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Agroforestry in Scotland – potential benefits in a changing climate

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Summary

The Scottish Government has set statutory targets for the reduction of GHG emissions in Scotland through the Climate Change (Scotland) Act 2009. One of the ways in which it aims to meet this target is through increased woodland cover from around 18% to 21% by 2032 (Scottish Government, Climate Change Plan, 2018, p18). Increased use of agroforestry in Scotland is one option that could help achieve these targets, while also supporting sustainable adaptation to a changing climate.

This report identifies the potential benefits of increasing the use of agroforestry practice in Scotland to both farmers and wider society and aims to support wider discussion and implementation.

Agro-forestry is the integrated use of trees on a Farm or small holding for a wide range of benefits. Where livestock are included, it is called silvo-pastoral; where crops are involved it is called silvo-arable.

Key Findings

- Agro-forestry takes many forms that include shelterbelts, wide spaced trees, groups of trees, hedgerows and woodland grazing.
- Agro-forestry can improve a farm's resilience to a changing climate by providing shelter to animals and crops, reducing feed costs, reducing risk of flooding, improving animal welfare, potentially reducing crop pests by housing beneficiary predators, reducing soil erosion and moisture extremes, and diversifying farm income.
- All forms of agroforestry have the potential to sequester carbon (C), although the benefits will vary depending on soil type, species, planting density and location. Evidence suggests that maximum C-sequestration benefits on a per-hectare-basis might be achieved on the highly productive lowland areas, although potentially at a high agricultural opportunity cost. Scotland-wide, significant benefits are also possible on the less productive lands, by avoiding disturbance of organic soil layers.
- There is a lack of quantitative information on the extent of (and trends in) agroforestry in Scotland. Filling this evidence gap would provide a benchmark against which to judge future developments in Scottish agroforestry.
- Woodlands in agricultural landscapes diversify wildlife habitats and can increase connectivity, which is argued to enhance biodiversity resilience in the face of climate change. This assumes good woodland management practices, including the management of deer pressure.

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Content

1 Introduction

The Scottish Government has ambitious woodland creation targets to contribute towards reducing net greenhouse gas (GHG) emissions as required by the Climate Change (Scotland) Act 2009. The current aim is that “By 2032, Scotland’s woodland cover will increase from around 18% to 21% of the Scottish Land Area” (Scottish Government, Climate Change Plan, 2018, p.18). Agroforestry is one possible option that could help reach these GHG emission reduction and woodland cover targets.

Agroforestry can facilitate climate change mitigation for agricultural land holdings through carbon capture (sequestration and reductions of net GHG emissions) (Briner et al. 2012; Beckhert et al. 2016), and also support climate change adaptation through improved resilience of the farmed landscape (Smith et al. 2012, 2013; Valatin et al. 2016).

At present agroforestry land cover in the UK is very limited (Committee on Climate Change 2016, p. 193), however, forms of agroforestry - for example, woodland grazing by farmed ruminants - have been taking place in Scotland for many hundreds of years (Sibbald 2006; Stewart, 2003, p96). -Stewart (2003) observed that while there is little documentary evidence on grazing in unenclosed upland woodlands, the practice historically was widespread. She notes (p100) that: “concessions were made to accommodate the needs of livestock even in woods which had been fenced off. For example, cattle or sheep might be allowed back into the wood five or six years after it was cut and enclosed.” This implies there was both a degree of regulation and recognition of the synergistic benefits of agroforestry.

Against this background, this report identifies the main agroforestry options that are currently applicable to Scotland. The benefits and challenges of each of the identified options are compared qualitatively, considering climate change mitigation and adaptation potential, wider benefits, monitoring metrics, market readiness and practicality of deployment in Scotland. The main options are also compared quantitatively for their potential carbon sequestration benefits, by using specified plant densities and species, and assessing suitable areas of different land capability classes. The focus is on identifying the practical benefits of agroforestry in helping the Scottish Government achieve its GHG emissions and woodland expansion targets whilst simultaneously making Scottish agriculture more sustainable and resilient to climate change.

2 What do we mean by agroforestry?

Agroforestry is a farm system that can be defined:

- Strictly as the combination of forestry and agricultural land uses *within the same plot of land*; or.
- More broadly as land-use where woody plants are grown with crops and/or animals *in neighbouring plots within the same proprietor unit* and where there are significant ecological and economic interactions between the two components (Hislop and Claridge 2000).

The latter definition therefore includes woodlands planted with the intention of sheltering stock or crops in neighbouring plots of land (i.e. trees and agriculture within the same land unit), and **it is this wider definition that is adopted here.** We have not considered other farm woodland uses that do not involve crops or livestock.

The two main agroforestry systems are:

- ***Silvo-pastoral*** – a farm system in which trees and/or shrubs are grown in grazed pasture and where planting patterns can be more varied; and
- ***Silvo-arable*** – a farm system in which crops are grown between rows of trees and/or shrubs at a spacing appropriate for the use of agricultural machinery.

Within the two main agroforestry systems, there are many options for combining woody plants and crops/animals in different spatial arrangements. The most relevant options are as follows (Figure 1):

- ***windbreaks*** and ***riparian buffer strips*** made of trees or shrubs, both of which are a type of **shelterbelt** and can be applied to both silvo-arable and silvo-pastoral systems;
- ***rows*** of trees or shrubs that are also applicable to both systems;
- ***single trees*** or ***tree cluster*** arrangements, best applied only to silvo-pastoral systems. The type of trees planted and their density and arrangement will depend on farmer's choice and farm types and objectives.

We used these different spatial arrangements as the basis for the analysis of 'agroforestry options' in this report.

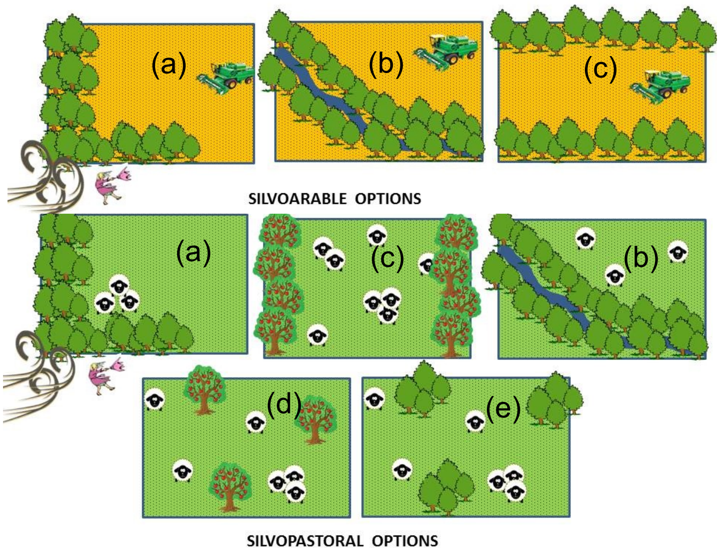

FIGURE 1: Agroforestry Options identified for Scotland: a) windbreaks, b) riparian buffer strips, c) rows, d) single tree, e) tree clusters.

3 The main agroforestry options applicable to Scotland

- There is a lack of evidence on the extent of agroforestry in Scotland, resulting in mostly qualitative assessments based largely on expert knowledge and judgement.
- The major agroforestry system currently practiced in Scotland is silvo-pastoral, in the form of woodland grazing, shelterbelts and buffer strips.
- Silvo-pastoral systems can exist in uplands and lowlands.
- Current silvo-pastoral systems tend to be unplanned consequences of land management adaptations.
- Silvo-arable agroforestry is very limited in extent, but can be found where significant wind erosion of soils occurs.
- Alternative options found in other parts of UK, may be suitable for Scotland in future climates.

Across the UK, only 3.25% (549,600 ha) of total agricultural land is under agroforestry use, with almost all of it in silvo-pastoral systems (der Herder et al. 2015). Silvo-arable systems are rare in UK (2,000 ha), with most found in England and Wales (Smith 2014; RSFS, 2012).

There is no *de facto* account of the extent of agroforestry in Scotland. However, based on the major agricultural types, we can deduce that the most likely examples found in Scotland are to be silvo-pastoral. Agriculture in Scotland is largely pastoral, with 80% of the 6.24 Mha agricultural land area either grazed or growing grass for silage or hay or growing other fodder for sheep and cattle (Scottish Government, 2016). In comparison, arable systems account for only 9% of the total agricultural land area and are constrained to specific localities (see Appendix 1, Fig. A1). Based on this information alone, it follows that the majority of current agroforestry in Scotland will - as estimated for the UK as a whole - be silvo-pastoral. Assuming this to be the case, the following silvo-pastoral system types are relevant:

- Silvo-pastoral systems in uplands: Where new woodlands are protected from stock and existing woodlands are open for grazing
- Silvo-pastoral systems in lowlands: Where new woodlands are protected from stock and existing woodlands are open for grazing
- Silvo-pastoral shelter belts (where trees are fenced off from stock)
- Silvo-pastoral buffer strip planting (including riparian buffers)
- Wide spaced trees with robust individual tree protection (limited to lowland areas as they do not provide the shelter necessary in the uplands)

Again, drawing on expert judgement and knowledge of the Scottish agricultural sector, the main silvo-arable system types suitable for Scotland are:

- Silvo-arable alley cropping
- Silvo-arable shelter belts
- Silvo-arable buffer strip planting (including riparian buffers)

The following gives an overview of the different systems in Scotland, while each of the options is described in more depth in Appendix 2.

1. Silvo-pastoral systems in upland and lowland Scotland

Most of the woodland pasture systems in Scotland are in the hill and upland areas, but they also have a place in lowland areas on mixed farms (Cook et al., 2015). Importantly, expert opinion suggests such areas are typically not planned agroforestry systems, but are adaptations of land management to particular bundles of land resources, where forest and farming are intermingled, rather than having a hard boundary. Typically farmers allow seasonal grazing of stock within partly wooded areas, however in some cases, ruminants are allowed access to woodland areas throughout the year. Calving may even take place in woodlands, where shelter can be beneficial.

Agricultural census data shows an apparent increase of 71% in Scottish farm woodland between 2007 and 2014, while grant aided woodland increased by only 10%. This suggests that since 2007, when the opportunity to include grazed open woodland as a recognised land use was first introduced, there has been a recognition of the benefit of the shelter and other services derived from farm woodland by land managers.

