Economic impacts of Net Zero land use scenarios

Report prepared for the Committee on Climate Change

Final

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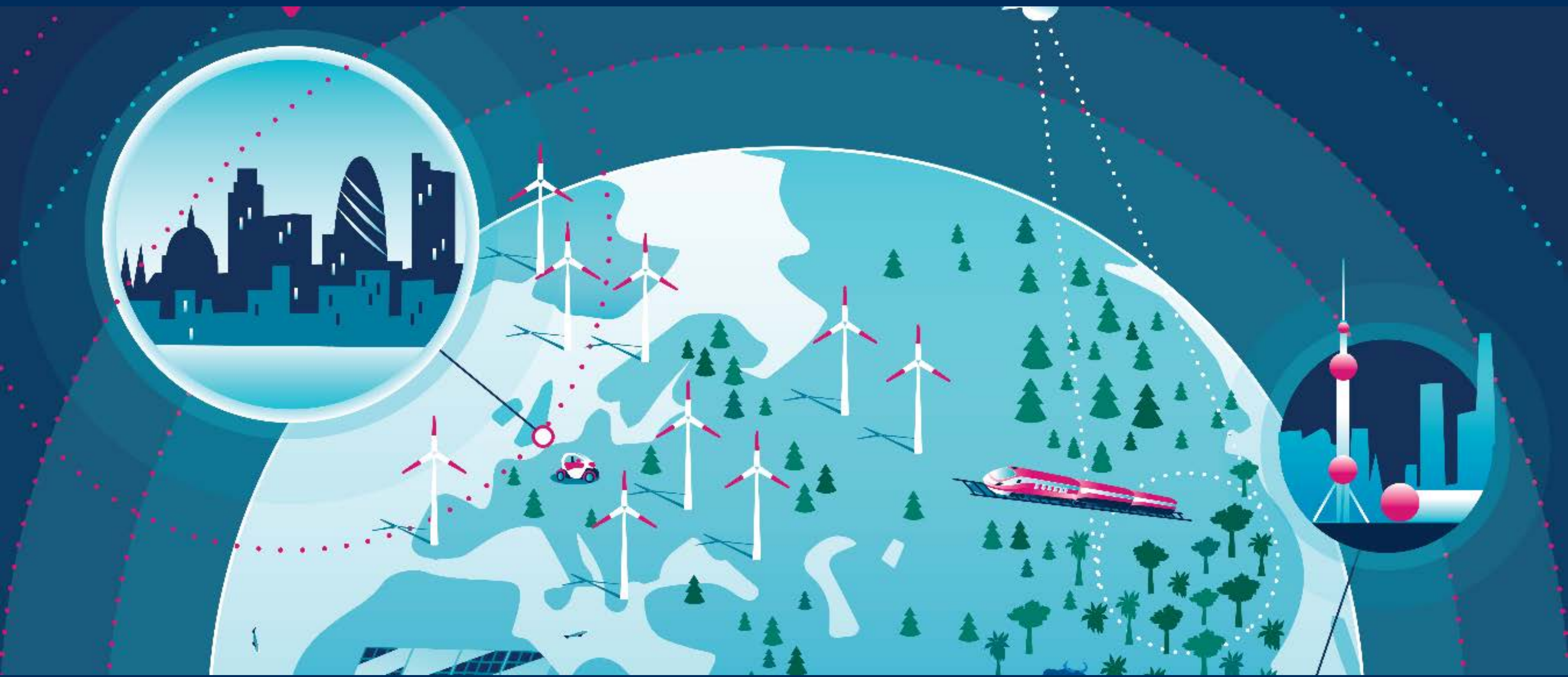

Executive Summary

This report estimates the market and non-market impacts of implementing the CCC Net Zero land use greenhouse gas (GHG) mitigation measures in the UK. Market impacts are the private costs and benefits from changing land use, including capital and operational costs of woodland creation and management, agroforestry and hedgerow creation, bioenergy crop planting, peatland restoration, and the implementation of agri-mitigation measures. The work also models the value of private benefits, including income from the production of biomass for bioenergy, harvesting of timber for wood products, and savings arising from the implementation of low carbon farming practices.

The non-market impacts of Net Zero land use change are estimated to assess the wider impact on society. Many land use options required to reduce GHG emissions in the UK generate ecosystem goods and services that are valued by society. These goods and services are often not priced in markets, so landowners do not receive remuneration for managing the land to avoid emissions and improve the environment. In this report we quantify the value of land use change in the CCC scenarios by estimating the monetary value of greenhouse gas (GHG) removals and emissions reductions, the provision of space for recreation and subsequent physical health improvements, air quality improvements due to filtration by vegetation and low emission farming practices, and flood risk mitigation.

The lifetime net private costs of land use change and adoption of low-carbon farming practices to achieve Net Zero GHG emissions in the UK by 2050 are £17 billion. This represents an annual net cost to landowners of £0.7 billion, or £1.4 billion excluding measures that are already cost-effective for farmers. These estimates illustrate that the total private costs of transforming land use outweigh the market benefits. This implies that currently there is a lack of market incentives to individual landowners to implement mitigation measures. There may also be further non-financial barriers to the take-up of these measures.

The wider non-market impacts of Net Zero land use total £96 billion in benefits by 2050. These impacts total £4 billion per year. The main benefit is from the avoidance or reduction of greenhouse gas emissions which total 64% of all benefits to society. The land use options also provide value in terms of recreation, health, cleaner air and flood mitigation. There are other benefits, including for biodiversity and improvements in water and soil quality that it has not been possible to include in this project.

The creation of new woodland, the restoration of peatlands and the planting of bioenergy crops require significant support to overcome lack of revenue. The conversion of areas of the UK into woodlands requires substantial capital expenditure to buy land and plant trees. Peatlands also require significant upfront expenditure to undertake restoration activities. In addition, revenues earned from forestry occur many years after planting and private revenue streams do not exist for most peatlands, suggesting that substantial public funding or support is needed to deploy these options. Most bioenergy crops are not financially viable for the private sector, highlighting the need for specific policies that address the economic barriers to grow energy crops.

Large scale transformation requires significant changes in the way landowners are incentivised to manage land and provide valuable public goods. Public money must address the lack of private incentives individuals have to manage land in the UK to avoid greenhouse gas emissions. This report estimates that on average landowners and managers should be compensated £0.42 for every £1 they spend on Net Zero land use change. Spending this money generates public goods in the form of greenhouse gas mitigation and wider co-benefits of better environmental stewardship. Aligning land use policy and financial support with the provision of valuable public goods is a significant opportunity to support livelihoods and improve the health and sustainability of land in the UK.

Funding is needed to address both the cost and non-cost barriers of implementing greenhouse mitigation activities in the UK land use sector. Credible and long-term funding is needed to fill the gap between costs and income to farmers and land managers. This must also be accompanied by the availability of financing and payment mechanisms that meet the specific needs of the land use sector, including high upfront costs and distant revenue streams. Policies should also take advantage of opportunities to adopt low carbon farming practices and technologies that lead to cost savings. This requires that the design of agricultural support policies addresses non-cost barriers that stop farmers utilising these beneficial practices.

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1 Introduction

1.1 Purpose and scope of the project

The purpose of this work is to assess the wider economic and environmental impact of CCC land use mitigation scenarios that are set out in the CEH (2018) and NetZero (CCC, 2019) reports. These reports set out scenarios for the level of GHG mitigation ambition and the impact of changes of land use required for the land sector's contribution to the UK to reach Net Zero emissions by 2050. In this report, we set out the methodology for estimating the economic impacts of achieving Net Zero in the land use sector in the UK and describe the results. The calculations supporting these results were produced for the CCC.

To assess the impact of these scenarios, the work estimates the market and non-market impacts of implementing mitigation measures as set out in the land use report. Market impacts refer to the costs and benefits from changing land use that are reflected in market prices and exchange. This covers the costs of woodland creation and management, agroforestry and hedgerow creation, bioenergy crop planting, peatland restoration, and the implementation of agri-mitigation measures. To estimate the costs borne by the private sector - landowners, land managers and farmers – we model the capital and operational expenditures that would be expected in implementing the measures. As well as considering costs, the work covers the market value of benefits that the land use is expected to generate. This includes income generated from the production of biomass for bioenergy, harvesting of timber for wood products, and any cost savings arising from the implementation of low carbon farming practices.

Non-market impacts cover the wider set of ecosystem goods and services that flow from forestry, bioenergy, agro-forestry, peatland restoration and low carbon farming. These goods and services generate benefits to society but are not generally priced in markets. Landowners therefore do not receive remuneration for managing land to provide these goods and services. In this work we quantify the economic value of land use change from greenhouse gas (GHG) removals and emissions reduction; the provision of space for recreation and physical health improvements; air quality improvements from air filtration by vegetation and reducing pollution from farming practices; and flood risk mitigation. These were the benefits for which robust data and methodologies for estimation exist.

The work examines the overall impact of land use change by considering the monetary value of undertaking a set of scenarios made up of carbon mitigation options. These options are grouped into five categories: forestry, bioenergy, agroforestry, peatlands, and agricultural practices and technology (AP&T). Each category is composed of several land use 'options', shown below in Table 1.

Table 1 Land use options assessed in this report

Option Grouping	Option
Forestry	New coniferous woodland planting
	New broadleaved woodland planting
	New management of existing broadleaved woodland
Bioenergy	Miscanthus
	Short rotation coppice
	Short rotation forestry
Agroforestry	Silvoarable agroforestry
	Silvopastoral agroforestry
	Hedgerow expansion
Peatlands	Restoration of upland peatland
	Restoration of lowland peatland
	Restoration of woodland to bog
Agricultural practices and technology (AP&T)	Crops and soils
	Livestock
	Waste and other

Source: Vivid Economics

1.2 Outline of approach

The total value of Net Zero land use scenarios is calculated by adding the market and non-market costs and benefits of changing land use in the UK. Market costs and benefits reflect the incentives that private land managers have to adopt the land use measures. Non-market impacts reflect the wider economic benefits that accrue to society. The value of these non-market benefits is estimated using techniques that are detailed in this report.

The costs in each scenario are presented as net present values (NPV) in both private and social terms. The private NPV shows whether the annual private benefits in terms of revenue from changing land use outweighs the costs land managers face over the lifetime of the implementation of each land use option. The social NPV extends this to include the total costs and benefits to society from adopting the land use changes set out in the scenario. In most cases, the NPV is calculated up to 2050 to reflect the costs of reaching net zero targets by 2050. In some cases, the NPV is calculated up to 2100 to account for the additional contribution that land use options such as woodland creation have in later years, when the trees reach maturity.

To estimate the costs and benefits of these options for land managers and wider society in the UK, we conduct the assessment using the following steps:

1. **Calculate the discounted net private costs for each land use option on a per hectare basis, accounting for the timing of costs and benefits.** These costs include any upfront capital expenditure, such as land acquisition and establishment costs, as well as ongoing maintenance and production costs incurred each year. Benefits include revenue that can be earned from the land, such as the production of bioenergy and timber products, valued at current market prices.

2. **Calculate the value of (discounted) non-market benefits from land use options per hectare.** Several important impacts of changing land use are not traded in markets. Accordingly, non-market economic valuation techniques are employed in order to quantify the public goods that are produced. These non-market benefits are divided into recreation and physical health benefits, local air pollution removal and flood risk reduction.
3. **Assemble the annual number of hectares of each agricultural and land use option converted under each scenario.** The figures are taken directly from the CEH (2018) work undertaken for the CCC and show the annual number of additional hectares of agricultural land converted to each option specified in Table 1. This data includes information on the type of agricultural land that is transformed for each option so that the opportunity costs of land conversion can be assessed.
4. **Multiply the per hectare estimates by the total amount of planting (or restoration) for the land use option in a particular year, summing over the period of 2019 to 2050.** The total costs and benefits per land use option are then added together to arrive at an estimate of the aggregate economic impacts of decarbonising the land use sector in the UK.

