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Incentivising agroforestry: A Real Options Analysis

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Abstract

Agroforestry has a potentially important role in helping agriculture address both the climate and biodiversity crises. It provides a means of producing additional marketable goods from agricultural land and enhancing biodiversity at the same time as increasing carbon sequestration and, in silvo-pastural systems, reducing carbon emissions assuming a reduction in livestock stocking rates. However, the uptake of agroforestry in the UK has been limited. This paper adopts Real Options techniques to explore how the decision to adopt agroforestry is influenced by the relative levels of returns from agriculture, forestry and the price of carbon, taking into account the options value of the farmer being able to change or postpone decisions based on current conditions. The results are compared to the equivalent findings from a standard Land Equivalent Value capital budgeting approach to agroforestry adoption. Analysis is based on data on from a case study upland livestock farm in Scotland, comparing the impacts of introducing agroforestry into the hill sheep enterprise or the low ground cattle and sheep enterprise. The policy implications of the analysis are considered including the potential for upfront support payments to further incentivise the adoption decision.

Key words: Agroforestry, carbon sequestration, livestock farming.

1 Introduction

Agroforestry is a land use system that deliberately integrates trees into animal or crop systems to take advantage of economic or ecological interactions among the components (Frey et al., 2013). It can be viewed as either as means of transitioning from agriculture to forestry, or as a new (permanent) approach to producing a wider range of marketable goods from agricultural land as well as additional social benefits (Briggs and Knight , 2019; Brown et al., 2018; Perks et al., 2018; Smith et al. 2012).

Agroforestry has the potential to be part of the transformational change required by the agricultural sector in the context of the climate and biodiversity crises. In the UK, the growing interest in afforestation of agricultural land has followed from the net zero targets for the sector and call for a green recovery following the economic impacts of the COVID-19 pandemic. An additional driver has been the Climate Change Committee's suggestion that the new UK Emission Trading System (ETS) should extend to agriculture and land use by 2026 (HM Government, 2020). This would provide incentives to land managers to not only reduce emission levels from production but also find ways of offsetting carbon emissions through woodland planting, peatland restoration and improved soil management.

In the UK, agroforestry practice is dominated by silvo-pastoralism, a system that combines livestock (mainly cattle and/or sheep) and trees. Several studies have shown the potential benefits of this form of agroforestry in terms of carbon sequestration (Giannitsopoulos et al. 2020) as well as livestock productivity benefits in terms of reduced feed costs, improved animal welfare, biodiversity benefits, improved water quality, reduced risk of flooding, reduced soil erosion and moisture extremes, and woody biomass for energy (Perks et al., 2018). However, despite recent policy incentives, uptake of agroforestry has been limited.

Against this background, this paper considers the economics of agroforestry adoption and, in particular, the financial and biophysical factors which influence the adoption on a case study upland livestock farm assuming a (hypothetical) context within which both the cost of carbon emissions from livestock and the benefits of carbon sequestration in trees are internalised in the decision-making process.

Analysis is based on a Real Options (RO) appraisal of agroforestry adoption within which the farmer's decisions are recognised as taking place in uncertain conditions. In particular, stochastic analyses using RO techniques provides a means of estimating the value of a farmer being able to delay decisions relating to agroforestry based on current conditions. The results are compared to a standard capital budgeting approach – Land Equivalent Value (LEV) – to show the importance of allowing for flexibility in the decision making process and, in particular the constraints to the adoption of agroforestry arising from the duration of the production cycle and uncertainty in carbon prices (returns to sequestration or penalties to livestock greenhouse gasses (GHG) in equivalent carbon emissions). The adoption decision in two different livestock enterprises are compared to illustrate the importance of biophysical factors on the decision-making process.

The results suggest that agroforestry adoption is less likely on both types of system than standard budgeting analyses may suggest. Therefore a scenario is explored where an upfront payment to cover establishment costs is made available to farmers. The paper concludes by considering the implications of the findings on policies to further incentivise agroforestry, plus the additional research needed to understand better the constraints to agroforestry adoption.

2 Agroforestry in the UK

Across the UK, an estimated 3.25% (549,600 ha) of total agricultural land is under agroforestry use, with almost all of it in silvo-pastoral systems (der Herder et al. 2015). Silvo-arable systems are rare in UK (2,000 ha), with most found in England and Wales (Smith 2014; RSFS, 2012). There is no *de facto* account of the extent of agroforestry in Scotland and where trees and agriculture do co-exist within a farmed system, this has not always been planned and the land is not necessarily being operated as an integrated agroforestry system (Perks et al., 2018).

The agriculture sector is currently facing a number of significant challenges, the most critical of which are the climate emergency and a biodiversity crisis. Both the recent IPCC (2019) and IPGC (2019) reports highlight that changes in land use and land management need to be at the forefront of efforts to shift towards a low carbon economy. For example, agriculture and related land use change contributed 9.6 MtCO2 equivalent emissions in Scotland by 2018, representing the second most important GHG emissions source in Scotland after transportation. Direct GHG emissions from livestock enteric fermentation, manure management and urine and dung deposited by grazing animals account for almost half of total agriculture and related land use change emissions in Scotland (Scottish Government, 2020). However, the majority of changes currently being considered by the agriculture sector are arguably too conservative and will not provide the magnitude of change required. While there are calls for a reduction in livestock numbers, much of Scotland's agricultural land has limited potential for alternative use and extensive livestock production. On top of this, these production systems have been shown to have positive biodiversity benefits within a high nature value system. Woodlands in agricultural landscapes can diversify wildlife habitats and increase connectivity, which in turn can enhance biodiversity resilience in the face of climate change (Brown et al., 2019; Burton et al. 2018).

Within this context, agroforestry has been suggested as a means of helping mitigate carbon emissions, while maintaining farm household livelihoods and also, conditional on how it is done, protecting or even enhancing biodiversity on agricultural land. A number of studies have explored the potential benefits of agroforestry highlighting from a production perspective the benefits it brings in terms of shelter it provides to animals and crops, a potential reduction in feed costs, reduced risk of flooding, improving animal welfare, potentially reduced crop pests by housing beneficiary predators, reductions in soil erosion and moisture extremes, and a means of diversifying farm income (Perks et al., 2018; Raskin and Osborne, 2019). In terms of climate change mitigation, while all forms of agroforestry have the potential to sequester carbon (C), the magnitude of benefits are highly context specific and vary according to location, soil type, choice of tree species, density of planting and, in the case of silvo-pastoral systems, density of stocking. Evidence suggests that maximum C-sequestration benefits on a per hectare basis will be achieved on more productive farmland but at a potentially high agricultural opportunity cost so there are clear trade-offs involved in the adoption of such systems and uptake is likely to vary spatially. Similarly, the impact on biodiversity will depend on the type of trees planted and where they are planted.

Several barriers to the adoption of agroforestry have been identified in the literature. These include practical barriers (including maintenance costs and a lack of arboriculture knowledge) and the impact on landscape aesthetic appeal. From a financial perspective, several studies have found economic benefits from agroforestry are greater than forestry alone , and, in some cases where land is marginal, agriculture alone (Lehman et al. 2020). Despite this, adoption rates remain limited suggesting that government support may be needed to compensate for the relative irreversibility associated with such a switch in land use and the risks and uncertainty intrinsic in such decisions. This paper explores the extent of these financial barriers, in doing so indicating the type and magnitude of policy incentives required to make adoption more likely.

3 Modelling approach

3.1 Real Options model

This paper uses a Real Options approach to examine the factors influencing agroforestry adoption on an upland livestock farm. The key advantage to using a Real Options approach, rather than its cashflow counterparts (i.e. standard capital budgeting approaches such as Net Present Value (NPV), Soil Equivalent Value (SEV) or Land Equivalent Value (LEV)) is that it inherently incorporates the nature of uncertainty and the value of information in decision making.

Real Option models are based on the Bellman equation (Adda and Cooper, 2003; Miranda and Fackler, 2004), which is premised on the principle that decision makers choose a management regime that maximises the sum of instantaneous and discounted expected future rewards (e.g. profit, utility, etc.). The Bellman equation for an infinite-horizon setting is stated as follows;

$$V(s) = \max_{x \in X(s)} \{ f(s,x) + \delta \cdot E_{\varepsilon}[V(g(s,x,\varepsilon))] \} \qquad [1]$$

where $V(s)$ is the value function denoting the total value of the land in state s; $f(s,x)$ is the reward function that maps the financial returns to the farmer in state s when decision x is taken; δ is the discount factor and $E[\cdot]$ is the expectation operator. $g(\cdot)$ is the transition function that shows the movement from one state to another, given the decision x taken and the shock ε experienced.