The planting of woodlands in shelter belts, to protect animals on adjacent parcels of land (as opposed to the integrated woodland pasture systems described above) appears common in many parts of Scotland (Cook et al., 2015). Whilst no statistical or census data has been completed, to date, for Scotland, the widespread occurrence of shelter belts is testament to their value in mainstream livestock systems, particularly for the upland fringe intensive livestock areas. These include Moray, Easter Ross, the Black Isle, the Borders and Fife in eastern Scotland. There is clear synergy between farm and forest systems, whereby animal maintenance requirements are reduced due to forest sheltering (SRUC 2011)

There is also evidence of farmers in Scotland using woodlands as a component of outdoor pig enterprise, or for outdoor poultry rearing (Brownlow et al., 2000). Here benefits include enhanced welfare of pigs and poultry for behavioural reasons, warmth and comfort.

2. Silvo-arable systems in Scotland

As noted above, the overall extent of silvo-arable agroforestry systems in Scotland is currently limited, although tree planting for sheltering crops does occur in some areas where there are significant problems of wind erosion of soils (e.g. Fort Farm, Fife). In particular, the primary area where such planting can be observed is the sandy and alluvial soils of the Moray Firth, where wind storms can have a major impact.

Case study examples of agroforestry systems in Scotland

The dominant source of agroforestry case studies available for review were those listed on the Forest Commission (FC) Scotland website (n=10), while others were from personal observations (see Appendix 4 for details). Based on these studies, we can say there is evidence that the main form of agroforestry practiced in Scotland are silvo-pastoral systems. The majority of the agroforestry activities are with sheep or beef suckler herds, which have been applied across a variety of land quality (LCA classes) and elevation gradients. Only two case studies presented a form of silvo-arable agroforestry, growing trees around arable fields as borders on part of the farmland (FC Scotland, 2013; Table A4.1).

Case study examples of agroforestry options practiced in other parts of UK, applicable to Scotland

We found additional agroforestry options practiced in other parts of UK which may be suitable to try in Scotland. For example:

- The use of cluster planting in Wales to reduce runoff, by improving infiltration and interception of peak flow events in flood prone areas (Lunka & Patil, 2016).
- While arguably not strictly an agroforestry option, hedgerows and field boundary trees are also valuable landscape and ecological features present throughout UK.
- Silvo-arable examples exist in England, and these may also have future potential in Scotland, particularly as climate changes. A comprehensive example is Wakelyns Farm, in Suffolk, England, where rows of short rotation coppice (with willow or hazel), fruit or timber trees form 10-20-m-wide alleys grown with wheat, barley, oats, oil seed rape and vegetables (Smith et al., 2014 & 2017).
- UK trials with walnut and sweet chestnut have been reported for fertile sheltered sites in southern England (Clark et al., 2008). In parts of Scotland such trees can produce fruit, but are strictly site limited.

Farms in more sheltered areas in Scotland might also consider growing fruit trees, such as apples, to either supplement farm income by harvesting and selling the fruit, or supplementing fodder for their grazing animals. In Scotland, fruit orchards are viable on low exposure sites with good soils, low frost risk and good rainfall (central and south), with remnant orchards prevalent, for example, in the Clyde Valley, and Carse of Gowrie. Grazing of mature orchards is possible for periods in each season (outside harvesting activity, thereby avoiding e-coli risk), but new orchards will require livestock exclusion during tree establishment. While the current extent of orchards in Scotland is a tiny fraction of the 6.24 Mha of agricultural land (i.e. only 714 ha, Scottish Government, 2018), past records indicate somewhat greater coverage (SNH PP786, 2014), suggesting this agroforestry option may be horticulturally possible should market conditions allow.

4 What are the benefits of agroforestry?

There is good documented evidence that each type of agroforestry has the potential to increase farm business adaptation and resilience to climate impacts, as well as having potential climate change mitigation benefits (Saunders et al. 2013). The various potential benefits of agroforestry in terms of their adaptation and mitigation potential, which we found in the literature, are summarised in Table 1 and discussed in the subsections below.

In summary, the case studies cited in Scotland, highlighted the farm benefits from the agroforestry managers perspective, which included:

- improved animal welfare
- improved ecological condition, especially of soils and water courses
- reduced pest load due to natural predation
- the 'legacy' effect of leaving land in a better ecological state for the next generation.

In addition several individuals have embarked upon biomass heating schemes, for homes or agricultural purposes (e.g. grain drying), which has brought additional value and benefit from the woodland resource on the land holding. Trees are also recognised by owners to improve the visual landscape.

Additional overall benefits of agroforestry we identified in literature, included:

- Carbon capture
- Nutrient retention and nutrient cycling
- Landscape (woodland) connectivity and biodiversity improvement
- Cost savings
- Income generation

By developing structural diversity within the farmed landscape, agroforestry more closely resembles a natural system and has benefits in terms of adaption potential for resilience to future climate variation through diversification. Structural and species diversity in tree choice are also proposed to provide resilience in the face of future pest and disease. These resilience measures not only reflect a more ecologically robust landscape but also more economically robust land management units.

TABLE 1. Summary of the adaptation and mitigation benefits of the main agroforestry systems to farming.

Type of Benefit	Silvo-pastoral systems	Silvo-arable Systems	Climate benefit [A] = Adaption [M] = Mitigation
Provision of shelter for outdoor livestock	X		[A] improved energetics & welfare
Additional fodder source for grazing animals	X		[A] reduced supplementary feed [M] reduced GHG associated with feed production
Reduced ammonia and nitrogen emissions from housed and/or free-range animal production facilities	X		[M] reduced GHG emission

Type of Benefit	Silvo-pastoral systems	Silvo-arable Systems	Climate benefit [A] = Adaption [M] = Mitigation
Reduced wind speeds over arable areas		X	[A] improved yield, lower water use
Reduced soil erosion	X	X	[M] improved soil C stock [A] resilient soil systems
Improved soil fertility through litterfall and the use of nitrogen-fixing species	X	X	[M] reduced fertiliser
Increased soil carbon stocks	X	X	[M] carbon sequestration
Reduced agricultural run-off into watercourses	X	X	[A] reduced pollution
Reduced flood and drought risk	X	X	[A] improved resilience
Lower evapotranspiration	X	X	[A]reduced irrigation
Increased farm biodiversity	X	X	[A] improved biological resilience, pest control
Income diversification (through for example game shooting)	X	X	[A] income diversification
Provision of timber for fuel wood	X	X	[M] reduce fuel cost

1. Benefits of woodlands and shelterbelts in animal welfare and reduction in soil erosion

Caborn (1957) has detailed the benefits of woodland shelters to farmers in terms of mitigating adverse effects of climate. The use of woodland pastures provides two primary benefits to the farmer. First, it allows for out-wintering of hardy ruminant stock and therefore 'protects' the better quality pasture or in-bye[1] land, for the 'early bite' (first spring grazing) or for silage cropping; in upland areas the amount of land for fodder or lambing pasture is often a limiting factor. Second, it reduces maintenance requirements of livestock considerably, because the shelter reduces chilling. The shade can also reduce heat stress during hot weather, which is becoming a higher risk (CCRA 2017, Chap. 3, p.63). Additionally managed grazing can retain understorey and allow the dominant trees to develop and maintain the open woodland. In lowland areas, the key farming benefit of woodland pasture is to free-up the very best quality land for high value crops, lambing pastures or silage production.

Replanting of existing shelterbelts, which have become "gappy", would provide multiple benefits with much reduced costs. On the western hills in Scotland, extensive productive conifer plantations are more common, whilst semi-natural woodland remnants provide rough-grazing silvopastoralism, delivering a similar farm livestock protection function. At appropriate stocking densities, shelterbelts can attract carbon payments under the UK Woodland Carbon Code.

In the case of silvoarable systems, tree planting can reduce the wind speed to below critical speeds and reduce soil erosion, and be an integral part of soil conservation management where topsoil loss is a concern. Based on this review we identify that additional information on the soil conservation benefits of shelterbelt forestry is required.

Finally, while arguably not strictly an agroforestry option, hedgerows and field boundary trees are also valuable landscape and ecological features. While they sequester relatively small amounts of carbon per hectare, hedgerows afford many of the farm benefits provided by shelter belts at a smaller scale, in particular shelter and stock control. They are a significantly increasing landscape features in many areas of Scotland, as a result of many years of grant support. More analysis of the relative benefits of hedgerows to Scotland from a carbon-sequestration-perspective and the shelter and fodder value would be useful to inform our understanding of their climate mitigation potential in the country.

2. Climate adaptation and mitigation benefits, including carbon-sequestration potential

In relation to carbon, GHG and climate change mitigation, tree planting can provide carbon sequestration in both the tree biomass and the soil with the amount depending on the soil type, the tree species, planting density and the environmental conditions that determine the tree growth rate. Typical agroforestry management alternatives (AFMA) are defined in Table 2. Here, the appropriate management type and woodland function are matched to agricultural land class type (LCA Class) with commentary on the carbon sequestration (mitigation) and adaptation potential of these systems.

Planting trees on highly organic soils is not advised, because the disturbance of such soils usually leads to carbon losses in the long-term (Cannell et al, 1993). In wood pasture systems, modelling

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[1] 'In-bye' land is that part of the farm which is used mainly for arable and grassland production and which is not hill and rough grazings.

provides clear underpinning evidence that the absence of ploughing provides an additional means of protecting soil carbon from the carbon losses associated with occasional ploughing and reseeding of upland pastures. In addition, some evidence exists that woodlands used for shelter may result in reduced fodder requirements, therefore reducing crop production and fertiliser use and thus reduced GHG emissions.

New woodland can also provide quantifiable carbon sequestration in the woody biomass. Additional climate mitigation benefits are also accrued if that timber is used in products that replace fossil fuel intensive materials, such as steel in construction being replaced by engineered wood structural components, or biomass fuel in energy production. Robust evidence for these additional substitution benefits exists, but these additional benefits are not accounted for in this report.

TABLE 2. Typical Agroforestry Management Alternatives (AFMAs) that could be deployed with key Land Capability for Agriculture (LCA) classes in Scotland, for the purpose of C-sequestration and climate adaptation. The AFMAs are not exclusive, as some species and management types will be suitable for more than one LCA class, but are indicative.