1.3 Summary of key findings

The net private costs of land use change and the adoption of low carbon farming practices to achieve net zero emissions in the UK by 2050 are £17 billion, which equates to an annualised net total of £0.7 billion. Whereas land managers will incur the equivalent of £1.6 billion costs per year to implement the land use changes, they can also expect to earn £0.9 billion per year in revenues from biofuel and timber production. Overall the private benefit-cost ratio (BCR) of implementing all the land use changes to 2050 remains low at 0.6. This highlights the gap between what individual landowners must spend to implement the required land use changes and the revenues they can expect to receive as a result.

The value of the wider benefits to society from the land use options totals over £105 billion by 2050, equivalent to £4 billion per year. The value of greenhouse gas emissions reduction is the primary contributor, providing 67% of the total value of non-market benefits, while the value of creating new woodlands for recreation contributes a further 18%. Value is also added from woodlands and low-carbon agricultural techniques reducing the amounts of local air pollutants, from physical health improvements due to space for exercise, and flood risk reduction. The social benefit-cost ratio of 3.3 times resulting from comparing total private and public benefits with costs underscores the wider value that the UK derives from the Net Zero land use changes.

The total private cost of land use change is highest in England, whereas the value of private and social benefits is greatest in Scotland. The total private costs are highest in England at £21 billion, where land managers derive £12 billion in private benefits and £3 8 billion in social benefits. In contrast, land managers in Scotland have higher private and social returns, incurring £12 billion in private costs and £6 billion in private benefits, as well as social benefits of £39 billion. In Wales, costs total £5 billion with £3billion and £14 billion in private and social benefits respectively. In Northern Ireland, private costs are £2 billion, with £2 billion in private benefits and £6 billion in social benefits. The difference in regional costs and benefits reflects economic and environmental factors, such as land acquisition costs, which tend to drive up costs in England. In addition, several options that generate significant private revenues, including forestry, are found in Scotland where a large share of woodland creation takes place. In Northern Ireland, where the private benefits equal the costs of implementing Net Zero, a significant proportion of land use options relate to low carbon agricultural practices which could save money for farmers.

The creation and management of broadleaf and conifer forests make up the largest share of costs by category but also lead to the greatest benefits to wider society. £18 billion needs to be spent on woodland creation by 2050 which totals 40% of the total private costs of Net Zero land use changes. However, tree planting creates nearly 70% of the benefits of Net Zero to wider society by providing large amounts of greenhouse gas removal, recreation opportunities, air filtration and flood risk mitigation.

Significant revenues and cost savings arise from low carbon farming practices and technology and from managing existing broadleaf forests. Several options, such as improving livestock health, precision farming and manure management, generate significant cost savings to farmers in terms of reduced veterinary bills, higher crop yields and lower fertiliser costs. These make up half of all private benefits of the scenarios: it is desirable that the agricultural sector adopts low carbon practices in order to deliver these benefits. In addition, the management of existing broadleaf forests and use of wood products offers a significant opportunity for landowners to generate revenues while contributing the UK's Net Zero ambitions.

The per hectare costs of Net Zero land use change exceed private benefits for most other options. In most cases, changing land use requires significant up-front investment to acquire land and conduct planting or restoration activities. Ongoing operational costs such as maintenance and harvesting add to private costs, which combined outstrip the revenues that can be earned. In addition, revenues from several options, such as woodland creation, accrue far into the future, more than 40 years after implementation, providing an additional barrier for landowners. Policymakers will have to address these funding gaps if they want landowners in large numbers to take up the options.

Forestry and peatland restoration options are most valuable to society, with social benefits far outweighing the costs of each hectare converted. The social NPV is £130,000 for a hectare of new coniferous woodland, and £90,000 for a hectare of new rural broadleaved woodland. The analysis examines the additional non-market benefits that could be achieved by planting broadleaved woodland in peri-urban areas, where additional non-market benefits in terms of recreation, health and air filtration occur due to proximity to urban areas. In these locations, a hectare would provide £140,000 in benefits by 2100. Peatland restoration similarly results in a high social return despite generating no private market benefits. Specifically, restoration of peatland in lowland sites generates a social return of £190,000 due to high emissions savings per hectare restored. Upland peat restoration yields a social return of £13,000 in net economic benefits for every hectare restored.

Cost uncertainties mean net private costs could be up to £25 billion by 2050 or as low as £9 billion (+/- 47% from the central estimate), with the widest range in costs for bioenergy and peatland options. Differences in the complexity of planting options and land acquisition costs across the UK explain the ranges on these estimates, which vary by around £10,000 per hectare either side of the central estimate, for miscanthus and SRC. Peatland restoration also exhibits uncertain costs, with lowland restoration and woodland to bog estimates particularly variable because of the difference in restoring peatlands in eroded versus near natural condition. The upper cost estimate of restoration for these peatland options is more than double the central estimate if the peatland is in poor condition. These ranges imply that local costs of implementing options could vary significantly across the UK.

1.4 Structure of the report

The rest of the report is structured as follows: Section 2 presents the results. Section 3 discusses the implications of the findings of the study and Section 4 documents the methodology used to calculate the costs, the parameters used in the valuation exercise and their sources.

2 Results

2.1 Total scenario economic impacts

The following section sets out the costs and benefits of a net zero land use scenario in the UK. Throughout the report we focus on the Multifunctional Land Use (MfLU) scenario, set out in the CCC 2018 Land use report, which was updated in the CCC 2019 Net Zero report, and represents the CCC's minimum level of ambition needed on land to achieve net zero by 2050. We refer to this scenario as the Net Zero scenario throughout the remainder of the report. The economic impacts of three additional scenarios set out in the CEH(2018) land use scenarios report were also assessed to illustrate the effects of different levels of ambition. The four scenarios assessed are the Net Zero scenario, Business as Usual (BAU), High Mitigation Uptake (HMU) and Technology Push (TP).

2.1.1 NPVs and annualised market and non-market impacts

The net private costs of the Net Zero scenario are £17 billion. Table 2 shows the present values of costs and benefits in the scenario until 2050 and their annualised equivalents. Total private costs amount to close to £40 billion, which represents an annual amount of £1.8 billion that must be spent by landowners to change land use. The private benefits that can be earned from net zero land use change, such as through the sale of timber or biofuels, amount to £23 billion by 2050 or £1.1 billion per year. This is reflected in the private benefit-cost ratio of 0.58, which shows that for each pound invested in net zero land use change, land managers would only receive 58 pence in returns on average. They would therefore need to be compensated by at least 0.42 pence on average for each £1 spent for the investment to be worthwhile.

Inclusion of the impacts of land use options to wider society yields net benefits of £89 billion by 2050. Investment in low carbon land use changes create market and non-market benefits. Although the market benefits of these investments would be lower than the costs, the non-market benefits of Net Zero, which benefit not just the landowner, but wider society, are nearly £105 billion by 2050. This means that Net Zero land use options generate £3.6 billion per year in net social benefits.[1] Put differently, each £1 invested in low carbon land use changes generate over £3.30 on average when both market and nonmarket benefits are considered.

These results demonstrate that landowners lack the private incentives to adopt many land use changes consistent with Net Zero. As shown in Table 2, a gap exists between the private revenue that landowners would earn from converting land and the costs incurred from doing so. Private market incentives alone are insufficient to create the land use changes required for Net Zero. For the necessary levels of investment to take place, landowners will need to be compensated for their efforts to decarbonise their land and maintain their current levels of income. Our results suggest that average compensation of at least £0.42 for every £1 spent would be needed to incentivise the land use changes required.[2]

[1] Net social benefits refer to the sum of private benefits and social benefits minus the private costs.
[2] These estimates exclude transaction costs.

Table 2 Present and annualised value of economic impacts for the Net Zero scenario, 2019 to 2050

	Net Zero Scenario	
	Present value to 2050	Annualised value to 2050
Total Private Costs	39	1.8
Total Private Benefits	23	1.1
Private NPV	-17	-0.7
Private BCR	0.6	
Total Social Benefits	105	4.3
Total Benefits	127	5.0
Social NPV	89	3.6
Social BCR	3.3	

Note: Estimates in present value terms are discounted at the UK social discount rate.
Source: Vivid Economics

The Net Zero scenario generates the highest rate of private and social returns for every pound invested compared to the other scenarios. Table 3 shows the present value of costs and benefits for the four land use scenarios considered. Each scenario summarises a narrative around the ambition of mitigation measures in the UK up until 2050. While the BAU scenario assumes that current trends in diet, land use and management continue, the other scenarios assume higher uptake of mitigation options. The Net Zero scenario is consistent with UK emissions reductions targets by 2050 is the scenario examined here. The TP scenario assumes a future where agricultural productivity increases the amount of land spared for mitigation measures. The HMU scenario assumes ambitious mitigation measures driven by changes in diet and reductions in food waste leading to more land spared for mitigation measures.

The private benefit-cost ratio is less than one for every scenario. The BAU scenario, which assumes that current rates of land use change are maintained into the future, has the lowest private BCR, below 0.1. The other three scenarios have private BCRs above 0.5. The Net Zero scenario has the highest private BCR out of the four scenarios. This holds when social benefits are incorporated, with Net Zero yielding a social benefit-cost ratio of 3.3, while the technology-led TP and the mitigation focused HMU scenarios generate a social benefit-cost ratio of 3.2.

Table 3 Present value economic impacts under all scenarios, 2019 to 2050

	Net Zero	BAU	HMU	TP
Total Private Costs	39	8	59	53
Total Private Benefits	23	1	26	26
Private NPV	-17	-7	-33	-27
Private BCR	0.6	0.1	0.5	0.5
Total Social Benefits	105	20	161	142
Total Benefits	127	21	187	168
Social NPV	89	12	128	115
Social BCR	3.3	2.6	3.2	3.2

Note: All estimates in present value terms, discounted at the UK social discount rate.
Source: Vivid Economics

Although the level of ambition of measures increases the value produced in land use to society, total costs also increase substantially. Since planting and restoration of habitats have high net social benefits, the most ambitious scenarios (HMU and TP) both have a social NPV of over £100 billion, considerably higher than the social NPV under BAU of £12 billion.

2.1.2 Economic impacts in England, Scotland, Wales and Northern Ireland

Total costs in the Net Zero scenario are highest in England due to the scale of land use change and higher land prices. Table 4 shows the costs and benefits disaggregated for England, Scotland, Wales, and Northern Ireland. England incurs the highest net total cost of implementing land use options of £9 billion by 2050, while landowners in Scotland and Wales must spend £6 billion and £2 billion respectively. Conversely in Northern Ireland, the costs to landowners are narrowly less than potential costs savings and revenues from deploying these options. Total costs in England are high due to the area undergoing land use change, which amounts to changes in Scotland, Wales and NI combined. Costs vary across regions, with land acquisition costs highest in England, reflecting the opportunity cost associated with more productive land. Moreover, planting rates for relatively expensive land use options like bioenergy crops are greater in England than other regions. For example, most of the planting for the two most expensive land use options on a £/ha basis, miscanthus and short rotation coppice, takes place in England. Relatively low net private costs in Northern Ireland reflect availability of options to alter agricultural practice and use technology that can potentially reduce farmers' costs.