3.1.1 State variables

There are three state variables in the model. These are (1) stand age, s^{SA}; (2) returns to conventional agriculture, s^{AG}; and (3) price of carbon, s^{CP}.

The first state variable, s^{SA}, represents land use and stand age of agroforestry. It is a discrete variable ranging from 0 to the maximum allowable stand age $maxsa$. When s^{SA} is 0, the land is in conventional agriculture. When s^{SA} is 1, a proportion of the land is used for forestry (i.e. a farmer is practising agroforestry), with the trees being in their first year. When s^{SA} is $maxsa$, it represents the end of the state space in the model. At this stage, the farmer may wish to cut and sell the timber, and replant in agroforestry; or revert the land to entirely conventional farming. However, the farmer may also choose to remain in that mixed, agroforestry, state. In that situation, the transition function returns to the same state indefinitely i.e. the timber volume remains the same indefinitely. The state space for s^{SA} ranges from 0 to 60. $maxsa$ is therefore 60.

The second state variable is s^{AG} which represents the annual net returns to conventional agriculture (£ha^{-1}). The third state variable is s^{CP} which represents the annual average price of carbon (measured in tonnes (t) of carbon dioxide (CO_2): £ tCO_2^{-1}).The analysis assumes that the cost of carbon emissions associated with agricultural production are passed back to the farmer in the form of a reduction in market returns while the carbon sequestration benefits of integrating trees within their system is rewarded providing them with additional source of income.

3.1.2 Decision variables

The farmer's decision variable x takes three values 0, 1 and 2. x takes a value of 0 if the farmer is in conventional agriculture only and decides to maintain that state, or the farmer is in agroforestry and decides to harvest the timber with a subsequent change to conventional agriculture only. x takes a value of 1 if the farmer is in conventional agriculture only but decides to switch to agroforestry; or is in agroforestry but decides to maintain agroforestry for one more year. x takes a value of 2 if the farmer is in agroforestry and decides to cut and sell timber but with subsequent replanting of agroforestry.

In the model, the farmer is allowed to choose any eligible value of x in any state in order to maximise the value function. This means that there are no predetermined periods for switching from conventional agriculture to agroforestry or vice versa. Optimal switching and/or harvesting of timber is determined endogenously on the basis of all the state variables.

There are financial barriers however to switching from conventional agriculture to agroforestry or vice versa. Switching from conventional agriculture to agroforestry involves site preparation and tree planting (see below). On the other hand ,switching from agroforestry to conventional agriculture involves removing stumps, roots, etc. from the land. These financial barriers prevent frictionless switching from one state to another, so that a farmer is more likely to stay in the same state or regime that s/he is currently in, rather than switching back and forth whenever minor shifts in prices or returns occur. Switching between states also affects carbon release from the ground but this is ignored in the current analysis.

3.1.3 Value function

Let $f(s^{SA}, s^{AG}, s^{CP}, x)$ represent the reward function of the farmer. The reward function is a function of the farmer's state variables (s^{SA}, s^{AG}, s^{CP}) and decision variable (x). When the farmer is in the conventional agriculture state and decides to maintain or switch to agroforestry, the reward function decomposes to the following:

$$f(s^{SA} = 0; x = 0{,}1) = s^{AG} - s^{CP} \qquad [2]$$

Let $TGY(s^{SA})$ and $MGY(s^{SA})$ represent the total growth yield and the marginal growth yield of timber (see sub-section 4.2) respectively, such that: $MGY(s_t^{SA}) = TGY(s_t^{SA}) - TGY(s_{t-1}^{SA})$.

When the farmer is within the first five years of agroforestry, the only decision available to the farmer is to maintain agroforestry, due to legal requirements. In this situation, the farmer's reward function decomposes to the following:

$$f(s^{SA}, s^{AG}, s^{CP}, x = 1) = \beta \cdot (s^{AG} - s^{CP} \cdot \omega) + (1 - \beta) \cdot (netCosts(s^{SA}) + s^{CP} \cdot MGY(s^{SA}) \cdot \varphi) \qquad [3]$$

$$1 \leq s^{SA} \leq 5$$

where β is the share of the land that remains in agriculture; ω is the level of emissions in conventional farming (tCO_2 ha^{-1}); φ is the carbon conversion factor (tCO^2 m^{-3}) and $netCosts(s^{SA})$ is a function capturing the farmer's planting and maintenance costs. These may include a subsidy for first year planting costs (which we call *upfront payment*) in which case these are subtracted from farmer's planting and maintenance costs). When the farmer is beyond five years of agroforestry and decides to maintain agroforestry, the reward function of the farmer decomposes to the following:

$$f(s^{SA}, s^{AG}, s^{CP}, x = 1) = \beta \cdot (s^{AG} - s^{CP} \cdot \omega) + (1 - \beta) \cdot (s^{CP} \cdot MGY(s^{SA}) \cdot \varphi) \qquad [4]$$

$$6 \leq s^{SA} \leq maxSa$$

When the farmer is beyond five years of agroforestry and decides to cut and sell timber but switch land to conventional agriculture, the reward function decomposes as follows:

$$f(s^{SA}, s^{AG}, s^{CP}, x = 0) = \beta \cdot (s^{AG} - s^{CP} \cdot \omega) + (1 - \beta) \cdot (netCosts(s^{SA}) + tprice \cdot GYT(s^{SA}) + s^{CP} \cdot MGY(s^{SA}) \cdot \varphi) \qquad [5]$$

$$6 \leq s^{SA} \leq maxSa$$

where $tprice$ is the price of timber (£ m^{-3}).

Finally, if the farmer is beyond five years of agroforestry and decides to cut and sell timber but maintain land in agroforestry, the reward function decomposes to the following:

$$f(s^{SA}, s^{AG}, s^{CP}, x = 2) = \beta \cdot (s^{AG} - s^{CP} \cdot \omega) + (1 - \beta) \cdot (tprice \cdot TGY(s^{SA}) + s^{CP} \cdot MGY(s^{SA}) \cdot \varphi) \qquad [6]$$

$$6 \leq s^{SA} \leq maxSa$$

3.1.4 State transition function

The state transition process of the stand age state variable is given as follows in Table 1;

Table 1 Description of the state transition process

Transition	Description
$s_{t+1}^{SA} = 0 \;\; \forall \;\; x = 0$	The farmer, in any state, transitions to stand age of 0 (i.e. state of conventional agriculture only) whenever a decision $x = 0$ is made.
$s_{t+1}^{SA} = s_t^{SA} + 1 \quad \forall \quad x = 1 \,\&\, 1 \leq s_t^{SA} \leq maxsa$	The famer, in a state of agroforestry, transitions to another year of agroforestry whenever a decision $x = 1$ is made.
$s_{t+1}^{SA} = maxsa \quad \forall \quad x = 1 \,\&\, s_t^{SA} = maxsa$	The farmer, in a state of agroforestry, with stand age of timber being at maximum stand age, transitions to another year of agroforestry with stand age at the same maximum age, whenever a decision $x = 1$ is made.
$s_{t+1}^{SA} = 1 \quad \forall \quad x = 2$	The farmer in a state of agroforestry, transitions to year 1 of agroforestry when a decision $x = 2$ is made (i.e. cut timber, sell timber, and replant for agroforestry)

We assume that the conventional agricultural returns and carbon prices follow a mean reverting random walk process. This implies that returns and prices tend towards a long-run equilibrium level over time. The stochasticity in the evolution of returns and prices is driven by shocks. We model the agricultural returns shocks and carbon price shocks with zero covariance. We choose the Ornstein-Uhlenbeck mean price reverting process such that;

$$s_{t+1}^{AG} = s_t^{AG} + \alpha^{AG}(ageq - s_t^{AG}) + \varepsilon_t^{AG} \qquad [7]$$

$$s_{t+1}^{CP} = s_t^{CP} + \alpha^{CP}(cpeq - s_t^{CP}) + \varepsilon_t^{CP} \qquad [8]$$

where:

α^{AG}	Mean reversion rate of agricultural returns (unitless)
$ageq$	Long run equilibrium level of agricultural returns, £/ha
ε_t^{AG}	Shocks in agricultural returns, £ ha^{-1}
α^{CP}	Mean reversion rate of carbon prices (unitless)
$cpeq$	Long run equilibrium level of carbon prices, (£ tCO$_2^{-1}$)
ε_t^{CP}	Shocks in carbon prices (£ tCO$_2^{-1}$)

By allowing the farmer to switch between land uses based on their expectations of future returns, the Real Options model ensures the most profitable use of the farmer's land. The model thus provides a powerful reflection of the kind of decisions farmers face and make.

