Understanding the economic barriers to the adoption of 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 if livestock stocking rates are reduced. 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 under the scenario where there are financial penalties from livestock Greenhouse Gas (GHG) emissions, financial benefits from carbon sequestration in trees and reversibility in land use decisions. The results are compared to the equivalent findings from a Land Equivalent Value capital budgeting approach to agroforestry adoption. Analysis is based on data 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 results suggest that the adoption of agroforestry is far less likely than would be suggested by standard budgeting approaches, especially in more extensive upland enterprises (hill area) where sequestration benefits are low relative to more productive farmland areas (low ground area). Upfront support payments are shown to increase the likelihood of agroforestry adoption. They also have the effect of reducing the rotation length of forestry in such systems.

Key words: Carbon sequestration, livestock farming, policy, carbon prices.

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 a 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, as in many developed economies, the growing interest in agroforestry has followed from the net zero targets for the sector and call for a green recovery in response to 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.

Agroforestry practice in the UK is currently 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; Montagnini and Nair, 2004). Agroforestry is deemed to bring multiple benefits including shelter to animals and crops, a potential reduction in feed costs, improved animal welfare, reduced risk of flooding, potentially reduced crop pests by housing beneficiary predators, reductions in soil erosion and moisture extremes, and a means of diversifying farm income (England et al., 2020; Perks et al., 2018; Raskin and Osborne, 2019). However, despite policy incentives, uptake of agroforestry in many countries has been limited. In the UK, an estimated 2.2% (547,600 ha) of total agricultural land is under agroforestry use, with almost all of it in silvo-pastoral systems (den Herder et al. 2017).

Several economic barriers to adoption have been identified. Bruck et al. (2019) found, using capital budgeting techniques, that monoculture (either agriculture or afforestation) provides higher returns than silvo-pastoralism in certain contexts. The authors note however that this is in the absence of policy mechanisms which reward the carbon sequestered by trees and that allowing for this externality could change optimal land use decisions. Other economic barriers to adoption of agroforestry include the high upfront costs associated with conversion and consequent impact on farm cash flows, uncertainty in the returns from forestry relative to those from agriculture, the long production cycle and perceived irreversibility of the land use decision, the associated loss of flexibility in land management, and, in some farming contexts, an impact on the food security of farm households (Gosling et al., 2020 Royal Forestry Society, 2020). From a more practical perspective there may be a lack of practical skills in establishing and maintaining trees (Royal Forestry Society, 2020). There can also be a cultural resistance based on a perception that farming and forestry are competing as opposed to complementary land uses.

Against this background, this paper considers the economics of agroforestry adoption and, in particular, the financial and biophysical factors which influence the adoption of agroforestry. Analysis is based on a Real Options (RO) appraisal of agroforestry adoption within which the costs associated with moving into and out of agroforestry are taken into account and the farmer's decisions are recognised as taking place in uncertain conditions. In particular, stochastic analyses using RO techniques provide 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 the significance of recognising the constraints to the adoption of agroforestry arising from the duration of the production cycle and uncertainty in carbon prices.

The paper makes a number of contributions to existing understanding of agroforestry adoption as a means of combatting climate change. First and foremost, from a policy perspective, the modelling framework explores the hypothetical, but arguably optimal, context within which both the cost of livestock greenhouse gases (GHG) in equivalent carbon emissions and rewards from carbon sequestration in trees are internalised in the decision-making process through appropriate policy mechanisms. Second, it provides new insights into the importance of biophysical factors on the agroforestry adoption decisions by comparing the results from livestock enterprises on two different areas of a case study farm. The model is parameterised using actual data from the farm including information collected from a mature agroforestry system originally established on the farm in the 1980s for research purposes.

The results suggest that agroforestry adoption is less likely in both types of enterprises than standard budgeting analyses may suggest. Therefore, an additional scenario is explored where an upfront payment to cover establishment costs is made available to farmers. This is shown to make agroforestry adoption the optimal choice over a much wider range of carbon prices and agricutural returns. The paper concludes by considering the additional research needed to understand better how to incentivise agroforestry adoption.

2 The economics of agroforestry

The agriculture sector is currently facing a number of significant challenges, the most critical of which are the climate emergency and biodiversity crisis. Both the recent IPCC (2019) and IPBES (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. At a global level, agricultural activities directly contribute 17% of the share of the greenhouse gas emissions that cause climate change and an additional 7-14% through land use changes (OECD, 2016). In Scotland, agriculture and related land use change represents about 23% of total GHG emissions being the second most important emissions source after transportation. Direct GHG emissions from livestock enteric fermentation, manure management and urine and dung deposited by grazing animals account for a significant proportion of total agricultural emissions with the level varying according to the intensity of production systems (Scottish Government, 2020).

A number of changes in livestock breeding and management practices are being developed which will reduce livestock emissions levels however these may not provide the magnitude of change required and there are calls for a reduction in livestock products consumption (Allen et al. 2018; Committee on Climate Change, 2020), which would lead to a reduction in livestock numbers. However agricultural land in less favoured, upland or mountainous areas can have limited potential for alternative use other than extensive livestock production. In addition, these more extensive livestock production systems have positive biodiversity benefits (Henle et al., 2008).

Within this context, agroforestry has been suggested as a means of helping mitigate carbon emissions, while maintaining farm household livelihoods and providing diverse positive externalities (England et al. 2020; 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, 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 carbon 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. In terms of biodiversity, 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). However, as with sequestration benefits, the biodiversity impacts will depend on the type of trees planted and where they are planted.