Table 4 Present value of Net Zero scenario by region, 2019 to 2050, £ billion

	England	Scotland	Wales	Northern Ireland
Total Private Costs	21	12	5	2
Total Private Benefits	12	6	3	2
Private NPV	-9	-6	-2	<1
Private BCR	0.6	0.5	0.5	1
Total Social Benefits	45	41	14	7
Total Benefits	57	47	17	9
SocialNPV	36	36	12	7
Social BCR	2.8	4.1	3.4	4.6

Note: All estimates in present value terms, discounted at the UK social discount rate.
Source: Vivid Economics

2.1.3 Total costs and benefits by option

Forestry options make up the largest contribution to total private costs in the UK, with £15 billion in private costs by 2050 which makes up 40% of Net Zero scenario costs. Table 5 shows the value of private costs and benefits as well as social benefits in the UK for all land use options. Costs and benefits for each option as a share of total costs and benefits are shown in parentheses in the table. Bioenergy options contribute an additional £9 billion which makes up a further 25% of total costs. Agroforestry options are worth15% of the total, while changes in agricultural practices and technology make up another 8%. The lowest share of total costs comes from peatland options, which constitutes only 5% of total costs.

Most private benefits accrue to farmers who utilise low carbon practices and technologies, along with potential revenue from harvesting wood from existing broadleaf forests. Cost savings to farmers who could use existing practices such as manure spreading or use new technologies such as precision farming or low emissions livestock breeding make up half of the stream of revenues or cost savings that could accrue to UK landowners. Broadleaf management contributes 32% of total value in terms of revenue, worth over £7bn by 2050. Although significant costs are associated with the creation of new conifer and broadleaved woodlands, these options do not produce a large share of benefits because newly planted woodlands do not reach harvest maturity for decades. Bioenergy crops such as miscanthus and SRC do yield significant private economic benefits, making up close to one tenth of benefits of the land use options by 2050. The private economic benefits of agroforestry could include improved productivity from better soil quality and harvesting of fruit if fruit trees are planted. However, these are currently not well researched and have not been included as potential revenue streams or costs savings. For peatlands, no private revenues were modelled.

The value of social benefits is dominated by the creation of new woodlands which make up 62% of the total benefits generated to society. This can be explained by the large contribution woodland plays in sequestering carbon as trees grow. A significant share of social benefits is generated by the adoption of low carbon agricultural practices, which make up 17% of social benefits. These are largely from the benefits that low carbon farming practices have in reducing emissions of local air pollution and impacts on health outcomes. These improvements in local air quality provide two-thirds of the social benefits of these options. Peatlands contribute a significant share at 16% of the total, generating around£16 billion in social benefits from avoided greenhouse gas emissions.

Table 5 Present value of costs and benefits per option (£ billion), 2019 to 2050

Options	Private costs	Private benefits	Societal benefits
New Coniferous Planting	6.1 (16%)	1.5 (7%)	32.1 (30%)
New Broadleaved Planting	9.3 (24%)	0.7 (3%)	33.4 (32%)
Broadleaved Management	3.6 (9%)	7.2 (32%)	0 (-)
Miscanthus	5.2 (13%)	1.6 (7%)	4.9 (5%)
Short Rotation Coppice	2.4 (2%)	0.3 (2%)	- 1.8 (-2%)
Short Rotation Forestry	2.6 (6%)	0 (-)	<0.1 (<2%)
Silvoarable Agroforestry	2.7 (7%)	0 (-)	2.2 (<1%)
Silvopasotral Agroforestry	0.9 (2%)	<0.1 (-)	0.4 (<1%)
Hedgerow Expansion	3.0 (8%)	0.1 (-)	0.5 (<1%)
Upland Peat Restoration	1.6 (4%)	0 (-)	6.1 (6%)
Lowland Peat Restoration	0.3 (1%)	0 (-)	10.2 (10%)
Woodland to Bog	0.1 (<1%)	0 (-)	0.2 (<1%)
Crops & Soils	0.6 (2%)	0.9 (4%)	6.1 (6%)
Livestock	1.9 (5%)	7.5 (33%)	8.3 (8%)
Waste & other	0.4 (1%)	2.9 (13%)	2.9 (3%)
Total	39.1	22.6	105.3

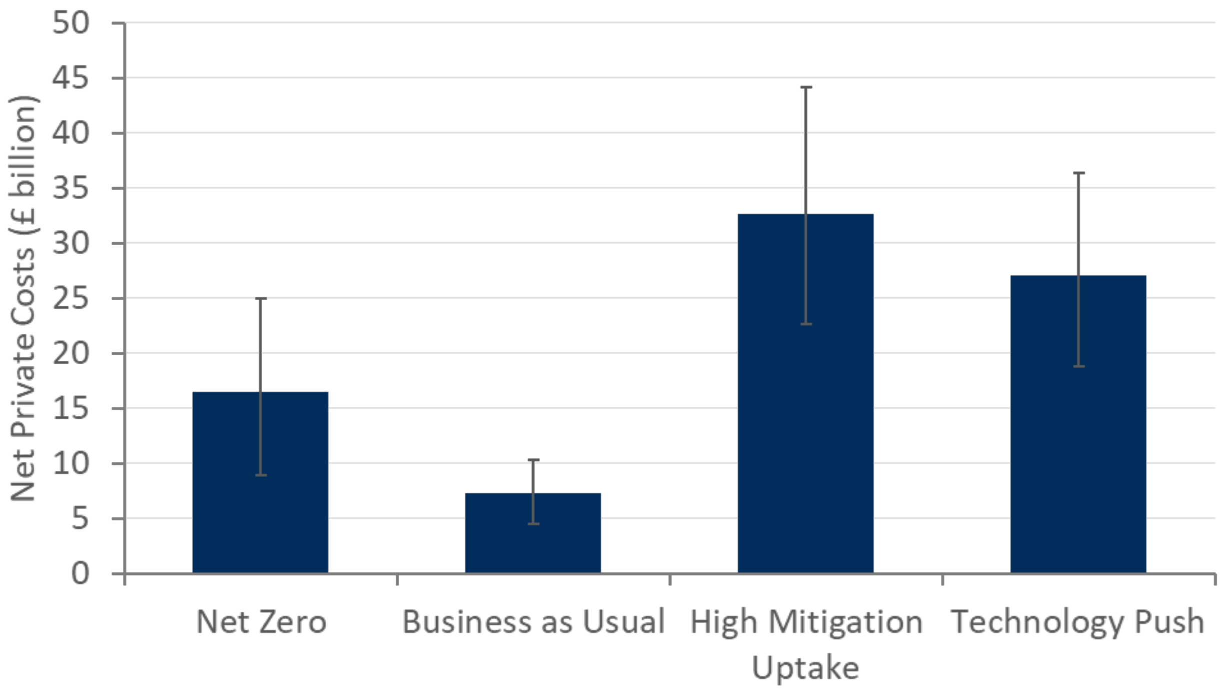
Note: All estimates in present value terms, discounted at the UK social discount rate. The corresponding share of scenario total costs are shown in parentheses for each option.
Source: Vivid Economics

2.1.4 Sensitivities

The economic impacts of each land use scenario are subject to sensitivities, as shown in Figure 1. On the costs side, key sensitivities include land acquisition, planting and establishment, and restoration costs, which vary by location of the land use change and the condition of the land. Accordingly, the net private costs could be up to £25 billion by 2050 or as low as £9 billion (+/- 47%). Although private benefits, such as the prices of timber products and bioenergy could change, these uncertainties in future prices are not considered. Moreover, productivity improvements and technological change underpinning yield assumptions by the CEH (2018) could also materialise differently, and no attempt has been made to quantify uncertainty around these assumptions. The ambition of the land use scenario affects the uncertainty of the estimates. For HMU and TP, uncertainty in parameter values could mean that net private costs vary by 30% around the central cost estimates for these scenarios.

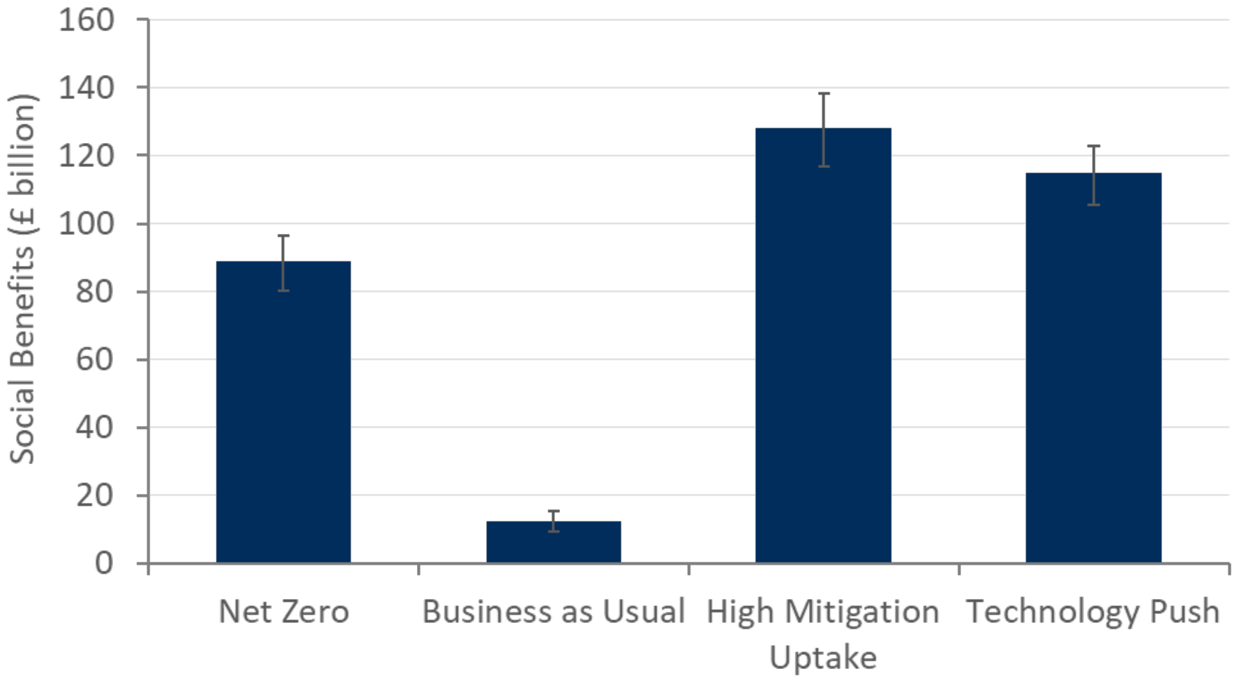
These sensitivities carry over to the societal NPV for each land use scenario shown in Figure 2. The NPV of social benefits of the Net Zero scenario are estimated to reach an upper bound of £100 billion or lower bound of £80 billion. Across all scenarios the social NPV is estimated to be about +/- 10% of the central estimate. The sensitivities shown for social benefits are limited. Note that social benefits for most land use options only include the value of greenhouse gas removals. These were modelled to remain consistent with CEH (2018) so estimation of sensitivities for avoided emissions was not possible.