3.2 Standard capital project evaluation methods

Empirical analyses of land use change decisions, such as the adoption of agroforestry, typically assume deterministic decision-making approaches and there are a number of different capital budgeting methods that can be used based on the Net Present Value (NPV) of returns to alternative land uses. In the most basic model of land conversion, the NPV is defined as the difference between the discounted value of the stream of benefit minus the discounted value of the stream of costs over the life of the project (T) which, in the case of agroforestry, is taken as the forest rotation length:

$$NPV_{AF} = \sum_{t=1}^{T} \delta^{t}((1-\beta)\cdot(s_t^{AG} - s_t^{CP}\cdot\omega_t) + s^{CP}\cdot MGY(s^{SA})_t\cdot\varphi + \rho\cdot s_t^{TB} - C_t^{AG}) \quad [9]$$

where S_t^{AG}, as previously defined, represents the rewards to conventional agriculture, s^{CP} the rewards/ penalty to carbon sequestration/emissions ω, $MGY(s^{SA})$ is the marginal timber growth and φ timber carbon conversion factor from timber volume to total carbon stock in above ground and roots tree biomass ($tCO_2\ m^{-3}$), t represents time in years ($t = 1, 2,\ldots,T$), s_t^{TB} the rewards to timber, C_t^{AG} are the cost of agroforestry, and δ the discount factor estimated as: $\delta=(1/(1+r))$, r being the discount rate.

The cost of the agroforestry project (C_t^{AG}) includes farmers' implementation (i.e., ground preparation and tree planting) and management, and β is the share of land that is set aside from conventional agriculture for planting tree. Carbon, timber and conventional rewards are assumed to remain constant over time. In addition, the NPV estimation consider a real discount rate of 3%.

Rewards to timber are estimated considering total timber volume at the rotation time T ($GYT(s^{SA})_T$), $tprice$, and σ which is a dummy variable that equals 1 when t = T (the rotation length) and 0 when t ≠ T is the costs of the agroforestry:

$$s_T^{TB} = \sigma\cdot tprice\cdot GYT(s^{SA})_T \quad [10]$$

$$\sigma = \begin{cases} 1 & if\ t = T \\ 0 & if\ t \neq T \end{cases} \quad [11]$$

NPV_{AF} represents the net present value of one agroforestry rotation at year 0 (the moment the project starts). In contrast, the Land Expectation Value (LEV) is estimated assuming infinite agroforestry rotation cycles, with periodic rewards equal *to* NPV_{AF}. Based on an infinite cycle of agroforestry, each with identical production, costs and income functions, the LEV of agroforestry estimated as:

$$LEV_{AF} = NPV_{AF}/(1-\delta)^{T} \quad [12]$$

For comparative purpose the land expectation value of the conventional agriculture (LEV_{AG}) is estimated as the capitalised net returns to conventional agriculture into perpetuity:

$$LEV_{AG} = (s^{AG} - s^{CP}\cdot\omega)/r \quad [13]$$

Using this approach, it is possible to estimate three carbon threshold prices, that is carbon prices at which agroforestry adoption would occur: a price for total carbon sequestered due to tree growth (c_S), a price that accounts for the penalties to carbon emissions (c_e), and a threshold price that accounts for both carbon sequestration and penalties to carbon emissions from conventional agriculture (c_{s+e}). The threshold prices are estimated based on the differences between Land Expectation Values of agroforestry and conventional agriculture and the difference in carbon sequestration and GHG emissions from each livestock systems.

$$c_s = -\frac{(LEV_{AF} - LEV_{AG})}{\sum_{t=0}^{T} \varphi\left(MGY\left(s_t^{SA}\right)\right)} \tag{14}$$

$$c_e = -\frac{(LEV_{AF} - LEV_{AG})}{(1-\beta)\omega_t - \omega_t} \tag{15}$$

$$c_{s+e} = -\frac{(LEV_{AF} - LEV_{AG})}{\sum_{t=0}^{T} \varphi\left(MGY\left(s_t^{SA}\right) - \beta\omega_t\right)} \tag{16}$$

We estimate carbon threshold values only when $LEV_{AF} - LEV_{AG} < 0$.

4 Empirical application

4.1 Glensaugh Farm

Although there is no legal definition for upland areas, they usually refer to areas contained in the upper limits of enclosed farmland containing dry and wet dwarf shrub heath species and rough grassland. The traditional basis for farming these areas is raising sheep and/or beef cattle in extensive land use systems. These farming systems usually have relatively low stocking rates between 0.2 and 0.4 standard livestock units ha^{-1} (Chapman 2017) and income levels per hectare are also relatively low.

The model application is based on the James Hutton Institute's research farm, Glensaugh which is located in the Grampian foothills of Aberdeenshire[1] . The farm is considered representative of Scottish upland sheep and beef-cattle farms. Two distinct livestock enterprises are operated at Glensaugh: (i) a low ground suckler cow herd and sheep flock, which rely on summer grazing and conserved winter feed, and (ii) hill sheep flock that rely on extensive grazing through the year. The overall system is based on the management of semi-natural grassland, rotational improved grassland, moorland, and permanent pastures that provide swards, haylage and silage to support livestock production. The farm already has some mature agroforestry plots, planted in 1988, using Scots pine (*Pinus sylvestris*), hybrid larch (*Larix X Eurolepis*) and sycamore (*Acer pseudoplatanus*). Those plots are a source of biomass, and are also grazed by ewes between April and November, with lambs at foot in spring and early summer.

The two distinct livestock enterprises have different costs and benefits, and hence agricultural returns. We have estimated the net revenues (revenues minus direct operating costs including inputs, labour costs, and consumption of fixed assets) for both the hill sheep and low ground sheep and beef enterprises

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[1] https://glensaugh.hutton.ac.uk/

per hectare of land used (see Table 2). To allow for variability we considered net revenue estimates covering the period 2006-2018, updated to 2018 prices using the UK GDP deflator.

Table 2 depicts the main characteristics of the hill and low-ground enterprises in terms of the type and area of land used and the average number of breeding animals and the equivalent standard livestock units supported by both systems.

Table 2 Main characteristics of the hill and low-ground conventional livestock systems in Glensaugh

Class[3]	Livestock enterprise	Land area used (in hectares)	Agricultural returns (£ ha^{-1})			Total livestock units (1) Average (2006-2018)		Stocking rate (LU ha^{-1})	
			Min	Max	Average	Average	SD	Average	SD
Hill area	Sheep	467.0	-15	70	30	65.8	9.4	0.14	0.02
Low-ground área	Sheep & Beef	112.4	-57	178	55	159.8	16.7	1.42	0.15
Total farm		579.4				256.4	13.1	0.44	0.02

Source: *Own elaborations* based on Ovando (2020)
Notes: (1) Livestock units following the Less Favoured Area Support Scheme (LFASS) guidance (Scottish Government, 2019), which indicates 1 LU for beef cow over 24 months of age; and 0.15 LU for breeding ewes and gimmers.

4.2 Modelling timber production and carbon dioxide sequestration from agroforestry

Estimates of the annual amount of carbon sequestration (measured in t CO_2 ha^{-1} y^{-1}) is based on the carbon stored in timber, branchwood and roots (referred jointly as total tree biomass). Tree biomass in branchwood and roots is estimated applying an expansion factor (φ that converts standing timber stock (in cubic meters (m^3) ha^{-1} y^{-1}) to t CO_2 m^{-3}:

$$\varphi = \rho \cdot \phi \cdot EF \cdot \kappa \qquad [9]$$

Where, ρ represents the density of timber assuming a relative humidity of 65%, which gives an equilibrium moisture content (MC) at 20°C of approximately 12% (Morison et al., 2012); ϕ represents the carbon content of oven dry biomass; EF the expansion factor that indicates the total volume of aboveground tree biomass and roots in relation to the standing timber stock, and κ the ratio of molecular weight to convert C to CO_2 (κ =3.667).

The parameters ρ, ϕ and EF differ between tree species. In this paper we consider Morison et al. (2012) timber density estimates, a carbon content that varies between 0.42 and 1.46 (Milne and Brown (1997), and expansion factors from Levy et al. (2012). We use Ovando (2020) timber stock functions to represent total growth yield (TGY), which in turn are based on the Forest Yield model timber production tables by tree species, forest stand age and yield class[2] (Matthews et al., 2016). Timber growth is then represented as an exponential function of tree age and yield class.