Despite the potential benefits from agroforestry, adoption rates remain limited. Gosling et al. (2020) adopted a multi-criteria mathematical programming approach to explore if and how much agroforestry should be included within farming systems in Eastern Panama. The authors found a large discrepancy between the optimal mix of land use suggested by the model and existing land use patterns. In particular, while agroforestry dominated the former, it is largely absent from land use patterns in the region. Further analysis showed that this was largely due to an inability for systems including agroforestry to adequately satisfy the immediate food security and liquidity priorities of farmers in the region.

Others have explored the agroforestry adoption using capital budgeting techniques that take into account the timing and value of annual cash flows from investment and the time value of money. The technique most commonly applied to agroforestry analysis is Land Equivalent ratios which measure the discounted present value of an investment in perpetuity thus allowing for comparisons between alternative land uses whose time horizons vary. The results from these capital budgeting analyses are inconsistent, reflecting the importance of geographically-specific biophysical factors on agroforestry adoption decisions. In some contexts, monoculture systems can be more profitable over the long run (Bruck et al., 2019). Others have found that agroforestry systems are more productive compared to monocultures by between 36–100% (Lehmann et al., 2019). A key point made by Bruck et al. (2020) is the need for policies which provide greater certainty to landowners who wish to implement agroforestry.

While capital budgeting techniques are a common approach for understanding land use change decisions, they have drawbacks when analysing investment decisions with long time horizons (for example over 25 years) and/or when there are risky and uncertain conditions (Regan et al., 2015; Frey et al, 2013). They are also more problematic when investments are not easily reversed and expenditures difficult to recover should market conditions deteriorate (Ross, 1995). Instead, Real Options techniques have been suggested as a more useful means of understanding land manager decisions relating to agroforestry.

Unlike capital budgeting approaches which assume perfect foresight, Real Options analyses explicitly recognise the value of a land manager being able to postpone actions based on current conditions. The value of having this added flexibility can be assessed by comparing the findings from stochastic Real Options analysis to that from deterministic capital budgeting approaches with studies finding that, in the presence of uncertainty, land managers intuitively value flexibility and invest later than suggested by standard capital budgeting methods. Findings also suggest that the rates of return from investment have to be higher than that suggested by standard budgeting approaches to allow for the perceived irreversibility of switching land use (Regan et al., 2015).

Frey et al., (2013) adopted a Real Option approach to analyse both forestry and agroforestry in the Lower Mississippi Valley, progressing previous studies by allowing for reversibility in the land use change albeit at cost. The results confirmed that farmers will be more hesitant to adopt both forestry and agroforestry than would be suggested by purely deterministic models. However, once adopted, both systems had fairly high dis-adoption thresholds. More recently, Dittrich et al. (2019) used a real option approach for analysing afforestation as a means of climate change adaptation. In this context, not only are investment decisions challenged by long time horizons and high upfront costs but the climate benefits are also far from certain.

The approach adopted in this paper follows Frey et al. (2013) in allowing for reversibility in land use decisions thus providing information on both adoption and dis-adoption thresholds. It also contrasts the findings from the Real Options analyses with those from a Land Equivalent Value approach to investment decisions. However, it goes further by testing the extent to which the introduction of upfront payments influences the findings, thus providing additional policy insights.

3 Modelling approach

3.1 Real Options model

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. 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 entirely to conventional farming. However, the farmer may also choose to remain in an agroforestry state in which case 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 ($maxsa$). A maximum stand age of 60 is chosen because it sufficiently represents agroforestry in the long-run whilst also limiting the computational complexity of the model and avoiding the curse of dimensionality arising from unduly large state spaces.

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 (in our case, livestock emissions) 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 provides them with additional source of income.

Table 1 summarises the state space calibration strategy in the model.

Table 1: Calibration of the state space variables

State variable	**Number of nodes on grid**	**Values**	**Comments**
Stand age, s^{SA}	61	Minimum: 0; Maximum: 60	Maximum stand age of 60 sufficiently captures agroforestry in the long-run whilst limiting model size
Agricultural returns, s^{AG} (£ha^{-1})	30	Minimum: -£800/ha; Maximum: £800/ha	Returns are uniformly distributed on the 30-node grid.
Carbon price, s^{CP} (£ tCO$_2^{-1}$)	30	Minimum: £0/tCO$_2$; Maximum: £1000/tCO$_2$	Prices are uniformly distributed on the 30-node grid.

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 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. x takes a value of 1 if the farmer is in conventional agriculture but decides to switch to agroforestry; or is in agroforestry but decides to maintain agroforestry for one more year. Finally, 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. 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 that they are 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) respectively, such that: $MGY(s_t^{SA}) = TGY(s_t^{SA}) - TGY\left(s_{t-1}^{SA}\right)$.

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:

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

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

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.

When the farmer is beyond five years of agroforestry and decides to maintain agroforestry, the reward function of the farmer decomposes to the following:

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

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

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:

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

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

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:

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

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

3.1.4 State transition function

The state transition process of the stand age state variable is given as follows in Table 2;

Table 2 Description of the state transition process

Transition	Description
$s^{SA}_{t+1} = 0 \ \forall \ x = 0$	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.
$s^{SA}_{t+1} = s^{SA}_t + 1 \quad \forall \quad x = 1 \ \& \ 1 \leq s^{SA}_t \leq maxsa$	The farmer, 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 conventional agricultural returns and carbon prices follow a mean reverting 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.

