to depths which are not accessible to ground vegetation; this is a major criterion in the selection of suitable agroforestry species. Pines, Douglas fir, silver fir (*Abies alba*), oak and sycamore (*Acer pseudoplatanus*) are particularly deep rooting, whereas noble fir (*Abies nobilis*), spruces, western hemlock (*Tsuga heterophylla*) and beech (*Fagus sylvatica*) root near the surface. Deep and widespread tree roots, in both silvoarable and silvopastoral systems, will intercept a proportion of the fertilizer lost to an herbaceous crop. This interception could significantly reduce eutrophication problems in watercourses. More than 50% of the nitrogen applied to pastures in Britain is estimated to be lost through leaching or denitrification, and phosphorus losses from arable areas are becoming increasingly apparent (Frissel 1978).

A significant advantage of energy mixtures, where the understorey is coppiced for fuelwood, may be the interaction between litter of different species. These interactions can speed the decomposition process and increase soil fertility. Birch (*Betula* spp.), for example, tends to develop a mull humus on many soils, with an increased pH, more exchangeable cations and an enhanced earthworm population (Miles 1986). Brown and Dighton (see page 65) have shown the nutritional benefit of growing trees in mixtures, particularly on sites where growth is limited by nitrogen.

Livestock grazing in silvopastoral systems can cause considerable damage to trees by browsing, bark-stripping, or trampling (Adams 1975). However, much of the damage is caused by stocking at excessive rates, planting on soils with impeded drainage which are particularly susceptible to compaction, or using inappropriate species like Sitka spruce which has superficial and easily damaged roots. Animals assist in the recycling of nutrients and often serve to maintain fertility on hill pasture (Floate 1970). However, silvopastoral shelter strips established in larger fields may encourage the excessive congregation of stock, and could suffer damage which would not occur if the whole field were planted with wide-spaced trees.

Hornung and Adamson (see page 57) have shown that clearfelling of forests can cause a significant loss of nutrients in runoff. It also leads to denitrification, ie loss of nitrogen to the atmosphere. Denitrification is favoured by the wet, anaerobic conditions which develop in British uplands following felling, and annual losses of approximately 10 kg N ha^{-1} have recently been measured in Kershope Forest (P Ineson pers. comm.). The felling of agroforests, or the removal of standards in energy coppices, is unlikely to cause any significant loss of nutrients because the roots of the associated species will take up any excess nutrients.

Finally, the prospects for nitrogen-fixing mixtures should be mentioned. Suitable species of alder, or perhaps false acacia (*Robinia pseudoacacia*) in the south of England, could be grown in row mixtures with crops, and could provide a saving in nitrogen fertilizers. Alder coppice is of proven benefit to intermixed broadleaves such as poplar (de Bell & Radwan 1979). Tree lupin (*Lupinus arboreus*) has been used as a nitrogen-fixing nurse for conifers and broadleaves (Marrs *et al.* 1982). Gorse (*Ulex europaeus*) has been recorded to fix more than 70 kg N ha^{-1} yr^{-1} on mining wastes in Cornwall (Dancer, Handley & Bradshaw 1977). Sea buckthorn (*Hippophaë rhamnoides*) and broom (*Cytisus scoparius*) are other nitrogen-fixing possibilities for use in mixture with wide-spaced timber trees.

Soil and water conservation

Of the arable land in England and Wales, 37% is considered susceptible to erosion. To this percentage must be added 7% of upland grazing land. Mean annual rates of soil erosion in fields on hill slopes up to 11 degrees can exceed 2 kg m^{-2}, and rates as high as 1.9 kg m^{-2} have been recorded for individual storms. Where gullying occurs, erosion rates can be much higher, and future arable production is seriously at risk in many parts of the country (Morgan 1985). Trees have a soil conservation role in arable areas which is widely recognized on the Continent. Road, rail and stream margins are often planted with poplars, and 15% of timber production in the Netherlands is gained from such 'linear features' (A Willems pers. comm.). Until recently, line plantings contributed 10% of the total timber production in Italy (Prevosto 1979).

Cumulative shelter is an important attribute of a landscape well-populated by trees, and can be expected as an eventual benefit of widespread agroforestry. Jensen (1954) demonstrated, for example, that the varied topography in central Jutland, with shelterwoods and hedgerows, produces more than twice the reduction in windspeed measured in similar winds blowing across the more featureless landscape in south Jutland.

Soil erosion is associated with the clearfelling of forests and is exacerbated by modern techniques of whole-tree harvesting, which may also cause excessive removal of nutrients and soil acidification (Malkonen 1976). Agroforests will retain a cover of ground vegetation at time of harvest, thereby reducing erosion. Indeed, this is one of the prime reasons for their increasing use in Australia and New Zealand (Reid & Wilson 1985). Tree canopies also limit erosion and the leaching of nutrients by reducing the quantity and intensity of rainfall reaching the ground.

The effect of afforestation on reservoir catchments has been accepted as a problem ever since Law (1956) calculated, in an area receiving 990 mm rainfall annually, that the annual moisture loss from a forest plantation was 290 mm greater than that from grassland. This increased loss is caused by the high interception of rainfall, and subsequent evaporation, from the dense canopies of many conifers. Law subsequently calculated that the water industry lost £500 ha^{-1} yr^{-1} from the afforested parts of a reservoir catchment. A sparse canopy of pruned trees at 10 m spacings will obviously intercept less rainfall than a conventional plantation, and may reduce evaporation from the pasture by providing shelter. It is uncertain, however, whether current models are good enough to predict the scale of this reduction, and experimental studies are needed on catchments with trees planted at agroforestry spacing. The possible hydrological advantage of agroforestry may be an important factor in those catchments which are used for water supply.