For both the Real Option and LEV analyses, we consider Scots pine which is a native conifer that has already being used in experimental agroforestry plots on Glensaugh farm. Estimated tree growth functions represent timber growth in tree-only systems, accounting for plantation spacings ranging from 1.7 to 2.5 m (with an average initial tree planting of 2000 trees ha^{-1}). The potential tree productivity for

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[2] Yield Class (YC) is an index used in the UK of the potential productivity of even-aged stands of trees. It is based on the maximum mean annual increment of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a standard management prescription (Matthews *et al.*, 2016).

Scot pine is also expected to vary between the hill and low ground areas, for instance the Ecological Site Classification (ESC) model map (Pyatt et al., 2001)[3] show often yield classes ranging from 6 to 8 for Scots pine in upland areas and ranging from 12 to 14 on lowland areas.

The effect of tree density and grazing on tree growth is based on the results of Scot pine agroforestry plantations on the farm after 12 years of trees being planted (Sibbald et al., 2001). The control plot consisted of a woodland plantation of an initial density of 2000 trees ha^{-1}, while the agroforestry plot kept a density of 400 trees ha^{-1}. After 12 years, the Scots pines in the agroforestry plot were shorter (3.7m) than in the woodland control (4.7m), and diameter at breast high (dbh) in the agroforestry plot was also smaller (8.8cm) than in the control plot (9.4cm). Assuming a perfect cylindric shape that would represent an average volume of 0.3256 m^3 per tree in the agroforestry plot and 0.4418 m^3 per tree in the woodland control. The later figures are translated into a reduction of 35.7% on individual tree volume in case of the agroforestry system. Although tree growth was slowed down in the agroforestry plot, Sibbald et al. (2001) also found that the mortality rate of agroforestry trees over the first 4 years since trees were planted was 6% lower. Based on a agroforestry tree density of 400 trees ha^{-1} and taking into account the grazing effect on tree growth and mortality, we calculate that agroforestry parcels will yield about 11% of total timber stock when compared to tree-only plantations.

The parameters of the timber stock functions and carbon expansion factors in the model are presented in Table 3. We consider a single timber standing price of £50 m^{-3} (Table 4).

Table 3 Parameters of the timber growth functions and carbon expansion factors for Scot pine

Dominant yield class(1) (YC)		Timber stock growth function (in m^3 ha^{-1})	Timber density (ρ) in t m^{-3}	Carbon content (φ) in tC t^{-1} of biomass	Expansion factor from timber to total biomass	Carbon conversion factor (φ) (tCO$_2$ m^{-3})
Hill	Low-ground					
7	13	$v_1 = \left(0.6952 \cdot (t \cdot YC)^{1.0249} \cdot e^{9.72 \cdot 10^{-4} t}\right) \cdot 0.11$	0.513	0.42	2.530	1.999

Note: (1)Dominant yield class in Glensaugh farm which is a (see Ovando (2020)).

Source: *Own elaboration* based on Ovando (2020) and Sibbald et al. (2001).

4.3 Livestock GHG emissions

Livestock emissions depend not only on the number and type of animals reared, but also manure management and their dependency on grazing and feed. In order to reflect GHG of a representative upland farming we use Ovando (2020) GHG emissions estimated for hill sheep and low-ground cattle and sheep enterprises in Glensaugh for the period 2002 -2018. In particular, the livestock unit GHG emissions are converted into per hectare basis using the stocking rate data from Glensaugh to analyse the effect of applying a penalty to livestock GHG emissions in hill and low livestock enterprises.

GHG emissions were estimated using the Cool Farm Tool (CFT) (Kayatz *et al.*, 2019). The CFT input information includes livestock numbers by species, sex and age class over the year, dry matter (DM) intake, the proportion of the time animals are grazing outdoors and housed, the annual dependency on different supplementary feeding stuff, and bedding and manure management. It is assumed that that stocking rate on land remaining in farming reduces proportionately to the reduction land area (ie by 20%) due to agroforestry adoption.

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[3] Data retrieved for a 100 m x 100 m grid resolution from: http://www.forestdss.org.uk/geoforestdss/

Estimated GHG emissions for the livestock enterprises at Glensaugh include emissions from enteric fermentation, manure management and bedding, grazing and feed supply. The estimated average GHG emission total 0.19 of carbon dioxide equivalent tonnes ($tCOe_2$) per hectare of land for the hill sheep enterprise and 2.42 $tCOe_2$ ha^{-1} per hectare in the low-ground. Beef-cattle are responsible for 58% of the low-ground emissions, while sheep contributes to the reminding 42%.

Figure 1 provides an overview of the relative levels of sequestration and emissions on the two enterprise types. The cumulative expected carbon sequestration associated to the introduction of agroforestry in the hill enterprise is 69 t CO_2 per hectare over a rotation period of 60 years ($maxsa$). This amount is almost doubled in low-ground areas where there are better tree growing conditions. Carbon sequestration due to agroforestry adoption in hill areas would offset emissions from sheep farming, while creating further opportunities to trade carbon offsets. In contrast, the sequestration benefits from agroforestry in the low ground enterprise, although higher, only just compensates for the remaining livestock GHG emissions. This suggests that additional measures would be needed in the transition to net -zero farming targets low ground areas, including incentives to reduce cattle stocking rates or switching to a higher proportion of sheep.

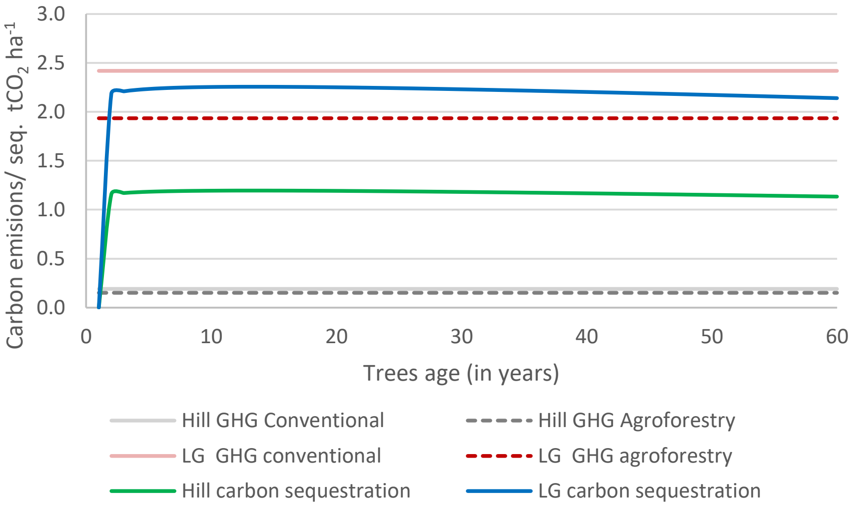

Figure 1 Carbon sequestration and GHG emissions in agroforestry and conventional farming systems for hill sheep and low-ground cattle and sheep enterprises

4.4 Agroforestry management and reversion costs

Afforestation investment (woodland creation) is estimated at £ 4,000 per hectare for a moderate disturbance to ground preparation when conifers are planted. This includes ground preparation and tree planting costs (including seedlings). Additional costs include two post-plant sprays and weeding in years 1 and 3 (£130 ha^{-1}each application), one beat up in year 2 (£230 ha^{-1}) and general maintenance/management (incl., Forest Agent/Craftsman, covering Years 1-5(£150 ha^{-1}) (Ovando, 2020). Agroforestry investment is estimated assuming that ground preparation would account for one third of ground preparation costs, while tree planting costs are based on an initial 400 tree ha^{-1} density (Table 4).

Table 4 Woodland and agroforestry planting and maintenance costs (2018, prices)

Class	Unit	Price (£/unit)	Woodland (forestry)	Agroforestry
Ground preparation and planting (year 1) (1)	ha		2,800	1,000(1)
Individual plant and protection (year 1) (2)	plant	0.5 /2.0	1,250	800
One beat up (year 2)	ha	230	230	150
Spraying and weeding (years 1 and 3)	ha	130	130	130
Maintenance	ha		150	150
Upfront payment for planting (80% plantation costs)	ha			1,440
Forestry reversion cost (3)	ha		2,800	1,800
Timber prices	m^3	50		

Notes: (1) It is assumed that ground preparation would account for close to one third of the woodland plantation ground preparation cost. (2) Agroforestry plants would need an individual tubing and guards (estimated in £1.5 unit^{-1}). (3) Forest reversion cost are assumed similar to the ground preparation cost.