3.2 Standard capital project evaluation methods

To provide an indication of how allowing for uncertainty influences the adoption decision, we compare the results from the Real Options analysis to those from a more standard capital project analysis of agroforestry adoption. In the most basic capital budgeting analysis 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} represents the net present value of one agroforestry rotation at year 0 (the moment the project starts).

$$NPV_{AF} = \sum_{t=0}^{T} \delta^t (\beta \cdot (s_t^{AG} - s_t^{CP} \cdot \omega_t) + s^{CP} \cdot \varphi \cdot MGY(s^{SA})_t + s_t^{TB} - C_t^{AG}), \quad [9]$$

where the variables are defined as above. In addition, t represents time in years ($t = 1, 2, \ldots, T$), s_t^{TB} is the reward to timber, C_t^{AG} the cost of agroforestry, which includes farmers' implementation (i.e., ground preparation and tree planting) and management costs, and δ the discount factor estimated as:

$\delta = (1/(1+r))$, r being the discount rate assumed to be equal to 3%. Carbon, timber and conventional agriculture rewards are assumed to remain constant over time.

Rewards to timber are estimated based on 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 equals the rotation length and 0 in any other case:

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

When dealing with infinite time horizon problems, analysts usually maximize the LEV) which represents the perpetual income stream produced by periodic crops starting from bare land. LEV is then estimated assuming infinite agroforestry rotation cycles, each with identical production costs and income functions. Hence with periodic values equal to NPV_{AF}:

$$LEV_{AF} = NPV_{AF}/(1-\delta)^T \qquad [11]$$

For comparative purposes, we estimate the LEV of rewards to conventional agriculture (LEV_{AG}) as the capitalised net returns to conventional agriculture over a period T in perpetuity:

$$LEV_{AG} = \sum_{t=0}^{T} \delta^t \,(s^{AG} - s^{CP} \cdot \omega)/(1-\delta)^T \qquad [12]$$

The threshold carbon price (c_{s+e}) is the minimum price that would make a farmer indifferent between maintaining conventional agriculture and adopting agroforestry. For an infinite sequence of agroforestry rotations, it happens when the *LEV* of conventional agricultural equals the corresponding agroforestry value ($LEV_{AF} - LEV_{AF} = 0$). In that way, we simultaneously account for carbon sequestration due to tree growth (c_s), and GHG carbon equivalent emission saving (c_e) from reducing stocking rate from agroforestry adoption by *1-β*.

$$s_t^{CP} = \frac{\sum_{t=0}^{T} \delta^t\left((1-\beta)\, s^{AG} - s_t^{TB} + c_t^{AG}\right)/(1-\delta)^T}{\sum_{t=0}^{T} \delta^t\left((1-\beta)\cdot\omega_t + \varphi MGY\left(s^{SA}\right)_t\right)/(1-\delta)^T} \qquad [13]$$

This requires discounting the physical carbon equivalent units. Following studies focussed on estimating carbon sequestration effectiveness (e.g., Richards and Stokes, 2004; Valatin and Price 2014), we use the same discount rate as used for discounting conventional agriculture and agroforestry rewards and costs.

4 Empirical application

The model application is based on the James Hutton Institute's research farm, Glensaugh which is located in Aberdeenshire, Scotland, UK[1]. The farm is representative of Scottish upland sheep and beef-cattle farms. Farming in this area is based on extensive land use systems with typical stocking rates between 0.2 and 0.4 standard livestock units ha^{-1} (Chapman 2017).

4.1 Conventional agriculture benefits and cost

Two distinct livestock enterprises are considered: (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 relies on extensive grazing through the year. The overall system on the case study farm, Glensaugh, 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 which provide a source of information to parametrise the models. The plots were planted in 1988, using Scots pine (*Pinus sylvestris*), hybrid larch (*Larix X Eurolepis*) and sycamore (*Acer pseudoplatanus*).

The two distinct livestock enterprises at Glensaugh have different costs and benefits, and hence agricultural returns. Table 3 shows estimated net revenues (revenues minus direct operating costs including inputs, labour costs, and consumption of fixed assets) for both enterprises per hectare of land.. Table 3 also shows the main characteristics of the enterprises in terms of the type and area of land used and the equivalent standard livestock units supported by both systems between 2006 and 2018.

Agroforestry adoption involves both investment and ongoing management costs. Investment costs are estimated at £4,000 per hectare based on moderate disturbance ground preparation practices and conifer plantations. It is assumed that ground preparation would account for a third of these costs, while tree planting costs are based on an initial 400 tree ha^{-1} density (Table 4). Additional costs consist of 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 and management during years 1 to 5 (£150 ha^{-1}) (Ovando, 2020).

Table 3 Main characteristics of the hill and low-ground conventional livestock systems in Glensaugh

Livestock enterprise	Land type	Area (in hectares)	Agricultural returns (£ ha^{-1})			Total livestock units (LU) [(1)]		Stocking rate (LU ha^{-1})	
			Min	Max	Average	Average	SD	Average	SD
Sheep	Hill área	467.0	-15	70	30	65.8	9.4	0.14	0.02
Sheep & Beef	Low-ground área	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 estimated 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.

