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The potential for agroforestry to reduce net GHG emissions in Scotland through the Woodland Carbon Code

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1 Executive summary

1.1 Context

Significant change is needed across all sectors – including land use – to meet the greenhouse gas (GHG) emissions reductions targets outlined in Scotland's Climate Change Plan[1] (CCPu). Woodland creation and tree planting targets are a key pillar in delivering this reduction.

Agroforestry is the combination of trees and agriculture on the same plot of land, with tree density varying dependent on agricultural land type, tree species and objective. There has been growing interest in agroforestry systems as an opportunity to integrate land management objectives and contribute to meeting tree planting targets and generate GHG reductions and removals. However, only 3.3% of the utilised agricultural area in the UK is managed for agroforestry at present (den Herder *et al.,* 2015). Carbon schemes, such as the Woodland Carbon Code (WCC) could offer a potential route to provide financial support for agroforestry and incentivise its creation.

This report examines existing evidence to assess the GHG mitigation potential of different forms of agroforestry suitable in Scotland, building on the recent Perks *et al.* (2018) report *Agroforestry in Scotland – potential benefits in a changing climate*. It also examines the economic viability of adopting such agroforestry practices.

1.2 Key findings

1.2.1 GHG reduction potential

- There is additional new evidence, predominantly drawn from studies in other parts of the UK, which provides some comparisons of the likely scale of GHG mitigation from adoption of agroforestry systems in Scotland. This new data includes evidence for hedgerows. This includes a central estimate based on studies in southern England

[1] https://www.gov.scot/publications/securing-green-recovery-path-net-zero-update-climate-change-plan-20182032/

that 200m of linear hedgerows at 2m width delivers 10.2 t CO_2 per hectare over 30 years (not accounting for establishment soil C losses). Although linear woody hedgerows do not meet current minimum land area occupancy criteria required for Forestry grant aid or the WCC, even if they remain excluded from these, they may be considered under wider carbon-related schemes.[2]

- We found new evidence for orchards and silvo-arable and silvo-pastoral systems, though these suggest limits to GHG benefits that are likely to be at or below the lower bounds of the estimates for GHG benefit provided, particularly due to soils and climate in Scotland.
- Additional evidence of relevance to Scotland was identified - predominantly derived from a major EU funded programme of research 'AGFORWARD'[3]. This merits further assessment of the benefits of silvo-arable agroforestry options in a Scottish context.
- The key findings of the Perks *et al.,* (2018) CXC report on agroforestry benefits remain valid – that all forms of agroforestry have the potential to sequester carbon, although the benefits will vary depending on soil type, species, planting density and location.
- The new evidence also suggests that the fastest rate of carbon sequestration is most likely to be achieved on highly productive lowland areas. Whilst benefits can also accrue on less productive uplands, avoiding disturbance of organic soil layers is a key consideration.

1.2.2 Economic and financial viability

- We found strong evidence that agroforestry systems which are suitable for Scotland are, by themselves, generally financially viable. That is, as a land use system, they very often generate positive income for farmers. Virtually all studies found the practices studied to be financially viable, with only a few specific exceptions for silvo-arable alley cropping.
- When compared to conventional agricultural and forestry systems, agroforestry systems were often found to be potentially more – if not the most – financially viable land use option. This was the case for every agroforestry type covered. However, such outcomes were subject to different factors and dependent on specific conditions holding true. These include:
    - the time horizon in consideration (long vs short run),
    - whether farmers can 'cash-in' on wider ecosystem service benefits from agroforestry in the form of Payments for Ecosystem Services (PES) and/or public grants,
    - the prices of agroforestry outputs, and
    - the business model a farmer adopts in managing an agroforestry system.
- It is important to note that aside from financial barriers to the adoption of agroforestry, other social, cultural, and regulatory barriers also exist (e.g. cultural resistance and lack of practical skills). Therefore, strong evidence of being potentially relatively more financially viable for farmers (conditional on the above factors) would not necessarily be expected to equate to widespread adoption of agroforestry practices.

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[2] A proposed Hedgerow Carbon Code could potentially unlock more than £60m income for farmers according to the Game and Wildlife Conservation Trust (gwct.org.uk)
[3] https://www.agforward.eu

- The evidence on financial viability identified is from relatively recent studies (within the last decade). However, outcomes from future assessments may change, due to sensitivity factors including:
    1. timber and woodfuel prices, which have increased significantly in recent years,
    2. post-Brexit changes in farm subsidies, and
    3. changes in market Carbon prices.

1.2.3 Integrated findings

- Overall, our findings suggest that silvo-pastoral 'wood pasture' agroforestry systems have good combined GHG mitigation and financial benefits for Scotland, though the relatively low density of planting means carbon gains will be constrained.
- Silvo-pastoral shelterbelts, and buffer strips are likely to improve carbon mitigation gains, and silvo-pastoral hedgerows were also identified to have potentially strong GHG mitigation benefits, but no evidence on their financial viability was found in this evidence review.
- We specifically investigated the effects of including monetised ecosystem services on the financial viability of agroforestry. Of the cases studied, all found that agroforestry is less financially viable than conventional agriculture unless relevant PES are included in the financial calculations.
- Therefore, there is strong evidence indicating the need for funding support for agroforestry through PES schemes, including the WCC. This would support the financial viability of agroforestry as a land use option for farmers.

1.2.4 Evidence gaps

- We found evidence gaps on the GHG reduction potential of agroforestry. These include gaps relating to:
    - the impact of site and soil conditions,
    - previous and ongoing land use, and
    - the impact of the interactions between the forest and agricultural components of these integrated systems.
    - Furthermore, the impact of future climate has not been widely considered (See Section 7.2.1 for more details).
- Further research is needed to verify if evidence on the economic viability of buffer strips and shelterbelts is available; as well as to compare the economic viability of different agroforestry systems with one another. There is also a need to further investigate uncertainty in decision making within future assessments of economic viability of agroforestry. This is so that existing findings, which have largely been derived from less flexible capital budgeting models, can be verified.
- Given the indicated importance of PES mechanisms in increasing the attractiveness of agroforestry, further research on understanding the general feasibility of incorporating agroforestry into the WCC as one of the potentially suitable PES schemes will be helpful.

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2 Glossary

AGB	Above Ground Biomass
Annuities	Measure of annual values of a land use system adopted by Böhm *et al*. (2011)
BGB	Below Ground Biomass
Bocage	Traditional agroforestry system typical of Brittany, France consisting of hedgerows planted on field boundaries. They are “often organized into a spatial network at the landscape scale” and are “associated with mixed livestock-cropping farming systems”. (Aviron, Thenail and Vlaud, 2016)
Capital Budgeting	Methodology used to evaluate investment decisions of a business entity and the associated cash flows of those investments.
CCPu	Scotland’s Climate Change Plan update
Equivalent Annual Value (EAV)	Expression of NPV in annual terms. Accounts for the number of years of an investment, allowing for comparisons of investments with different time horizons.
GHG	Greenhouse gas
Gross Margins/Income	Market value of production output less variable costs.
Infinite Net Present Value (iNPV)	NPV over an infinite, as opposed to bounded, time horizon.
Internal Rate of Return (IRR)	Discount rate which equates the NPV of all cash flows to zero in the context of a discounted cash flow analysis.
LCA Class	the Land Capability for Agriculture class
Multicriteria Decision Analysis (MCDA) Performance Rank	Measure of performance of a land use option relative to other options based on multiple criteria (Palma *et al.*, 2007)
Net Ecosystem Service Value	Measure of net monetary value of ecosystem services and disservices from a land use system adopted by Kay et al. (2019).
Net Financial Benefits of Biomass Production	Measure of net monetary value of biomass produced from a land use system adopted by Kay et al. (2019).

Net Margins	Gross margins less direct labour and machinery costs incurred by a farm enterprise. Alternatively, output less ‘complete enterprise costs’ (i.e., profits).
Net Present Value (NPV)	Difference between present value of cash inflows and present value of cash outflows over a period of time.
PES	Payments for Ecosystem Services
Real Options Analysis	An approach used in economic investment decision analysis that allows for flexibility in decision making as opposed to assuming fixed/deterministic decisions.
Real Options Value	Measure of the “sum of instantaneous and discounted expected future rewards (e.g. profit, utility, etc.)” from transitioning between land use options, as obtained via Real Options analysis (Abdul-Salam, Ovando and Roberts, 2022)
SOC	Soil Organic Carbon
WCC	Woodland Carbon Code

Notes:

- Definitions were obtained from a combination of sources including Investopedia (no date), the 2022 John Nix Pocketbook (Redman, 2021), and from specific studies reviewed.
- We note that the exact definitions and formulas adopted differ across studies.

3 Introduction

To meet the GHG emissions reductions targets outlined in Scotland's Climate Change Plan update (CCPu), significant change is needed across all sectors, including land use. Woodland creation and tree planting offer a route to sequester carbon, and woodland creation targets are embedded in policy in the CCPu.

Agroforestry presents one opportunity to integrate land management by bringing trees and agriculture together, helping to meet tree planting targets and generate additional GHG reductions and removals (Slee, 2014; Soil Association, 2018), along with other benefits such as habitat connectivity, provision of shelter for livestock, income diversification and improved biodiversity provision (Perks et al., 2018). There are different types of agroforestry systems suitable in Scotland (Perks et al., 2018), with different benefits and variable opportunities for GHG emissions reductions.

Currently only 3.3% (551,700 hectares) of the utilised agricultural area in the UK is managed as agroforestry, with almost all classed as silvo-pastoral (den Herder *et al.,* 2015). Silvo-arable systems are rare, with only around 2,000 hectares in the UK; whilst 14,200 hectares are under 'high value' tree systems such as orchards (den Herder *et al.* 2015). As for the area of agroforestry in Scotland specifically, no documented evidence has been found. Social, cultural, regulatory, and financial barriers to woodland creation, including agroforestry, have been documented for the UK[4].

Carbon schemes, such as the Woodland Carbon Code (WCC), offer a potential route to provide financial support for agroforestry creation. To be incorporated into such a carbon scheme, the carbon sequestration benefits must be underpinned by robust evidence and carbon finance must be material in their economic viability.

This report reviews the available evidence for the potential of agroforestry systems to contribute to GHG reduction targets in Scotland. It also assesses the available evidence for the financial viability of agroforestry systems in the UK and Scotland, before integrating the findings.

4 Agroforestry

4.1 Agroforestry systems

Agroforestry is the integration of trees and agriculture on the same plot of land. These land use systems are more than just co-located as there are interactions between the components which can provide ecological and economic benefits.

There are many types of agroforestry systems in the UK, which can be grouped by both farm type and the spatial arrangement of the tree component:

The two main agroforestry types by farm system are:

- Silvo-pastoral – trees and/or shrubs are grown in grazed pasture
- Silvo-arable – trees and/or shrubs are grown alongside crops, often in rows

[4] Ambrose-Oji, A. (2019) Ambrose-Oji, B., Robinson, & O'Brien, 2019; Beauchamp & Jenkins, 2020; Lawrence *et al.,* 2010; Lawrence & Dandy, 2014; Lawrence & Edwards, 2013; Royal Forestry Society, 2020; Thomas *et al*., 2015)

The spatial arrangement of the tree component can be:

- Rows of trees – shelterbelts, riparian buffers, hedgerows, alley cropping, orchards
- Clustered trees – wood pasture
- Single trees – wood pasture

The planting arrangement will depend on the farm type and objective of the agroforestry system. Silvo-pastoral systems allow for more variable planting patterns, whilst silvo-arable systems often incorporate rows of trees in a wide spacing to allow the use of agricultural machinery. Shelterbelts and riparian buffers can be incorporated into both systems.

4.2 Agroforestry in Scotland

Whilst the exact area and type of agroforestry in Scotland is not known, Perks *et al.* (2018) conclude that most agroforestry in Scotland will be silvo-pastoral, consistent with the proportion evident for the UK as a whole, and because the predominate agricultural type in Scotland is pastoral (80% pastoral vs 9% arable; Scottish Government, 2016).