Source: *Own elaboration* based on Ovando (2020).

In subsequent analysis we consider the impact of an upfront (subsidy) payment to forest planting which operates in a similar way to a woodland expansion grant and is not linked to carbon sequestration. In our application we assume this upfront payment covers 80% of the ground preparation and tree planting costs.

4.5 Carbon prices

A central barrier to reducing emissions arises from the fact that private actors do not face the full costs of their GHG emissions. Carbon pricing is a policy option that aims to internalise the true costs of emissions into the firm's production decisions to induce a cost-effective way of emissions abatement. Two main carbon pricing policy instruments are carbon taxes and emission trading systems (ETS). Carbon taxes place a set price per unit of emissions, while ETS limits the volume of emission allowances in a jurisdiction (e.g., EU or the UK) and allow firms to trade, and market prices for these allowances are results of these interactions.

The biggest emission trading system in the world is the EU Emissions Trading System (EU ETS). A UK Emissions Trading Scheme (UK ETS) will replace UK participation in the EU ETS from 30 April 2021 onwards. As this system is not yet operative, the EU ETS is currently the only reference for carbon allowances prices in Europe. The EU ETS carbon pricing system does not consider land use, land use change and forestry it does however provide a source of information on the variations observed in carbon prices since 2008 when EU ETS became operative.

Figure 2(a) shows the variation in the observed daily EU carbon allowance prices from January 2008 to December 2020[4], while Figure 2(b) the distribution of those prices considering the observed range from £3 tCO_2 to £33 tCO_2. Nominal carbon prices were updated to 2018 prices using the Euro zone GDP deflator (World Bank 2020). EU carbon allowance prices showed a trend to decrease since the start of the ETS market with a recovery since 2018. Over the last year (2020) ETS carbon prices ranged between £15 tCO_2 to £33 tCO_2. Given the recent strong rising trend in carbon prices observed in the EU ETS market, we use a central carbon value £30 tCO_2^{-1} while the state space for the carbon prices in the Real Option model was chosen to range from -£0 tCO_2^{-1} to £1000 tCO_2^{-1}.

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[4] Available online: https://www.sendeco2.com/es/precios-co2

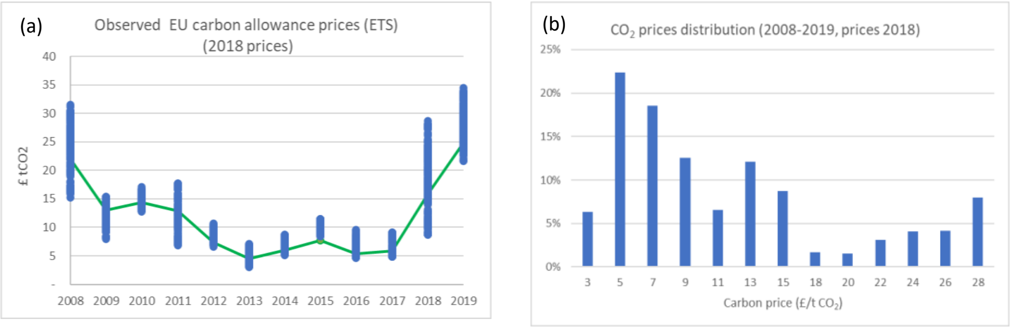


Figure 2 EU ETS carbon price distribution period 2008-2019 (in 2018 prices)

5 Results

5.1 Optimal agroforestry adoption using a real option model

The real options model produces a set of functions for the farmer showing the optimal decision for each state.

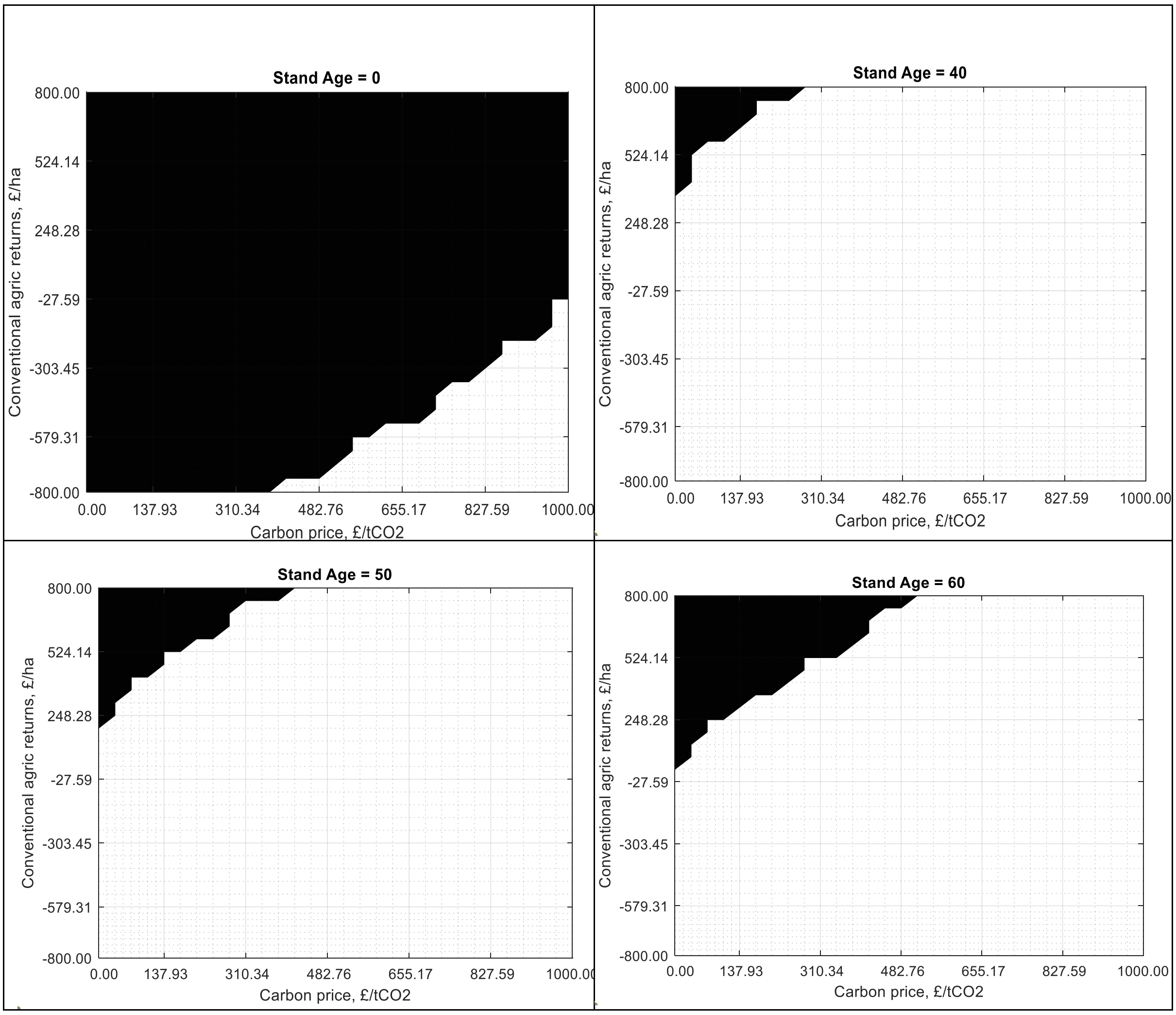
Figure 3 is a graphical representation of the farmer's optimal function for the hill sheep enterprise. It shows the optimal decision matrix for two dimensions (agricultural returns and carbon prices) for the entire modelled state space, for four different stand ages. The figures use the same axes to facilitate comparison. The level at which a farmer crosses from non-adoption of agroforestry to adoption represents the RO adoption threshold.

In stand age 0, the land is in conventional agriculture only. The black coloured cells represent the points at which the optimal decision of the farmer is to maintain the farm in conventional agriculture for one more year. The white coloured cells represent the points at which the optimal decision of the farmer is to switch from conventional agriculture to agroforestry.

From the figure, the adoption frontier is diagonal suggesting that the farmer's optimal decision is driven by both the state of conventional agriculture returns and the price of carbon. Because the white section of the figure is small, it suggests that switching to agroforestry is very unlikely to be an optimal decision for this type of enterprise unless either agricultural prices are very low or carbon prices extremely high. For example, even when the conventional agriculture returns are -£-300/ha, the farmer switches to agroforestry only when the price of carbon is £830/tCO_2 (ie orders of magnitude higher than observed levels to date). Below this price level, the optimal farmer decision would be to maintain conventional farming.