LAND YIELD & PRODUCTIVITY	AGRICULTUTRAL LAND TYPE AGROFORESTRY TYPE [LCA CLASS]	PREDOMINANT AGROFORESTRY MANAGEMENT OPTION	LAND POTENTIAL TREE PRODUCTIVITY	CARBON SEQUESTRATION POTENTIAL (C Stock @ Year 40) [t C ha-1]	ADAPTATION POTENTIAL	PREDOMINANT MANAGEMENT FOCUS
LOW	Lowest Quality Rough Grazing Silvopastoral: “Sheep & Trees” [LCA 7.0]	Upland wood pasture (single trees or clusters) Native Scots pine woodland & Low productivity native broadleaf (AFMA 1) (AFMA2)	Extensive upland Poor Do not plant peat>50cm deep	Negative to Moderate [-6.2 to 45.6] Negative C stocks possible with organo-mineral soils	Diversification of low value (LFA) land. Flood amelioration. Improve soil quality. Forage. Improve husbandry.	Low intervention, long retention. Favour assisted natural colonisation & regeneration.
	Poor Quality Upland Silvopastoral: Rough Grazing “Sheep & Trees” [LCA 6.1 – 6.3]	Lowland wood pasture (single trees or clusters) Multipurpose Broadleaf & Multipurpose Conifer (AFMA 3) (AFMA4/5/7)	Extensive upland Moderate-Good	Negative to Moderate [-6.2 to 51.5] Negative C stocks possible with organo-mineral soils	Forage. Improve husbandry and animal welfare. Long-term managed woodland with woodfuel (bdlv) and timber element.	Long retention. Low impact silviculture. Planted woodland. Favour assisted broadleaf regeneration.
	Improved Grassland Silvopastoral: “Livestock & Trees” [LCA 5.1 – 5.3]	Shelter Belts for Livestock: Multipurpose Broadleaf & Productive Conifer (AFMA 3) (AFMA 7/8)	Intensive upland Moderate-Very Good	Low to Moderate [1.1 to 62.5]	Forage. Improve husbandry and animal welfare. Long-term managed woodland with woodfuel & quality timber element.	Long retention. Low impact silviculture Planted woodland. High quality hardwood.
	Mixed agriculture Silvopastoral: “Livestock & Trees” [LCA 3.2 – 4.2]	Buffer Strips or Shelter Belts for Livestock: Productive Broadleaf & Productive Conifer (AFMA 3/9) (AFMA 6/7)	Lowland Very Good – Excellent	Good [12.8 to 77.5]	Improve water quality, reduce run-off. Improved forage and animal welfare. Long-term woodland capable of growing quality timber.	Variable retention planted woodland. Coppice, woodfuel, structural timber. High quality hardwoods.
HIGH	Arable agriculture Silvoarable: “Crops & Trees” [LCA 2.0 – 3.1]	Rows and buffer strips for Arable Short Rotation Forestry, Productive conifer and broadleaves, silvo-arable planting (AFMA 9) (AFMA 7)	Lowland Very Good - Excellent	Good [12.8 to 77.5]	Reduced soil erosion. Reduced runoff. Potential N-addition with species like Alder. Resource capture (water, nutrients) with little root competition.	Short retention hardwood or conifer biomass. Mixed agriculture options (LCA 3.2-4.2) apply

3. Additional wider benefits

Agroforestry can increase the provision of several other ecosystem services:

- Woodlands in agricultural landscapes diversify wildlife habitats and can increase connectivity, which is argued to enhance biodiversity resilience in the face of climate change. This assumes good woodland management practices, including the management of deer pressure.
- Woodlands, if correctly sited, can also reduce flood risk by slowing run-off (Environment Agency 2017a, b). The presence of woodlands in wet areas or adjacent to watercourses is likely to reduce soil erosion and nutrient leaching into watercourses (Sweeney and Newbold, 2014; Environment Agency 2017a, b) and provide *de facto* buffer strips (FRMRC undated).
- Trees can improve local microclimate and, whilst they do compete for sunlight, the different rooting depths compared to fodder and arable crops enhances nutrient capture and recycling.
- Tree planting along water courses can also reduce water temperatures and maintain oxygenation during warm weather, benefitting fish and other aquatic organisms (Sweeney and Newbold, 2014).
- Finally, trees and woodlands can provide habitats for pest predators, and pollinators (Vanbergen et al., 2014). These roles may become more important as the climate changes (CCRA 2017, Chap. 3, p. 36).

In relation to amenity values, previous studies have suggested that treeless landscapes are widely viewed as less attractive than partially wooded landscapes and open woodlands are generally deemed more attractive than solid blocks of even-aged monocultures (Haines Young and Chopping, 1996 p.420ff). Not all types of agroforestry satisfy these preferences, especially mono-species shelterbelts, which can produce rather rectilinear feature. However, the legacy hardwood shelterbelts from the 19th century are very distinctive and highly valued features and their regeneration and recovery is considered highly desirable (Sheldon 1980).

5 The main challenges to wider adoption of agroforestry in Scotland

Several challenges and opportunities were identified in the literature to the wider adoption of agroforestry in Scotland. These included:

- practical barriers (including maintenance costs)
- farmer perception
- landscape aesthetic appeal
- a lack of policy incentives.

Other barriers more specific to each type of agroforestry are detailed in Table 3 below.

Practical barriers:

A key barrier to wider use of silvo-arable systems in Scotland is the opportunity cost of arable land. More generally though, the climate and nature of arable production in Scotland arguably does not lend itself well to such systems, as the growing season is short and. As a result there is little current farm-knowledge of implementing such systems in Scotland. On the very highest quality land, potatoes and other high value tuber crops do not lend themselves to alley cropping as well as barley or oilseed rape, due to differences in cultivation. Furthermore, some studies have shown that introducing shelterbelts around crops or alley cropping could potentially reduce crop productivity in areas immediately next to the tree rows. Alley cropping may require modifications to current practice such as spacing adjustments for machinery and altered management to account for variability in crop ripening. Despite these potential yield losses and extra management costs, the overall environmental benefits through improvements of shelter and added farm income diversity outweighed the relatively small yield losses. An example, utilising fruit trees and designed to suit modern farm machinery, to the south of Peterborough, England, has been recently implemented on a farm outside Newburgh in Fife, Scotland. Very little other evidence was found. The lack of evidence and knowledge on silvo-arable systems in Scotland, highlights the need for further investigation of tree intercropping with arable crops to provide clarity to the benefits of such practices to underpin knowledge, acceptance and uptake.

The cost of establishment and subsequent management of silvo-pastoral agroforestry systems are generally higher than conventional woodlands and forests, which may impede agroforestry uptake (Slee et al. 2012; Smith et al. 2016). In all cases, successful implementation of a managed woodland in agricultural landscapes requires an understanding of the woodland's management needs in addition to those of the livestock. A major constraint is the impact of deer on establishment and regeneration success. While livestock & other herbivores must be excluded during establishment of any woodland, the unit costs are likely to be higher for small planted areas and particularly for individual trees that may require protection from livestock. In addition, the forest canopy requires active management to maintain the productivity of both the grass sward and the trees, especially if timber production is one of the farm's objectives (Hislop & Claridge, 2000). Such management requires a degree of arboricultural knowledge, which may not be readily available on the farm. Networks and demonstrations highlighting good agroforestry practice would be beneficial. Finally, the length of the proposed tree crop rotation may be longer than the longevity of the farm tenancies, which may pose additional logistical and ownership challenges.

In relation to the maintenance of developing woodlands, including existing silvo-pastoral systems, another key practical challenge is that trees do not regenerate readily. Trees, particularly short-lived trees such as birch, die and are not replaced naturally. Any regeneration will tend to be browsed, if not by farmed ruminants then by wild herbivores. However, natural regeneration is possible under well thinned canopies, where light penetrates to the ground and the sward is managed through a disturbance regime to provide a seedbed for natural regeneration or by herbicide control. Natural regeneration then provides a low-cost opportunity to restock the woodland matrix for a second cycle of benefits in terms of shelter, timber and other ecosystem services. Thus, the key for supporting the majority of existing "natural" wood pasture systems is to support interventions, which allow the regeneration of trees without undue cost. The Forestry Commission provides annual grants to support livestock exclusion and inclusion in woods.

Finally, introducing livestock into existing woodland can also be challenging, as many woodlands would need to be thinned to allow grazing under the trees. Thinning is also likely to increase the risk of wind damage to the remaining forest component, especially the upland areas of Scotland and on exposed slopes, further reducing any carbon sequestration and adaptation benefits. There is also high potential for poor woodland condition if access is not managed sympathetically. More generally farmers may face increased management and maintenance costs with agroforestry, associated with the increased complexity of land-use. However, where existing stands are in sheltered locations or are relatively young (prior to or at closed canopy), thinning can provide both biomass as a by-product and also lead to a well-spaced and naturally regenerating stand of trees.

Policy incentives

Since the introduction of farm woodland grants in the late 1980s, support has always existed for integrating land-use. Farmers were 'compensated' for converting land to forestry by annual grants that in many cases were higher than their subsidy payments on the same area of land. Since the introduction of Common Agricultural Policy (CAP) reform and the rural development programme, land under woodland or converted to woodland became eligible for the basic payments. There is now a suite of Forestry Grants in the Strategic Rural Development Programme (SRDP), many of which can be used for agro-forestry in its wider context. There is one specifically related to establishing wide-spaced trees (misleadingly called Agro-forestry). This grant is currently restricted by area and Land Capability for Agriculture Class (3.1 to 4.2 inclusive), as the practice is more suited to lowland and in-bye areas, where shade is more important than wind shelter. Generally, land poorer than 4.2 is higher up the hill where shelterbelts are of most value. Currently the grant offer under SRDP does not cover wood pasture, either for establishment or maintenance.

Silvoarable systems are not currently eligible for grant support.

Farmer attitudes and perceptions

Anecdotal evidence suggests that the issue of farmer acceptance is a common problem to all forestry options. This has not been helped by largely separate forestry and agricultural advisory systems and knowledge and information systems which, arguably, impede integrated thinking and practice.

A critical barrier to agroforestry adoption is the reticence for agricultural land managers to contemplate woodland as an active and contributory agent to farm development (Slee, 2014). Until the recent past, agriculture and forestry have been viewed largely as competitors for land rather than complementary land uses in a single proprietary unit (Nicholls 1969). The hills and uplands have often been a contested space. This sense of competition appears to remain a powerful discourse among many farmers, although formal evidence remains limited. For example, a study in Ireland from 1996 to 2006 found that decisions were often based on (intrinsic) values and beliefs about the nature and purpose of farming and that many agricultural land managers focus on the potential loss of productive land when areas are exclusively converted to woodland. This has led to reluctance to introduce a woodland element into agricultural land areas (Duesburg et al. 2013).

Though introducing agroforestry will require additional skills, and understanding of arboriculture, it is a farming system - trees are integrated in the livestock and arable production systems. Traditionally in Europe, farmers used trees much more than they do now, it was an integral part of the way of farming in many systems- with inter-generational knowledge being lost with recent agricultural intensification. Research into agroforestry and its adoption are promoted globally targeting those who manage land for food production. This highlights the need for communication with and amongst farmers in Scotland, in order to demonstrate and showcase tree benefits as an intrinsic and essential part of land husbandry.