Site and soil conditions influence the farm system and also the tree species and management options for the tree component. In Scotland, whether the site is in the uplands or lowlands has a significant influence upon the Land Capability for Agriculture (LCA) type, current land-use and agroforestry system suitability (Perks *et al.* (2018). The carbon and economic benefits associated with agroforestry systems similarly scale to 'land class'.

Perks *et al.* (2018) outline the agroforestry systems suitable in Scotland. We also consider hedgerows (including bocages) and orchards alongside these in this evidence review:

- Woodland pasture grazing in the uplands. No stock exclusion. Predominately composed of conifer species. Silvo-pastoral.
- Woodland pasture grazing in the lowlands. No stock exclusion. Broadleaf species are more common, but they are also suitable for native Scots pine. Silvo-pastoral.
- Shelter belts in the uplands or lowlands (with stock exclusion). Often in poor condition due to lack of management. Silvo-pastoral.
- Buffer strips, including riparian buffers. Broadleaf species mixes should predominate. Silvo-pastoral
- Alley cropping. Rows of trees and crops, often high-value trees or woodfuel biomass. Silvo-arable
- Shelter belts. Provides soil conservation benefits. Silvo-arable
- Buffer strips, including riparian buffers. Predominately broadleaf species. Silvo-arable
- Hedgerows. Typically broadleaf and shrub species. Silvo-arable or silvo-pastoral.
- Bocage. Traditional mixed arable-woodland-hedgerow-pastoral agricultural systems typical of Brittany, France but can be solely silvo-arable or silvo-pastoral.
- Orchards. Fruit trees with permanent grassland or with pigs or poultry

4.2.1 Opportunity & constraints for agroforestry in Scotland

The available land area for each agroforestry type also influences its GHG reduction potential. As pastoral land has the greatest extent in Scotland, it can be assumed to offer the greatest opportunity for increasing agroforestry area in Scotland by land area. It is important to consider constraints on woodland creation, including peat soils, historic landscapes, and areas with biodiversity sensitivities in considerations of potential land area. In combination with economic viability, consideration of the social, cultural, and regulatory factors is also necessary.

5 The Potential for Agroforestry to Contribute to GHG Emissions Reductions

Agroforestry systems can provide a range of benefits, including carbon sequestration. In this section we summarise evidence of the GHG emissions reductions potential of the agroforestry systems, to evaluate their potential to contribute towards GHG reductions targets for land use in Scotland.

5.1 GHG emissions reductions, carbon storage & sequestration

Anthropogenic emissions of carbon dioxide and other greenhouse gases (GHGs) are a primary driver of climate change. Trees sequester and store carbon, reducing atmospheric carbon dioxide levels. Carbon storage refers to the amount of carbon stored per unit area, in this report values are reported in tonnes of carbon dioxide per hectare (t CO_2 ha^{-1}). Where available data was identified, soil carbon stock change is reported, though for some study systems (notably hedgerows) establishment disturbance losses are lacking; these are likely minimal as exemplar studies are on mineral soils. Positive values represent GHG removal and emissions reductions. We do not consider the carbon in wood products after harvest or the substitution benefit they provide 'beyond the farm gate'. This approach is consistent with the boundaries of the Forestry Commission Woodland Carbon Code.

5.2 Evidence for the carbon storage & sequestration potential of agroforestry systems

5.2.1 Hedgerows

In Perks *et al*. (2018) the suite of agroforestry options identified hedgerows and field boundary trees as potential contributory 'activity' in agricultural landscapes for carbon sequestration, but the assessment did not explicitly include estimates of hedgerow carbon. There is evidence for hedgerows to provide an 'agroforestry benefit' (Soil Association, 2018; Woodland Trust, 2014; Gregg *et al.*, 2021). The creation, restoration and management of hedgerows has been considered as an opportunity to increase carbon sequestration and storage in woody biomass on farms, with minimal impact on productive farm area (Crossland, 2015; Axe, 2020; Gregg, 2021).

Proposed interventions include the creation of new hedgerows on farm or field boundaries, widening existing hedgerows, restoration of degraded hedgerows through laying and planting gaps, and allowing hedgerows to develop into tree lines. Only hedgerow creation is considered in this review, as only new planting would be eligible under the Woodland Carbon Code (WCC). No studies of systems with standard trees within hedgerow elements were evident. We note that hedgerows do not meet the definition of woodland under the WCC, when considering canopy cover and stems per hectare, although the code could be expanded. Furthermore, a pilot project developing a Hedgerow Carbon Code is underway[5].

In most UK studies hedgerows are considered in agricultural landscapes at between 4% (200 m ha^{-1} at 2 m width), and 8% (400 m ha^{-1} at 2 m width) coverage so would not meet current regulations for inclusion in forestry grant aid schemes but may be covered by agricultural subsidies. However, per unit area the reviews evidence that whilst

[5] Proposed Hedgerow Carbon Code - Game and Wildlife Conservation Trust (gwct.org.uk)

hedgerows can make a carbon contribution in agricultural settings, this does not deliver comparable net GHG benefit as the same land would under new trees in woodland or agroforestry systems. Figure 5.1, adopted from Drexler *et al.,* (2021) mirrors closely the documentation and assessment of contribution that underpins woodland carbon credits within the WCC. Further details of published values are presented in Appendix 5, including reported values per unit length; values here are provided per hectare for comparison to woodland data.

UK studies show wide variations in carbon storage estimates in hedgerows, due to differences in hedgerow height, width, age, and management. Above ground biomass ranges from 91.7-476.7 t CO_2 ha^{-1} with a central range of 146.7-165.0 t CO_2 ha^{-1} (Axe 2015, 2017) and 172.4 ± 106.3 t CO_2 ha^{-1} (Drexler *et al.,* 2021) in a meta-analysis including shelterbelts, windbreaks and field margins. Lower estimates were from recently coppiced hedgerows (Axe 2020, Crossland 2015) and the upper estimate for very wide hedgerows up to 6m (Crossland, 2015). Above-ground biomass carbon stocks increased with years since the last coppicing and with hedgerow height (Drexler *et al.,* 2021). Hedgerow management has a significant impact on stored carbon, flailing removes above ground biomass, typically on a 3-year cycle, and hedgerows require laying or coppicing at around 25 years, see Figure 5.1. Management increases stem and branch density but constrains the overall carbon storage potential compared to open grown trees or woodland. Regular hedgerow management to gradually increase height is important to reduce knuckle formation and degradation in hedgerow condition, which would otherwise lead to thinning, gaps and a loss of stored carbon. See *The Hedgerow Management Cycle* by Nigel Adams.[6]

Hedgerows can accumulate a significant amount of below ground biomass, with regular hedgerow management promoting woody root and stump formation. Values of 49.5 – 160.6 t CO_2 ha^{-1} are reported by Axe (2020) and Crossland (2015). Hedgerow laying and coppicing to regenerate hedgerows conserves this below ground biomass.

Regular hedgerow management throughout the natural life cycle of the hedge promotes sequestration in soil organic carbon through increased fine root cycling. As with all soil sample values, the depth of the sample is a significant source of variation. Values of total soil carbon stock of 157 t CO_2 ha^{-1} are reported for a mineral soil (Axe 2017).

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[6] http://nigeladamscountrysidemanagement.co.uk/pdf/hedgelink-hedgerow-management.pdf

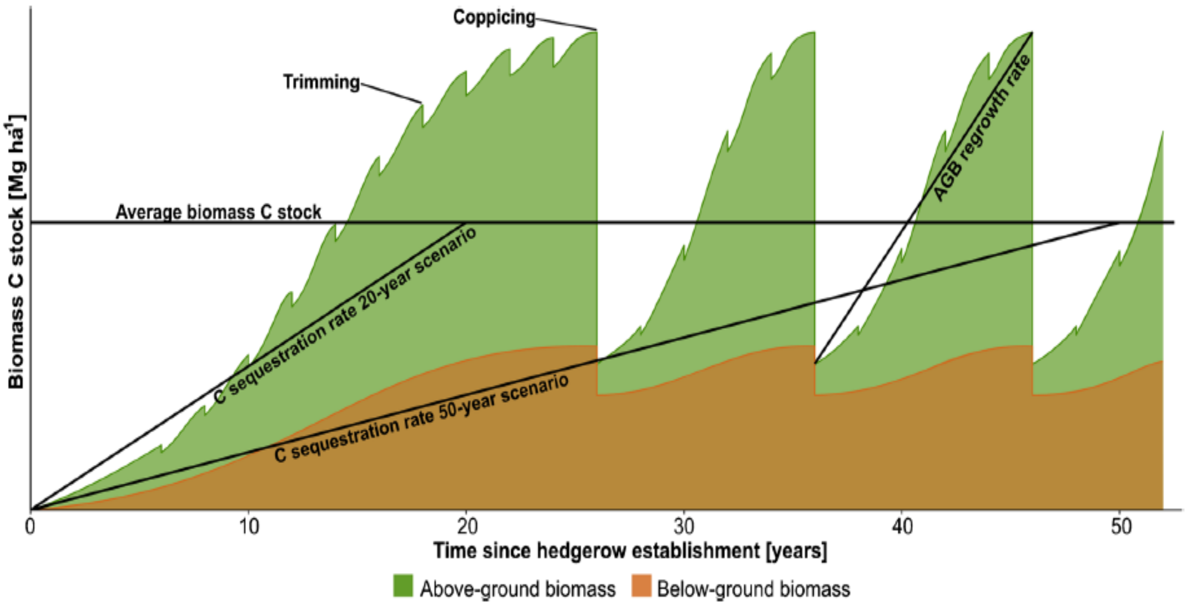

Figure 5.1: Graph illustrating the variation in above and below ground carbon storage and sequestration over the lifecycle of a typically managed hedge.

Figure 5.1 is reproduced from Drexler *et al.,* 2021 and shows the variation in above ground and below ground carbon storage and carbon sequestration over the lifecycle of a typical managed hedge.

Wolton (2014) reported the rate of carbon sequestration as 1.8 t CO_2 ha^{-1} yr^{-1} each for both above and below ground biomass, which is consistent with the value of 3.71 t CO_2 ha^{-1} yr^{-1} in above and below biomass combined reported by Axe (2015). Kay *et al.* (2018) studying East Anglian silvo-arable hedgerows estimated aboveground C accrual of ~0.73 t CO_2 ha^{-1} yr^{-1}, and more broadly in the European context (Kay *et al.* 2019) found a range in values of 0.37- 1.65 t CO_2 ha^{-1} yr^{-1}. Faloon *et al.,* (2004) estimated combined biomass and soil sequestration as 3.7 t CO_2 ha^{-1} yr^{-1}. Drexler *et al.,* (2021) calculated a SOC sequestration rate of between 1.1 (50-year scenario) and 3.3 t CO_2 ha^{-1} yr^{-1} (20-year scenario) for the establishment of hedgerows in silvo-arable systems. These values are confirmed by a SOC meta-analysis by Meyer *et al.* (2020) with alley-cropping (silvo-arable) and hedgerow systems accruing 1.17 ± 0.84 t CO_2 ha^{-1} yr^{-1} dependent on soil sampling depth, whilst Silvo-pastoral systems showed small losses of -0.62 ±0.11 t CO_2 ha^{-1} y^{-1}. Ford *et al* (2020) provide evidence from a study in Conwy, north Wales, that soil properties (gleyed or mineral soils) and the influence of seasonal summer droughts show hedgerow soils can become sources of soil CO_2 in dry summer conditions for gleyed soils [also see Appendix 5].

Reported values are broadly consistent, but there are a limited number of studies and a wide range of values. Further studies of carbon sequestration are needed to develop our understanding of the effects of management, site and soil conditions on hedgerow carbon storage and sequestration. There is minimal evidence relating to previous land use in hedgerow creation, or for the influence of arable or pastoral systems on hedgerow carbon balance. Published data are not available for the impacts of allowing hedgerows to develop into treelines or incorporating trees into hedgerows. There is an opportunity for future analysis to integrate data sources for open-grown or wider spaced trees.

Consideration of potential restriction on hedgerow creation is necessary on deep peat soils, on boundaries in areas with shared access such as common ground, where historic stone walls are prevalent and when land is managed under a Tenancy agreement.