Figure 1 Net private cost sensitivities in the UK for different land use scenarios (£ billion)



Note: All estimates in present value terms, discounted at the UK social discount rate
Source: Vivid Economics

Figure 2 Social net present value sensitivities in the UK for different land use scenarios (£ billion)



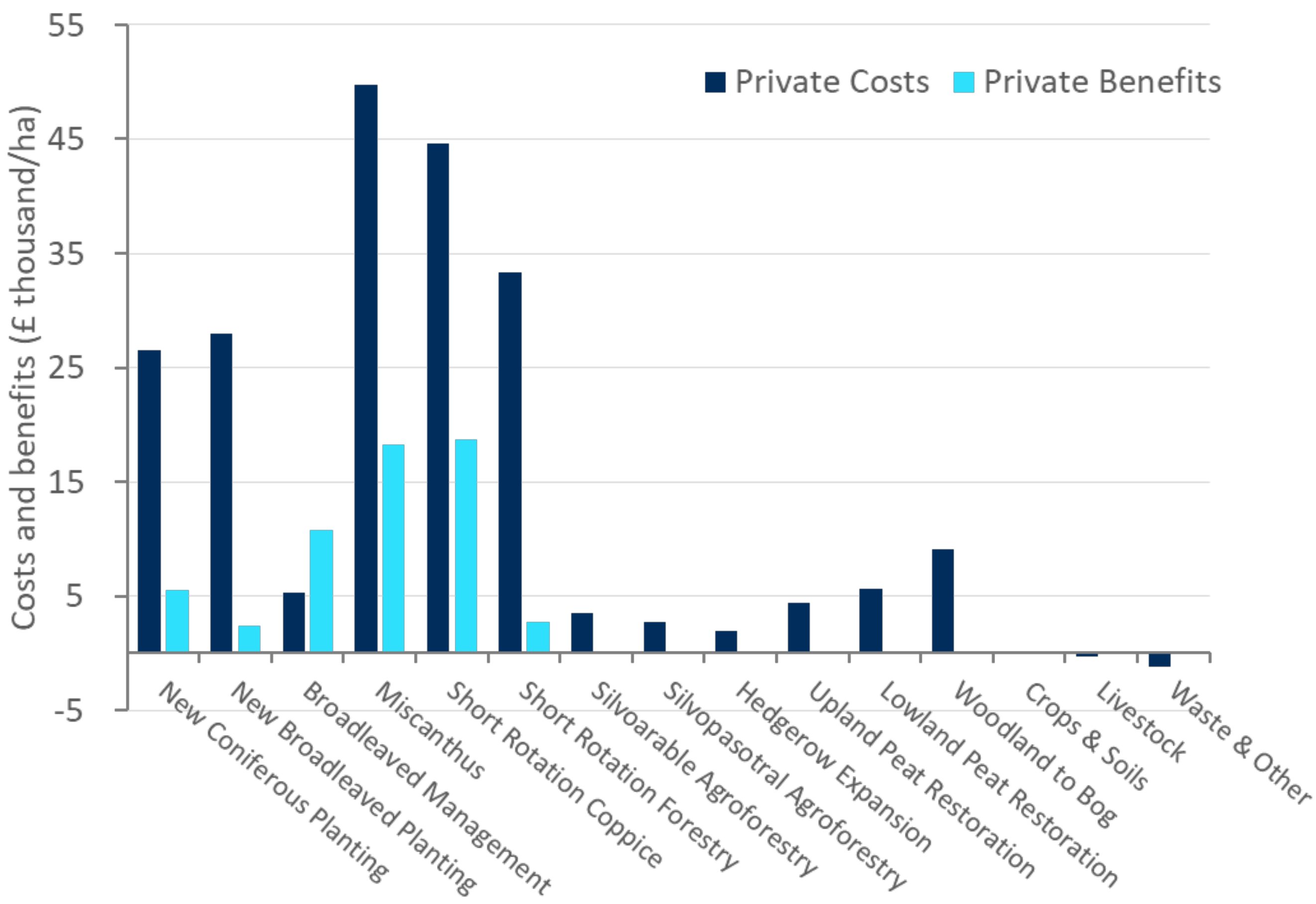
Note: All estimates in present value terms, discounted at the UK social discount rate.
Source: Vivid Economics

2.2 Per hectare economic impacts

The section summarises the estimates of per hectare costs and benefits each land use option. We begin by discussing the market costs and benefits and follow this with consideration of the social benefits. We then discuss a breakdown of social benefits by type and how examine how social benefits vary across options. A detailed description of the parameters and sources used to estimate these costs and benefits is included in Section 4.

2.2.1 Private costs and benefits

Figure 3 Private costs and benefits by option (thousands £/ha)



Note: All estimates in present value terms, discounted at the UK social discount rate.
Source: Vivid Economics

The costs of peatland restoration are low compared to woodland and bioenergy options but peatland yields no private revenues. Figure 3 shows the private costs and benefits for each land use option on a per hectare basis up until 2050. Unlike other land use options, peatland restoration is assumed to take place without a change of ownership of the land. However, the opportunity cost of restoring peatland is counted and included in operating expenditure (opex). With opex of approximately £100 per year, peatland restoration is still typically cheaper than the ongoing costs associated with maintaining and running a commercial woodland or bioenergy crop. Under a central cost scenario, total lifetime peatland restoration costs are £4,400 per hectare for upland locations, £5,600 per hectare for lowland locations, and £9,100 per hectare for the conversion of woodland to bog. In this report we assume that no private revenues stem from peatland restoration.

The establishment of a broadleaf woodland costs around £28,000 per hectare while planting conifers costs around £26,000 per hectare. Most costs accrue in the first year due to land acquisition and costs of planting trees. While ongoing costs are required to maintain the woodland, the upfront costs of forest creation underscore the potential costs of changing land use. While forestry can generate private returns from selling timber, these revenues do not accrue for more than 50 years, which is the reason for the relatively small present value of private benefits. Coniferous and broadleaved woodland only recoup 20% and 9% respectively of the costs associated with establishing and maintaining a new hectare of woodland.

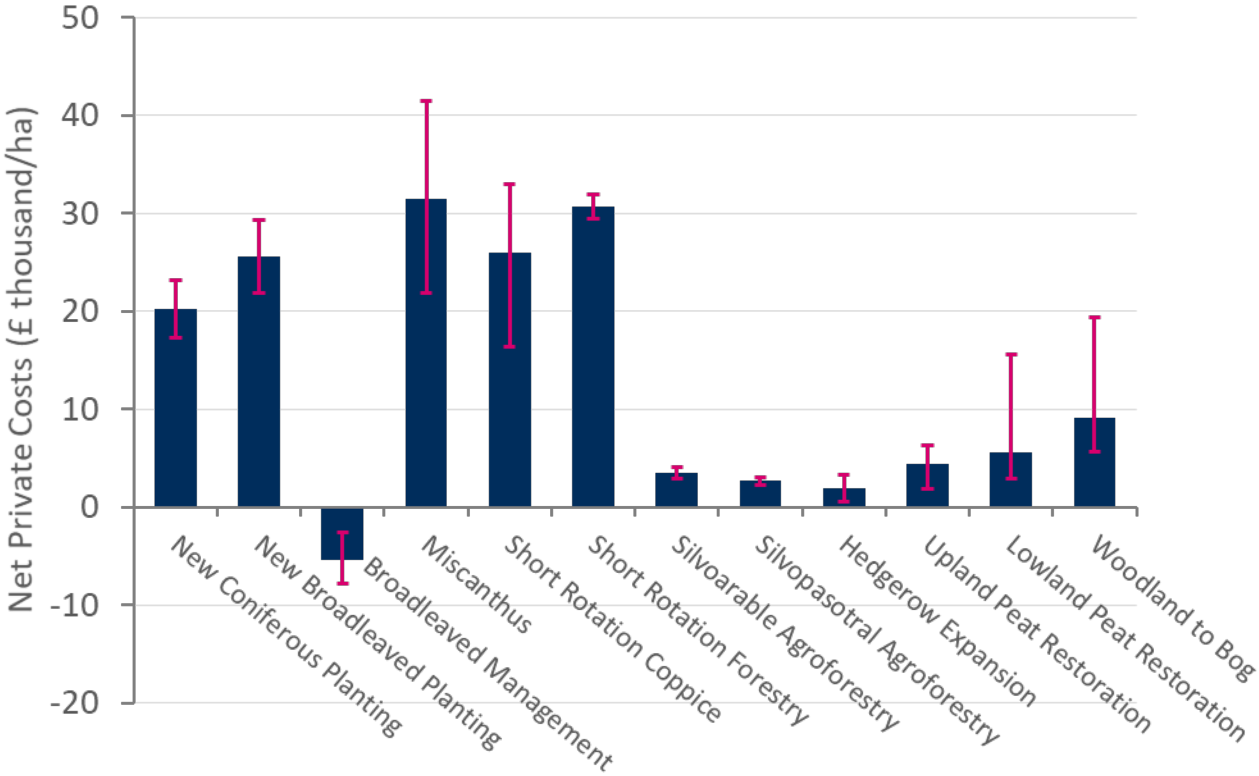
The costs of silvoarable agroforestry, where trees are grown in between crop rows, are calculated using the assumption that trees take up 18% of cropland, which costs £3,500 per hectare. Similarly, silvopastoral agroforestry takes up 10% of some pastureland at a cost of £2,800 per hectare. For hedgerows, the costs reflect planting of rows along a perimeter of fields. Hence, hedgerows displace about 1% of a hectare of farmland. Establishing a perimeter of hedgerows on cropland costs about £2,000 per hectare. For agroforestry options, no private benefits were assumed due to lack of evidence.

The planting of bioenergy crops is the most expensive land use change per hectare due to high land acquisition costs and on-going production costs. The costs of farming miscanthus over 2019 to 2050 are £49,700 per hectare, driven by high land acquisition costs for cropland as well as ongoing production costs that increase with the amount of biomass produced. SRC has production costs that also increase with output, but overall has lower costs (£44,600 per hectare) due to the relatively lower price of grassland, which it is assumed to displace. The final bioenergy option, SRF, costs £33,400 per hectare over 2019 to 2050 despite having lower opex. This is due to high planting and establishment costs of forestry at lower planting densities relative to larger commercial woodlands. Bioenergy crops yield significant private benefits, with miscanthus and SRC generating around £18,000 per hectare each in revenues. SRF generates significantly less revenue due to the long time between planting and harvesting (25 years).

Agri-mitigation options and new management of existing broadleaved woodland both yield net private benefits. While the costs of specific AP&T measures will vary, all three sets of options generate private benefits that recoup the costs of implementation. Specifically, crops and soils, livestock, and waste and other AP&T have annual net private benefits of £58 per hectare, £322 per head of livestock, and £1,184 per waste treatment plant, respectively. Aside from these options, broadleaved management generates revenues from woodfuel and timber of over £10,000 per hectare until 2050—double the costs of bringing the woodland under management.

The most uncertain private cost estimates are for some bioenergy crops and peatland restoration. Figure 4 shows the central estimates and ranges of costs per hectare. The widest range in costs are for bioenergy crops miscanthus and SRC. Differences in the complexity of planting options and land acquisition costs across the UK explain the ranges on these estimates, which vary by around £10,000 per hectare either side of the central estimate, for each crop. Peatland restoration also exhibits uncertain costs, with lowland restoration and woodland to bog estimates particularly variable because of the difference in restoring peatlands in eroded versus near natural condition. The upper cost estimate of restoration for both peatland options is more than double the central estimate if the peatland is in poor condition.