Local climate

The effects of a tree canopy on local climate are to:

i. intercept and redirect rainwater, thereby ameliorating excesses and shortages of moisture;

ii. reduce the quantity, and alter the quality, of light reaching the ground;

iii. insulate the field layer and reduce temperature extremes;

iv. reduce windspeed and possible mechanical damage to crops.

These effects on moisture, light and temperature at the ground surface will, in turn, influence the growth of plants and the performance of animals. However, the effect of shelter on the yield of agricultural crops and grasses is still not fully explained, despite many decades of research and speculation. Dramatic increases in crop yield have been reported from windswept continental climates (see reviews of van Eimern *et al.* 1964; Marshall 1967; Sturrock 1984). However, the effects are more moderate in cool oceanic climates. Increases in soil moisture content due to shelter are normally of little importance in the wetter parts of Britain, but higher daytime temperatures in spring can produce a useful 'early bite' of grass growth (Alcock 1969). Seasonal variation makes it difficult to draw conclusions. Alcock, Harvey and Tindsley (1976), working in Wales, found that shelter increased the yield of rye-grass by more than 50% at the end of June, but that there was no effect of shelter at the end of July. In contrast, Russell and Grace (1979) found no effect of shelter on the dry matter production of rye-grass in spring, but recorded a 28% increase during the summer regrowth period. Crop yields in western Britain are likely to benefit less from shelter than in the east. Significant moisture stress commonly develops up to 360–450 m OD in eastern hills (Grant & King 1969), and the shade of deeply rooting trees will be a factor in reducing evaporation.

Several useful attempts have been made to model the effect of trees on crop growth (eg McMurtie & Wolf 1983), but anomalies exist within the literature on shelter effects and highlight the need for practical experimentation in agroforestry. It is even more complicated to predict the multiple consequences of shelter, shade, and competition for moisture and nutrients.

Shelter has a well-established benefit for stock, and this can be crucial during lambing time in the hills and uplands. Although it is possible to establish the metabolic saving to animals due to shelter from the sun (Priestley 1957) or wind (Grace & Easterbee 1979), the possible increases in lambing percentages and live weight gain have not yet been included in any economic models of agroforestry.

14.5 Employment and enjoyment

Whitby (see page 31) has discussed the impact of afforestation on rural employment and has concluded that, where conifer forests replace agriculture, there will be a net loss of jobs over the length of a forest rotation on all but the least intensive of upland agriculture. This conclusion should be contrasted with the analysis of Mutch and Hutchinson (1980), where the establishment of farm forestry on 17 000 ha of hill land caused the numbers of full-time farm employees to decrease from 35.5 to 32, whilst forestry jobs increased from 1.5 to 28. Experience from other countries (eg Prevosto 1976) confirms that agroforestry will largely sustain the agricultural labour force, whilst also creating jobs in forestry and related industries. It is an advantage that farmers and farm workers can use slack time on the farm to manage trees. Agroforestry requires the careful control of stock and cultivation methods. These skills are labour intensive, and will demand enthusiasm for both farming and forestry.

It is harder to predict the consequences for the landscape of widely spaced planting. Neat arrays of pruned clonal conifers could be as oppressive as dense plantations, but agroforestry requires careful management, and it is unlikely to proceed on the scale of plantation forestry. Broadleaved trees can only improve the arable landscape, even in the regular rows used in many parts of Europe.

14.6 Conclusion

The likely advantages and disadvantages of agroforestry are presented in Appendix I. However, many, if not most, of the assumptions in this Appendix require substantiation by further research. It is encouraging, therefore, to report that a co-ordinated programme of research is now under way linking the Agricultural and Food Research Council, the Natural Environment Research Council, the Department of Agriculture for Northern Ireland, and a number of universities.

It is noticeable that temperate agroforestry has been most successful in New Zealand, a country with no state subsidy for agriculture or forestry. The subsidies available in Britain for conventional agriculture or forestry make it difficult for agroforestry to guarantee a comparable financial return.

It will be unfortunate if a grant system in favour of conventional timber species, traditional spacings, and of block sizes exceeding one ha, precludes the options for farmers to integrate arboriculture more closely with cropping or grazing. This presumption also misses an excellent opportunity to encourage the recreation of parklands (Plate 6) and fails to recognize that trees outside the forest, which are properly looked after, can make a valuable multiple contribution to timber production, to the farm enterprise, and to conservation.

Appendix 1. The possible effects of agroforestry compared with intensive forestry or agriculture

	Yield	Environment	Economics
Advantages	Longer canopy duration Efficient canopy architecture Use of moisture and nutrients at different depths Lessening of climatic extremes Disease less damaging in mixtures Crop fertilizers increase tree yields Wide-spaced trees grow faster Mutual effects of species on nutrient mobilization	More diverse species + structure Less leaching and eutrophication Less wind and water erosion Reduced nutrient loss after felling Less fire risk than forestry Less intensive use of pesticides and herbicides Preservation of rural employment	Several saleable crops More regular revenue than forestry Shared infrastructure costs Less spasmodic use of labour Supplementary sporting income Tree component can be stored to await favourable prices Silvopastoral systems have lower evaporative losses than forestry Wide-spaced trees more windfirm Shelter and shade increase animal production
Disadvantages	Difficult to predict yields in long term Fertility reduced by multiple harvests	Uniform tree rows unattractive Some suggested energy crops are invasive weeds	Silvopastoral fertilizer use may damage timber structure Pesticide applications more difficult Less regular revenue than farming Soil and tree damage by animals Less flexible than farming Dispersed production means high transport costs for wood fuel Greater evaporative losses than farming Greater management effort Cultivation difficult in second rotation

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