A useful concept that may help improve farmer perception is the ‘Land Equivalent Ratio (LER)’ (Mead & Wiley, 1980; Newman 1986; Serenke et al. 2015), which considers the return from a multi crop approach on the same area of land. For example a single crop (barley) would have a value of 1/unit of land. If integrated with fruit trees for example, there is evidence to suggest that the LER can increase to 1.6/unit of land. So a crop of barley and a crop of apples from the same area of land in the same year is more profitable before other ancillary benefits are considered.

Additional tools and resources are available to decision makers and farmers regarding agroforestry adoption, such as the Woodland Grazing Toolbox (Forestry Commission Scotland, 2016), the Silvopastoral Agroforestry Toolbox (Macaulay Land Use Research Institute, 2000), and Sustainable Forest Management (SFM) Toolbox (FAO, 2018).

It may be also useful to highlight to farmers that agroforestry is relevant to the Woodland Carbon standards. Wide-spaced (>3m) agroforestry will fall out with the UK Woodland Carbon Code Scheme, while shelterbelts will be admissible with the proviso that organic soils are avoided.

TABLE 3. Summary of the benefits and challenges of the potential agroforestry options for Scotland in terms of their climate mitigation and adaptation potential, as well as their relative extent and level of support. Key supporting references are highlighted in the final column, although many other references in the bibliography were drawn on when compiling the table.

Option [brackets refer to App. 4 exemplars]	History / occurrence	Farm Adaptation benefit	Climate Mitigation Benefit	Other public good benefits	Current support	Specific Issues	Key Sources
Silvo-pastoral systems – upland wood pasture: Woodland pasture grazing (where trees are not fenced off from grazing animals following establishment) [6, 7, 13]	Widespread throughout upland fringe and in highlands.	Used for out-wintering or cool season grazing. Shelter for livestock (animal welfare benefits plus improved performance); reduced feed costs; More varied diet for livestock; amenity benefit; relieves pressure on better quality grassland during winter; Potential source of fuel wood; Habitat for game; On-farm flood risk reduction; Potential for marketing "woodland" derived products.	Medium but needs to be considered alongside soil carbon accumulation as land never ploughed. Depends on tree species, spacing and soil type. Also highly contingent on stocking density; Biomass provision	Very good for biodiversity. High public amenity value; flood risk reduction.	Woodland Improvement Grants, Restructuring and Planning including specific Woodland Grazing Plan possibility.	Regeneration may be compromised so maintenance may be a challenge; Out-wintering could increase sediment burden in streams; "Fit" with public payment and monitoring systems. Often unmanaged and in poor ecological condition.	Saunders et al (2016); Sibbald, AR. (2006); WEAG. (2012); SAC technical note TN634 2011; Barbour 2016; Farm woodland case studies.
Silvo-pastoral systems lowland wood pasture (where trees are not fenced off from grazing animals) [1, 7, 8, 10]	Not uncommon in areas where have a juxtaposition of good quality land and poorer land. Some outdoor poultry examples.	As for silvo-pastoral systems in uplands plus important sacrificial use to maintain better quality pasture; Potential for nutrient management and reduction of diffuse pollution; very beneficial in outdoor poultry; Potential for marketing "woodland" derived products.	Potentially high. Depends on tree species, spacing and soil type. Also highly contingent on stocking density; Biomass provision.	Very good for biodiversity and landscape. High public amenity value; Flood risk reduction.	Available on planned new sites; woodland improvement and sustainable management grants.	May result in lower soil carbon under trees but ploughing of grassed areas unlikely; May be perceived as "locking away" useful land; Restocking difficulties.	Upson, Burgess et al 2016. Woodland Trust guide 2014.
Silvo-pastroal shelter belts (where trees are fenced off from stock). Occasional clump plantings for landscape reasons. Can include Shelter belts planted around poultry production sites [1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 13]	Regionally concentrated in eastern Borders, Central Belt and some parts of Eastern Scotland.	Shelter and shade for livestock. Reduces effects of wind-chill on maintenance requirements. Some amenity benefits. Some fuelwood provision; Game benefits.	High as long as peaty soils are avoided; especially so on gleyed wet soils.	Can enhance biodiversity but depends on species mix (if mono-species, benefits limited). May benefit water quality if stream flows through shelter belt. Shelter belts downwind from poultry production site, can intercept ammonia emissions and particulates.	Available for new woodland creation.	High fencing costs per unit area.	Agriculture Victoria (LC0136 2009) Shelter belt design; Woodland Trust & BFREPA (2014).

Option [brackets refer to App. 4 exemplars]	History / occurrence	Farm Adaptation benefit	Climate Mitigation Benefit	Other public good benefits	Current support	Specific Issues	Key Sources
Silvo-arable systems (e.g.alley cropping)	Very rare	Shelters crops from wind and frosts; Potential for fruit and nut production (farm diversification); can increase incidence of pollinators and natural enemies to pests (Pumariño, L et al 2015).	High per unit area but, because of lack of suitability in Scotland, overall potential low.	Wildlife habitat and corridors, increased biodiversity and enhanced landscape. Nutrient recycling.	None	Shading may be in an issue once trees are mature (orientation of tree rows important & pruning may help); Limits agricultural machinery use if not spaced out properly; increased demands on farm labour (including tree maintenance).	Palma et al (2007); Pumariño et al (2015); Graves et al (2017); https://www.agroforestry.co.uk/about-agroforestry/silvoarable/
Silvo-arable shelter belts [1, 7, 8]	Limited to certain areas of Scotland.	Crucial in mitigating wind erosion in areas where major wind borne soil erosion is an issue; Can reduce flooding; Some fuelwood provision	Few estimates available but avoids soil carbon loss, avoids nutrient loss and provides C sequestration	Biodiversity enhanced.	Woodland creation grants, farm or small woodland option. Some targeting	Possible effects of roots on field machinery; negative effects of shading on crop ripening; increased demands on farm labour.	Farm woodland case studies, FCS; Agriculture Victoria LC0136 2009; Carroll, Bird et al 2004; Amadi, Van Rees, et al 2016
Silvo-pastoral and silvo-arable buffer strip planting (including riparian buffers) [1, 4, 8]	Common but not necessarily planned as agroforestry system.	Nutrient and runoff management; soil erosion reduction; May improve game habitats. May utilise high cost-low yield areas such as wet headlands, so result in net savings.	High per unit area; Reduced soil C loss.	Improved water quality; Water cooling effect benefits salmonids & pearl mussel as does mixed vegetation and water turbidity reduction. Good for landscape. Increased biomass. Improved landscape connectivity for wildlife.	Woodland creation grants: farm or small woodland option and area specific schemes in N and W Isles.	Cover for predating game and vermin.	Thomas, Griffiths et al 2016; Stutter, Chardon, Kronvang 2012.

6 Comparative analysis of options

This section considers the relative magnitude of benefits from agroforestry, focussing on the options most suited to Scotland. We first summarize the comparison of the overall benefits and challenges of agroforestry in Scotland, as discussed in Section 5 above. We then provide a detailed comparison of the different carbon sequestration potentials for various options.

Based on the literature review, a comparison of the benefits and challenges for each of the agroforestry options for Scotland, from the point of view of climate mitigation and climate adaptation, was given in Table 3 (Section 5 above). The lack of evidence on the extent of agroforestry in Scotland means that many of the findings are qualitative only and this is particularly the case for the information on history/occurrence, which was based on expert judgement alone. A systematic study of farms and woodlands in Scotland to understand the degree of agroforestry practiced (whether currently acknowledged as such or not) would be highly beneficial and would provide a better basis for understanding the magnitude of benefits shown in Table 3.

Comparison of carbon sequestration potential

To better understand the carbon sequestration potential of different agroforestry options in Scotland, we used the methods of Saunders et al. (2013), modifying them for a number of suitable different species and different tree management options (see Table 4). Details of the calculations and assumptions are given in Appendix 5, but briefly, the predominant forest type is constrained to a soil class with an average productivity described for the system. This does not preclude, for example, high yielding conifers on mineral soils. All instances were not modelled, only wide scale management types. A tree density of 400 stems per hectare was adopted for the analysis, as this is the maximum density currently supported under one of the woodland creation schemes agroforestry option. The C-sequestration potential was evaluated for periods of 20, 40 and 80-years from planting.

The key findings from the analysis were as follows:

- All agroforestry types deliver the highest carbon benefits on well drained mineral soils.
- The majority of current agricultural land in Scotland is predicted to be suitable to support woodland development, based on soil type, present climate and assumed minimum tree growth performance (minimum volume yield threshold). This suggests there is significant potential for growth in the use of agroforestry as a means of carbon sequestration.
- Coniferous tree species can tolerate poorer drainage soils, such as organo-mineral soils, but require longer times to sequester on-site carbon due to the disturbance of the organo-mineral soil at planting.
- Even for the poor quality rough grazing land classes, there are locations where shelterbelts can provide high productivity Douglas fir and Sitka spruce, which provides the best climate mitigation and wood product (economic) return.
- Broadleaf tree species can provide excellent long-term carbon storage and biomass, but to provide valuable timber requires considerable investment in silvicultural management to ensure the highest value timber trees. The economic returns from high value timber are therefore only likely to accrue for the next generation from broadleaf ‘target-tree selection’ systems.
- Broadleaf species of particular interest in terms of their productivity and ease of management include Alder and Aspen. There is a potential concern with Alder in that it is a nitrogen fixing symbiont species and as such may invoke additional nitrous oxide (soil) emissions, which could outweigh its improved growth performance, though the GHG balance of Alder requires further

study. Aspen reproduces through suckers so its cultivation and regeneration is relatively simple, but with an increased potential risk for disease within stands as there is a lack of genetic diversity.

- Whilst not explicitly calculated in this report, the substitution benefits from predominantly conifer crops are considerable and are likely to more than compensate for any soil losses and outperform broadleaf species in terms of total carbon mitigation potential, when life-cycle climate benefits are calculated. This is primarily due to the increased wood volume production from conifers and the longevity of structural grade softwood products which would arise from conifer shelterbelt systems: timber products can replace more intensive GHG materials (steel, concrete) particularly in building construction. In other agroforestry systems broadleaf plantings provide are likely to predominate as they provide improved understorey grassland sward, and significant ancillary benefits in terms of fodder, nutrient cycling, and biodiversity.
- The primary determinant of the carbon mitigation potential of any new woodland is the productivity of the site, which is governed primarily by soils and secondly by climate. To maximise the benefit of agroforestry mitigation ‘better quality’ soils should be targeted. The site objectives will then drive the species choice, management and the overall timescale for return on investment.