Figure 4 Net private cost sensitivities in the UK for different land use options (£/ha)



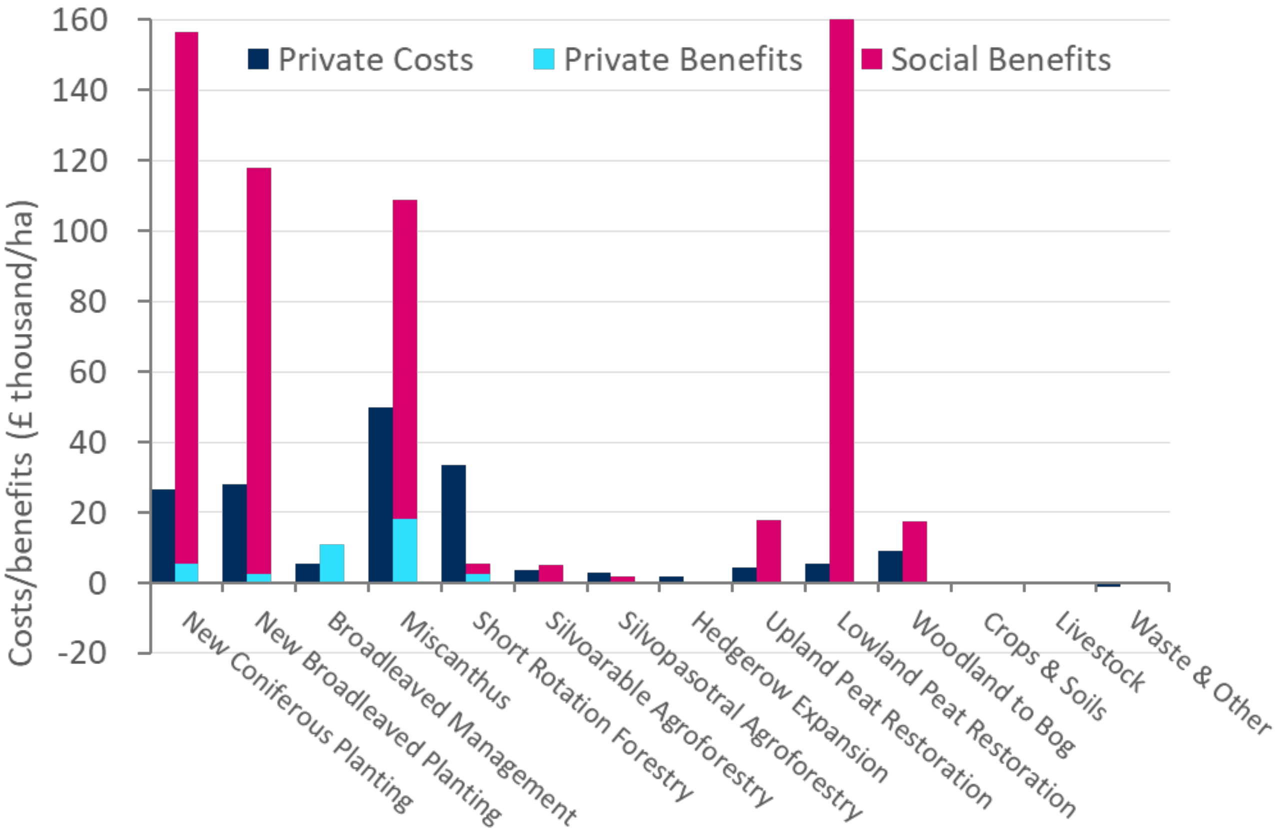
Note: All estimates in present value terms, discounted at the UK social discount rate.
Source: Vivid Economics

2.2.2 Comparing private and social impacts of Net Zero

Most land use options provide more value to society than they cost. Figure 5 includes social benefits (shown in pink) in addition to the private benefits that were considered in Figure 3. Woodland creation and peatland restoration offer societal benefits at least twice as large as the corresponding private costs. Miscanthus and silvoarable agroforestry have a social BCR greater than one. The remaining bioenergy and agroforestry options, SRC, SRF, silvopastoral agroforestry and hedgerow expansion, all offer benefits less than the costs of implementation.[3] However, there are likely to be wider benefits of agro-forestry and hedgerow expansion that it was not possible to monetise in this project.

[3] The value of greenhouse gas emissions reduction for bioenergy options only considers changes in soils and the composition of vegetation and is therefore likely to be an underestimate of broader social benefits from using bioenergy products in other sectors.

Figure 5 Land use option societal costs and benefits (thousands £/ha)

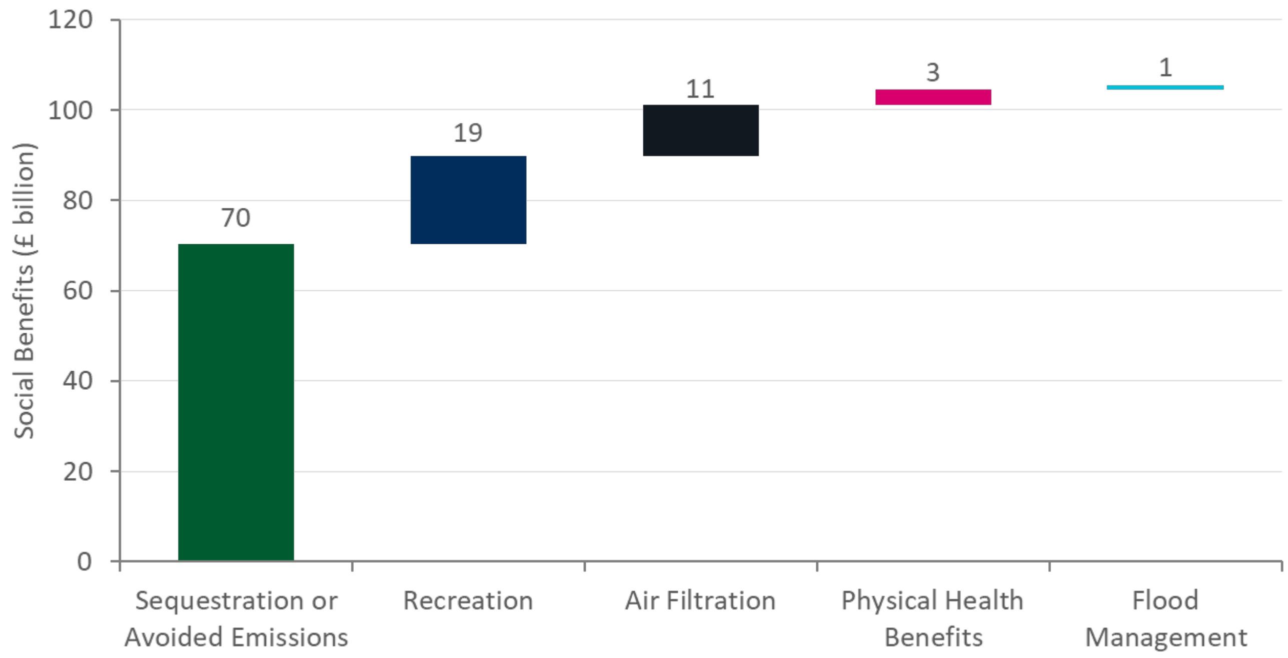


Note: All estimates in present value terms, discounted at the UK social discount rate. Short rotation coppice costs and benefits are not included in this diagram. Social costs per hectare are £132,000.
Source: Vivid Economics

New woodland planting and peatland restoration have the highest social benefit-cost ratio. The valuation evidence for woodlands is well developed and a range of social benefits can be quantified in monetary terms. These include greenhouse gas removals, recreation, physical health benefits, air quality regulation and flood management, resulting in a BCR of 4.2-5.9. Peatlands also provide a high return, particularly in lowland areas which confers large savings due to raising water levels on grassland and cropland. The social benefits for peatlands are mainly driven by avoided greenhouse gas emissions, though a moderate recreation value is also included. Social benefits were limited to GHG impacts for other land use options due to a lack of robust evidence. The incorporation of greenhouse gas removals for SRC reveals that this land use option is a net cost to society. Specifically, the net emissions created by planting SRC decrease its NPV from -£26,000 to -£158,000, making the option even less economically viable. This is a result of the assumption that SRC is planted on grassland rather than cropland, which results in GHG emissions release rather than removal. In practice, it is likely that SRC will be grown on cropland in some cases, in which case the economic case for growing it will be stronger. In addition, this analysis does not consider the GHG impacts of using harvested products in other sectors (e.g. with carbon capture and storage in the power sector).

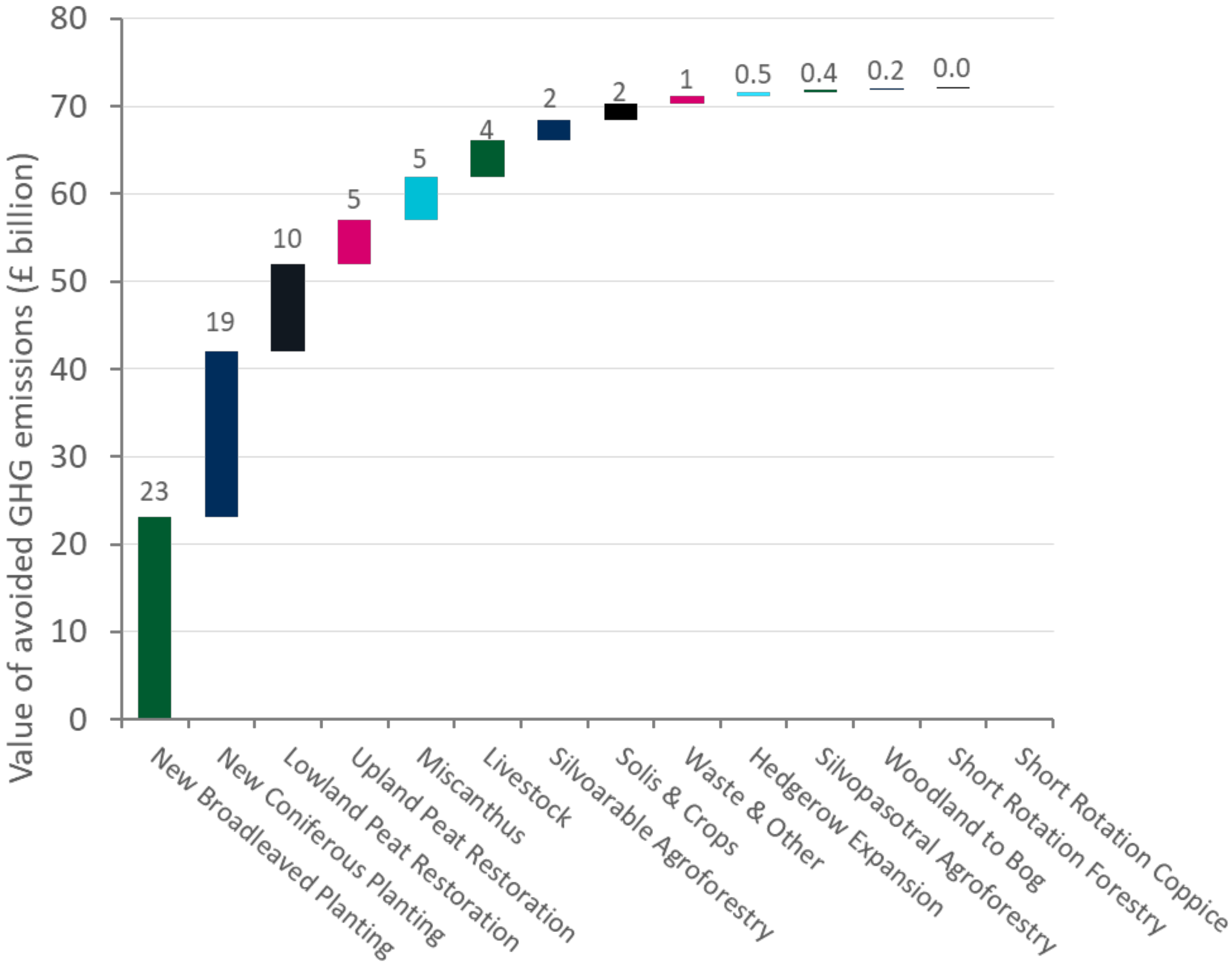
The value of greenhouse gas emissions reduction makes up the majority (67%) of total monetised social benefits. Figure 6 shows the aggregate social benefits of the Net Zero scenario by benefit type. The combined value of emissions reductions from all land use options in the Net Zero scenario total £70 billion in present value terms. Recreation, though limited to woodland and peatland land use options, is the second largest contributor to total social benefits, generating £19 billion in value, 18% of all social benefits. The combined social benefits of air filtration, physical health benefits (through exercise) and flood management amount to £15billion. Other benefits, such as mental wellbeing and visual amenity of landscape, have not been quantified. Throughout this report we have made conservative assumptions about the value of social benefits where there is uncertainty about parameters used to estimate economic values. Therefore, we expect the value of estimated social benefits to be underestimates of actual benefits to the UK. Details of the assumptions made to estimate the value of social benefits are detailed in Section 4.