Table 4 Woodland and agroforestry planting and maintenance costs (2018, prices[(1)])

Class	Unit	Price (£/unit)	Woodland (forestry)	Agroforestry
Ground preparation and planting (year 1)	ha		2,800	1,000[(1)]
Individual plant and protection (year 1)	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

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

Maintenance	ha		150	150
Upfront payment for planting (80% plantation costs)	ha			1,440
Forestry reversion cost	ha		2,800	1,800
Timber prices	m^3	50		
Carbon price[(2)]	tCO_2	30		

Notes: [(1)] Average revenues for the period 2006-2018, updated to 2018 prices using the UK GDP deflator. [(2)] Price based on the range of prices observed in 2020 in the EU Emissions Trading System (converted to 2018 values).

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

In subsequent analysis we analyse 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. The upfront payment is assumed to cover 80% of the initial ground preparation and tree planting costs.

4.2 Timber production and carbon dioxide sequestration

For both the Real Option and LEV analyses, we consider Scots pine as the selected tree species. Timber growth is estimated using a correction factor on Ovando (2020) Scots pine timber yield growth (TGY) which depend on the yield class (YC)[2]. Scot pine YC is expected to vary between the hill and low ground areas (Pyatt et al., 2001), with YCs of 7 and 13 assumed for each area respectively.

$$v_1 = \left(0.6952 \cdot (t \cdot YC)^{1.0249} \cdot e^{9.72 \cdot 10^{-4} t}\right) \cdot 0.11 \qquad [15]$$

The estimated correction factor (0.11) accounts for the expected effect of tree density and grazing on tree growth based on data collected for Scots pine agroforestry plantations at Glensaugh planted at a density of 400 trees ha^{-1} compared to a control woodland plantation of an initial density of 2000 trees $ha^{-1.}$ after 12 years (Sibbald et al., 2001). Agroforestry plot trees were both shorter, and of a lower average diameter, which translated into a reduction of 35.7% on individual tree volume. Sibbald et al. (2001) also found that the mortality rate of agroforestry trees over the first 4 years was 6% lower than in the control plot. Considering an initial tree density of 400 trees ha^{-1} (20% of trees), and differences in tree growth and mortality, we calculate that agroforestry parcels will yield 11% of total timber stock compared to tree-only plantations.

Carbon sequestration (measured in t CO_2 ha^{-1} y^{-1}) accounts for additional carbon stored every year in timber, branchwood and roots (referred jointly as total tree biomass). Total tree biomass is based on the expansion factor (φ) estimated by Ovando (2020) for Scots pine of 1.999 t CO_2 per standing cubic meter.

4.3 Livestock GHG emissions

Livestock emissions depend not only on the number and type of animals reared, but also manure management and the dependency on grazing and feed. We use the average GHG emissions estimated for hill sheep and low-ground cattle and sheep enterprises in Glensaugh for the period 2002 to 2018 (Ovando, 2020). GHG emissions per livestock unit are converted into per hectare basis using the stocking rates at Glensaugh.

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

[2] Yield Class 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.

emission total 0.19 of carbon dioxide equivalent tonnes ($tCOe_2$) per hectare of land for the hill sheep enterprise and 2.42 $tCOe_2$ per hectare for the low-ground beef and sheep enterprise. Beef-cattle are responsible for 58% of the low-ground emissions, while sheep contributes to the reminding 42%. It is assumed that that stocking rate on land remaining in farming reduces proportionately to the reduction land area (i.e., by 20%) due to agroforestry adoption.