TABLE 4: Carbon (C) sequestration potential of different agroforestry options, under 400 stems/ha planting density, but variable tree arrangement and management options. The carbon stocks are estimated at 20, 40 and 80 years after harvest, and take into account soil C changes. For more details see Appendix 5.

System	Option	Example of Tree Type	Soil Type	Management Type	Carbon sequestration potential (t C/ha)**		
					20 y	40 y	80 y
Silvo-pastoral system	Woodland Pasture (Single tree or cluster)	Scots pine	Organo-mineral	Continuous cover forestry	-4.2	-6.2	3.7
Silvo-pastoral system	Woodland Pasture (Single tree or cluster)	Sycamore, ash* or birch	Mineral podzol	Continuous cover forestry	29.5	45.6	64.6
Silvo-pastoral system	Windbreaks or riparian buffer strips (Shelterbelt)	Sycamore, ash* or birch	Mineral gley	Multipurpose clearfell harvest	30.9	51.5	78.9
Silvo-pastoral system	Windbreaks or riparian buffer strips (Shelterbelt)	Sitka spruce	Organo mineral	Multipurpose clearfell harvest	-1.4	3.7	7.6
Silvo-pastoral system	Windbreaks or riparian buffer strips (Shelterbelt)	Japanese larch*	Mineral gley	Multipurpose clearfell harvest	0.8	4.4	8.4
Silvo-pastoral system	Windbreaks or riparian buffer strips (Shelterbelt)	Douglas fir	Mineral soil	Intensive even-age (clearfell and replant)	4.4	12.6	24.3
Silvo-pastoral system	Windbreaks or riparian buffer strips (Shelterbelt)	Sitka spruce	Organo mineral	Intensive even-age (clearfell and replant)	-0.1	6.1	11.8
Silvo-arable	Shelterbelt	Japanese larch*	Mineral gley	Intensive even-age (clearfell and replant)	2.0	5.8	11.0
Silvo-arable	Shelterbelt	Aspen	Mineral	Short rotation woody biomass (coppice management)	43.1	77.5	142

*NB Ash and Larch are currently not supported through the Forestry Grant Scheme as there are disease issues of National importance with impact on forest health for these species.

** AHDB (2011) calculated that typical arable farming practice produced 1tC per hectare per year, which is broadly similar to a mixed production (beef suckler and arable) Scottish farm emissions reported by SAC (200*)

7 Conclusions

This report has explored the potential benefits to farmers and wider society of different agroforestry options in Scotland, in terms of climate change mitigation, adaptation and other societal benefits. The options considered included systems which involve forestry and agricultural uses within the same plot of land, in addition to woodlands planted with the intention of sheltering stock or crops in neighbouring plots of land, but within the same farm. We have not considered other types of farm woodland that do not involve crops or livestock.

Analysis was based on findings from a desk-top review of both academic and industry-related literature on agroforestry relevant to Scotland, supplemented with information from key informants. The analysis also involved estimating the carbon sequestration potential of relevant agroforestry options using methods developed by Saunders et al (2013).

A key finding from the review was the lack of accurate quantitative information on the current extent of agroforestry practiced in Scotland. Filling this evidence gap would provide an important benchmark against which to judge future developments in Scottish agroforestry and provide a better basis for understanding the magnitude of benefits highlighted in this report. Furthermore, stronger evidence on the range of different types of agroforestry practiced across Scotland may help encourage farmers to consider introducing agroforestry in their own businesses.

Where trees and agriculture did co-exist within a farmed system, this has not always been planned and the land was not necessarily being operated as an integrated agroforestry system. Silvo-pastoral type systems currently dominate in terms of existing use and also in terms of market readiness.

Having noted the above shortcomings, the literature review indicated that the following agroforestry options had potential use in Scotland:

- **Silvo-pastoral systems in uplands**: Woodland pasture grazing (where trees are not fenced off from stock). Such systems are currently predominately composed of conifer species, although broadleaf species are possible. Establishment requires deer exclusion.
- **Silvo-pastoral systems in lowlands**: Woodland pasture grazing (where trees are not fenced off from stock). Currently in these systems broadleaf species are more common, but they are also suitable for native Scots pine.
- **Silvo-pastoral shelter belts** (where trees are fenced off from stock). Their current ecological condition is often poor due to lack of management of the tree canopy.
- **Silvo-pastoral buffer strip** planting (including riparian buffers). Broadleaf species mixes should predominate.
- **Silvo-arable alley cropping**. Few examples, demonstration and research is a key priority.
- **Silvo-arable shelter belts.** Most prevalent where soil conservation issues are a key consideration.
- **Silvo-arable buffer strip** planting (including riparian buffers). Broadleaf species mixes should predominate

Despite initial costs to implement, agroforestry practices can make farms more resilient by providing shelter to animals and crops, improving animal welfare and thus growth, reducing crop pests by housing beneficiary predators, reducing soil erosion, mitigating soil temperature and moisture extremes, and diversifying farm income. Agroforestry can also provide wider environmental benefits, such as improved water quality and increased biodiversity.

Significant net carbon sequestration benefits could be possible by increasing the use of agroforestry systems in Scotland. The maximum, per hectare benefits, can be achieved on Land

Capability for Agriculture (LCA) classes of 2.0-4.2. On improved Grassland class (LCA 5.1-5.3), considerable carbon benefits from silvo-pastoral systems and shelterbelt planting are still likely. On LCA of 6.1-7.0, carbon sequestration benefits will be maximised through the avoidance of planting, and thereby disturbing, soils with an organic layer. Finally, on LCA of 7.0, land animal exclusion by fencing with natural regeneration of woodland is the key strategy to increase carbon benefits. Whilst the best quality land has the highest potential to return climate mitigation benefits, on a per hectare basis, through afforestation by agroforestry (i.e. silvo-arable), such action will have a high agricultural opportunity cost. Thus at a country level, C-sequestration capacity should focus on silvo-pastoral systems in Scotland: although silvo-pastoral systems sequester less carbon per hectare, the net area potential is such that considerable C-sequestration potential exists at reduced opportunity cost.

In relation to **carbon sequestration,** a key finding of the analysis is that **the benefits are highly context specific** and vary according to location, soil type, choice of tree species, density of planting and, in the case of silvo-pastoral systems, density of stocking. Many of these factors will, in turn, depend on individual business needs, and the farmer's preferences. Another concept that should be kept in mind is the Land Equivalent Ratio, when returns from multi-crop occupancy of the same area of land can provide enhanced economic benefit compared to a single crop monoculture.

Several barriers were identified in the literature to the wider adoption of agroforestry in Scotland. These included practical barriers (including maintenance costs and a lack of arboriculture knowledge on farms), farmer perception, landscape aesthetic appeal, and a lack of policy incentives. The challenge for promoting further agroforestry in Scotland is to minimise the real or perceived barriers to increasing agroforestry on farms while maximising climate change mitigation, adaptation and wider benefits of this approach. This in turn will require improved communication between various stakeholders (i.e. between different regulatory bodies, between regulatory bodies and farmers, between farmers and foresters), as well as training and maintenance support to farmers to help plant and maintain any newly established trees on their farms.

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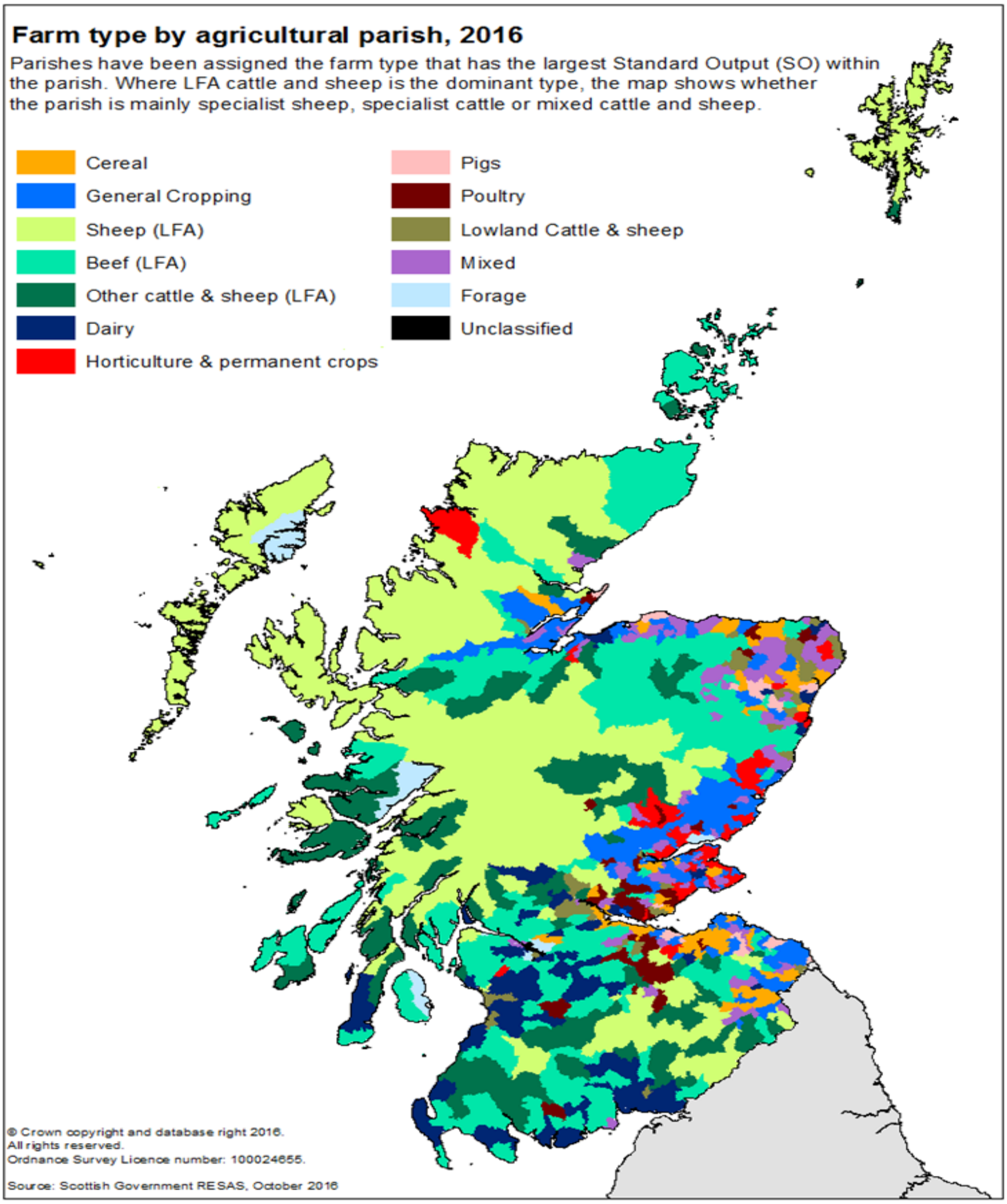
APPENDIX 1: Predominant agricultural farm land types in Scotland