Figure 6 Social benefits by type



Note: All estimates in present value terms, discounted at the UK social discount rate.
Source: Vivid Economics

Figure 7 Value of avoided or removed greenhouse gas emissions by option



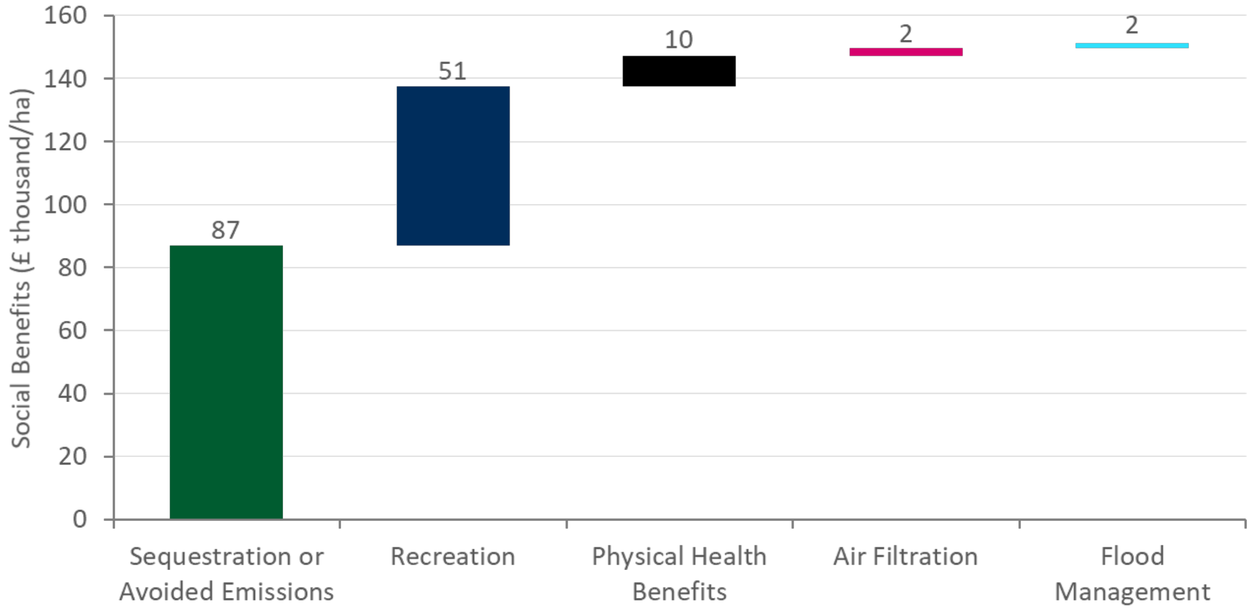
Note: All estimates in present value terms, discounted at the UK social discount rate.
Source: Vivid Economics

New planting of coniferous and broadleaved woodland contribute the most benefits in terms of greenhouse gas removal over their lifetime. New woodland is responsible for over£40 billion in economic benefits from GHG removals, analogous to 67% of the value of all avoided greenhouse emissions under the Net Zero scenario (see Figure 7). Peatland restoration is the second most valuable land use category for GHG removals and responsible for £15 billion of total value of GHG emissions reduction. The value of woodland creation and peatland restoration are evaluated up until 2100 to reflect that these benefits accrue over a longer time period than bioenergy and agri-mitigation options which are only evaluated until 2050.

New coniferous and broadleaved woodland generates the largest number of distinct ecosystem services. Unlike most other options, for which social benefits are primarily attributable to carbon sequestration, new woodland planting creates social benefits through a host of different ecosystem services. Figure 8 shows a breakdown of the social benefits from new coniferous woodland to illustrate this. Although more than half of the social benefits are derived from carbon sequestration, new coniferous woodland simultaneously generates over £60,000/ha of other ecosystem services. Foremost among them is recreation value, which provides over £50,000 in nonmarket benefits over the lifetime of the woodland. Physical health benefits due to space for physical activity additionally amount to £10,000 per hectare. The removal of harmful air pollutants is also a significant social benefit of woodland creation, removing £2,000 worth of pollutants that harm human health. The value of trees for water storage was also estimated at £2,000 per hectare.

The analysis of non-market impacts was limited by the availability of robust evidence. Whereas the evidence base for non-market benefits derived from woodlands is well developed, for most of the other land use options, including peatland restoration and agro-forestry, the evidence base available is limited. There is a case for further research to fill the gap in evidence.

Figure 8 Social benefits of new coniferous woodland (£ thousand/ha)



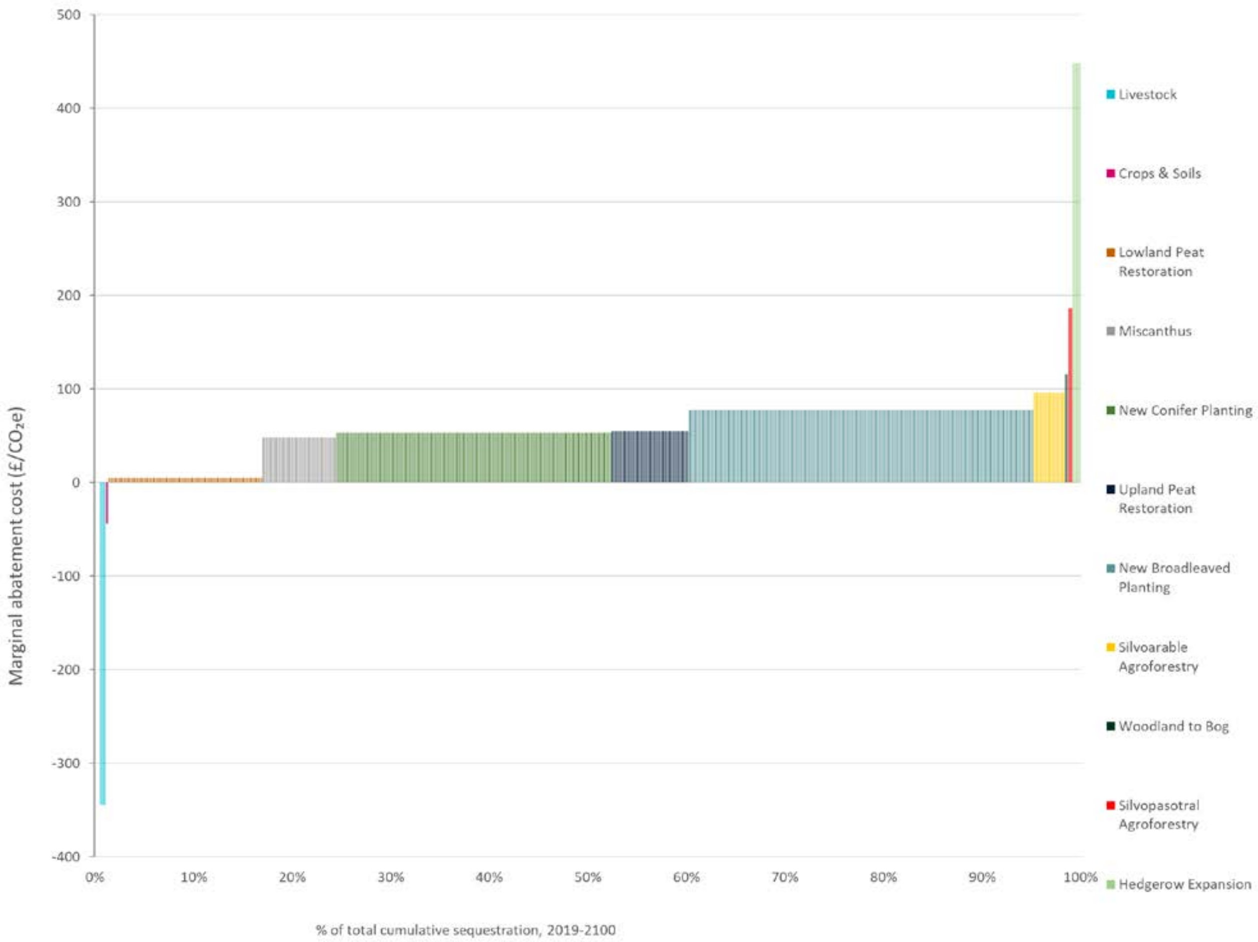
Note: All estimates in present value terms, discounted at the UK social discount rate.
Source: Vivid Economics

2.3 Marginal abatement cost curves

Figure 9 shows that most land use options save carbon at a private cost of less than £100/tCO_2e. Marginal abatement cost (MAC) curves show the cost-effectiveness of reducing carbon emissions for each land use option. Net cost figures show the private benefits less private costs of each land use option between 2019 and 2100. As a category, low carbon agricultural practices have negative marginal abatement costs, avoiding carbon emissions while also avoiding saving private costs. Lowland peat restoration is the next most cost-effective option for avoiding emissions at a cost of around £5/tCO_2e. Broadleaf woodland planting, conifer woodland planting, upland peat restoration and farming of miscanthus contribute most of the total emissions reduction and all do this at less than £80/tCO_2e. The agricultural option, Waste and other, is by far the most cost-effective measure at avoiding emissions, with each avoided tonne of CO_2e also saving costs of over £2,000 (this figure is excluded from the MAC curve for formatting purposes).