5.2.2 Orchards

Orchards in the UK are dominated by fruit trees and can be described as either traditional or intensive. Traditional orchards consist of widely spaced trees on permanent grassland that may be grazed by livestock or cut for hay (Gregg *et al.*, 2021). Intensive orchards are densely planted with dwarf root stocks and the trees managed at low heights or as espaliers to promote fruit growth and ease of picking (Gregg *et al.,* 2021). The surrounding vegetation may be mown or managed with herbicides (Robertson *et al.,* 2012).

The different form, size and spacing of the trees between these systems influences their carbon storage and sequestration. Carbon storage is higher in traditional orchards (31.5 - 121.7 t CO_2 ha^{-1}) than intensive orchards (35.2 - 67.5 t CO_2 ha^{-1}) due to accumulation in woody biomass (Robertson *et al.,* 2012; Anthony 2013) whereas intensive orchards are managed to promote fruit, and limited by their short lifespan, it being 15–30 years before trees are replaced to maintain high levels of production (Anthony 2013; Demestihas *et al*., 2017). Conversely, Robertson *et al.,* (2013) estimate that intensively managed orchards accumulate carbon at higher rates in their biomass (3.2- 4.4 t CO_2 ha^{-1} yr^{-1}) than traditional orchards (0.43 - 2.6 t CO_2 ha^{-1} yr^{-1}). This is due to the significant amount of carbon removed from the system each year through the fruit harvest (40–70%) and through pruning, and the young age of trees, whereas some traditional orchards became net emitters due to reduced growth with age (Robertson *et al.*, 2013; Gregg *et al.*, 2021). Staton *et al*. (2022) estimated carbon benefits of up to 0.46 t CO_2 ha^{-1} yr^{-1} for apple intercropping in arable production system for four UK sites (in England) the majority of the carbon benefit being attributable to sequestration by trees.

The trends for soil carbon are similar, with traditional orchards storing higher levels of soil carbon than intensively managed orchards, due to minimal ground disturbance in traditional systems, compared to intensive systems which experience regular soil disturbance from the removal and replanting of trees (Robertson *et al.,* 2013). Intensive sites may accumulate carbon at greater rates (1.17–1.32 t CO_2 ha^{-1} y^{-1}), compared to traditional sites (0.11–1.91 t CO_2 ha^{-1} y^{-1}) (Robertson *et al.,* 2013) however due to the small amount of evidence and significant impact of site conditions and previous management this is inconclusive (Gregg *et al.*, 2021).

The carbon storage and sequestration potential of orchards is high per unit area (Demestihas *et al*., 2017), but the available agricultural area in Scotland is lower than elsewhere in the UK, as they are limited to sheltered sites and good soils. The GHG reduction benefits of traditional orchards is higher than many other agroforestry systems, reflecting the age of the trees and the accumulation of soil carbon, however, new orchards would likely be managed on intensive rotational systems and be subject to carbon caps, similar to thinned and felled forestry currently within the WCC. Orchards do not deliver the same level of GHG reduction as shelterbelts due to regular pruning and lower spacing. The substitution benefits of orchards are lower than systems where biomass and timber are produced. Orchards provide the additional benefits of fruit production, hay production or grazing for animals, including pigs and poultry (Gregg *et al.*, 2021).

5.2.3 Silvo-arable alley cropping

Palma *et al.* (2017) identified from a model-based approach a soil carbon accrual under silvo-arable systems of 0.46 t CO_2 ha^{-1} yr^{-1} under sparsely planted intercropping with poplar (77 stems ha^{-1}). De Jalon et al. (2018) estimated mean carbon sequestration in a silvo-arable system (determined only as carbon stored as timber) was 4.0 t CO2 ha-1 yr-1, and an increase in soil carbon at a depth of 20-40 cm of 2.82 t CO_2 ha^{-1} yr^{-1}, relative to the arable system was observed. However, the effect was not significant when greater depths were considered (Upson and Burgess, 2013). A separate comparison review which included an assessment of UK silvo-arable productivity (Crous-Duran *et al*. 2022) evidenced poplar providing 4.58 t CO_2 ha^{-1} yr^{-1}. Additional benefits were noted in terms of reduced nitrogen and phosphorous losses and decreases in soil erosion.

5.2.4 Silvo-pastoral

A recent study of a silvo-pastoral (ash-grassland) system on mineral brown earth soils in Northern Ireland showed that there was no change in near-surface soil carbon (0-20cm) though a switch to recalcitrant (stable) carbon forms in the soil was evident under widely spaced trees, when compared to the grass and woodland counterfactuals (Fornara *et al.* 2018). Across Europe, Cardinael *et al.,* (2018) evidenced carbon benefits of silvo-pasture (n=4) with average tree density of 225 (±126) stems ha^{-1}, estimating an above-ground carbon (biomass) accrual rate of 7.95 ± 0.95 t CO_2 ha^{-1} yr^{-1} and a below-ground (soil) carbon accrual rate of 2.05 ± 1.02 t CO_2 ha^{-1} yr^{-1}.

Wood pasture is a silvo-pastoral agroforestry system exemplified by single, widely spaced and often individually-protected trees, sometimes referred to as a type of 'Policy Woodland' these systems have not been studied for their carbon sequestration benefit. There have been some Scottish examples of this type of integrated land-use and assessments of the contribution of lone trees could be augmented through their study.

5.2.5 Shelterbelts, windbreak (Linear) forestry, and riparian plantings

There is no new evidence on the carbon storage or sequestration benefits of riparian plantings and silvo-arable or silvo-pastoral buffer strips. Perks *et al*. (2018) using model-based analysis showed these systems to have high carbon sequestration potential as they are often on good quality soils in lower elevation sites, especially riparian buffers. The value of biomass production in riparian strips is less likely to be realised due to the other benefits the woodland provides in terms of reducing nitrogen leaching, thereby enhancing water quality, but some selective thinning for local woodfuel is possible.

No further evidence has come to light in this review of the carbon or ancillary benefits of shelterbelts. These are common landscape features in improved and upland grazing for extensive beef and lamb production systems, where the carbon value is readily represented by standard forestry carbon accounting procedures.

5.2.6 Modelling

A number of papers discussed the development of agroforestry models, including Hi-SAFE (Dupraz *et al.,* 2019) and Yield-SAFE (Palma *et al.,* 2018) and Yield-SAFE coupled to the economic model Farm-SAFE (Garcia de Jalon, 2018). However, existing evidence on the carbon sequestration impacts of agroforestry is based on a disparate range of studies rather than systematic modelling. This compromises the extent to which all the findings can be compared as they will be specific to specific contexts and methodologies. Furthermore the development of the 'SAFE' models has focussed on silvo-arable systems so additional validation work for silvo-arable systems would be required to enable robust comparisons.

Follow up work could explore these models' suitability to effectively compare agroforestry systems in Scotland. Alternatively, additional climate responsive modelling of agroforestry systems may be considered through the application of common forestry models coupled to agricultural crop-growth models.

5.3 Summary of GHG emissions reductions by agroforestry system

Table 5.1 New collated evidence of the likely GHG contribution of agroforestry systems. Positive values represent GHG removal and emissions reductions.

Agroforestry System	ABG_C	BGB_C	SOIL C	Notes
	t CO_2 ha^{-1} (t C ha^{-1})	t CO_2 ha^{-1} (t C ha^{-1})	t CO_2 ha^{-1} (t C ha^{-1})	
Silvo-pastoral	210 - 267 (57.3 - 72.9)	-	30.8 - 92.4 (8.4 - 25.2)	Assumed 30-year horizon, ground occupancy of ~20%
Silvo-arable	121-137.5 (33.0 - 37.5)	-	84.7 (23.1)	Assumed 30-year horizon, ground occupancy of ~3%
Hedgerow	146.7-165 (40.0 - 45.0)	55-66 (15 - 18)	0.62-62.3 (0.17 - 17.0)	Central estimates (UK), Assumed 30-year horizon. NB actual ground occupancy will be around 4-8% (of quoted value).
Riparian / Buffer	-	-	-	No specific agroforestry data. Suitable data could be drawn from woodland studies
Orchards - Intensive	35.2-67,5 (9.6 - 18.4)		6.2 – 15.0 (1.7 - 4.1)	

ABG_C = above ground biomass carbon stock
BGB_C = Below ground carbon biomass stock
SOIL_C = soil carbon stock

In contrast, newly created woodland could sequester 120 to 330 tonnes of CO_2 per hectare over a 30-year period, with the lowest values in the range from lower-yielding broadleaves, and the highest values from fast growing Sitka spruce stands (Gregg *et al.*, 2021).

5.4 Conclusions on GHG emissions reduction by agroforestry

In this review we have identified papers citing additional empirical values for carbon storage and sequestration in agroforestry systems since the review by Perks *et al.,* (2018). We have included a review of evidence for orchards and hedgerows. There is no new evidence on the carbon storage or sequestration benefits of silvo-arable or silvo-pastoral buffer strips or shelterbelts. There are no specific agroforestry data available for riparian buffer strips. Suitable data could be drawn from woodland studies to evaluate both shelterbelts and riparian buffer strips, as more evidence is available for woodland systems.

All systems report net sequestration over the lifecycle of the system, when avoiding organic soils. Short periods of GHG emissions are reported, including following soil disturbance at establishment, which should be kept to a minimum, and during periods of drought or age-related decline. The carbon balance is also impacted by the use of the woody biomass harvested at the end of the rotation, or cyclically in the case of hedgerow management, which are not considered within the scope of this synthesis report.

Comparison of the ability of different agroforestry systems to sequester and store carbon in Scotland is hampered by the small number of studies, the majority of which are located in England, and the wide range and variation in values and the lack of models to enable systematic analysis across different types of agroforestry. Intensively managed Orchards have the lowest potential to store carbon based on the available evidence. Hedgerow values presented are per hectare of hedge, therefore values per hectare of field or farm would be lower. Shelterbelts, silvo-pastoral, and alley cropping systems are relatively higher. We note the relatively high soil carbon storage values for all agroforestry systems.

In all instances, agroforestry systems in Scotland would be unlikely to reach the reported values, due to climatic differences between the case studies in England, especially for systems including broadleaved tree species.

There are insufficient data and studies to apply these values across a range of climatic, soil and site properties. Comparative data could be drawn from equivalent woodland studies. We expect the site carbon sequestration potential of agroforestry systems to broadly mirror the findings for extensive forestry systems reported by Matthews *et al.,* (2020) in that better LCA classes of land, with better soils, will provide the most significant benefits in terms of GHG reduction through high carbon sequestration by tree components. On poorer quality upland soils, especially those soils of ‘peaty’ organo-mineral composition, net benefits from agroforestry will be unlikely to accrue for decades where options involve ground disturbance at planting coupled with low productivity tree species.

The available land area for each agroforestry type also influences its GHG emissions reduction potential. A brief consideration of potential in Scotland is presented in section 7, whilst a full evaluation is outside the scope of this report.

5.4.1 Time horizon (short vs. long term GHG emissions reductions)

As with forest systems, agroforestry carbon storage and sequestration values change with time since establishment, and following management interventions such as thinning, pruning or harvesting. In the short term there may be an initial loss of carbon due to soil disturbance, which is recovered in the soil, below ground biomass and above ground biomass over time. In systems where wood products are harvested, stored carbon is moved into harvested wood products.

5.4.2 Substitution effects

Harvested wood products may offer GHG emissions reductions through substitution benefits, by replacing more energy intensive products in construction, manufacture, and energy provision. Broad categories include wood fuel or woody biomass for heat and energy, and timber for construction. We do not consider the carbon stored in wood products after harvest or the GHG emissions reductions substitution benefits they provide on the farm or ‘beyond the farm gate’, but we note some key considerations. Agroforestry systems which undergo regular management such as thinning of trees or flailing of hedgerows, will produce biomass through the lifecycle, whereas unmanaged systems will not be harvested for biomass until the end of their rotation or natural life. Regular hedgerow management produces small diameter cuttings, which have a low GHG substitution effect compared to timber, as do small diameter thinnings. The consideration of substitution effects would alter the GHG emissions reduction benefits in favour of higher yielding conifer species, although the smaller scale of agroforestry and increased exposure of some agroforestry systems, such as shelterbelts, reduces the growth rate and viability for timber, in relation to commercial forestry, and instead the benefits provided support longer-term retention.