Figure A1: Scottish Government mapping of predominant agricultural farm land type based on largest Standard Output within parish boundaries. LFA = less favoured area land mapping from Scottish Government website. For further details see http://www.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/AgriculturalMaps



APPENDIX 2: Analysis of agroforestry options for Scotland

1. Silvo-pastoral systems in upland Scotland

Description & farm purpose

Silvo-pastoral systems in upland Scotland were historically important in Scotland (Sibbald, 2006) and although there is a lack of data on their current extent, from a simple visual perspective, their presence remains widespread. They are primarily limited to a system where trees are not fenced off from grazing animals. Thus, this open pasture woodland can be used for wintering of livestock outside ('outwintering') or cool season grazing. The trees provide shelter for livestock, (particularly against wind chill and rain, but also reduce the risk of heat stress), reducing maintenance and feed requirements. Trees may provide some forage material too; 'leaf hay' from tree tending (pruning) can provide supplementary fodder and nutrient intake for grazing livestock, especially during summer drought. Additionally tree tending improves the long term timber quality of the broadleaf component. Livestock manure may improve soil fertility and tree growth. Woodland areas may also be used as 'sacrificial areas', preventing damage to better quality land during outwintering. However, puddling and soil poaching problems within the wooded area can occur.

Other farm benefits include:

- Habitats for game (providing an opportunity for income diversification)
- Providing amenity values for farmers/land owners
- Potential for marketing "wood based" products

Evidence for Climate Change Benefits

Mitigation: Upland pasture woodland will provide some carbon sequestration as trees grow, but it will not be at a high rate, given the typical climate and soil conditions in upland Scotland. The main advantage is conservation of soil carbon as it is not ploughed. However, on peaty soils, disturbance by livestock could result in carbon loss. The analysis conducted as part of this report highlights that the potential carbon sequestration benefits of upland silvo-pastoral systems depend critically on tree species, spacing, age and soil type. They will also be highly dependent on animal stocking density. A key strategy should be encouraging natural regeneration of existing silvo-pastoral systems as well as considering expansion of such areas in the uplands. A major determinant of regeneration success is deer pressure, which needs to be addressed at the landscape scale, or through fenced enclosures. There may be other benefits in livestock ammonia emissions absorption by the trees, but there is no quantitative evidence on this.

Adaptation: Improved farm resilience through potential diversification of animal feed, protection of animals from extreme weather, seasonal relief from overgrazing for better quality pastures, and, if correctly sited, flood risk mitigation. Also provides a potential source of wood fuel.

Wider benefits

There is good evidence of enhanced biodiversity with silvo-pastoral systems, although it will depend on the tree species planted; a mixture of species will have more advantages, although may require additional management. Increasing landscape connectivity may enhance biodiversity resilience. Trees in the landscape can be very good for landscape attractiveness and aesthetic benefits, if woodland areas are appropriately designed. Creation of woodland may provide forest tracks, helping access to higher ground.

Disadvantages

As noted above, outwintering can cause puddling and soil poaching problems, which could increase the sediment burden in streams within the catchment and increase management needs.

Market readiness and practical implementation

Woodland pasture systems are already currently widespread throughout the upland fringe and in the highlands suggesting market readiness is high. However, the condition of many upland woods that are used as part of livestock systems are poor: often degraded and with poor ecological diversity and lack of regeneration and recruitment most commonly due to unmanaged deer pressure.

There are some current examples of woodland use for outdoor poultry rearing, where woodland access provides welfare benefits to the poultry with a premium paid for 'woodland eggs' and (potentially) other livestock products. For example, Burgess et al. (2014) reported that premiums exist for woodland egg products, which accounted for 3.5% of UK market sales in 2013.

Establishing a good growing stock of trees may present considerable practical challenges, as does ensuring regeneration of trees in existing schemes, given they are susceptible to grazing and trampling by livestock. Only suitable for non-palatable tree species, or those large enough to be able to withstand physical contact by livestock.

Woodlands used for livestock may require a rest period, to allow the soil and ground vegetation to recover.

Figure A2.1: Picture of silvo-pastoral system in upland Scotland: Dinnet, Aberdeenshire.

2. Silvo-pastoral systems in lowland Scotland

Description & farm purpose

In the lowlands, good quality and poorer land plots are frequently adjacent, offering the potential to grow trees on the lower quality land plot to provide livestock shelter and access. Historically, woodlands provided a native habitat to some farm species such as pigs and chickens.

Current Evidence for Climate Change Benefits

Range of potential farm benefits are similar to those of upland pastoral systems and include shelter to livestock (animal welfare benefits), lower feed costs, supplementary fodder, timber or woodfuel, while livestock manure may improve soil fertility and tree growth.

Mitigation: Carbon sequestration in lowland silvo-pastoral systems is potentially higher than for upland systems given the better climate and soil conditions, but the magnitude depends critically on tree species, spacing, soil type, and stocking density. Analysis suggested that maximum benefits will be achieved on LCA land classes 2.0-4.2. Sycamore and red alder have been shown to be good choices for significantly enhancing soil organic carbon in silvo-pastoral grassland (Kitila et al. 2011; Beckhert et al. 2016; Upson et al. 2016; Pardon et al. 2017). As well as improving soil carbon and soil quality, trees can provide an additional source of nutrition for livestock (Luske & van Eekeren, 2014; Smith et al. 2014). Burgess (2017) describes a UK silvo-pastoral farm where both species were chosen for their nutritional and medicinal fodder properties, though the contribution to animal feedstock is likely to be small.

Adaptation: Improved farm resilience through potential income diversification and savings in animal feed, protection of animals from extreme weather, and, if correctly sited, flood risk mitigation. In winter or wet conditions the lowlands woodlands can have significant benefits, allowing the farmer to bring the livestock off quality pasture so as to keep the latter in better condition. In particular, in lowland areas, woodland pasture can be used to protect better quality land for high value crops, lambing pastures or silage production with the wooded and shrubby areas used 'sacrificially'. There is also potential for nutrient management and reduction of diffuse pollution.

Wider benefits and/or disadvantages

There is strong evidence of biodiversity enhancement in carefully managed grazed rather than ungrazed woods in Scotland (Vanbergen, pers comm.) and, if sympathetically designed, woodland pasture systems can enhance landscape attractiveness. Creation of woodland may provide forest tracks, increasing public access. Again, however, the unmanaged impacts of deer grazing is detrimental to the woodland component of many existing lowland silvo-pastoral systems. Furthermore, the impact of overstocked woodlands especially in adverse weather can lead to poor woodland condition and compromise long-term benefits from the tree component.

Market readiness and practical implementation

Examples of existing lowland silvo-pastoral systems are limited suggesting low market readiness. Any agricultural opportunity costs are likely to be higher than for upland silvo-pastoral systems. Farmer acceptance is a key to addressing "locking away" land and potentially loosing access to farm subsidies.

Figure A2.2: Picture of silvo-pastoral system in lowland Scotland: Fort Farm, Wormit, Fife.

3. Shelter belts for livestock

Description & farm purpose

Usually these are linear features, but the woodlands can be clump plantings for landscape aesthetic reasons. A key difference from other silvo-pastoral systems is that trees are planted with the chief purpose to provide shelter for adjacent livestock. There are thus no grazing or browsing benefits, although the shelter means that there are animal welfare benefits and reduced feed costs.

Current Evidence for Climate Change Benefits

Mitigation: The growth of trees will provide some carbon sequestration, particularly if peaty soil sites are avoided. The overall carbon sequestration benefit will depend on tree species, spacing, and soil type. Analysis suggests maximum per hectare benefit being achieved on LCA land classes 2.0-4.2. However, on improved grassland (LCA 5.1-5.3) considerable carbon benefits from shelterbelt planting are still likely. Shelterbelts also have the potential to reduce diffuse air pollution and mitigate ammonia release from agricultural livestock sheds and intensive egg production units (Bealey et al., 2015; Bealey et al., 2016).

Adaptation: If positioned effectively, shelter belts can mitigate against flooding. For example Keenleyside (2013 p20) notes that "the Pontbren results have shown conclusively that strategically planted narrow, fenced shelter belts of trees across slopes capture surface run-off from the pasture land above and allow it to soak more rapidly into the soil."

Wider benefits and/or disadvantages

As with other woodland areas on farms, shelterbelts will compete for grazing land, but the impact can be reduced if lower quality land is used.

Shelter belt planting can enhance biodiversity, but many existing shelter belts are mono-specific and so such benefits are limited. The biodiversity benefits will be higher in the case of historic shelter belts with mixed species and broadleaves, and older trees. Shelter belts may benefit water quality, if the stream flows through the shelter belt.

Many farmers who provide game shoots, plant shelter belts for cover for birds and enhancing the quality of the shoots. Other benefits include:

- Some provision of timber for woodfuel
- Some amenity benefits for farmers/landowners

Public amenity value depends on placement plus species mix. As with existing woodland pastures in upland areas, there may be is a case for supporting the maintenance of older mixed species shelter belts which have high public amenity value.

Market readiness and practical implementation

Shelterbelts are very common, but regionally concentrated in eastern Borders, Central Belt and some parts of Eastern Scotland. Barriers to practical implementation include high fencing costs per unit area planted. Farmer acceptance, lack of arboricultural skills, and concerns about reduced access to future farm subsidies are barriers to increased uptake. On the other hand, increased returns from a unit of land, due to multiple-crop use (e.g. biofuel and livestock or barley and apple crops), may provide farmer incentives to adopt agroforestry practices in their farm systems.

Figure A2.3a: Picture of upland silvo-pastoral shelterbelts: Towie, Upper Donside

Figure A2.3b. Picture of silvo-arable shelterbelts: Foulis, Evanton, Easter Ross

4. Silvo-arable alley cropping

Description & farm Purpose

Trees are planted in rows alongside crops, usually with a broad spacing between tree rows to enable machinery access (sometimes referred to as alley cropping). Tree shape is maintained by pruning. Potential for diversification through fruit and nut production.