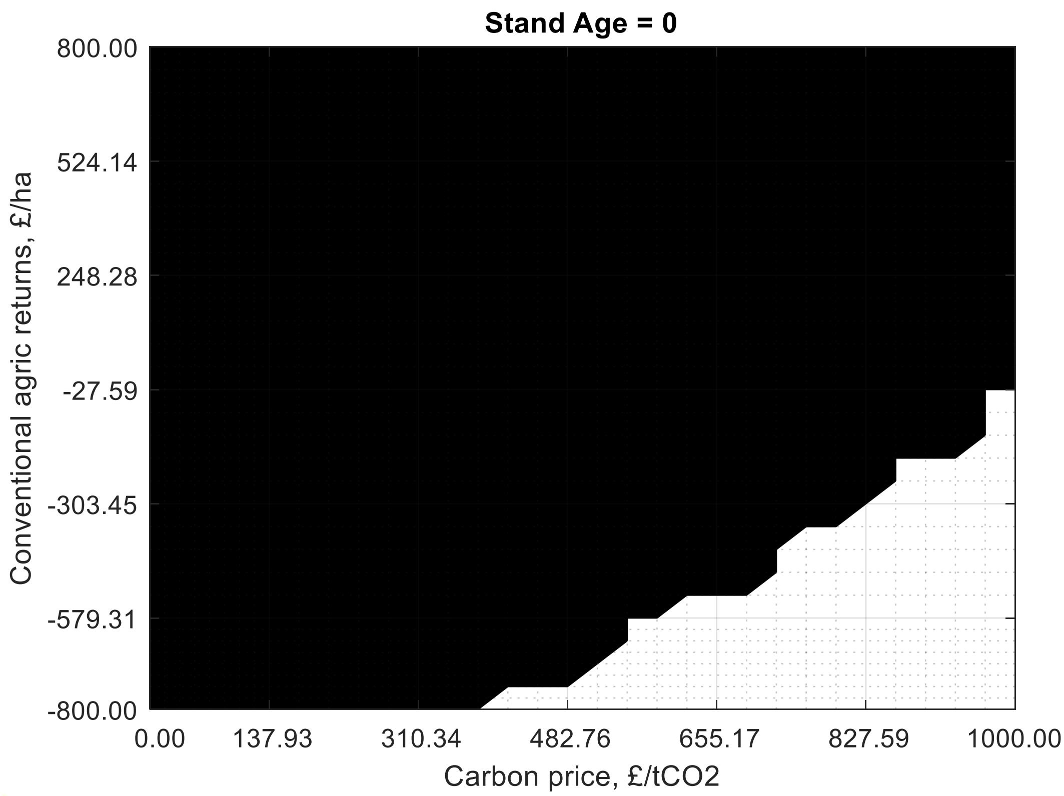
5 Results and discussion

5.1 Optimal agroforestry adoption from the RO analyses

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

Figure 1 is a graphical representation of the farmer's optimal function for the hill sheep enterprise at stand age 0. It shows the optimal decision matrix for two dimensions (agricultural returns and carbon prices) for the entire modelled state space. At 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. The level at which a farmer crosses from non-adoption of agroforestry to adoption represents the RO adoption threshold.

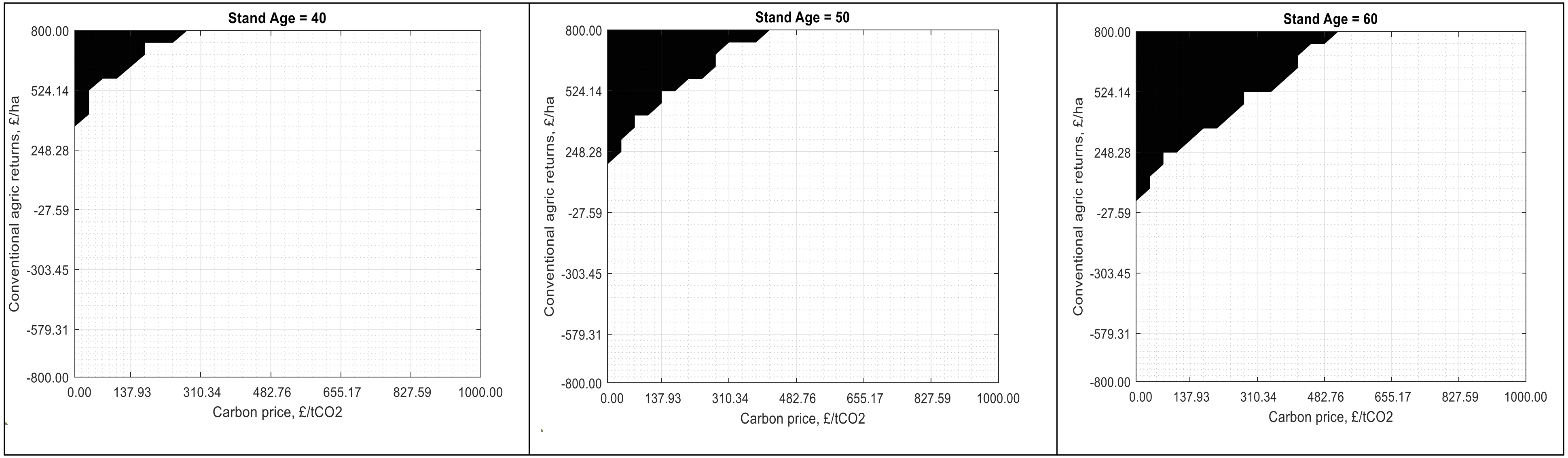
From the figure, the adoption frontier is diagonal suggesting that the farmer's optimal decision is driven by both the state of conventional agriculture returns and the price of carbon. The white section of the figure is small and suggests that switching to agroforestry is very unlikely to be an optimal 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 (i.e., orders of magnitude higher than observed levels to date). Below this price level, the optimal farmer decision would be to maintain conventional farming.



Black region = maintain conventional agriculture, white region = adopt agroforestry.

Figure 1: Hill sheep enterprise optimal policy function when land is in conventional agriculture

Figure 2 is a graphical representation of the farmer's optimal functions for the hill sheep enterprise when agroforestry is present at three different stand ages, 40, 50 and 60. The figures use the same axes to facilitate comparison. 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. The level of agricultural returns above which a landowner reverts from the agroforestry back to agriculture represents the RO dis-adoption threshold.