At stand ages 40, 50 and 60, the land is in agroforestry. In this case, the white cells represent maintaining agroforestry at least until next year, whereas the black cells represent clearing the planted trees and returning to agriculture. In this case, the level of agricultural returns above which a landowner reverts from the agroforestry back to agriculture represents the RO dis-adoption threshold.

As shown in Figure 3, the dis-adoption threshold varies with the age of the stand. At stand age 40, even with zero carbon prices, the optimal decision is to maintain the land in agroforestry unless agricultural prices are above £524/ha. The threshold frontier to convert to agriculture shifts to the right as the stand age increases because the marginal value of one more year of additional timber at this age falls and thus lower agricultural returns are needed to make the optimal decision to convert 100% of the land back to agriculture.



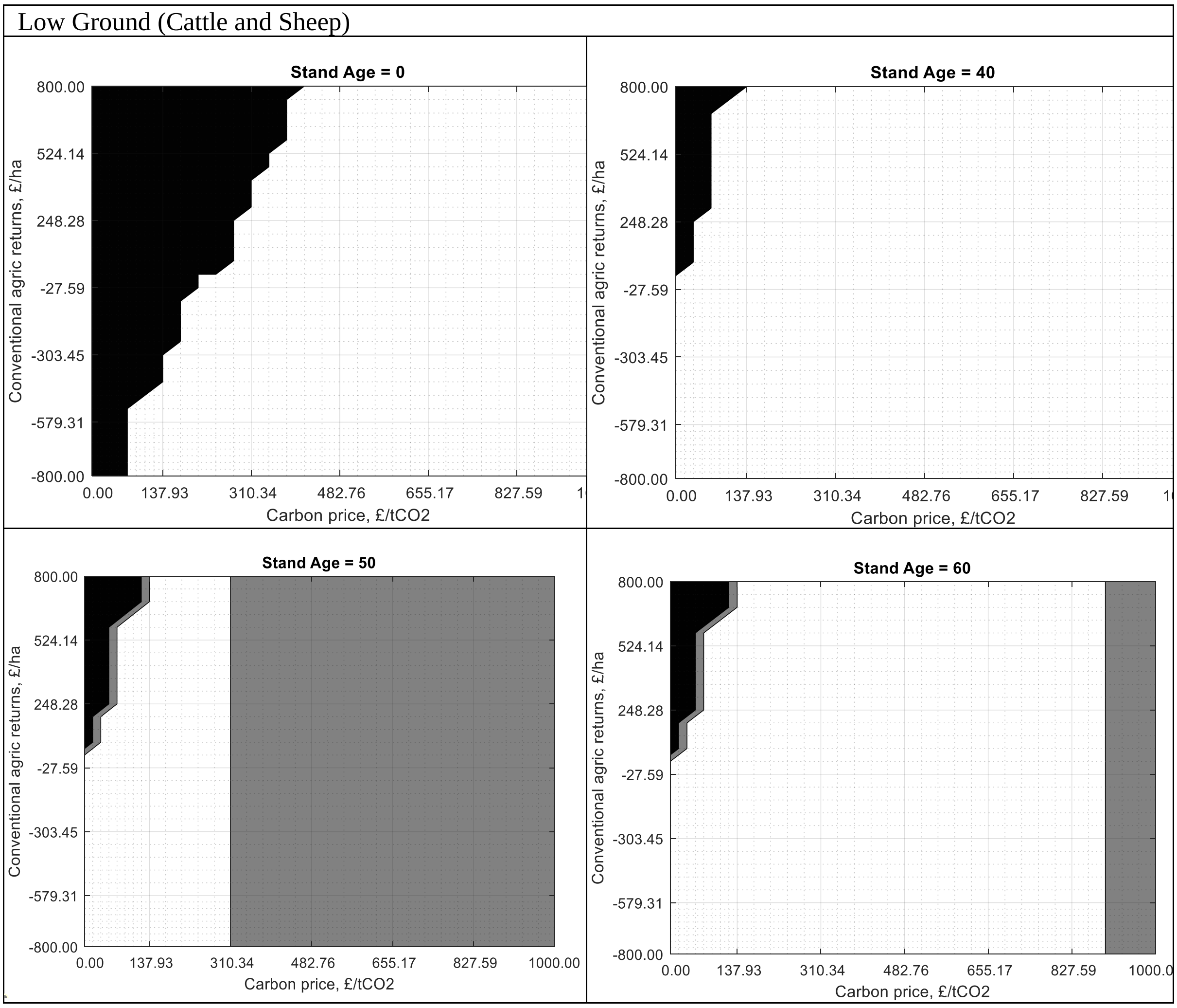
Black region = maintain conventional agriculture, white region = adopt (stand age 0)/retain (stand age 40, 50 and 60) agroforestry.

Figure 3: Hill sheep enterprise optimal policy function at different stand ages

Figure 4 shows the equivalent optimal functions for the low ground cattle and sheep enterprise at the same four stand ages. Compared to the previous case, lower carbon prices are required for a farmer to adopt agroforestry at stand age 0. For example, when the conventional agriculture returns are -£-300/ha, the farmer would choose to switch to agroforestry when the price of carbon is £138/tCO_2 as opposed to £830/tCO_2 in the hill sheep enterprise case. Below this price level, the optimal farmer decision would be to maintain conventional farming.

At stand age 40, the white cells represent maintaining agroforestry at least until next year, the black cells represent clearing the planted trees and returning to agriculture. The dis-adoption frontier in this case is somewhat different to that found in the case of the hill sheep enterprise. With zero carbon prices, the farmer would chose to switch back to agriculture when agricultural returns are above zero, ie at a lower level than was the case for the hill sheep enterprise. However, even small increases in carbon prices will result in the farmer opting to stay in agroforestry for another year unless agricultural prices are high (the dis-adoption frontier is much steeper).

At stand ages 50 and 60 another state is observed and shown in the figure: when the farmer choses to cut and re-establish agroforestry rather than revert to agriculture. This is represented by white cells with the grey cells representing cases where the farmer retains the stand for at least another year. As expected the decision to replant increases with stand age. For carbon prices higher than £310.34 tCO_2^{-1} the penalties to livestock emissions carbon emissions are so high as to make the optimal function insensitive to returns from conventional agriculture within the state space simulated.



Black region = maintain (revert to) conventional agriculture; White region = adopt (stand age 0), retain (stand age 40), cut and re-establish agroforestry (stand age 50 and 60); Grey region = retain agroforestry.

Figure 4: Cattle and Sheep optimal policy functions at different stand ages

5.2 Agroforestry adoption using deterministic capital project evaluation methods

Table 5 shows the Land Expectation Values for both from adopting agroforestry and staying in conventional agriculture, (LEV_{AF} and LEV_{AG} respectively). Values are estimated for different payment levels for carbon sequestration and penalties to carbon emissions ranging from no payments to the observed average ETS carbon prices in 2020 and analyses the sensitivity of adoption for carbon prices ranging from £0 tCO_2 to £100 tCO_2. Likewise, we analyse the sensitivity of adoption to agricultural returns as given in section 4.1. To facilitate comparison with the results from the Real Option analyses, a maximum tree age (*T*) of 60 years is taken as the project time horizon.

When there are no payments for carbon sequestration or penalties for GHG emissions (i.e. carbon prices are equivalent to zero: £0 tCO_2^{-1}) the results suggest agroforestry would not be adopted (LEV_{AF} <LEV_{AG}). Furthermore, payments for carbon sequestration in the range of prices observed in the EU ETS market in 2020 provide insufficient incentives for agroforestry adoption in the hill sheep enterprise but do make agroforestry adoption efficient for the low ground sheep and cattle enterprise. Indeed, carbon prices close to £25 tCO_2^{-1} for carbon sequestration would render agroforestry adoption an efficient decision for the low-ground enterprise (assuming no penalties to GHG emissions).

In a scenario with penalties to carbon emissions, values of between £300 to £400 per ton of CO_2 equivalent are required to favour agroforestry adoption for the hill sheep enterprise. In contrast, in the low ground cattle and sheep enterprise where GHG emissions are many orders of magnitude higher, carbon penalties in between £20 tCO_2 equivalent and £40 tCO_2 equivalent would be sufficient to suggest agroforestry adoption. Finally, when both payments for carbon sequestration and penalties to carbon emissions are simultaneously considered, threshold values would be significantly higher for the low-ground cattle and sheep enterprise as carbon sequestration from agroforestry is relatively low compared to the GHG emission levels from livestock.