5.4.3 Reduction in agricultural emissions

Whilst not evaluated in this report, where woodland creation, including agroforestry, results in reduced stocking density, there are immediate and significant GHG reduction benefits. In estimating the GHG benefit of agroforestry options, the counterfactual land use is an important component in considering net benefit. Approaches to evaluate the net benefit of adopting agroforestry systems have highlighted the importance of other ecosystem service benefits and highlighted potential frameworks for deriving ecosystem service valuations and Natural Capital Accounting (NCA) to agroforestry decision-making at the farm scale. In some cases, this saving in emissions is equal to or significantly greater than the carbon storage in the forest component (ERAMMP, 2020). This analysis is outside the scope of the report but should be considered in a full assessment of agroforestry systems, in particular alongside the initial years following establishment where stored carbon values are at their lowest, and in comparison to long term woodland creation. There is potential for woodlands to increase the area of land available for livestock grazing, as once the woodland component is established it can provide shelter in exposed areas.

6 Economics of agroforestry

The current state of knowledge in this fast-developing area of forestry economics is still partial and incomplete. This report aims to contribute to a better understanding of the economic viability of agroforestry. Further details on the scope of the review and methodology applied are given in Appendices 1 and 2 respectively.

6.1 Definitions of economic and financial viability

While the terms ‘economic’ and ‘financial’ may be considered by some to have equivalent meanings, for the purposes of this report, we interpret them as distinct. We take the former to be a broader term which includes financial matters but also other economic concepts such as externalities. This means, for example, that an agroforestry practice can be economically viable without necessarily being financially viable. ‘Economic’ thus encompasses 'financial' and is not used interchangeably in this report. Furthermore, we interpret ‘financially viable’ in this evidence review to mean a positive value of net income (where net figures are not available, gross income is used instead). This means if a farmer’s net income from a particular land use system at a particular time is negative, the system is determined to be not financially viable. Lastly, we consider financial viability of the tree and agricultural system components of agroforestry in a combined manner as opposed to the viability of the two components individually.

6.2 Evidence on financial viability of agroforestry

Our review found studies spanning the diversity of agroforestry practices described in Section 4. These studies employed various methodologies and financial performance indicators across a range of different time horizons, with some financial indicators being used more commonly than others. Table 6.1 below contains a full list of these indicators ordered by the number of studies using them. The indicators are described in the Glossary in Section 2 of this report. A focus on different measures of financial returns in different studies hampers a detailed comparison across studies. Nevertheless, we compiled evidence from across these heterogenous studies to investigate the financial viability of individual agroforestry systems.

Table 6.1: List of financial indicators used across the reviewed studies ordered by the number of studies explicitly using them

Financial performance indicators	No. of studies explicitly using them
Net Present Value (NPV)	8
Gross Margins/Income	6
Net Margins	6
Equivalent Annual Value (EAV)	6
Infinite Net Present Value (iNPV)	5
Internal Rate of Return (IRR)	1
Annuities	1
Multicriteria Decision Analysis (MCDA) Performance Rank	1
Net Financial Benefits of Biomass Production	1
Net Ecosystem Service Value	1
Real Options Analysis Value	1

The following sections contain high-level summaries of the evidence identified, organised by geographical region. We first examine studies which cover the UK, either solely or inclusively. This is followed by studies which focus on neighbouring countries in North-West Europe determined to have compatible climates, be it at present or in the future. A summary table (Table 6.2 in Appendix 1) consolidating the most important aspects of the studies reviewed is provided to aid with summary of findings.

6.2.1 Financial viability in the UK

Examining studies covering the UK, we found strong evidence that agroforestry is, in general, financially viable. That is to say we found that agroforestry systems by themselves largely tend to generate positive net income for farmers. However, we identified several factors that create exceptions and add qualifications to this, and that also altered the degree to which agroforestry is financially viable when compared to conventional agriculture and forestry. These include the time horizon in consideration, the extent to which farmers can receive payments for ecosystem services for the wider societal benefits from agroforestry, as well as context specific elements. The following sub-sections explain these factors in turn, highlighting how financial viability of agroforestry changes with each of them.

Time Horizon: short vs. long run income

Staton *et al.* (2022) modelled and compared income generated from a 16 ha hypothetical apple orchard intercropping system with that from equivalent conventional arable systems, both of which received subsidy payments. They found that the agroforestry system had negative cash flows in the initial years whilst the non-agroforestry system did not. This was due to additional establishment costs and a time-lag in returns from apples incurred by the agroforestry system.

In contrast, by the end of the 20-year modelled period, cash flows from the orchard system became not only positive, but also greater than the arable system in most of the modelled scenarios. This is regardless of whether data inputted into the model was theoretical (83% of cases) or empirical (75.7% of cases). This greater level of income was possible either within 7-14 years (theoretical data) or an average of 17.8 years (empirical data) according to the model estimations. These findings therefore suggest that orchard intercropping systems are financially viable in the longer term and supports the need to subsidise upfront establishment costs.

Findings of additional establishment costs within agroforestry systems are, however, not limited to orchard intercropping systems (see section 6.2.2). For instance, Lehmann *et al.* (2020) found additional establishments costs in relation to the tree component of an alley cropping system, which lowered the overall gross margin of the whole system.

Internalisation of agroforestry benefits: payments for ecosystem services

Many of the studies reviewed examined the financial viability of agroforestry from not only farmers' perspectives, but also through that of society. This was done by accounting for ecosystem service benefits from agroforestry to society at large. The premise being that the financial viability of agroforestry for farmers may improve if such benefits, which are well documented in the literature, can be internalised (i.e., 'cashed-in') by farmers. This internalisation can be in the form of Payments for Ecosystem Services (PES) or provision of public money for public goods, and is in essence the finding from several of the studies reviewed.

Estimating financial viability from the perspective of a farmer on a 3.5ha farm in Bedfordshire over 30 years, García de Jalón (2018) found that a conventional arable system was more financially viable than both a poplar silvo-arable and a pure forestry system. This was the case by a factor of approximately 2.6 and 5.1 respectively, regardless of whether agricultural or forestry grants were available. Kaske *et al.* (2021), who also studied a 30-year, poplar silvo-arable system located in Bedfordshire but in a different site using similar financial indicators found the same pattern of results. The conventional arable system was again the most financially viable, followed by the poplar silvo-arable and pure forestry system. While the authors do not explicitly acknowledge this, these findings are likely due to the additional costs associated with agroforestry highlighted in the previous subsection, which reduces the net income of the agroforestry systems.

Adopting a different financial assessment whereby farmers' incomes are proxied using monetary valuations of biomass produced instead of measured through capital budgeting, Kay *et al*. (2019) also arrived at similar findings. The authors studied a variety of agroforestry systems, covering both silvo-arable and silvo-pastoral ones across several Atlantic and Continental countries. These include hedgerow-arable systems in UK, France, and Germany; wood pastures and orchards in Switzerland; as well as 'soutos', which are traditional Iberian chestnut orchards (Kay *et al.*, 2018), in North-West Spain. The results showed that the net financial benefits of the non-agroforestry systems to farmers were, on average, higher than the agroforestry counterparts by a factor of approximately 1.3. These smaller differences in financial viability compared to those identified above in García de Jalón (2018) and Kaske *et al.* (2021) are likely due to differences in empirical methodologies adopted. Notwithstanding, these findings suggest that agroforestry systems, particularly the types mentioned above, are generally less financially viable than non-agroforestry ones when examining them purely from a farmer's perspective. It is important to note, however, that while they are relatively less financially viable, the studies found them to be nevertheless financially viable.

Looking instead from a societal perspective and including monetised ecosystem service benefits from agroforestry in the financial assessments, García de Jalón (2018) and Kay *et al*., (2019) found that the economic performance of agroforestry becomes as good as, if not better than, non-agroforestry practices. These two studies, however, included estimations of values for a range of benefits which farmers do not currently get paid for directly (e.g., reductions in soil erosion). They therefore arguably do not currently provide the best representation of the possibilities for farmers to internalise external agroforestry benefits through PES.

Nevertheless, Kaske *et al.* (2021) demonstrate that even the inclusion of only carbon related monetary benefits and drawbacks in farmers' cash flows can make silvo-arable systems more financially viable than conventional arable systems. This only held true if financial assessments adopted carbon values calculated by the UK Department for Business, Energy & Industrial Strategy (DBEIS) and not current market carbon prices. A similar finding was also obtained by Abdul-Salam, Ovando, and Roberts (2022) who also incorporated carbon payments in assessing the financial viability of sheep and cattle silvo-pasture systems in Aberdeenshire. The authors found that it is only financially optimal to switch from an initial land use of conventional agriculture to a silvo-pasture if market carbon prices are significantly higher than 2020 EU Emissions Trading System price of £30/tCO_2. For the hill sheep system investigated, prices needed to be higher by a factor of at least 12; whilst for the low ground cattle and sheep system, a factor of at least two.

These findings point to major policy needs in terms of developing more robust and comprehensive PES systems. With such systems, wider non-market benefits from agroforestry can be better internalised by farmers, allowing for agroforestry to become more financially viable and thus economically appealing (Jordon *et al*., 2020).

Context specific elements

A number of context specific elements affected the financial viability of agroforestry across the studies reviewed. As the name suggests, these elements are specific to the agroforestry practices being considered and the associated financial assessments conducted. They can thus vary from one context to another, and they include the following:

- **Diversity and value of arable crops planted**. In their cross-country studies comparing alley cropping systems in UK (Suffolk) and Denmark (Taastrup), Lehmann *et al.* (2020) and Smith *et al.* (2022) found that annual gross margins per hectare in the two systems were positive. However, the Suffolk site observed much higher margins of approximately 45 times that of the Taastrup site. The authors identified this difference to be mainly caused by a combination of higher diversity of crops and crops which were higher in value being planted in Suffolk.
- **Type of business used to manage an agroforestry system**. This finding was derived from Burgess *et al.* (2017) who compared a silvo-pastoral sheep-apple system in Herefordshire with an alternative scenario where the two individual components are separately managed. While the analysis found that the agroforestry system generated higher gross margins, this gap in margins was

larger when the system was managed by a single business entity as opposed to two. A single business refers to when one entity owns the orchard and pasture solely. In contrast, a dual-entity business refers to when two entities separately own the two components but mutually agree to form an agroforestry system. Furthermore, the analysis also showed that the positive income from the single business agroforestry system was much less susceptible than the dual entity one to any reductions in apple yields caused by use of agroforestry.

- **Prices of agroforestry outputs and costs of inputs.** As with any conventional agricultural or forestry land use, a farmer's net income from agroforestry is affected by both the prices at which their output is sold, and the costs incurred for certain inputs. For example, Yates *et al.* (2007) demonstrate that the financial outcome of a poultry silvo-pasture system in Oxfordshire was highly sensitive to the price of broilers achievable, as well as the costs of chicks and their feed. Although their financial model found that the silvo-pasture can generate a much higher internal rate of return than conventional alternatives, this outcome could easily change when the above prices and costs change. Such a finding is supported by the above study by Burgess *et al.* (2017). Specifically, the authors found that the price obtained for hay produced and the costs of fences purchased can render the agroforestry option relatively less financially viable.

It is important to note that the elements identified above are not exhaustive. Other existing evidence reviews investigating the financial viability of agroforestry such as Doyle & Waterhouse (2007) and Jordon *et al.* (2020) cover some of these elements, but they also highlight the existence and importance of others. These include elements such as the discount rate chosen for financial analyses, the assumptions made about intercrop productivity, and farm site conditions.

6.2.2 Financial viability in neighbouring north-west European countries

Examining studies focusing on neighbouring countries, we found very similar patterns of findings on the financial viability of agroforestry to those identified from UK-based studies. Financial viability is again positive in general and affected by time horizon. In addition, the degree of financial viability is similarly affected by the same factors outlined in the previous section, but an additional context specific element of grant availability was identified. The following subsections illustrate this.