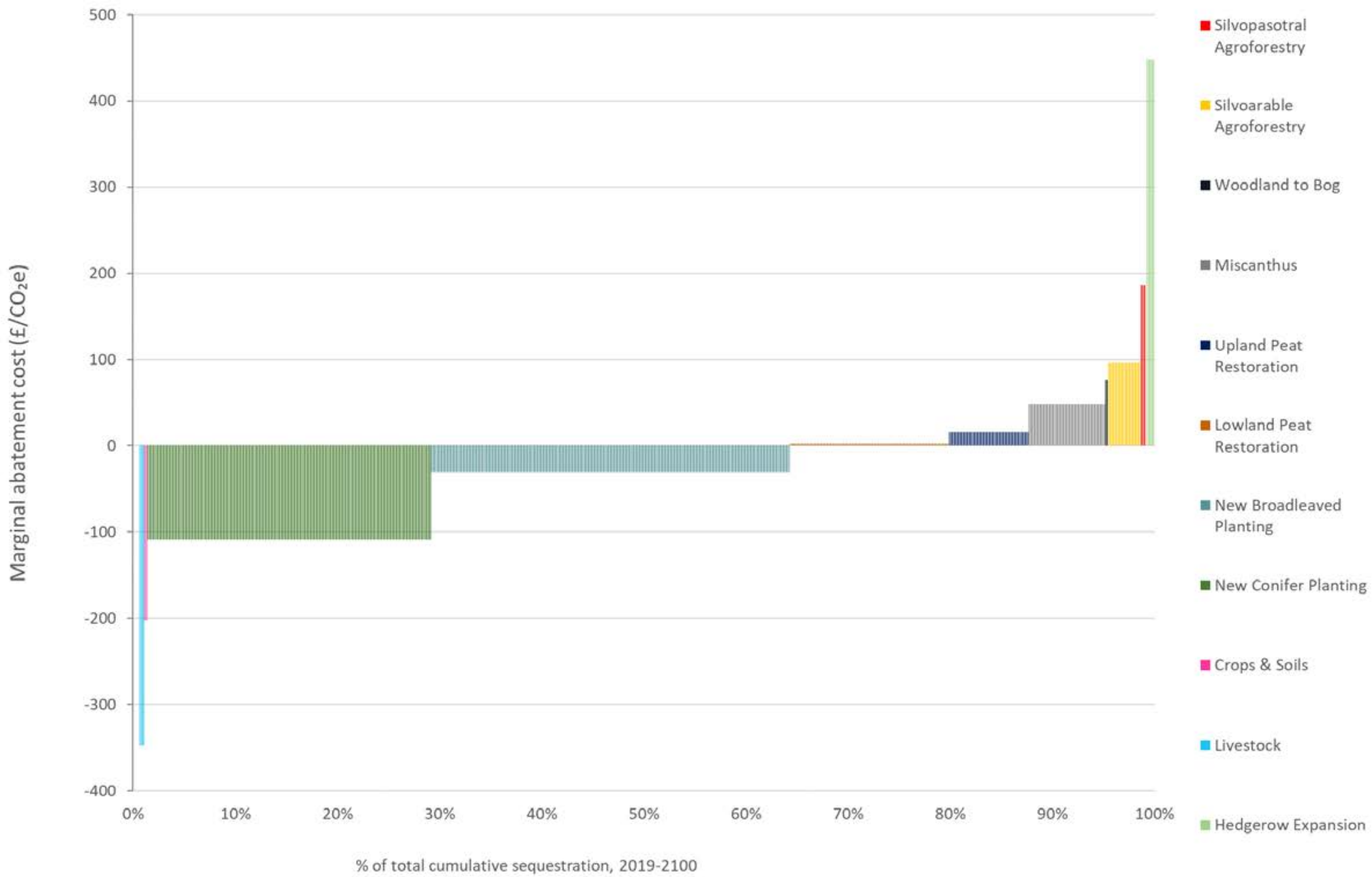
Incorporating the value of social benefits means that around two-thirds of emissions could be avoided at negative cost. Figure 10 shows marginal abatement costs when the social value of land use options is added to net private costs. These affect woodland planting options that generate social benefits in terms of recreation, health, air filtration and flood management. For each hectare of conifer created, this reduces each tonne of CO_2e while also yielding around £100 in net social benefits per hectare. Broadleaf woodland planting reduces a tonne of CO_2e while also generating around £30 in benefits. These two woodland options combined contribute over 60% of greenhouse gas emissions reduction. Agri-mitigation options generate additional benefits in terms of avoided ammonia emissions, which makes these options even more cost-effective at reducing greenhouse gas emissions. Peatland restoration generates modest benefits from additional recreation opportunities meaning lowland restoration reduces greenhouse gas emissions at £2/tCO_2e and upland restoration at £16/tCO_2e.

Figure 9 Private marginal abatement cost curve for land use options, 2019-2100



Note: Marginal abatement costs for 'Waste and other' and SRF are not shown on this diagram due to axis scale. Costs for Waste and other are -£1,318 and SRF is £2,145.
Source: Vivid Economics

Figure 10 Social marginal abatement cost curve of land use options, 2019-2100



Note: Marginal abatement costs for 'Waste and other' and SRF are not shown on this diagram due to axis scale. Costs for Waste and other are -£1,937 and SRF is £2,145.
Source: Vivid Economics

3 Conclusions

3.1 Funding requirement

The land use sector can contribute to the UK's target of net zero emissions if it receives funding to close the gap between the private costs of converting land and private benefits. The private costs to landowners of implementing the Net Zero scenario are £1.4 billion annually. These costs are partly offset by opportunities for cost savings totalling £700 million per year. The scale of funding is about £700 million per year to 2050, if perfectly targeted and efficiently deployed, to support the costs of land use change and deliver emissions reductions.

The funding required to fill the gap between private costs and benefits varies across land use options. While the private costs outweigh private benefits for most options on a per hectare basis, this gap is especially large for new woodland creation and bioenergy crops. Peatland restoration also requires significant upfront investment yet offers little private return. This means that graduated support for land use change according to activity might better reflect the incentive landowners have to implement individual practices and ensure cost-effective spending of public money. The central figures reported here will also vary according to, for example, the amount of mitigation undertaken by a landowner (which brings opportunities for economies of scale) and where in the country these activities take place. To be efficient, support policies and funding will accommodate this distribution of costs.

There are opportunities to take advantage of negative cost options in the agricultural sector, though even these require interventions to address non-cost barriers to adoption. Options such as livestock breeding and manure application have been identified as reducing on-farm emissions while also leading to cost savings. Overcoming the barriers to adoption is valuable given the potential cost savings if deployed. Policies that address actual or perceived barriers to adoption, such as reducing the risk of using new technologies or improving information about viable options, will be a key component of the cost-effective deployment of low carbon farming practices and technology. The management of existing broadleaved woodland can also generate significant private revenues and underscores an opportunity to engage with the forestry sector in management of the UK's existing woodlands.

The timing of costs and benefits may require financial support to address upfront capital costs and many years of waiting before private benefits are realised. For instance, the creation of broadleaf woodland requires an initial capital expenditure of around £26,000 to acquire land and plant trees and the private benefits of the timber harvest do not accrue for over 90 years. To bridge these gaps, policymakers must ensure that the cost structure of these measures is taken into account when innovative financing policies are used.

3.2 Social benefits

Landowners can deliver valuable social benefits and public goods by undertaking net zero land use change but are not currently rewarded for them. To meet the UK commitment to net zero emissions, individual landowners would be adequately incentivised to undertake land use practices. This is consistent with the Government's policy to place environmental stewardship at the core of UK land use policy, by rewarding landowners for the provision of public goods and services.

Net Zero options could be targeted spatially to maximise co-benefits such as recreation, health, air quality and flood risk reduction. Targeting based on co-benefits generates value primarily to those who live near newly created forests through recreation and natural flood management. In particular, planting could be targeted in peri-urban areas with significant residential and commercial populations and where there are few existing local recreational green spaces. This process would require policymakers at national and local levels to use a strategic and long-term planning process to maximise the value and opportunities from emissions reductions.

3.3 Evidence gaps and directions for future work

The analysis presented in this report is based on the current state of knowledge on the market and non-market benefits of land use in the UK. It employs a significant body of current data and evidence but has identified gaps that preclude a more detailed assessment. The recommendations of improvements in evidence are grouped into two categories: environmental impacts and economic impacts.

- The underlying scenario data constructed by CEH does not account for the following effects and future work could examine impacts in the following areas:
  - ◊ **Location-specific effects**: the current scenarios are specified at the country-level and do not specify locations for land use change. A better understanding of environmental and the associated economic impacts on specific habitats of land use change could be improved by more spatial downscaling of scenarios.
  - ◊ **Spill over effects**: the effects of land use change on other habitats are not well understood or the explicit focus of this report. Examination of the effects on neighbouring habitats can help policymakers ensure that land use change occurs without damaging existing habitats in the UK.
  - ◊ **Impact of land use change on ecosystem services**: There is a need for readily accessible robust evidence linking land use change to pollination, water quality and biodiversity. At the habitat level, the most evidence was available for woodlands. There is a particular need for evidence on the impacts of peatland restoration on water quality and flood risk. The impact of agroforestry and bioenergy on ecosystem services would also benefit from better evidence.
- **Evidence on economic impacts of land use change**. Key evidence gaps in this area relate mainly to the impact of non-market impacts:
  - ◊ **Monetary value of ecosystem goods and services**: the key areas for improvements in knowledge include the value of a greater range of pollinator species and the value of water quality improvements to different user groups, such as water utilities and recreational users. Better methods for valuing avoided flood risk are needed to improve those included in this report given current estimates are based on simple replacement cost measures that probably do not reflect the full costs and benefits of flood management.
  - ◊ **The value of biodiversity**: there remains a poor understanding about how changes in biodiversity affect society. The definition of biodiversity remains an obstacle. The evidence would benefit from pathways through which changes in biodiversity at scales relevant to individual landowners affect economic and environmental outcomes. Methods to value changes in biodiversity would also be useful.

4 Methodological annex

In this section, the methodology for estimating the market and non-market impacts of the land use scenarios is set out. First, the section describes the overarching approach to estimating aggregate costs and benefits. This combines the annual rates of land use change for options modelled by CEH (2018) and the per hectare estimates of monetary value of costs and benefits. Second, the section lays out common assumptions on discount rates and price levels. Third, it sets out full descriptions of the approach taken to estimate the cost and benefit figures for each land use option.

4.1 General approach

4.1.1 Calculating aggregate costs and benefits

The method for calculating the aggregate values for each scenario applies four steps:

1. calculate the market costs and benefits for each option on a per hectare basis;
2. apply the non-market benefit estimates;
3. assemble the annual planting rates for each option;
4. calculate the total costs and benefits for each land use scenario.

A more detailed description of each step follows below.

Step 1:Calculation of per hectare market costs and benefits for each option

Market costs span capital expenditures (capex) and operational expenditures (opex). Fifteen options, grouped under the headings Forestry, Bioenergy, Agroforestry, Peatlands, and Agricultural practice and technology, are shown in Table 6. Capex means one-off, upfront costs, typically converting land from its former use, including the price of land acquisition as well as planting and establishment costs. The costs of finance incurred by borrowing to pay for the initial investment have been included in the capex estimate. In the calculations, the capital investment is repaid over a period of 20 years with a financing cost (cost of capital) of 7% per year. Opex refers to the recurring expenses associated with each option. These include annual maintenance costs, such as replacing fencing or pest control, and periodic costs of harvesting marketable goods for biofuel or timber.

Market benefits are the products derived from agricultural and land use options that can be sold in markets. The market price of these goods is applied to the physical amount of biomass or harvested wood produced over the lifetime of the option. The physical amounts in the land use scenarios are set out in CEH (2018). Several options create multiple streams of revenue, such as income from thinning trees and harvesting at the end of the rotation period. A time profile tracks the production and harvesting schedule for each option. Prices for harvested wood products are reported on a £ per cubic meter (£/m^3) basis, with prices being for standing trees i.e. green bark. The price of biomass is reported on a £/oven dry tonne (odt) basis, which reflects the price paid for dried wood products, such as woodchip.

Table 6 Individual land use options and categories

Option Grouping	Option
Forestry	New coniferous woodland planting
	New broadleaved woodland planting
	New management of existing broadleaved woodland
Bioenergy	Miscanthus
	Short rotation coppice
	Short rotation forestry
Agroforestry	Silvoarable agroforestry
	Silvopastoral agroforestry
	Hedgerow expansion
Peatlands	Restoration of upland peatland
	Restoration of lowland peatland
	Restoration of woodland to bog
Agricultural practices and technology (AP&T)	Crops and soils
	Livestock
	Waste and other

Source: Vivid Economics

Step 2: Calculation of per hectare non-market (social) benefits

Non-market benefits are the impacts that land use options have on wider society. These benefits are often 'public', meaning that they benefit society at large rather than the individual who owns the land. These include various ecosystem goods and services, such as the regulation of air quality by removal or abatement of air pollutants, the provision of recreational space and physical health, and value of reduced flood risk.

Public goods and services are not traded in private markets, so market prices are not available and alternative approaches are employed to obtain estimates of value. These methods of non-market valuation generally fall under two categories: revealed and stated preferences, or avoided costs. Revealed preferences may be found where non-market goods and services are implicitly traded in secondary markets(Atkinson et al., 2018). For example, the value of a national park can be indirectly inferred from spending on travel to visit those places. When revealed preferences are not available, economists might turn to stated preference methods. These methods, such as contingent valuation, survey people, asking them how much they would be willing to pay for a good or service. A combination of revealed and stated preferences are used here to monetise the nonmarket benefits of the land use options.

The valuation estimates were selected after a review of methods used in other UK studies. The social benefits included in our analysis were limited to the ecosystem goods and services shown in Table 7, for which physical and value estimates are available.