Table 5 Estimated land expectation values for conventional agriculture and agroforestry under different farm income and carbon price levels for carbon sequestration and carbon emissions (2018 prices)$^{(1)}$

	Farming enterprise					
	Hill sheep			Low-ground cattle and sheep		
	Average (£ 30 ha^{-1})	Lower range (£ -20 ha^{-1})	Higher range (£ 70 ha^{-1})	Average (£ 55 ha^{-1})	Lower range (£ -60 ha^{-1})	Higher range (£ 180 ha^{-1})
	Land Expectation Value (LEV) (£ ha^{-1})					
Conventional agriculture (LEV_{AG})						
No carbon payment/penalty (£ 0 tCO_2)	1,000.0	-666.7	2,333.3	1,833.3	-2,000.0	6,000.0
Average carbon price (£ 30 tCO_2^{-1})	810.0	-856.7	2,143.3	-586.7	-4,420.0	3,580.0
Low carbon price (£ 10 tCO_2^{-1})	936.7	-730.0	2,270.0	1,026.7	-2,806.7	5,193.3
High carbon price (£ 100 tCO_2^{-1})	366.7	-1,300.0	1,700.0	-6,233.3	-10,066.7	-2,066.7
Agroforestry total (LEV_{AF})						
No carbon payment/penalty (£ 0 tCO_2)	-2,390.40	-3,723.73	-1,323.73	-1,393.29	-4,459.95	1,940.05
Average carbon price (£30 tCO_2^{-1})	-1,379.49	-2,712.82	116.27	95.99	-2,970.68	3,380.05
Low carbon price (£ 10 tCO_2^{-1})	-1,681.59	-3,014.92	-312.82	-563.53	-3,630.20	1,645.32
High carbon price (£ 100 tCO_2^{-1})	-322.13	-3,685.40	-614.92	2,404.32	-2,692.28	2,175.13
	Carbon sequestration/emissions and carbon price threshold					
Accumulated carbon sequestration (tCO_2 ha^{-1}) $^{(2)}$	69.3	69.3	69.3	130.6	130.6	130.6
Threshold price for carbon sequestration (c_s)	48.95	44.14	52.80	24.70	18.83	31.08
Accumulated GHG emissions conventional agriculture (tCO_2e ha^{-1})	9.1	9.1	9.1	116.2	116.2	116.2
Threshold price for carbon penalty (c_e)	371.8	335.2	401.0	27.8	21.2	35.0
Net carbon sequestration (tCO_2e ha^{-1})	60.1	60.1	60.1	14.5	14.5	14.5
Threshold price for carbon sequestration and carbon penalty (c_{s+e}))	56.4	50.8	60.8	223.2	170.2	280.9

Notes: $^{(1)}$ Real discount rate (r) 3%. $^{(2)}$ Total carbon sequestration, total livestock GHG emissions and carbon threshold prices estimated over a 60-years' time horizon. Threshold carbon prices are estimated considering the LEV for comparison purposes.

To facilitate comparison with the results from the Real Options Analysis, we contrast the carbon threshold prices from the LEV analysis for agricultural returns ranging from £-800 ha^{-1} to £800 ha^{-1}. These are the carbon prices at which agroforestry adoption would be the financially optimal choice of land use (Figure 5). The figure confirms that the relative irreversibility of agroforestry adoption along with uncertainty in carbon prices makes the adoption of agroforestry even less likely than standard budgeting techniques would suggest.

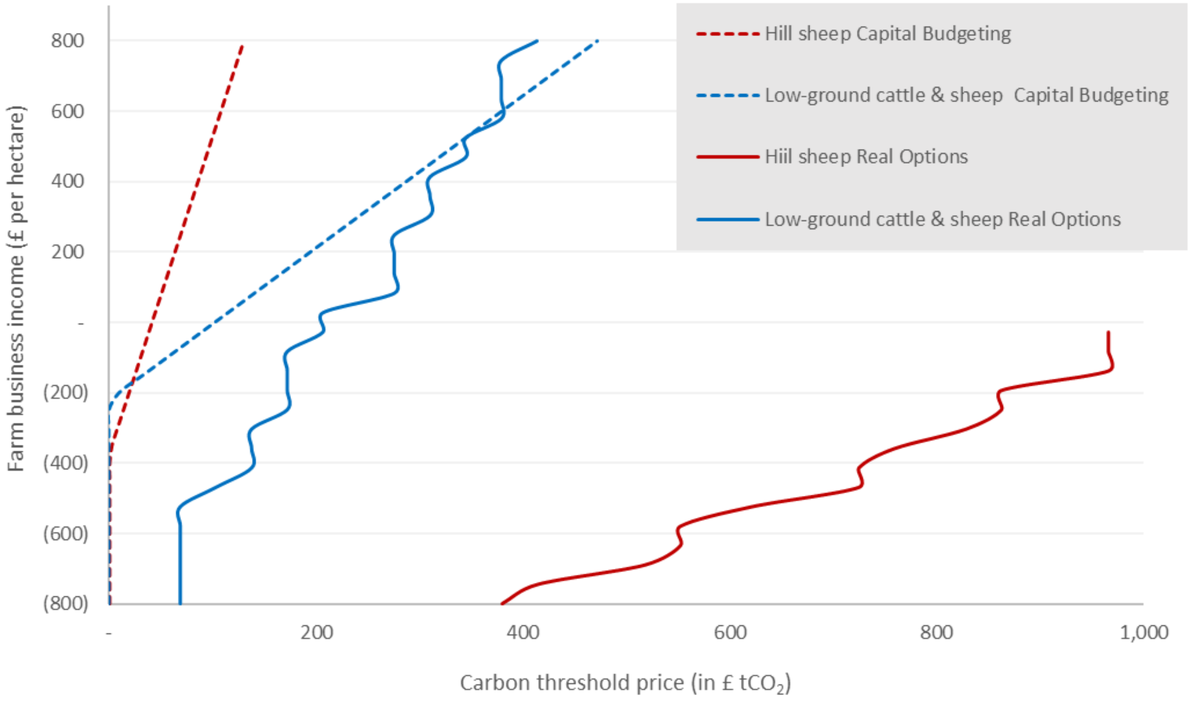
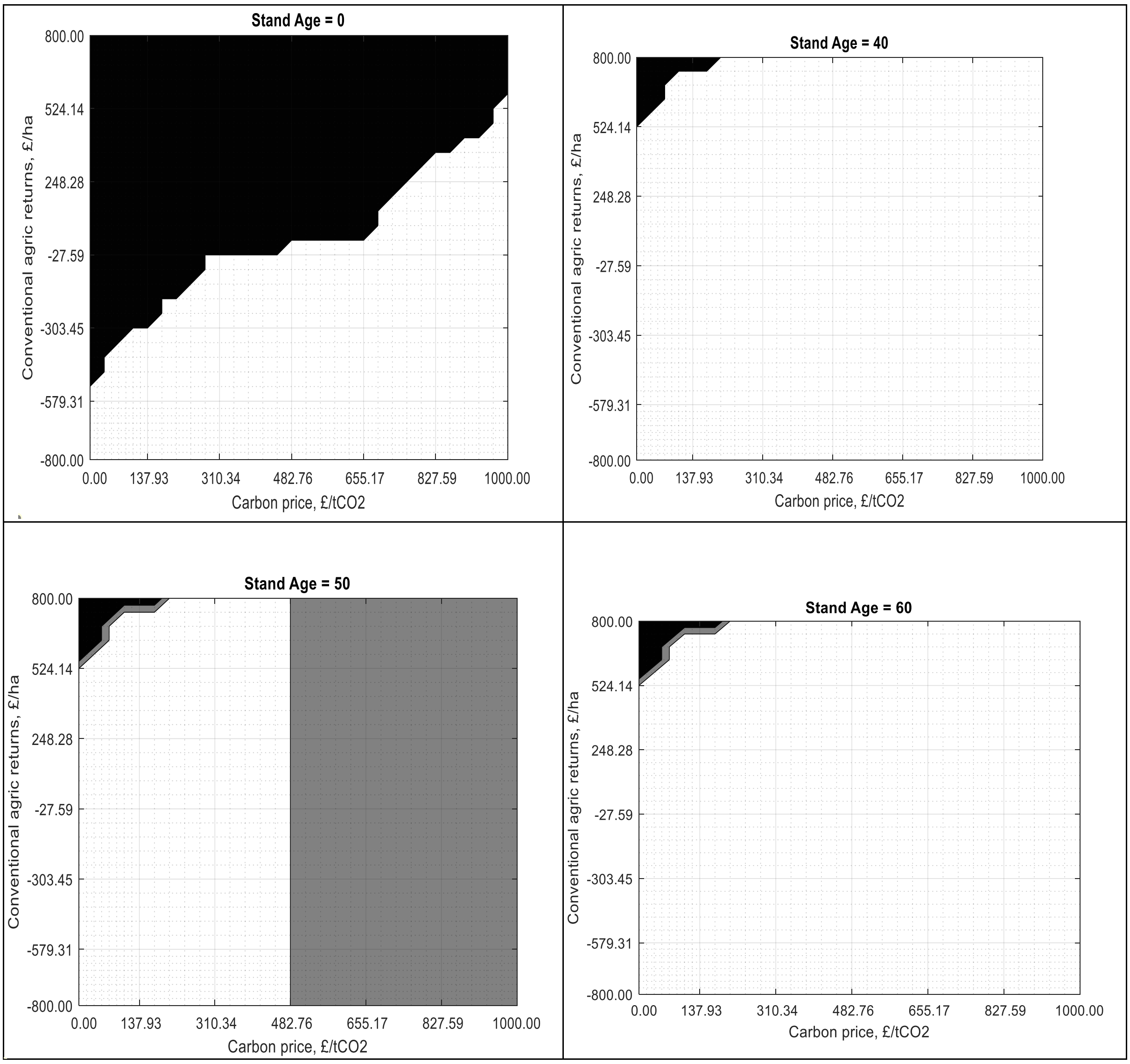