Time horizon:short vs long run income

We identified two studies supporting the findings of Staton *et al.* (2022) and Lehmann *et al.* (2020) described above. One of them is Böhm *et al.* (2011), who compared an alley cropping system to conventional arable and short rotation coppicing (SRC) systems in Brandenburg, Germany; all of which received no subsidies. The authors found that over a 24-year period, while the cash flows of all three systems were negative in the beginning, those of the SRC and alley cropping system were more negative by a factor of more than three. Furthermore, these negative cash flows persisted much longer for the latter two systems than the conventional arable system, lasting at least 8-12 years as opposed to only four.

The other study identified is Sereke *et al.* (2015), who compared tree-crop (silvo-arable) and tree-grass (silvo-pasture) systems with monoculture crop and grassland systems in the Swiss Plateau over a period of 60 years. These systems, unlike in Böhm *et al.* (2011), all received different direct payments specific to the systems themselves. While not the study's main findings, the financial estimates indicated negative income values after the first 10 years for 35% of silvo-arable scenarios modelled. This was not the case after the first 30 and 60 years, with income found to be positive for 100% of silvo-arable scenarios. These two studies therefore reinforce the finding that agroforestry tends to be less financially viable in the short run and more so in the long run.

Internalisation of agroforestry benefits: payments for ecosystem services

While we identified relatively few non-UK-inclusive studies investigating the potential for ecosystem service benefits from agroforestry to be internalised by farmers, we nevertheless found some relevant evidence. In the aforementioned study by Sereke *et al.,* (2015), the authors also included in their analysis scenarios where agroforestry farmers either did or did not receive ecological direct payments equivalent to ecosystem service benefits from agroforestry either being internalised by farmers or not. The results showed that in scenarios where no ecological payments were obtained, agroforestry was not always more financially viable than the monoculture systems. In contrast, when ecological grants were obtained (i.e. when farmers could 'cash-in' on agroforestry related ecosystem service benefits to society), agroforestry was always the most financially viable land use option.

Besides that, Palma *et al.* (2007), who studied silvo-arable systems in the Netherlands and France, also obtained findings which somewhat support this, albeit through a less conventional ranking methodology. Their findings showed that when ranking different agricultural options by financial indicators alone, silvo-arable systems ranked lower than conventional arable ones in the Netherlands. However, when ranking them by an integration of financial and environmental indicators, silvo-arable systems ranked the highest. As for France, although silvo-arable systems were found to rank the highest even when ranking by financial indicators alone, the gap in rankings between agroforestry and non-agroforestry systems grew larger when ranking by a combination of financial and environmental indicators. These findings may not directly prove the case at hand, but they essentially support the notion that enabling farmers to internalise wider agroforestry related ecosystem service benefits can make agroforestry more financially viable.

Context specific elements

Several of the studies described so far in this section produced findings which demonstrate the importance of context specific elements in determining the financial viability of agroforestry. Böhm *et al.* (2011) found that when using average, German-wide wood chip prices in their financial assessment, alley cropping became more financially viable than the conventional arable system by the end of the modelled production cycle. This was not the case if Brandenburg-specific prices, which are lower, were used.

In addition, Palma *et al.* (2007) found that when specifically comparing different options of silvo-arable systems in France, those that contained higher-value or faster-growing tree species tended to be relatively more financially viable. This finding was corroborated by Graves *et al.* (2007) who also studied silvo-arable systems in France and found their relative financial viability to very much depend on whether the tree species used was poplar, walnut, or cherry. These findings therefore reiterate the significance of agroforestry output prices and the value of crops planted in influencing the financial viability of agroforestry.

One additional context specific element illustrated by Graves *et al.* (2007) which was not heavily studied in the UK-specific studies reviewed is the availability of grants to farmers. Through modelling, the authors found that silvo-arable systems were generally more financially viable than conventional arable systems in a no-grant scenario in both France and the Netherlands. However, when grants under the EU Common Agricultural Policy

(CAP) were in place in both countries, silvo-arable systems became less financially viable in comparison.

These findings are in contrast with those from Xu *et al.* (2019) who found no impact of the availability of EU green payment grants on a combined food and energy (CFE) silvo-arable system in Denmark. The study showed that, regardless of whether such grants were included in calculations, the CFE system was the most financially viable when compared to a wheat monoculture and short rotation woody crop system.

While these two studies do not provide a like-for-like comparison, they nevertheless illustrate how the availability of grants, and their inherent nature, can potentially affect the financial viability of agroforestry in the UK. A case study by Morgan-Davies *et al.* (2008) on a hill sheep agroforestry system in West Perthshire, Scotland provides some evidence on this, with the agroforestry system found to be financially viable only with subsidies. Further detailed discussions of the impacts of grants on financial viability is, however, out of the scope of this report. Further research on this is therefore warranted for findings to be made clear. This is especially the case given the on-going replacement of EU CAP rules following Brexit (Marshall and Mills-Sheehy, 2022)

6.3 Financial viability of individual agroforestry systems

Following our discussion of the findings on financial viability of agroforestry as a whole, this section examines the findings on financial viability for each of the individual agroforestry systems and types outlined in Section 4. Table 6.3 (in Appendix 2) provides a summary of these findings.

The agroforestry system with the most coverage across the studies reviewed was alley cropping, with nine studies focusing on it. This is followed by upland wood pastures (four studies); silvo-pastoral and silvo-arable orchards (three studies each); and lowland wood pastures (two studies). The systems with the least coverage were silvo-arable hedgerows and bocages, with one study each. No study within the review on financial viability covered shelterbelts, buffer strips, or silvo-pastoral hedgerows.

Overall, we found virtually all agroforestry systems to be financially viable in the long term. Only alley cropping was found to have scenarios whereby income from the system was negative. These were two specific scenarios, one each in Smith *et al.* (2022) and Graves *et al.* (2007). Smith *et al.* found the annual net margins of an alley cropping system in Denmark to be negative, whereas Graves *et al.* found negative EAVs for a walnut silvo-arable system in the Netherlands specifically in a no grant and pre-2005 CAP scenario. In the former, however, the authors acknowledge that the financial assessment lacked a temporal dimension as it only covered a time horizon of one year. Given the findings discussed in the previous section on the importance of the time horizon on financial viability, this finding is arguably not a good representation of the financial potential of the system. Similarly for the latter, only a single walnut silvo-arable site in the Netherlands was used for financial assessment, and findings may change if several sites were used instead. These two specific exceptions of negative income are therefore eclipsed by the majority finding of positive income from the agroforestry systems reviewed.

As for the financial viability of agroforestry systems relative to conventional arable and forestry systems, the overall evidence is less conclusive. No single agroforestry system had unequivocal evidence of the system being definitely more or less financially viable. Instead, the systems were less financially viable in certain circumstances but more financially viable in others. These circumstances are discussed throughout Sections 6.2.1 and 6.2.2, as well as noted in Table 6.2 (in Appendix 1) for each of the studies.

6.4 Summary of economic findings

6.4.1 Financial viability of agroforestry alone

Our review found strong evidence that agroforestry is generally financially viable for farmers, both in the UK and in neighbouring countries of North-West Europe. Of the seven agroforestry systems covered within the reviewed studies, we found evidence of six of them being financially viable. These six were wood pastures (both lowland and upland), orchards (both silvo-arable and silvo-pastoral), hedgerows, and bocage systems. Only one of the seven systems, alley cropping, was found to have scenarios where the system was not financially viable. These scenarios were, however, specific, and present in only two of seven studies. Thus, barring these scenarios, the evidence we reviewed suggests that agroforestry is financially viable, particularly when considering the seven systems reviewed and when relatively longer time horizons are considered.

6.4.2 Financial viability of agroforestry relative to non-agroforestry land uses

As for the financial viability of agroforestry relative to conventional agriculture and forestry systems, we found that all seven agroforestry systems covered could potentially be more, and if not the most, financially viable. Such outcomes were, however, found to be dependent on various factors. These include:

- the time horizon in question,
- extent to which farmers can receive PES for wider societal benefits, and
- context specific elements.

In the short run, agroforestry systems tended to negative cash flows and hence were relatively less financially viable than conventional agriculture systems. This is due to high initial establishment costs and a delay in income from biomass, timber, or fruit production. In contrast, the same systems often become more viable than conventional agriculture systems in the long run.

Several of the studies also illustrated how agroforestry systems can only become more financially viable than conventional agriculture if PES are made available to farmers. The rational is that agroforestry provides various ecosystem services which benefit society, but such benefits are not currently a part of farmers' incomes. Therefore, by enabling farmers to 'cash-in' on such benefits, agroforestry is likely to become more financially viable than conventional agriculture.

Lastly, we found relative financial viability to be sensitive to various context specific elements which varied across studies. These include the inherent value of crops and tree components, the business model adopted, as well as the prices of outputs and costs of inputs.

Of the 15 empirical studies on financial viability reviewed (Table 6.2 in Appendix 1), the top four financial indicators most used in assessing financial viability were capital budgeting related. These were NPV, gross margins, net margins, and EAV; all of which were used in at least 6 of the 15 studies. Even though all the 15 studies involved a time dimension in them, only 5 explicitly investigated differences in financial outcomes across time. Of these 5 studies, 4 produced findings indicating that agroforestry is not financially viable in the short run but is so in the long run. Lastly, 6 of the 15 studies investigated the idea that agroforestry is more financially viable when wider ecosystem service benefits are accounted for; and of these 6, all of them found evidence in support of this notion.

7 Evidence synthesis & discussion

7.1 Integration of evidence

Table 7.1 provides an integrated summary of our findings on the overall GHG reduction potential and economic viability of agroforestry systems in Scotland. The GHG reduction potential per unit area of each system is given along with the potential land area and combined to present the mitigation benefit for Scotland. The degree of overall financial viability for each agroforestry type in the final column of Table 7.1 is determined based on a combination of factors. These include the number of studies reviewed, the financial outcomes identified in those studies, and the general quality of the studies' findings.

Barring the agroforestry types which were not covered within the evidence found on financial viability, we deemed all agroforestry types except silvo-arable hedgerows to have a medium degree of overall financial viability. This is because scenarios where they were relatively more financially viable were virtually always dependent on various conditions holding true (Section 6). As for silvo-arable hedgerows, we assigned a low degree of overall financial viability. The reason being that not only did scenarios of it being relatively more financially viable depend on various conditions, but there was also only one study covering the system and it used a more theoretical monetary valuation approach.

Table 7.1 : Integrated Summary of GHG reduction potential and economic evidence of financial viability of agroforestry in Scotland

Agroforestry System		**GHG Reduction Potential**					**Economic Viability**
Farm System	**Agroforestry Type**	**Upland or Lowland**	**Conifer or Broadleaf**	**Land Area in Scotland**	**Mitigation Benefit/ unit area**	**Potential Mitigation Benefit for Scotland$^{\Sigma}$**	**Evidence of Overall Financial Viability**
Silvo-pastoral	Woodland Pasture	Uplands	Conifers	H	M	M	M
Silvo-pastoral	Woodland Pasture	Lowlands	Broadleaf/ S. pine	M	M	M	M
Silvo-pastoral	Shelterbelts	Both	Both	H	M-H	M-H†	No Evidence
Silvo-pastoral	Buffer strip	Both	Broadleaf	H	L-H	L-M†	No Evidence
Silvo-arable	Shelterbelts	Lowlands	Both	L	H	M-H	No Evidence
Silvo-arable	Buffer strip	Lowlands	Broadleaf	L	M-H	M	No Evidence
Silvo-arable	Alley Cropping	Lowlands	Broadleaf	L	H	L	M
Silvo-pastoral	Hedgerows	Both	Broadleaf	H	L	M	No Evidence
Silvo-arable	Hedgerows	Lowlands	Broadleaf	L	L	L	L

Agroforestry System		GHG Reduction Potential					Economic Viability
Farm System	Agroforestry Type	Upland or Lowland	Conifer or Broadleaf	Land Area in Scotland	Mitigation Benefit/ unit area	Potential Mitigation Benefit for Scotland$^{\Sigma}$	Evidence of Overall Financial Viability
Silvo-pastoral	Orchards	Lowlands	Broadleaf	L	M	L	M
Silvo-arable	Orchards	Both	Broadleaf	L	M	L	M

H = High level, M = Medium level, L = Low level

† Note that carbon benefits reduce in uplands.