Current Evidence for Climate Change Benefits

Mitigation: Although the soils and climate will typically be better than for other agroforestry options, the carbon sequestration potential is low, because of the wide spacing required to grow crops between tree rows and associated low tree density (*cf.* Briggs 2011). In future warmer climates tree rows may have benefits by reducing evapotranspiration losses and drought risk, particularly in windier locations.

Adaptation: Row planting may improve growing conditions for some crops by reducing airflow between the tree rows, increasing air temperatures and reducing wind damage. Increased farm resilience through reduced soil erosion and potential diversification of crops (ex. fruit trees and traditional crops), protection of crops from wind, frost and potentially drought and heat stress, increased biodiversity that can lead to increase in pollinators and decrease in pests due to increase in their predators (Pumariño, L et al 2015); reduce soil erosion by wind and water; flood risk mitigation; improved nutrient recycling.

Wider benefits and/or disadvantages

Additional benefits include: enhanced public amenity value associated with more mixed arable landscapes and increased farm employment.

Some disadvantages include tree shading of adjacent crops (the amount depending on spacing and row structure), which may provide cooler conditions on hot summer days, but at other times of year could increase frost risk adjacent to rows. Shade is likely to reduce yield particularly in

Scottish conditions. Shade and temperature effects can also produce uneven maturation, with consequent harvesting problems. Shading impact can be reduced by choice of more upright tree species and pruning, but there is a management cost.

Silvo-arable systems have a high opportunity cost with trees reducing the land area available for crops for a long time period. There are likely to be higher farm labour costs associated with increased maintenance plus roots can cause problems with farm machinery use.

Market readiness and practical implementation

Currently, of little relevance in Scottish conditions, except for wind eroded soils in Moray. However, it may have benefits in future warmer conditions. Barriers to practical implementation include high agricultural opportunity cost, high maintenance costs, farmer acceptance, lack of arboricultural skills. However, as per the comment above under silvo-arable lands, the concept of Land Equivalent Ratios applies and may provide incentives for farmers to incorporate trees on their land for increased economic return.

Figure A2.4a: Picture of silvo-arable system in England. Source: https://www.agforward.eu/index.php/en/silvoarable-agroforestry-in-the-uk.html

Figure A2.4b: Picture of silvo-arable system in Bedfordshire, England. Source: Agroforestry Research Trust [Image from farminguk.com]

5. Silvo-arable shelter belts

Description & farm Purpose

The planting of belts of woodland to provide shelter for arable land. Only common in areas of Scotland where there is a risk of wind erosion on light soils and in drier climates (e.g. Moray Firth).

Current Evidence for Climate Change Benefits

Mitigation: Few estimates available. Potentially high per hectare. As with livestock shelter belts, the overall carbon sequestration benefit will depend on tree species, spacing, and soil type.

Adaptation: Increased farm resilience through reduced soil erosion and potential diversification of income, protection of crops from wind, frost and potentially drought and heat stress, increased biodiversity that can lead to increase in pollinators and decrease in pests due to increase in their predators; reduce soil erosion by wind and water; flood risk mitigation; improved nutrient recycling. Shelter belts on arable land can also help reduce flooding and can provide woodfuel.

Wider benefits and/or disadvantages

- Enhance public amenity value associated with more mixed arable landscapes
- Increased farm employment
- Negative effects of shading on crop ripening and increased demands on farm labour associated with tree and crop maintenance.

Market readiness and practical implementation

Crucial in mitigating wind erosion in areas like the Moray Firth but, because of high agricultural opportunity cost of arable land, uptake in other areas of Scotland likely to be limited. In addition to a lack of farmer acceptance, and lack of arboricultural skills, practical barriers include additional farm labour requirements and possible adverse effects of roots on field machinery.

Figure A2.5: Picture of shelter belts for arable land, Source: Woodland Trust. In Farmers Academy (Farmers Weekly). Undated.

https://www.fwi.co.uk/academy/lesson/where-to-plant-trees

6. Buffer strips (including riparian buffer strips)

Description & farm purpose

Wooded areas which act as a buffer between adjacent land uses. Riparian buffer strips are buffer strips located next to streams. Buffer strips can have multiple benefits for a farmer including reduced soil erosion, lower nutrient loss and reducing agrochemical runoff into water courses.

Placement in high cost/low yield parts of the farm (such as wet headlands) can lead to net savings in farm costs. Although riparian planting is a possibility, farmers often prefer to have arable headlands uncropped by trees to aid turning farm machinery.

Current Evidence for Climate Change Benefits

Mitigation: Potentially high per unit area, but will depend on tree species, spacing, and soil type. Key benefits include reduced soil carbon loss (through reduced leaching into watercourses).

Adaptation: Riparian tree plantings, in both silvo-pastoral and silvo-arable systems, help capture diffuse water-borne pollution and reduce peak flow events, thus improving farm resilience during extreme precipitation events (Kitila et al., 2011) and delivering a drought provision to downstream 'actors'. The shade provided by riparian woodland helps reduce water temperatures, and reduces risk of low oxygen conditions (Johnson and Wilby, 2015). It has also been demonstrated to benefit brown trout and other fish in UK conditions (Broadshade et al 2010).

Wider benefits and/or disadvantages

- Increased biodiversity and amenity values.
- Improved water quality and reduced water turbidity.

Buffer strips are commonly observed, but may not always be "planned" parts of the farm. As noted above, buffer strips can offer potential net savings to farmers and thus there is potential for increasing uptake. Practical problems (over and above lack of farmer acceptance) include cover for predating game and vermin.

Figure A2.6. Upland silvo-pastoral shelterbelts & lowland riparian woodland. Knock, Huntly

APPENDIX 3 Literature Review methodology

This project involved an assessment through application of a “quick scoping review” underpinned by the guidance at http://nora.nerc.ac.uk/512448/. The review includes all relevant available published and grey literature since the publication of the Forestry Commission Bulletin “Agroforestry in the UK” (Hislop & Claridge, 2000) and up to and including December 2017. In the first instance relevant publications specific to Scottish Conditions were targeted. Additional literature representing similar conditions to Scottish forestry was consulted when it was thought likely to address uncertainties and knowledge gaps, or provide exemplars or direct relevance to Scotland.

Research objectives

A brief systematic review was adopted to provide an understanding of the extent of research into agroforestry. This review considered two main research questions:

1) Relevant research on agroforestry, including silvo-arable and silvo-pastoral systems.
2) Effects of agroforestry systems on any of the main identified benefits of increased adoption – namely in terms of management benefit, carbon benefit, runoff.

For the purposes of refining the literature search, the following definitions were placed on the search components:

- *Geographical locations*: Principally Scotland but including the whole of the UK and Ireland, Northern Europe, New Zealand and Canada. The search also included “Temperate” and “Oceanic”.
- *Language restrictions*: Some searches were constrained to English language literature only, others had no language restriction imposed however only English language literature was found.
- *Date restrictions*: Mixed. Some searches were restricted to 2000 – December 2017, the remainder had no date restrictions.

Search strategy

The primary aim was to capture a robust sample of relevant published and ‘grey’ literature.

Accordingly, a range of different sources of information were searched in order ensure coverage. Database searches were restricted to literature published since 2000. Additionally, unpublished (‘grey’) literature was obtained by Forest Research and the James Hutton Institute, based on expert knowledge of existing relevant research, reference to the Agroforward EU project and generic web engine (Google©) search.

Databases

The following databases were searched using the terms detailed in the search terms section:

- ISI Web of Science (previously known as Web of Knowledge)
- ScienceDirect
- Google Scholar (Assessments were limited to the first 100 hits returned for each search)
- Google (Assessments were limited to the first 100 hits returned for each detailed search)

Documented returns were then filtered further by a combination of location, year, & publisher.

By this means it was possible to make a reasonable sum of titles to scan. Titles were only then included if the researcher thought they might have direct relevance to the aims of the study. Abstracts of those deemed eligible were then scanned and only publications of direct relevance were retained. It should be noted that some of the more policy focused publications were omitted due to this approach, as they essentially provided no evidence but opinion based on expert judgement.

Search terms

Search terms provided in Table A3.1 were used:

Table A3.1. Search terms used in database searches

Primary search terms	Management/intervention search terms	Additional Measurement search terms
Agroforest*	Silvo-past*	Carbon
Agriculture	Silvo-arable	GHG
	Riparian	Climate
		Scotland
		UK
		Canada
		New Zealand
		Oceanic
		Temperate

Inclusion/exclusion criteria

Following selection from the initial literature search, each article was required to contain certain criteria to be considered for inclusion in this review. These criteria were as follows:

- *Location:* Agroforestry systems in the UK, Ireland and climatically similar regions
- *Management/intervention:* Silvo-arable and silvo-pastoral systems with afforestation and shelter, mitigation and adaptation.
- *Measurement:* Carbon or other GHG, other adaptation and mitigation metric (biodiversity, water quality etc.).
- *Study type:* Any primary study or similar grey literature report

APPENDIX 4 Case Study examples of agroforestry in Scotland

TABLE A4.1. Examples of current example agroforestry schemes on farms across Scotland

Most of these case studies are available as PDF documents at: http://scotland.forestry.gov.uk/supporting/grants-and-regulations/farm-woodlands/farm-woodlands-case-studies