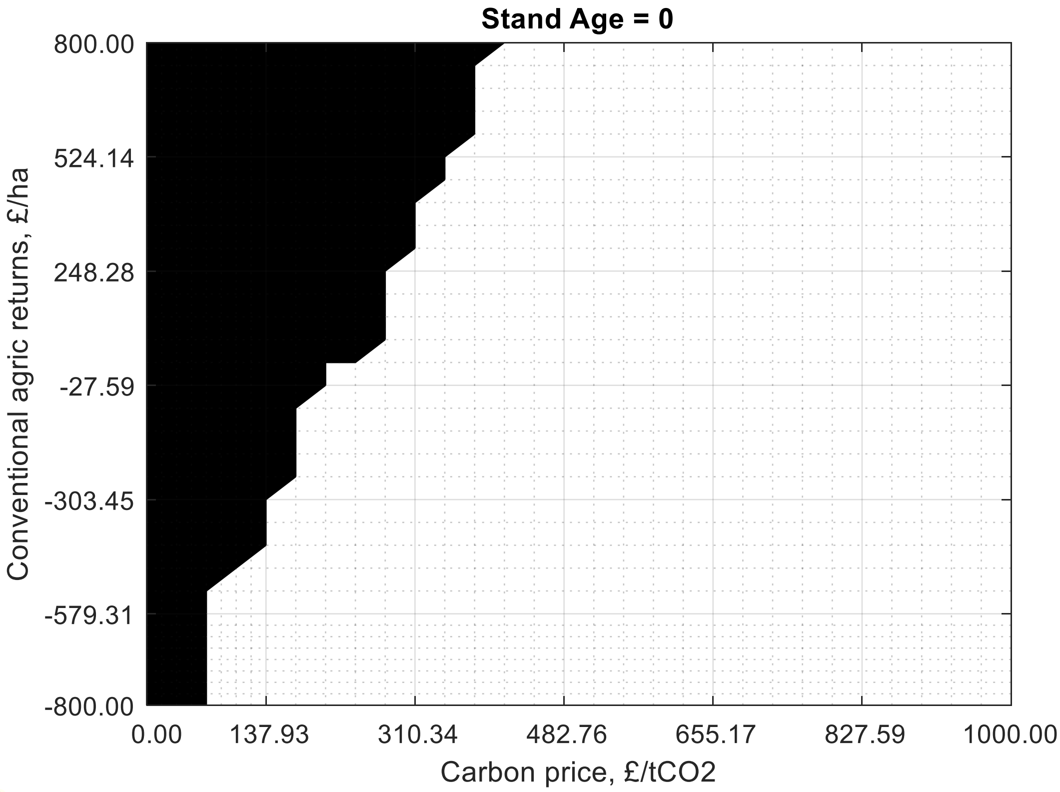


Black region = switch/return to conventional agriculture, white region = maintain agroforestry.

Figure 2: Hill sheep enterprise optimal policy functions at different stand ages for land in agroforestry

Figure 2 shows that 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 returns are above £358/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.

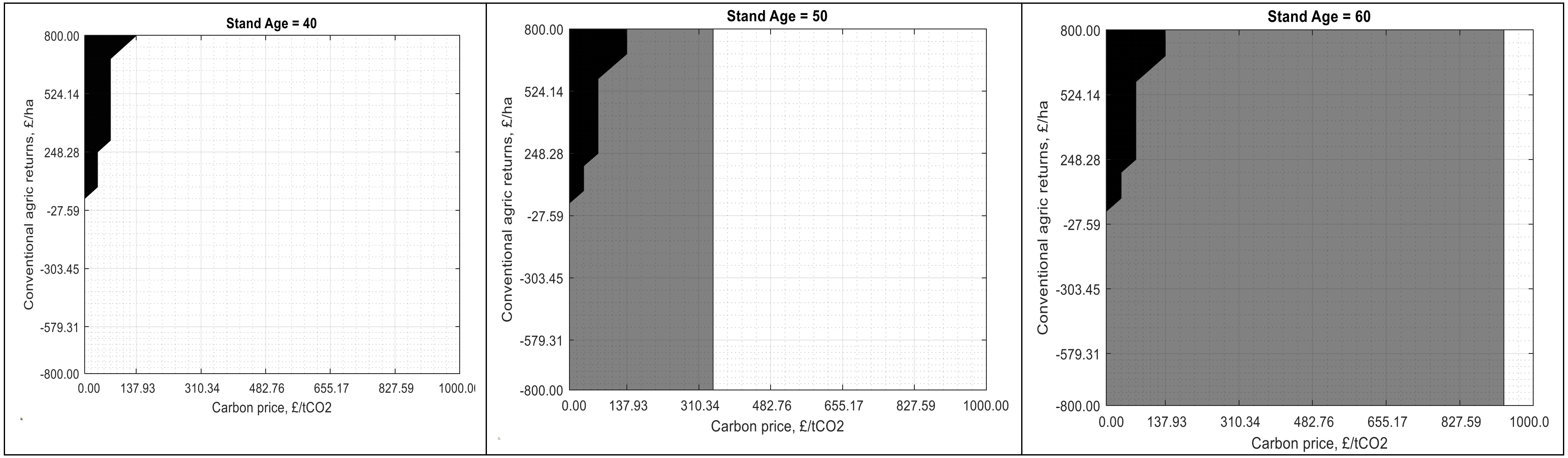
Figure 3 shows the equivalent optimal functions for the low ground cattle and sheep enterprise in stand age 0. Compared to the previous case, lower carbon prices are required for a farmer to adopt agroforestry at stand age 0. For example, when the conventional agriculture returns are -£300/ha, the farmer would choose to switch to agroforestry when the price of carbon is only £138/tCO_2 as opposed to £830/tCO_2 in the hill sheep enterprise case. Below this carbon price level, the optimal farmer decision would be to maintain conventional farming.



Black region = maintain conventional agriculture; White region = adopt agroforestry.

Figure 3: Low ground cattle and sheep enterprise optimal policy function when land is in conventional agriculture

Figure 4 is a graphical representation of the farmer's optimal functions for the low ground cattle and sheep enterprise at stand ages 40, 50 and 60. For this enterprise, the results are more complex than observed for the hill sheep enterprise. 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. With zero carbon prices, the farmer would choose to switch back to agriculture when agricultural returns are above zero, i.e., at a lower level than was the case for the hill sheep enterprise.