* Note that the upland/lowland and conifer/broadleaf classifications only apply to the findings on GHG reduction potential and not on economic viability

Σ This is a qualitative judgement based on land area and mitigation benefit

Overall, a combination of our findings on GHG reduction and economic viability suggests there is reasonable evidence for silvo-pastoral woodland pastures ('sheep and trees') to be the most suitable agroforestry system for contributing to Scotland's GHG reduction targets, though the GHG mitigation benefit scales with planting density and is strongly influenced by the yield (productivity) class of chosen tree species and soil carbon content. Shelterbelts are another option for silvo-pastoral management and likely return higher GHG mitigation benefit per hectare. Not only are silvo-pastoral systems potentially more financially viable than silvo-arable systems, pastoral systems also currently occupy a relatively high amount of Scotland's land area. It is important to note, however, that this finding is purely based on metrics of economic viability and GHG reduction potential. Inclusion of other metrics on the various ecosystem service benefits from agroforestry highlighted above may alter this outcome.

7.1.1 Potential land area

The available land area for each agroforestry type also influences its potential GHG reduction potential. As silvo-pastoral land has the greatest potential extent in Scotland, it can be assumed to offer the greatest opportunity for increasing agroforestry in Scotland by land area. However, as evidenced by Matthews *et al.* (2020) the prevalence of organo-mineral soils in upland agriculture provides significant additional constraints on the carbon mitigation potential of less productive species and/or lower density planting. Perks *et al.* (2018) noted that silvo-arable agroforestry systems were not eligible for grant aided support, except for small woodland options, whilst silvo-pastoral shelterbelts offer high potential benefits currently grants are restricted to LCA classes 3.1-4.2 inclusive. It is also important to consider constraints on woodland creation, including peat soils, historic landscapes, and areas with biodiversity sensitivities in considerations of potential land area. Social, cultural, regulatory, and financial barriers to woodland creation, including agroforestry, have been documented for the UK (Ambrose-Oji, A. (2019) Ambrose-Oji, B., Robinson, & O'Brien, 2019; Beauchamp & Jenkins, 2020; Lawrence *et al.,* 2010; Lawrence & Dandy, 2014; Lawrence & Dudley, 2012; Lawrence & Edwards, 2013; Royal Forestry Society, 2020; Thomas *et al.*, 2015).

7.1.2 Payment for ecosystem services

Approaches to evaluate the net benefit of adopting agroforestry systems have highlighted the importance of other ecosystem service benefits and highlighted potential frameworks for deriving ecosystem service valuations (Kay *et al.* 2017) or Natural Capital Accounting (NCA) approaches to agroforestry decision-making at the farm scale (Marais *et al.* 2019). Studies by Kay *et al.* (2018) report that ecosystems services were more abundant in all agroforestry landscapes in comparison to agricultural (mainly arable) ones. Where soil loss is of particular concern for arable systems (e.g. Moray Firth, East Lothian) then adoption of silvo-arable systems may help ameliorate soil loss. Agroforestry systems can enhance the resilience of agro-ecosystems towards climate change. For agroforestry systems not suitable under the WCC, other carbon codes or routes to provide payments for ecosystem service benefits could be considered. A pilot project to develop a UK Farm Soil Carbon Code is underway, led by the Farming and Wildlife Advisory Group South-West (FWAG) and funded by the Environment Agency[7].

Hardacre *et al* (2021) identified that agroforestry as a land-sharing strategy provides high levels of in-situ ecosystem service benefits, whereas land-sparing strategies (full afforestation options) are likely to require consideration of livelihood shifts for land managers. Farmers, landowners and other stakeholders perceive environmental factors such as biodiversity and soil conservation as positive aspects of agroforestry systems in temperate regions, while cashflow and management costs are seen as negative factors (García de Jalon *et al.*, 2018).

Our findings on the economic viability of agroforestry systems are strongly interlinked with our findings on their GHG reduction potential. Given that one of the major factors identified to improve the financial viability of agroforestry systems is the ability for farmers to ‘cash-in’ on wider ecosystem service benefits, strong GHG reduction potentials strengthen the case for agroforestry related PES, particularly carbon PES, to be developed.

Besides that, our findings also indicated that the time profile of costs and benefits is an important factor and is worse from the landowner’s perspective for agroforestry in comparison to conventional agriculture. That is, agroforestry often involves large upfront costs of tree planting and establishment whilst benefits and gains often appear significantly later (after 15 to 20 years). This negative factor could again be partially alleviated by PES schemes, be it carbon related ones such as the Woodland Carbon Code (WCC), or ones related to other ecosystem services such as Biodiversity Net Gain (BNG). In fact, Giannitsopolous *et al.* (2020) find that if multiple ecosystem benefits from agroforestry are considered as packages instead of separately, the threshold by which agroforestry can be more financially viable can be lowered further. Nevertheless, the idea here is that negative cash flows incurred by farmers in the early stages of an agroforestry system can then be somewhat eliminated early on (e.g., after verified tree establishment).

7.1.3 Financial sensitivity and uncertainty

It is worth noting that although the studies on financial viability reviewed are mostly from the past decade, and hence relatively recent, findings on financial viability will likely continue to change in the future for a few reasons. Firstly, there is the ongoing phaseout of the CAP in the UK following Brexit. The uncertainty in the specificities of agricultural policies and grant schemes in the devolved countries as a result of this (Marshall and

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Mills-Sheehy, 2022) will likely have an impact on future financial assessments. Whether the effects are positive or negative will depend on factors such as the level of grants associated with agroforestry and conventional agriculture in the coming years.

Secondly, there has been a significant increase in UK timber prices in recent years (Forest Research, 2021) and also domestic wood fuel prices. For example, the Coniferous Standing Sales Price Index for Great Britain increased in real terms by approximately 122% in the last ten years, of which roughly 105 percentage points of the 122% increase happened in the last five years (to September 2021). As identified in our review, agroforestry output prices are an important factor in determining relative financial viability. A continued rise in timber and wood fuel prices will therefore likely have a positive effect on future income from the tree components, which in turn would positively impact the overall financial viability of agroforestry systems.

Similarly, the “social value of carbon” has also increased significantly following a major revision of estimates by the UK DBEIS in 2021 (DBEIS, 2021). Were GHG emission penalties and sequestration payments also included within financial assessments of agroforestry for farmers, and DBEIS values used, the latest social values of carbon would also have significant positive impacts on the future financial viability of agroforestry.

Lastly, recent severe weather events in the UK have highlighted the wind risks that tree-components of agroforestry may face (Marshall, 2022). Such risks are projected to increase over time given the global climate change trajectory, and they may also potentially affect the future financial viability of agroforestry in the UK. The incorporation of these risks into future financial assessments is therefore worth consideration, but the practicality of doing so is beyond the scope of this review.

Further research is required on the sensitivity of the results to various assumed parameter values including the choice of discount rate and the relationship between the volatility of timber and carbon prices and agroforestry adoption. The current analysis does not take into account the potential production benefits from integrating trees into livestock systems or the biodiversity benefits of agroforestry which, if rewarded (e.g. with the currently developing BNG scheme), could incentivise adoption further. Beyond the economic constraints, barriers to agroforestry include cultural resistance, a lack of practical skills in establishing and maintaining trees, and lack of awareness of the potential economic benefits of trees in farm systems. Thus, there is need for more in-depth qualitative research to understand these factors too before the potential for agroforestry can be fully underpinned by quantitative evidence.

7.2 Evidence gaps & next steps

7.2.1 Evidence gaps (GHG reduction)

We have reviewed a range of publications that report on the GHG emissions reductions potential of agroforestry systems, however there are evidence gaps relating to the impact of site and soil conditions, previous and ongoing land use, and the impact of the interactions between the forest and agricultural components of these integrated systems. The impact of future climate has not been widely considered. There are only a small number of studies per system, therefore additional studies would improve the certainty and allow assessment of system versus site-based variation.

GHG balance data for trees and woodlands under wider spacing have not yet been published, as growth models for these spacings are not yet available. These are, however, being developed. These data will benefit the evaluation of agroforestry systems such as wood pasture, riparian belts, and tree lines. Published data are not available for allowing hedgerows to develop into treelines or incorporating trees into hedgerows. Integrating data for open grown and wider spaced woodland with hedgerow data will also be beneficial. The use of pollarding to cut/coppice trees above grazing height is a historic silvo-pastoral woodland and tree line management practice, particularly along the edges of woodland. There is minimal evidence available for GHG reduction potential of this practice.

7.2.2 Evidence gaps (economics)

We also identified several noteworthy evidence gaps in the economics research on the financial viability of agroforestry. One of these is the seeming lack of studies on the financial viability of shelterbelts and buffer strips for farmers. While our evidence search was restricted mainly to studies published after 2010, we did not identify any studies investigating the economics of these agroforestry systems. This is significant given our finding that these agroforestry systems have high GHG reduction potentials.

Another gap is the lack of studies employing less deterministic economic evaluations (i.e. evaluations which account for risk and uncertainty factors) when studying the adoption of agroforestry. As explained by Abdul-Salam *et al.* (2022), who used a Real Options economic approach, these are evaluations which incorporate real-life uncertainty and irreversibility in investment decisions when modelling the adoption of agroforestry. They therefore generate more realistic results than those obtained from more deterministic economic models such as capital budgeting, which was found to be the most common methodology adopted within the literature reviewed. Another less deterministic methodology that could prove insightful is the financial portfolio approach, which has been applied to assess agroforestry in other countries but not, to the best of our knowledge, the UK (Paul, Weber and Knoke, 2017). In essence, the approach applies the Modern Portfolio Theory in financial economics to investigate the idea that by integrating various tree and crop components together, the risks and returns of agroforestry can be minimised and maximised over and above those of monospecific land uses (Paul, Weber and Knoke, 2017). While such methodologies often involve more complex data requirements, they are arguably worth exploring given their ability to generate potentially more realistic findings.

Besides that, there is a lack of evidence on the financial viability of agroforestry systems relative to one another. Most of the studies we identified in the literature focused on comparing agroforestry with non-agroforestry systems, with little to none comparing solely agroforestry systems in a particular location. Whilst we could have compared financial outcomes of different agroforestry systems across studies, we deemed it impractical and erroneous to do so due to the vast differences in financial indicators, assumptions, and study contexts. Given our findings that agroforestry systems can be more financially viable than conventional agriculture and forestry under certain conditions, comparisons amongst agroforestry types are perhaps warranted.

One final major gap of note is the relatively low number of studies investigating the potential for the viability of agroforestry to be enhanced using relevant PES. This is especially important given the strong existing evidence showing agroforestry to be more financially viable when wider ecosystem service benefits are internalised on the part of farmers. Such studies would facilitate the creation of well-designed agroforestry related PES markets in the UK, which in turn would improve the economic appeal of agroforestry and potentially its adoption. Note that in the context of carbon related PES, inclusion of agroforestry under the WCC would be subject to the standard’s additionality tests, which include demonstrating that a project would only be viable with carbon finance and unviable without it.

7.2.3 Next steps

The AGFORWARD project was an EU collaborative project with exemplars for the UK focussed on silvo-arable agroforestry systems. Two models were produced which are of potential applicability in Scotland, YieldSAFE which predicts silvo-arable yields, and FarmSAFE which predicts economic value. Extension of these models to silvo-pastoral systems could be very valuable for examining farm level GHG emissions and economics and comparing options

Financial assessments from FarmSAFE focus specifically on using capital budgeting. Data for parameterising financial models can be obtained from the John Nix pocketbook on farm management (Redman, 2021), which contains useful information on costings of individual agroforestry components in the UK. This was done in some of the studies reviewed (Yates *et al.*, 2007; Burgess *et al.*, 2017).