Agroforestry Type(s)	Exemplar ID	Location	Agroforestry & Agricultural Holdings	Primary Aim(s)	Additional Management Info
Lowland wood pasture: shelterbelts & woodland grazing	1	St Fort, Wormit, Fife	Shelterbelts Beef suckler & sheep Field margin woodland Arable	Shelter for beef cattle and sheep. Woodland grazing. Soil conservation	Arable crop strip adjacent to wooded field margins harvested later than main 'in field' crop
Upland shelter belts: biomass	2	Newhill, Glenfarg, Ochills.	Shelterbelts Beef suckler & sheep	Wood fuel. Provision of shelter.	Planted on LFA barley/grazing land.
Upland wood pasture: woodland grazing	3	Netherurd, Peebles, Scottish Borders.	Shelterbelts, woodland pasture Beef & sheep	Timber.	Planted on LFA grazing, plus in-field specimen broadleaf trees. Pheasant rearing.
Upland wood-pasture: shelterbelts. Buffer strips: lowland riparian woodland	4	Knock, Huntly, Moray	Woodland blocks, Riparian planting Beef suckler & sheep	Timber / woodfuel. Riparian buffer strips	Multiple Benefits incl. biodiversity, wood biomass & environmental goods.
Upland shelterbelts	5	Ifferdale, Kintyre	Shelterbelts Beef & sheep	Timber / woodfuel.	Conifer and broadleaf planting
Upland wood-pasture: woodland grazing and shelterbelts	6	Glensaugh, Aberdeenshire	Pasture woodland & shelterbelts Beef, sheep & deer	Woodfuel	Conifer and broadleaf planting
Lowland wood-pasture & Upland shelterbelts	7	Glencraigs, Campbeltown, Argyll	Shelterbelts Beef suckler	Woodfuel	Planted on LFA grazing Conifer and broadleaf planting
Lowland wood-pastoral & Upland shelterbelts	8	Foulis, Evanton, Black Isle	Shelterbelts Beef suckler	Timber & woodfuel	Planted on mixed agriculture class 4. Conifer and broadleaf planting
Lowland & Upland wood-pasture	9	Corrimony, Glenurquhart	Shelterbelts Beef suckler & sheep	Wood fuel. Provision of shelter	Planted on LFA upland grazing. Conifer and broadleaf
Lowland shelterbelts: biomass	10	Carbeth, Balfron	Woodland blocks & riparian planting Sheep	Wood fuel. Provision of game bird shelter	Conifer and broadleaf
Lowland & Upland wood-pasture	11	Barcloy, Kirkudbright	Shelterbelts Beef suckler & sheep	Wood fuel. Shelter.	Conifer and broadleaf.
Lowland & Upland wood-pasture	12	Balring, Aberdeenshire	Shelterbelts Beef suckler & cereals	Wood fuel. Shelter.	Conifer and broadleaf.

Agroforestry Type(s)	Exemplar ID	Location	Agroforestry & Agricultural Holdings	Primary Aim(s)	Additional Management Info
Upland wood-pasture	13	Bolfracks, Perthshire	Shelter, pasture woodland, rows Sheep	Broadleaf timber. Shelter & woodland grazing	Broadleaf
Lowland shelterbelt	14	Glenrath Farms, Scottish Borders	Chickens	Woodland access & ammonia abatement	Conifer

APPENDIX 5 Carbon sequestration benefits of agroforestry

Methods for C-sequestration estimates

To estimate the potential of agroforestry to sequester carbon in this assessment we analysed the species suitability and yield potential of exemplar tree species grown under different tree management types. These have been derived by modifying a set of "Forestry Management Alternatives" (FMAs) of woodland types appropriate for Scotland (Mason & Perks, 2011). For this project, nine Agroforestry Management Alternatives (AFMAs) were derived based on current experience (Table A5.1), all of which are within the range of silvo-pastoral and silvo-arable types described earlier, and are applicable across agricultural land capability classes in Scotland (Table A5.2). We did not include alley cropping (wide spaced tree rows) or single tree systems as growth models at these spacing's are not available.

Table A5.1. The Agroforestry Management Alternative (AFMA) definitions used in the analysis of potential carbon sequestration benefit

No	AFMA Name	Species, Yield Class (m3 ha-1 y-1), spacing	Previous land use and soil type	Management & rotation length
1	Native Conifer	Scots Pine YC4, 2.5m	Pasture, Organo-Mineral	MT, CCF
2	Native Broadleaf	Sycamore, Ash and Birch YC4, 2.5m	Pasture, Mineral podzol	NT, CCF
3	Multi-Purpose Broadleaf	Sycamore, Ash and Birch YC6, 2.5m	Pasture, Mineral gley	MT, 70 y
4	Multi-Purpose Sitka Spruce	Sitka Spruce YC12, 1.7m	Pasture, Organo-Mineral	MT, 50 y
5	Multi-Purpose Conifer	Japanese Larch YC8, 1.7m	Pasture, Mineral gley	MT, 50 y
6	Production Douglas Fir	Douglas Fir YC18, 1.7m	Arable/ Pasture, Mineral	MT, 50 y
7	Production Sitka Spruce	Sitka Spruce YC16, 2.0m	Pasture, Organo-Mineral	MT, 50 y
8	Production Conifer	Japanese Larch YC10, 1.7m	Pasture, Mineral gley	MT, 50 y

No	AFMA Name	Species, Yield Class (m3 ha-1 y-1), spacing	Previous land use and soil type	Management & rotation length
9	Short Rotation Aspen	Aspen YC10, 2.5m	Arable/Pasture, Mineral	NT, 25 y

Notes:

MT indicates thinning according to standard management tables; NT indicates no thin, and CCF indicates managed as continuous cover forestry, with no final harvest (thus no rotation length shown).

After a change in land management the balance of C uptake and loss may be positive or negative over time, depending on soil disturbance degree and vegetation growth rates. For the establishment of an agroforestry system the time pattern is likely to be one of initial C loss due to soil disturbance at tree planting, diminishing over time and potentially being offset by later accumulations in standing trees. In the calculations reported here, the changes in soil carbon follow the procedure in the Woodland Carbon Code (https://www.forestry.gov.uk/forestry/infd-8jue9t) where it is assumed that organo-mineral soils will lose some carbon initially due to planting disturbance (dependent on the ground preparation), while mineral soils will lose little carbon at planting, particularly if previously arable soils. The estimates of soil C accumulation are considered conservative (West, 2011). Although there is no direct evidence in a Scottish context, the assumption that tree planting on lowland grassland does not increase soil C stock has been supported by a silvo-pastoral study on a clay soil in Bedfordshire (Upson et al. 2016).

Native woodland options retain complete forest cover for longer periods with a requirement for management (e.g. thinning and herbivore exclusion) for natural “under canopy” seedling regeneration. However, this analysis does not report the additional net C emissions reductions obtained from tree products (for example woodfuel, or timber housing materials) substituting for fossil-fuel intensive materials. This additional benefit ‘beyond the farm gate’ was out of scope for this review but would very probably alter the C benefit estimates in favour of managed higher yield tree species, even where they may occur on organo-mineral soils, such as is assumed in AFMA4.

Estimated C sequestration amounts

For each of the nine AFM Alternatives aboveground C stock is reported at years 20, 40 and 80 (Table A5.2), using a tree density of 400 stems/ha as this is the density currently supported under woodland creation schemes. The percentage area equivalent occupied by trees in each AFMA that is shown reflects the spacing between trees adopted at planting as ’standard practice’. This is an important consideration for farmers as 400 trees/ha closely planted (1.7m spacing) will, on reaching canopy closure, occupy approximately 12% of the agricultural landholding, whereas planting at 2.5m spacing will occupy 25% of the land. At wider spacing (e.g. 5x5m), as might be considered for some wood pasture (Quelch 2013) or deer lawns, occupancy will reach in excess of 75% of available land. Over time as the tree canopy develops standard silvicultural practice is to remove a proportion of the trees (thinning) to reduce competition and select the trees with superior shape (form). At wide spacing a grass sward can be maintained between canopies with appropriate thinning intervention. At tree planting the net area occupied by the trees will be lower as the young tree canopy is small (circa $1m^2$), though the land may be taken out of agricultural production in order to ensure the successful establishment of the trees, especially by the exclusion of livestock and other herbivores (rabbits/deer). These thinnings provide woodfuel, another potential net C emissions reduction benefit. To enable C gain between the AFMA scenarios to be compared they have all been scaled to 25% occupancy (Table A2, figures in bracket). This analysis shows that there are significant carbon advantages to the use of productive broadleaf trees grown on short rotations and close spacing. There are some notable high C net uptake values for native woodland managed with minimal intervention (Table A2), though there is minimal additional emissions reduction benefit from native woodlands managed as a carbon store

A comparison of the AFM Alternatives illustrates the additional net C uptake benefit of planting on low organic carbon content soils. For the same species planting on mineral soils will both increase tree yield and reduce soil C losses. On agricultural land with mineral soils, the scenarios presented are likely to underestimate the potential C benefits that could be obtained because the actual yields are likely to be higher than those of the exemplar trees used in our conservative estimates.

Table A5.2. The calculated carbon benefit based on planting density of 400 trees per hectare for the nine AFMAs described in Table A5.1. C stocks are shown for trees only, and including soil carbon stock changes which are modelled using the Forestry Commission WCC approach which is simplistic but consistent with available evidence, and probably conservative in estimating increases.

No.	AFMA Name	Species and Yield Class	Area planted	Carbon stock change at particular times after planting, in the trees and including soil					
		YC = Yield Class ($m^3\ ha^{-1}\ y^{-1}$)	% of ha equiv.	20y		40y		80y	
				trees	+soil	trees	+soil	trees	+soil
1	Native Conifer	Scots Pine YC4	25%	0.07	-4.0	0.75	-6.2	7.5	3.7
2	Native Broadleaf	Sycamore, Ash and Birch (SAB) YC4	25%	2.0	29.5	11.2	45.6	23.3	64.6
				20y		40y		80y (70+10)	
3	Multi-Purpose Broadleaf	Sycamore, Ash and Birch (SAB) YC6	25%	2.9	30.9	9.2	51.5	17.5	78.9
				20y		40y		80y (50+30)	
4	Multi-Purpose Sitka Spruce	Sitka Spruce YC12	11.6% (25%)	0.9 (2.0)	-1.4 (-3.8)	4.3 (9.3)	3.7 (1.1)	8.6 (19.0)	7.6 (3.0)
5	Multi-Purpose Conifer	Japanese Larch YC8	11.6% (25%)	2.1 (4.4)	0.8 (1.6)	4.5 (9.6)	4.4 (9.6)	8.7 (18.7)	8.4 (18.1)
				20y		40y		80y (50+30)	
6	Production Douglas Fir	Douglas Fir YC18	11.6% (25%)	3.9 (8.4)	4.4 (9.1)	8.3 (17.9)	12.6 (26.9)	16.3 (35.3)	24.3 (45.5)

7	Production Sitka Spruce	Sitka Spruce YC16	16% (25%)	1.8 (3.9)	-0.1 (-0.6)	5.7 (12.3)	6.1 (12.8)	11.3 (24.4)	11.8 (24.9)
8	Production Conifer	Japanese Larch YC10	11.6% (25%)	2.7 (5.8)	2.0 (4.0)	5.1 (11.1)	5.8 (12.2)	10.0 (22.0)	11.0 (23.0)
				20y		40y (25+15)		80y (3x25+5)	
9	Short Rotation Aspen	Aspen YC10	25%	7.7	43.1	15.4	77.5	37.0	142

Potential AFMAs that are likely for each broad Agricultural Land Classification (LCA) class are also shown in Table 2, with the range of estimated carbon sequestration and other benefits.