Black region = switch/return to conventional agriculture; White region = maintain agroforestry; Grey region = cut and re-establish agroforestry.

Figure 4: Low ground cattle and sheep enterprise optimal policy functions at different stand ages for land in agroforestry

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). However, at stand ages 50 and 60 another state is observed and shown in the figure: when the farmer chooses to cut and re-establish agroforestry rather than revert to agriculture. This is represented by grey cells with the white 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.

5.2 Agroforestry adoption using from the LEV analysis

For comparative purposes, Table 5 shows the Land Expectation Values for both agroforestry adoption 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 £0 tCO_2 to £100 tCO_2. Likewise, we analyse the sensitivity of adoption to agricultural returns. 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 equal £0 tCO_2^{-1}) the results suggest agroforestry would not be adopted ($LEV_{AF} < LEV_{AG}$). In a scenario with both payments to carbon sequestration and penalties to carbon emissions, threshold carbon prices would be significantly lower for the low ground beef and sheep enterprise. Values close to £70 per ton of CO_2 equivalent are required to favour agroforestry adoption for the low-ground cattle and sheep enterprise. In contrast, in the hill sheep enterprise where GHG emissions are many orders of magnitude lower, carbon prices that almost double the threshold prices for low-ground beef-sheep enterprise would be needed to encourage agroforestry adoption.

Table 5 Estimated land expectation values for conventional agriculture and agroforestry for average farm income level and carbon threshold prices (2018 prices)[(1)]

	Farming enterprise	
	Hill sheep	Low-ground cattle and sheep
	Land Expectation Value (LEV) (£ ha^{-1})	
Conventional agriculture (LEV_{AG})		
No C payment/penalty (£ 0 tCO_2)	1,000.0	1,833.3
Average carbon price (£ 30 tCO_2^{-1})	810.0	-586.7
Agroforestry total (LEV_{AF})		
No C payment/penalty (£ 0 tCO_2)	-2,390.40	-1,393.29
Average carbon price (£30 tCO_2^{-1})	-1,379.49	95.99
	Carbon balance and price threshold	
Carbon balance (tCO_2e ha^{-1}) (T=60 years)	25.6	47.1
Threshold price for carbon sequestration and carbon penalty (c_{s+e}))	131.67	68.10

Notes: [(1)] Real discount rate (r) 3% . 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 significantly less likely than standard budgeting techniques would suggest for both types of enterprises, particularly the hill sheep enterprise.

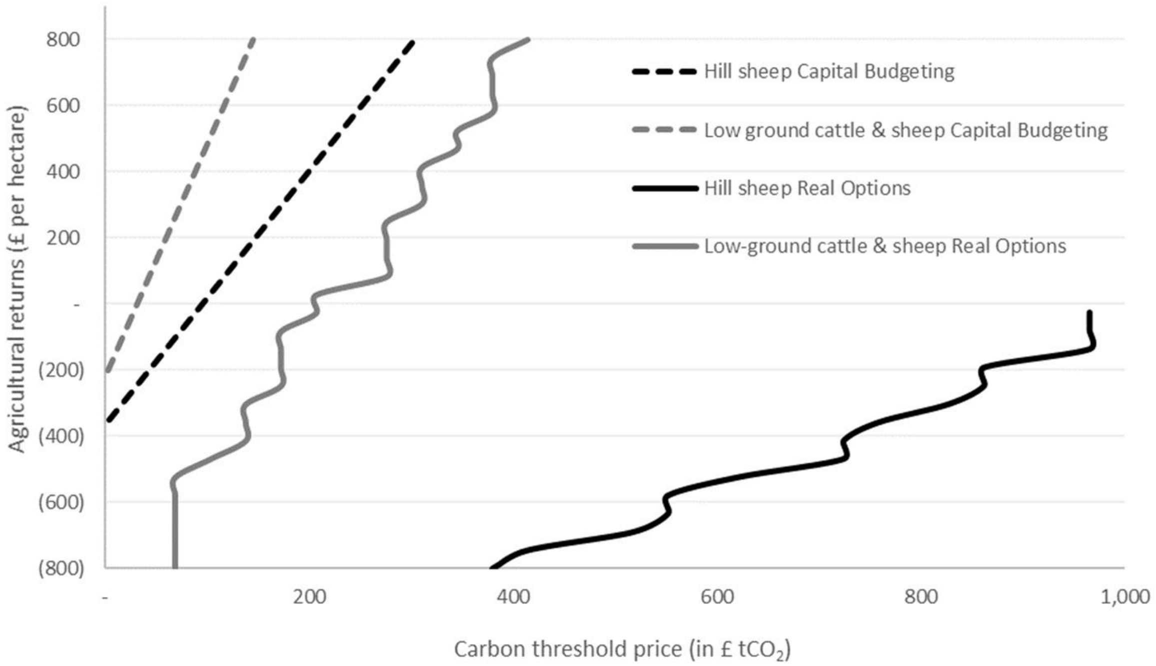
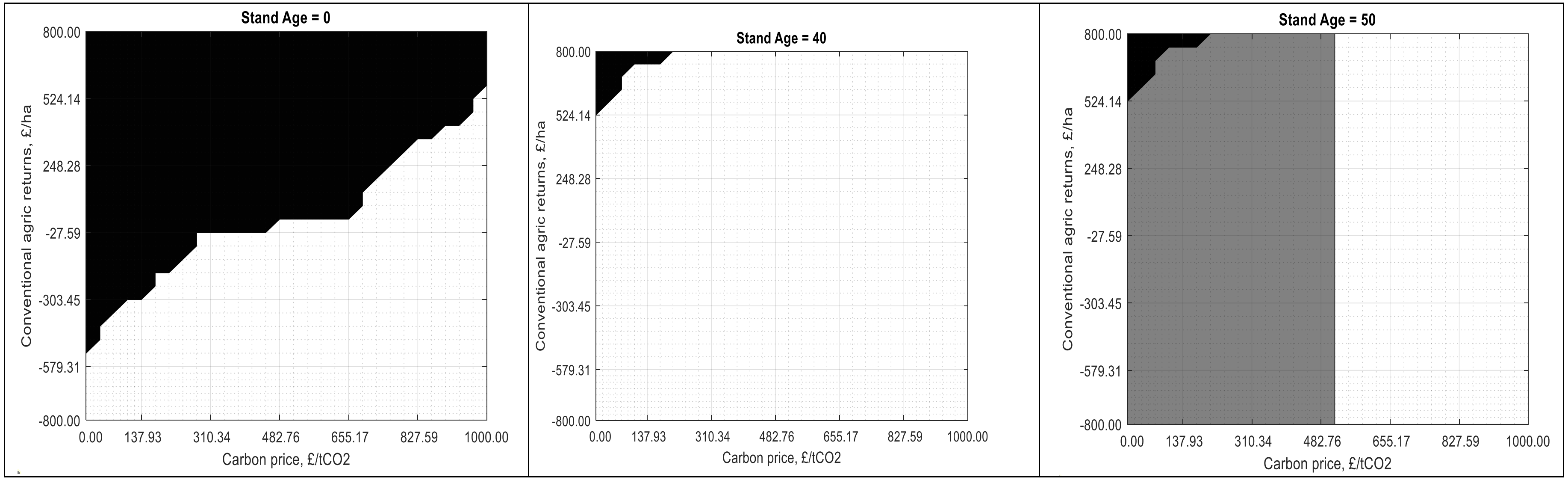