There is therefore also potential for the project to extend beyond capital budgeting methods and to adopt more flexible economic models such as the Real Options approach described in the previous subsection. Mostly importantly, however, there is need to incorporate wider ecosystem service benefits, as well as disservices, from agroforestry into economic assessments, regardless of the methodology adopted. In this way, the ‘true’ economic value of agroforestry can be better represented.

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9 Appendices

9.1 Appendix 1: Economic evidence summary Table 6.2

Table 6.2 : Summary of all reviewed studies which investigated the financial viability of agroforestry.

Study	Agroforestry practice studied	Location Studied	Methodology	Discount Rate Adopted (1)	Financial Indicators	Time Horizon (years)	Study Area Size (ha)	Financially Viable? (2)	Relatively More Financially Viable? (3) (4)
Staton *et al.* (2022)	Silvo-arable (Orchard Intercropping)	England (Nottinghamshire, Norfolk, Cambridgeshire, Oxfordshire)	Capital Budgeting	3.5%	GMI; NPV; EAV	20	16	**Y**	**Y** (in the long run)
Garcia de Jalon *et al.* (2018)	Silvo-arable	England (Bedfordshire)	Capital Budgeting; Monetary Valuation of ES	4%	Net Margins; NPV; EAV	30	3.5	**Y**	**P** (if PES included in calculations)
Kaske *et al.* (2021)	Silvo-arable	England (Bedfordshire)	Capital Budgeting; Monetary Valuation of ES	4%, 3.5%	NPV; EAV	30	N/A	**Y**	**P** (if carbon related PES included & carbon prices higher than existing ones)

Study	Agroforestry practice studied	Location Studied	Methodology	Discount Rate Adopted (1)	Financial Indicators	Time Horizon (years)	Study Area Size (ha)	Financially Viable? (2)	Relatively More Financially Viable? (3) (4)
Kay *et al.* (2019)	1. Silvo-arable (Hedgerow-Arable; Orchard) 2. Silvo-pastoral (Orchard; Wood pasture) 3. Agrosilvo-pastoral (Bocage)	1. England, Germany, Spain, Switzerland 2. Spain, Switzerland 3. France	Monetary Valuation of ES	N/Ap	'Net Financial Benefit of Biomass Produced'; 'Net Ecosystem Service Value'	5	100 (8x in each country)	**Y**	**P** (if PES included in calculations)
Lehmann *et al.* (2020)	Silvo-arable (Alley Cropping)	1. England (Suffolk) 2. Denmark (Taastrup)	Capital Budgeting	N/Ap	Gross Margins	Unclear	England: 22.5 Denmark: 11.1	**Y**	**N/A**
Smith *et al.* (2022)	Silvo-arable (Alley Cropping)	1. England (Suffolk) 2. Denmark (Taastrup)	Capital Budgeting	N/Ap	Gross Margins; Net Margins	1	England: 22.5 Denmark: 11	<u>Gross Margins</u> England: **Y** Denmark: **Y** <u>Net Margins</u> England: **Y** Denmark: **N**	**N/A**
Burgess *et al.* (2017)	Silvo-pastoral (Grazed Orchard)	England (Herefordshire)	Capital Budgeting	N/Ap	Gross Margins	1	2	**Y**	**Y** (but sensitive to changes in prices/costs)

Study	Agroforestry practice studied	Location Studied	Methodology	Discount Rate Adopted (1)	Financial Indicators	Time Horizon (years)	Study Area Size (ha)	Financially Viable? (2)	Relatively More Financially Viable? (3) (4)
Abdul-Salam, Ovando, & Roberts (2022)	Silvo-pastoral (Hill sheep & low ground cattle and sheep enterprises)	Scotland (Aberdeenshire)	Real Options Analysis; Capital Budgeting	3%	Real Options Value; NPV	Real Options: ∞ Capital Budgeting: 60	579.4	**Y**	**P** (if carbon PES included & carbon prices significantly higher)
Yates *et al.* (2007)	Silvo-pastoral (Poultry-Tree)	England (Oxfordshire)	Capital Budgeting	8%	Gross Margins, Net Margins, IRR	120	4.4 (2x 2.2ha)	**Y**	**Y** (BUT sensitive to changes in prices/costs)
Morgan-Davies *et al.* (2008)	Silvo-pastoral (Hill sheep-Woodland)	Scotland (West Perthshire)	Capital Budgeting	N/Ap	Margins (specific type unclear, but seemingly Net Margins)	5	850	**Y** (BUT only if subsidies available)	**Y** (BUT only if subsidies available)
Palma *et al.* (2007)	Silvo-arable	1. France 2. The Netherlands	MCDA Outranking	Unclear	iNPV	∞	400 (FR: 7x; NL: 3x)	**Y**	France: **Y** Netherlands: **P** (if environmental indicators used in addition to financial ones in ranking; i.e., if PES made available)

Study	Agroforestry practice studied	Location Studied	Methodology	Discount Rate Adopted [1]	Financial Indicators	Time Horizon (years)	Study Area Size (ha)	Financially Viable? [2]	Relatively More Financially Viable? [3] [4]
Graves *et al.* (2007)	Silvo-arable	1. France 2. The Netherlands	Capital Budgeting	4%	Net Margins; NPV; iNPV; EAV	∞	400 (FR: 7x; NL: 3x)	**M**	**P** (if no CAP grants in place)
Böhm *et al.* (2011)	Silvo-arable (Alley Cropping)	Germany (Brandenburg)	Capital Budgeting	5%	Annuities	24	7	**Y** (BUT only in the long run)	**P** (in the long run & if higher woodchip prices used
Sereke *et al.* (2015)	1. Silvo-arable (Tree-Arable & Fruit-Arable → i.e., alley cropping) 2. Silvo-pastoral (Tree-Grassland & Fruit-Grassland)	Switzerland (Swiss Plateau)	Capital Budgeting	3.5%	NPV; iNPV; EAV	60	Unclear	**Y** (especially in the long run)	Silvo-arable: **P** (in the long run & if PES provided) Silvo-pastoral: **P** (in the long run & if PES provided)
Xu *et al.* (2019)	Silvo-arable (Alley Cropping)	Denmark (Taastrup)	Capital Budgeting	3%	Gross Margins; Net Margins; Cumulative Net Margins; NPV; iNPV; EAV	21	10.85	**Y**	**Y**

[1] N/Ap = 'Not applicable'
[2] **Y** = 'Yes' | **N** = 'No' | **M** = 'Mixed' (i.e., 'Yes' for some cases and 'No' for others)
[3] Relative here is taken to mean relative to non-agroforestry systems, particularly conventional agriculture and forestry systems.
[4] **Y** = 'Yes' | **N** = 'No' | **P** = 'Potentially' | **N/A** = evidence 'not available'

9.2 Appendix 2: Economic evidence summary Table 6.3

Table 6.3 : Summary of financial viability of individual agroforestry systems.

Agroforestry Systems		No. of Studies Reviewed w/ Respective Agroforestry Types	Financially Viable (Long Term) (1)	Time At Which Becomes Financially Viable (years)	Relatively More Financially Viable (2) (3)	Time At Which Becomes Relatively More Financially Viable (years)	Evidence
Farm System	Agroforestry Type						
Agrosilvo-pastoral	Bocage	1	Y	N/A	M (1/1)	N/A	(Kay *et al.*, 2019)
Silvo-pastoral	Buffer Strips	0					
	Hedgerows	0					
	Orchards	3	Y	N/A	M (2/3)	N/A	(Sereke *et al.*, 2015; Burgess *et al.*, 2017; Kay *et al.*, 2019)
	Shelterbelts	0					
	Wood Pasture (Lowlands)	2	Y	N/A	M (1/2)	N/A	(Yates *et al.*, 2007; Abdul-Salam, Ovando and Roberts, 2022)
	Wood Pasture (Uplands)	4	Y	Mostly -ve income at 10, but all +ve by 30 and 60 (based on Sereke et al.)	M (3/4)	Without Ecological Payments: ≥30 With Ecological Payments: ≥10 (based on Sereke et al.)	(Morgan-Davies *et al.*, 2008; Sereke *et al.*, 2015; Kay *et al.*, 2019; Abdul-Salam, Ovando and Roberts, 2022)

Agroforestry Systems		No. of Studies Reviewed w/ Respective Agroforestry Types	Financially Viable (Long Term) (1)	Time At Which Becomes Financially Viable (years)	Relatively More Financially Viable (2) (3)	Time At Which Becomes Relatively More Financially Viable (years)	Evidence
Farm System	**Agroforestry Type**						
Silvo-arable	Alley Cropping	9	M (2/9 studies found some evidence of negative income in the long run)	Lower wood chip prices: ≥ 12 Higher wood chip prices: ≥ 8 (based on Böhm et al.)	M (6/7*) *2 studies (Lehmann *et al*. & Smith *et al.*) did not investigate relative financial viability	Lower wood chip prices: Never Higher wood chip prices: ≥ 8 (based on Böhm et al.)	(Böhm *et al.*, 2011; García de Jalón *et al.*, 2018; Graves *et al.*, 2007; Kaske *et al.*, 2021; Lehmann *et al.*, 2020; Palma *et al.*, 2007; Sereke *et al.*, 2015; Smith *et al.*, 2022; Xu *et al.*, 2019)
	Buffer Strips	0					
	Hedgerows	1	Y	N/A	M (1/1)	N/A	(Kay *et al.*, 2019)
	Orchards	3	Y	Theoretical Data: Approx. 5-10 OR Empirical Data: N/A (based on Staton et al.)	M (2/3)	Theoretical Data: 7-14 OR Empirical Data: 17.79 (based on Staton et al.)	(Sereke *et al.*, 2015; Kay *et al.*, 2019; Staton *et al.*, 2022)
	Shelterbelts	0					

(1) We assigned each agroforestry system to one of three categories to indicate whether they are financially viable:
Y = ‘Yes’ | N = ‘No’ | M = ‘Mixed’ (i.e., ‘Yes’ in some cases and ‘No’ in others)

(2) In terms of relative financial viability, agroforestry systems were also assigned to one of three categories to indicate whether they are more financially viable:
Y = ‘Yes’ | N = ‘No’ | M = ‘Mixed’ (i.e., ‘Yes’ in some cases and ‘No’ in others)

(3) The numbers in parentheses indicate the proportion of studies finding mixed results (i.e., with a designation of ‘P’ in the far right column of Table 6.2)

9.3 Appendix 3: Objectives & structure

9.3.1 Objectives

Specific objectives are to:

- Conduct a literature review to assess the GHG removal potential of different forms of agroforestry suitable in Scotland, adding any new evidence to the 2018 CXC agroforestry report by Perks *et al.,* (2018)
- Carry out an evidence review and examine the economic viability of adopting agroforestry practices
- Summarise the options examined, including those which might/might not be suitable
- Produce a summary analysis of evidence and any gaps, with specific reference to the data required to support consideration of inclusion under the Woodland Carbon Code

9.3.2 Scope

We review the potential for agroforestry systems to contribute to GHG reduction targets through above and below ground biomass and soil carbon sequestration in the tree or shrub component. The effect on the GHG balance of the agricultural practice are outside the scope of this report. We do not consider GHG emissions reductions from tree products substituting for fossil-fuel intensive materials, such as woodfuel or construction timber.

The review of economic viability is a rapid evidence review, as opposed to a comprehensive systematic review with searches for evidence restricted to publications since 2010. A few studies were identified from snowballing. The review focuses on financial viability and does not investigate productivity. Furthermore, detailed considerations of grant payments and their impacts on economic viability are outside the scope of this report; although where necessary elements of grant aid are discussed. A final assessment of the suitability of incorporating agroforestry into the Woodland Carbon Code is outside of scope.

9.3.3 Evidence review structures

The evidence review for GHG reduction is structured by agroforestry typology, as this has a significant influence on carbon sequestration potential and is necessary to respond to the brief and support land manager and policy decision making. The evidence review of economic viability is structured by economic assessment and summarised by agroforestry system

9.4 Appendix 4: Methodology

9.4.1 Literature review search strategy

The literature review will be conducted following the Quick Scoping Reviews (QSR) and Rapid Evidence Assessment (REA) guidance (Collins *et al.*, 2015) by DERFA and NERC. Scopus was used to search for published papers using the search terms below.