Figure 5 Sensitivity analysis of carbon threshold prices to agricultural returns (without upfront payments).

5.3 Incentivising adoption through an upfront payment

To explore the sensitivity of the results to the timing of costs and returns from agroforestry, both the Real Options analysis and LEV analyses were repeated but, in this case, providing an upfront payment for converting to agroforestry. The payment, similar to a grant for expansion for woodland, is unrelated to carbon sequestration and instead set to cover 80% of the initial investment costs for converting to agroforestry.

The impact on the Real Options adoption and dis-adoption frontiers for the hill ground sheep enterprise at Glensaugh are shown in Figure 6. Comparison with Figure 3 showns that the upfront payment makes the adoption of agroforestry the optimal choice over a much wider range of carbon prices and at lower agricutural returns. At stand age 50, at carbon prices below £482 tCO$_2^{-1}$ over a range of agricultural returns, the optimal decision is to cut and replace with agroforestry rather than continue with the existing stand. Carbon prices above £482 tCO$_2^{-1}$ would make retaining the existing agroforestry stand for one more year the optimal decision. Finally, by stand age 60, the optimal decision is to cut and replant trees (replace with agroforestry). Agroforestry dis-adoption is only optimal for extremely high return to conventional agriculture above £524 ha^{-1}. At stand age 50, at carbon prices below £482/tCO$_2$ over a range of agricultural returns, the optimal decision is to cut and replace with agroforestry rather than continue with the existing stand. Carbon prices above £482 /tCO$_2$ would make retaining the existing agrofortesry stand for one more year the optimal decision.



Black region = maintain (revert to) conventional agriculture; White region = adopt (stand age 0), retain (stand age 40), cut and re-establish agroforestry (stand age 50 and 60); Grey region = retain agroforestry.

Figure 6: Hill sheep enterprise optimal policy function at different stand ages with upfront payment

The results for the low ground cattle and sheep enterprise (not shown) followed the same pattern suggesting such schemes do have significant potential for increasing the adoption of agroforestry all other things remaining constant but will also reduce agroforestry production cycles.

The standard budgeting approach results indicate that an upfront payment alone would still not create enough incentives to farmers to adopt agroforestry. Additional carbon finance incentives to carbon sequestration close to £28 tCO$_2^{-1}$ could create incentives for agroforestry expansion in the case of the hill sheep enterprise, and at half of this price in case of low-ground cattle and sheep enterprise (Table 6). When both payments for carbon sequestration and penalties to carbon emissions are simultaneously considered, and upfront payment would reduce carbon threshold values significantly to almost half prices estimated for agroforestry adoption scenarios depending mainly on carbon finance.

Table 6 Estimated land expectation values for conventional agriculture and agroforestry under different farm income and carbon price levels for carbon sequestration and carbon emissions (2018 prices)(1)

	Farming enterprise					
	Hill sheep			Low-ground cattle and sheep		
	Central price (£ 30 ha^{-1})	Lower range (£ -20 ha^{-1})	Higher range (£ 70 ha^{-1})	Central] price (£ 55 ha^{-1})	Lower range (£ -60 ha^{-1})	Higher range (£ 180 ha^{-1})
	Land Expectation Value (LEV_{AF}) (£ ha^{-1})					
No carbon payment/penalty (£ 0 tCO_2) + Upfront payment	-950.40	-2,283.73	116.27	46.71	-3,019.95	3,380.05
Central carbon price (£ 30 tCO_2^{-1})	60.51	-1,272.82	-2,284.56	-248.01	-3,314.68	-326.42
Low carbon price (£ 10 tCO_2^{-1})	-241.59	-1,574.92	-2,586.66	281.80	-2,784.87	203.39
High carbon price (£ 100 tCO_2^{-1})	1,117.87	-2,245.40	-1,227.20	-2,102.35	-7,198.95	-2,180.76
	Carbon sequestration/emissions and carbon price threshold (£ tCO_2^{-1})					
Threshold price for carbon sequestration (c_s) (with upfront payment)	28.16	23.35	32.01	13.68	7.81	20.06
Threshold price for carbon penalty (c_e) (with upfront payments)	213.9	177.3	243.1	15.4	8.8	22.6
Threshold price for carbon sequestration and carbon penalty (c_{s+e}) (with upfront payments)	32.4	26.9	36.9	123.6	70.6	181.3

Notes: (1) Real discount rate (r) 3%.

6 Discussion and Conclusion

The agricultural sector, like all sectors, is required to reduce its net GHG emissions to zero over the next three decades. Within this context, agroforestry as a land use system offers considerable potential through the carbon sequestration from tree growth plus possibly reduced carbon emissions form livestock if stocking rates are reduced. It also offers other production and biodiversity benefits although these are not considered in the current paper.

Barriers to woodland establishment on farmland include cultural resistance, based on a perception that farming and forestry are competing land uses, a lack of practical skills in establishing and maintaining trees, and lack of awareness of the potential economic benefits of woodland. However economic analyses often fail to recognise the disincentive effect associated with the relative irreversibility of woodland planting and lack of flexibility once decision made. This is further exacerbated by the length of the forestry production cycle in a context where yearly returns are the norm and uncertainty in future prices which also influences land use decisions.

To understand further the impact of risk and uncertainty on agroforestry adoption decisions, a Real options analysis was conducted focussing on two different types of livestock enterprise on an upland farm. The case study farm analysed was Glensaugh, a research farm managed by the James Hutton Institute for which the data required for the analysis was available.

The results show that even when there is a charge on livestock emissions and a return provided for carbon sequestration, the uncertainty and irreversibility of switching to agroforestry makes the adoption decision suboptimal except at extremely low level of agricultural return or extremely high carbon price levels compared to those observed to date. The results quantify and confirm the importance of different biophysical and financial factors on the economic efficiency of agroforestry with adoption relatively more attractive for the low ground enterprise because greater sequestration benefits. The optimal conversion thresholds from the Real Options modelling are significantly higher than those from the Land Expectation Value model which does not account for return uncertainty (Schatzki, 2003). However even in the latter, adoption of agroforestry in hill enterprises (where agricultural opportunity cost is lower) is not optimal at observed carbon prices to date.

Providing an upfront payment to farmers is shown to significantly increase in the likelihood of agroforestry adoption over range of different carbon prices and expected agricultural returns. Thus policy changes such as the Small Woodland Loan scheme introduced recently by Scottish Forestry to help with cash flow issues should be effective means of helping farmers looking to offset their GHG emissions.

Further research is required on the sensitivity of the results to various assumed parameter values including, for example, the relationship between the volatility of carbon prices and agroforestry adoption, as well as to understand further the perceived barriers to increasing agroforestry on farms.

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