Figure 5: Sensitivity analysis of carbon threshold prices to agricultural returns (without upfront payments).

5.3 Incentivising adoption through an upfront payment

To explore the sensitivity of the results to the timing of costs and returns from agroforestry, the Real Options analyses were repeated, but in this case providing an upfront payment for converting to agroforestry. The payment, like 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 2 and Figure 6 show that the upfront payment makes the adoption of agroforestry the optimal choice over a much wider range of carbon prices and at higher agricutural returns. For example, a carbon price of £137.93 tCO_2 without upfront payment would be insufficeint for agroforestry adoption to be optimal even in the cases of expected negative agricultural returns, while the same carbon price with upfront payment would make agriforestry adoption the optimal decision should farmers be in a state where agricultural returns are below £303.45 ha $^{-1}$. The upfront payment also influences decsions in relation to the length of agroforestry rotations, making rotations shorter than would otherwise be the case, *ceteris parabis*: 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.



Black region = maintain (revert to) conventional agriculture; White region = adopt (stand age 0), retain (stand age > 0) agroforestry; Grey region = cut and re-establish 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 followed the same pattern suggesting that upfront payments do have significant potential for increasing the adoption of agroforestry all other things remaining constant but will also reduce agroforestry rotation lengths.

6 Conclusions

Agroforestry offers considerable potential through the carbon sequestration from tree growth plus possibly reduced carbon emissions form livestock if stocking levels are reduced.

Many economic analyses of agroforestry have in the past failed to recognise the disincentive effect associated with the relative irreversibility of tree planting and lack of flexibility once decisions are 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 influences land use decisions. Thus, 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 a case study upland farm for which the data required for the analysis was available.

The results suggest that even when there is a charge on livestock emissions as well as 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 prices compared to those observed to date. This is the case for both the hill sheep and the low ground cattle and sheep enterprises on the farm. However, the results do 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. For example, when the conventional agriculture returns are -£300/ha, the farmer would choose to switch to agroforestry when the price of carbon is only £138/tCO_2 as opposed to £830/tCO_2 in the hill sheep enterprise case. This suggests that additional measures would be needed in the transition to net -zero farming targets upland areas, including incentives to reduce cattle stocking rates. As anticipated, 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 uncertainty (Schatzki, 2003).

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. In the case of the hill sheep enterprise for example, a carbon price of £137.93 tCO_2 without upfront payment would be insufficeint for agroforestry adoption to be optimal even in the cases of expected negative agricultural returns, however the same carbon price with upfront payment would make agriforestry adoption the optimal decision should farmers be in a state where agricultural returns are below £303.45 ha $^{-1}$. Thus, policy changes such as the Small Woodland Loan scheme introduced recently by Scottish Forestry (2021) to help with cash flow issues should increase adoption. However, the upfront payment does shorten the expected rotation length of agroforestry and, even with upfront payments, unless carbon prices increase significantly, the results suggest adoption will not be widespread.

Further research is required on the sensitivity of the results to various assumed parameter values including the choice of discount fact and the relationship between the volatility of 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, 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 from more in-depth qualitative research to understand these factors too before the potential for agroforestry can be fully realised.

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