Grey literature (i.e. reports not published in peer reviewed journals) will be sought through Google Scholar searches and advice of the project steering group. Also, we would employ snowballing technique: if the reviewed paper contains some relevant references they will be followed up too.

9.4.2 Economics of agroforestry

To conduct the evidence review, we used Scopus as our primary search database. Three main search strings encompassing various combinations of search terms agreed amongst the project steering group were used.

9.4.2.1 Search terms

The table below presents the search terms focusing on two major themes: agroforestry and economics in the first two columns, and some possible filters to limit the search in the third column.

Land Management Theme	Economic Aspect of Question	Filters
- Agro-forest* (Agro-forestry/ Agro-forest); Agroforest* - Silvo-past* (Silvo-pasture/ Silvo-pastoral); Silvopast*; “Wood pasture” - Silvo-arable; Silvoarable Potentially Relevant: - Monoculture - (Conventional) Agriculture/Farming - Forestry/ Woodland/ Tree*/ Coppic*	- Profit* (profits/profitability) - Return*/Revenue*/Loss* - Viability/Feasibility - Financ* (… “Financial benefit”; “financial viability”; “financial value”) - “Monetary value” - “Net present value” - “Internal rate of return” - “Gross margin” - Yield* - “Opportunity Costs” - Income - “Cost benefit” Potentially Relevant: - “spill-over effects” - “marketable ecosystem services” - Compar* (compare/comparison) - Alternative* - Relative - Versus	Geographical: - Temperate Countries: 1. United Kingdom; Scotland; England; Northern Ireland; Wales 2. Ireland/Irish Republic; France; Netherlands; Denmark; Germany; Belgium 3. United States/North America; Canada; New Zealand Time: - 2010 onwards

9.4.2.2 Scopus Searches (31 January 2022)

(Agro-forest* OR agroforest* OR silvo-past* OR silvopast* OR silvo-arab* OR silvoarab* OR "Wood pasture") AND (profit* OR finance* OR viab* OR feasib* OR return* OR revenue* OR "net present value" OR "internal rate of return" OR "gross margin" OR yield* OR "opportunity costs")

Limiting this search query to publications in English and after 2010 yielded 2011 results. When limiting to publications in English and after 2010, as well as geographic regions of interests, 251 results remained. When limiting to publications in English and after 2010, but to those which are economics related instead, 64 results remained. Two formal rounds of manual screening of publication titles and abstracts for relevance were conducted on these search results.

9.4.3 Agroforestry carbon sequestration

To conduct the evidence review, we used Scopus as our primary search database. Three main search strings encompassing various combinations of search terms agreed amongst the project steering group were used. Search results from the database were all restricted to publications made after 2017, building on Perks *et al.,* (2018). We utilised Google Scholar as a supplementary search engine in searching for grey literature.

9.4.3.1 Search terms

The table presents search terms focusing on two major themes: agroforestry and carbon in the first two columns, and additional filters to limit the search in the third column.

Land Management Theme	Carbon Terms	Filters
String 1: - Agro-forest* - Agroforest* - Silvo-past* - Silvopast* - Wood pasture - Silvo-arable - Silvoarable - Shelterbelt - Coppic* - Farm woodland String 2: - Forest* OR woodland* OR Tree* AND - Agri* OR Farm*	- carbon - CO2 - carbon dioxide - greenhouse - GHG - climate change - yield - biomass - mitigate* (mitigate/mitigation)	Countries: United Kingdom; Time: 2017 onwards

9.4.3.2 Scopus searches (16 February 2022)

<u>Search string 1</u>:

(agro-forest* OR agroforest* OR silvo-past* OR silvopast* OR silvo-arab* OR silvoarab* OR "Wood pasture" OR Shelterbelt* OR "Farm woodland") AND (carbon OR CO2 OR carbon dioxide OR yield* OR biomass OR greenhouse OR GHG OR mitigate* OR "climate change")

- 5880 results

Limiting this search query to publications in English and after 2017 yields

[As above] AND PUBYEAR > 2017 AND (LIMIT-TO (LANGUAGE , "English"))

- 2620 results

When limited to UK: 162 Results.

A Manual check through the titles limited this to 56

<u>Search string 2</u>:

This second search string changes only the first part of the search:

(((Agri* OR FARM*) AND (Forest* OR Wood* OR Tree*)) AND (carbon OR CO2 OR carbon dioxide OR yield* OR biomass OR greenhouse OR GHG OR mitigate* OR "climate change"))

AND PUBYEAR > 2017 AND (LIMIT-TO (LANGUAGE , "English"))

When limited to UK: 307 results.

A manual search identified an additional 42 references to the 56 identified, identifying 98 papers warranting an abstract check. After reviewing the abstracts 48 papers remained and warranted review of the full paper.

36 of these contained useful information, with additional references identified through snowballing.

9.5 Appendix 5: Hedgerow carbon stocks

In this section we present the available evidence for hedgerow carbon storage and the overall range, per hectare (Table A5.1) per unit length (Table A5.2) and the rate of carbon sequestration (Table A5.3).

Note that in this Appendix we report values as they are published, in tonnes of carbon per hectare (t C ha^{-1}) or in tonnes of carbon per kilometre (tC km^{-1}), and their equivalent units of change; whereas in the main report values are reported in tonnes of carbon dioxide per hectare. Positive values represent GHG removal. We do not consider the carbon in wood products after harvest or the substitution benefit they provide 'beyond the farm gate'.

AGB	Above Ground Biomass
BGB	Below Ground Biomass
Biomass	AGB + BGB
SOC	Soil Organic Carbon

A5.1 Hedgerow Carbon Stocks per Hectare

Source	**Description**	**Tonnes of Carbon**	**Reference**
AGB	1 year after coppicing (0.55–1.5m width)	25.65 - 34.35 t C ha-1.	Crossland 2015
AGB	Uncoppiced 3.5-6m wide	45.08–131.5t C ha-1	Crossland 2015
AGB	flailed Height 1.9m	32.2 ± 2.76 t C ha−1	Axe 2017
AGB	flailed Height 2.7m	40.6 ± 4.47 t C ha−1	Axe 2017
AGB	untrimmed for 3 yrs 3.5m tall 2.6-4.2m wide	42.0 ± 3.78 t C ha−1	Axe 2017
AGB	Minimally managed	45.8 ± 12.26 t C ha-1	Axe 2015
AGB		25-55 t C ha-1	Axe 2020
BGB	1 year after coppicing (0.55–1.5m width)	13.52 – 39.45	Crossland (2015)
BGB	Uncoppiced	15.03 – 43.83	Crossland (2015)
BGB		38.2 ± 3.66 t C ha−1	Axe 2017/2020
Biomass		60 – 96.86 t C ha-1	Axe 2020
Biomass		25-46 t C ha−1	Gregg *et al.*, 2021
Biomass		5- 45 t C ha-1	Warner, 2011; Robertson et al., 2012 in Crossland 2015
SOC		43 – 136.8 t C ha-1	

Source	Description	Tonnes of Carbon	Reference
SOC	1 year after coppicing (0.55–1.5m width)	66.5 – 95.3 t C ha-1	Warner, 2011; Robertson et al., 2012; Crossland (2015)
SOC	Uncoppiced	74.0–111.9 t C ha-1	Crossland (2015)
SOC		166 t C ha-1	Follain (2007)
SOC	2-3m width	68.2 t C ha-1	Ford *et al.,* (2019)
SOC		67-176 t C ha−1	Gregg *et al.*, (2021)
SOC	2.6-4.2 width, 1.9-3.5m height	98.7 t C ha-1	Axe (2015)
SOC	depth 15-100 cm	50-130 t C ha -1	Axe (2020)
Total	1 year after coppicing	120.2-162.4 t C ha-1	Crossland (2015)
Total	Uncoppiced	145.5-287.3 t C ha-1	Crossland (2015)
Total	Established hedges	100 t C ha-1	Wolton *et al.,* (2014)
Total		92-222 t C ha−1	Gregg *et al.*, (2021)
Total		110 – 226 t C ha -1	Axe (2020)
Total		48 – 182 t C ha -1	Warner (2011); Robertson (2012)
Wood chip	Coppicing year 1	45.08 - 131.5 t C ha-1	Crossland (2015)
AGB	Range of values (median hedge) Range 1yr after coppicing Range for large/overgrown	30 – 45 25 - 35 45 - 130	Crossland (2015), Axe (2015, 2017, 2020)
BGB	Range of values	15 – 45	all
AGB+BGB	Range of values	45 - 90	all
SOC	Range of Values	45 - 176	all
Total	Range of values (median hedge) Range 1yr after coppicing Range for large/overgrown	90 – 266 (mid 176) 120 – 160 135 - 287	all

A5.2 Hedgerow Carbon Stocks per length

Source	Description	Tonnes of Carbon	Reference
AGB	1 year after coppicing	0.74 - 2.52 t C km−1	Crossland (2015)

Source	Description	Tonnes of Carbon	Reference
AGB	Uncoppiced	18.03 - 46.02 t C km−1	Crossland (2015)
AGB	Height 1.9m	9.9 t C km−1	Axe (2017)
AGB	Height 2.7m	11.4 t C km−1	Axe (2017)
AGB	untrimmed for 3 years 3.5m tall 2.6-4.2m wide	14.0 ± 1.94 t C km−1	Axe (2017)
AGB	Favourable (+ baseline for field margin)	3.97 - 4.23 kg C m-1	Axe (2020)
BGB	1 year after coppicing	5.41 - 13.81 t C km−1	Crossland (2015)
BGB	Uncoppiced	6.01 - 15.34 t C km−1	Crossland (2015)
BGB		11.5 t C km−1	Axe (2017)
BGB	Favourable (+ baseline for field margin)	3.42 - 3.82 kg C m-1	Axe (2020)
SOC	1 year after coppicing	53.22 -76.25 t C km−1	Crossland (2015)
SOC	Uncoppiced	59.2 - 89.55 t C km−1	Crossland (2015)
SOC	Favourable. depth 30cm (+field margin)	1.36 - 9.87 kg C m-1	Axe (2020)
Total	1 year after coppicing	62.51 - 90.8 t C km−1	Crossland (2015)
Total	Uncoppiced	92.3 - 150.91 t C km−1	Crossland (2015)
Total	Favourable (+ baseline for field margin)	8.64 - 17.92 kg C m-1	Axe (2020)
Woodchip	From coppicing year 1	18.03 - 46.02 t C km−1	Crossland (2015)
AGB	Range of values (median hedge) Range After coppicing Range Large/overgrown	4 - 15 0.5 - 2.5 18 - 46	all
BGB	Range of values (median hedge)	4 - 15	all
AGB+BGB	Range of values	8 - 30	all
SOC	Range of Values	53 - 90	all
Total	Range of values (median hedge) Range After coppicing Range Large/overgrown	60 –120 60-90 90 - 150	all

A5.3 Rate of Carbon Sequestration Tonnes of Carbon per Hectare per Year (t C ha-1 yr-1)

Source	**Description**	**Tonnes of Carbon**	**Reference**
Biomass + soil	shrubby hedge	1 t C ha^{-1} yr^{-1}	Falloon et al., (2004); in Crossland (2015)
AGB	uncut shrubby hedges	0.5 tC ha^{-1} yr^{-1}	Wolton et al (2014)
BGB	uncut shrubby hedges	0.5 tC ha^{-1} yr^{-1}	Wolton et al (2014)
AGB	silvo-arable hedgerows European hedgerows	~0.2tC ha-1 y-1 0.1- 0.45 tC y-1	Kay et al (2019)
Total	unmanaged hedges	2.74 - 12.19 t C ha^{-1} yr^{-1}	Falloon et al., (2004); in Crossland 2015
Total	Non flailed	Min 2.20 t C ha^{-1} yr^{-1} Max 11.40 t C ha^{-1} yr^{-1} mid 6.37 t C ha^{-1} yr^{-1}	Taylor (2010) in Crossland (2015)
	Range (median hedge) Range (newly planted) Range (unmanaged)	2.23 t C ha^{-1} yr^{-1} 2.2 2.2 – 12.2 (mid 6.4)	

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