The value of some non-market benefits are subject to considerable uncertainty and conservative assumptions have been made. These assumptions can be related both to the number of people affected by a given land use change and the impact on those who are affected. Where there is a range of available evidence to estimate these impacts, lower bound assumptions are used to avoid the risk of overestimating benefits. The specific assumptions used in these estimations are detailed in the following sections.

Due to lack of evidence, the benefits of services of biodiversity and water quality are not included in this analysis. For instance, while there is evidence that the creation of new woodland habitats support biodiversity broadly, there is no widely accepted way to value biodiversity (Bateman & Faccioli, 2018). Other studies point to the benefits that land use change can have in improving surrounding water quality, increasing pollinator numbers, and reducing soil erosion. There was insufficient evidence to merit including these in the present study.

Table 7 Social benefits included in the analysis

Social Benefits	Description of Methods	Options
Carbon sequestration	Vegetation captures and stores atmospheric carbon dioxide while peatland restoration and low-carbon farming practices reduce emissions. We rely on the land use option sequestration rates modelled by CEH (2018) and value the reduction in atmospheric carbon using the price of untraded carbon for the UK, based on BEIS values (BEIS, 2019).	- All options
Recreation	Recreation value for woodlands is calculated using visit numbers estimated for newly created woodlands in the UK. These figures are estimated using the ORVal tool (Day & Smith, 2018) which estimates numbers of recreational visits to natural environments across the UK. This is monetised using responses to stated preference surveys, which found that UK residents have a £1.66/visit willingness to pay for recreation in UK woodlands. These methods are estimate and value the number of visits for a newly created hectare of the woodland (Forest Enterprise England, 2016). For peatland restoration, recreation value is based on previous work by Vivid Economics.	- New coniferous woodland - New broadleaved woodland - Peatland restoration
Physical health benefits (exercise related)	We apply methodologies from the World Health Organisation and others, to calculate physical health benefits. Visitors achieve physical health benefits from undertaking activity in natural environments, including walking, running and playing sports. The resulting improvements for individual long-term health outcomes are estimated and measured in terms of a relative reduction in the risk of pre-mature, all-cause mortality—specifically, the reduction attributable to exercise occurring in the environment provided by the land use option. The valuation of these improvements is based on surveys which elicit the value that society is willing to pay to prevent a fatality. The value of a prevented fatality (VPF) that we use to monetise improved health outcomes is £2.2 million (Department for Transport, 2019). We do not extend this analysis to estimate the benefits of visits to woodlands on wellbeing and mental health. This is an evolving area of work in the UK. Further evidence on the how visits to woodlands affect mental health outcomes is needed in order to perform a full economic assessment.	- New coniferous woodland - New broadleaved woodland

Social Benefits	Description of Methods	Options
Air quality	Vegetation sequesters air borne pollutants such as particulate matter and ammonia, thereby increasing air quality, while measures to reduce N_2O emissions on-farm lead to reduced ammonia emissions. We calculate the amount of a pollutant that is sequestered over the lifetime of a land use option on a per hectare basis. A dose response function between atmospheric concentrations of air borne pollutants and health outcomes is then used to monetise the annual avoided health damages of a specified reduction in some pollutant. This is based on a study conducted for the Office of National Statistics by Jones et al., 2017.	New coniferous woodland New broadleaved woodland - Farming measures: Soils and crops - Farming measures: Waste and other
Flood management	Flood management benefits are ascertained by calculating how much water is held by existing UK woodlands. This is valued by calculating the cost to hold an equivalent amount of water in UK reservoirs, a replacement expenditure approach. We use figures for the amount of water stored and the value of avoided expenditure from work conducted by Broadmeadow et al. (2018) for Forest Research. We assume that per hectare water storage will be the same for new woodlands once they have reached maturity as for existing woodland. The avoided expenditure approach used in this study was chosen because of the lack of evidence linking water storage capacity and flood damages. This replacement cost method therefore is indicative of the value to society of managing water. Due to the lack of evidence for alternative water management value estimates, the per hectare values for flood management used in this study should be considered as indicative of the benefits of managing water. Further research in this area is required to understand these benefits more fully.	- New coniferous woodland - New broadleaved woodland

Source: Vivid Economics

Step 3: Assembling land use data

The annual rates of planting and restoration for each agricultural and land use option as well as land displaced are taken from models developed by CEH (2018). For each option included inTable 6, we obtained annual kilo hectares (kha) of land displaced or converted. Individual options have their own planting and restoration schedules which take place between 2019 to 2050.The annual planting rates are determined by the land use scenarios, of which there are four: Net Zero, Business as Usual (BAU), High Mitigation Uptake (HMU), and Technology Push (TP). The land use scenarios are built on underlying assumptions about the level of ambition concerning deployment. For instance, BAU assumes low ambition in mitigation whereas HMU features the most ambitious levels of mitigation. The scenarios are made up of options undertaken at different levels of ambition. Further details about these underlying assumptions can be found in CEH (2018). Where different levels of ambition affect the costs and benefits of options, separate figures are given for each level of ambition.

Information on the locations of land use change is not given in the scenarios. Each scenario is described for England, Scotland, Wales, and Northern Ireland, as well as for the UK.

Step 4: Calculate total scenario costs and benefits

Total costs and benefits of scenarios are calculated by multiplying the per hectare estimates by the number of hectares of land converted. All cost and benefits that occur after 2019 are discounted. To illustrate this, Table 8 shows a simple scenario where one species of woodland is planted over a period of five years at an increasing rate. In year 1, a single hectare is planted, whereas in year 5, five hectares of new woodland are planted. We further assume that an additional cost of £1,000/ha is required to establish the woodland and annual maintenance is £100/ha. The table below shows the aggregate scenario cost timeline for this simple scenario, where the discount factor is shown in brackets beside each year.[4]

Table 8 Numerical example for calculating aggregate costs and benefits

Planting Rates	**2019** (1.0)	**2020** (0.97)	**2021** (0.93)	**2022** (0.90)	**2023** (0.87)
2019 - 1 ha	£1,000 * 1	£100 * 1	£100 * 1	£100 * 1	£100 * 1
2020 - 2 ha	-	£1,000 * 2	£100 * 2	£100 *2	£100 *2
2030 - 3 ha	-	-	£1,000 * 3	£100 * 3	£100 *3
2040 - 4 ha	-	-	-	£1,000 *4	£100 * 4
2050 - 5 ha	-	-	-	-	£1,000 * 5
Annual Total, Present Value	£1,000	£2,037	£3,069	£4,140	£5,220

Source: Vivid Economics

The annual total is calculated by vertically summing all the costs that take place in that year, which is a unique combination of capex and opex, and multiplying this value by the discount factor in that year. The total scenario costs are the horizontal summation of the discounted total annual costs, equal to £15,466 in this example. Hence, we arrive at the formula for calculating costs and benefits for each option:

$$Total\ £\ for\ Option\ n = 1_{Land\ Use\ Scenario,\ \ Region}\ \ (\mathbf{Eq.1})$$

$$= \frac{(Capex_{t=1} * \ Planting_{t=1})}{(1 + discount\ Rate)^1}$$

$$+ \frac{(Capex_{t=2} * \ Planting_{t=2}) + (Opex_{t=1} * \ Planting_{t=1})}{(1 + discount\ Rate)^2}$$

$$+ \frac{(Capex_{t=3} * \ Planting_{t=3}) + (Opex_{t=2} * \ Planting_{t=2}) + (Opex_{t=1} * \ Planting_{t=1})}{(1 + discount\ Rate)^3}$$

$$+ \cdots + \frac{(Capex_{t=T} * \ Planting_{t=T}) + \cdots + (Opex_{t=1} * \ Planting_{t=1})}{(1 + discount\ Rate)^T}$$

where each row of the calculation corresponds to a new year up to the year, *T*. The total scenario costs or benefits for every option is therefore the summation of $Total\ £\ for\ Option\ n$, where *n* is one of N different options , over the time horizon, *T:*

[4]A rate of 3.5% in line with the UK social discount rate is used in this example.

$$Total\ £_{\ Land\ Use\ Scenario,\ \ Region} \qquad \textbf{(Eq. 2)}$$

$$= Total\ £\ for\ Option\ n = 1_{Land\ Use\ Scenario,\ \ Region}$$

$$+ Total\ £\ for\ Option\ n = 2_{Land\ Use\ Scenario,\ \ Region}$$

$$+ \dots +$$

$$+ Total\ £\ for\ Option\ n = N_{Land\ Use\ Scenario,\ \ Region}$$

Three cost scenarios are included to account for spatial heterogeneity and pre-conversion land condition. Significant heterogeneity in the costs of implementing the same option is possible for reasons including soil quality, proximity to transport infrastructure and previous condition of the land. The range of costs is shown in square brackets [].

4.1.2 General assumptions

A set of general assumptions that affect all the £/ha estimates for every option in the analysis:

- **Consistent with public sector practice of cost-benefit analysis (CBA) in the UK, we use a declining social discount rate as recommended in the Green Book (HM Treasury, 2018).**A social discount rate of 3.5% is used for the first 30 years of our analysis. The discount rate then declines in 2050 to 3% and again in 2095 to 2.5%.
- **Financing costs are calculated such that capex is repaid over a 20-year period, and the cost of capital is 7% pre-tax real.** This reflects the cost of raising capital in the private sector.
- **Carbon sequestration rates are matched to the sequestration rates of the CEH land use scenarios.**
- **The prices are expressed in 2019 terms unless otherwise stated.**

4.2 Summary of cost and benefit items by option

The categories of cost and benefit included for each option are shown in Table 9. A detailed description of the assumptions and parameter values of each is presented in the next section.

Table 9 Land use options and including components of costs and benefits

Option	Private costs	Private benefits	Social benefits
New coniferous woodland	- Land acquisition - Planting and establishment - Financing costs - Maintenance - Harvesting and production	- Wood fuel revenue - Timber revenue	- Greenhouse gas emissions reduction - Recreation - Physical health - Air quality (PM2.5) - Flood risk
New broadleaved woodland	- Land acquisition - Planting and establishment - Financing costs - Maintenance - Harvesting and production	- Wood fuel revenue - Timber revenue	- Greenhouse gas emissions reduction - Recreation - Physical health - Air quality (PM2.5) - Flood risk
New management of existing broadleaved woodland	- Maintenance - Harvesting and production	- Wood fuel revenue - Timber revenue	N/A

Option	Private costs	Private benefits	Social benefits
Miscanthus	- Land acquisition - Planting and establishment - Financing costs - Maintenance - Harvesting and production	- Biofuel revenue	- Greenhouse gas emissions reduction
Short rotation coppice	- Land acquisition - Planting and establishment - Financing costs - Maintenance - Harvesting and production	- Biofuel revenue	- Greenhouse gas emissions reduction
Short rotation forestry	- Land acquisition - Planting and establishment - Financing costs - Maintenance - Harvesting and production	- Biofuel revenue	- Greenhouse gas emissions reduction
Silvoarable agroforestry	- Planting and establishment - Financing costs - Maintenance - Harvesting and production	- Wood fuel revenue - Timber revenue	- Greenhouse gas emissions reduction

Option	Private costs	Private benefits	Social benefits
Silvopastoral agroforestry	- Planting and establishment - Financing costs - Maintenance - Harvesting and production	- Wood fuel revenue - Timber revenue	- Greenhouse gas emissions reduction
Hedgerow expansion	- Planting and establishment - Maintenance - Harvesting and production	- Biofuel revenue	- Greenhouse gas emissions reduction
Restoration of upland peatland	- Restoration - Monitoring and management - Opportunity costs	N/A	- Greenhouse gas emissions reduction - Recreation
Restoration of lowland peatland	- Restoration - Monitoring and management - Opportunity costs	N/A	- Greenhouse gas emissions reduction - Recreation
Restoration of woodland to bog	- Restoration - Monitoring and management - Opportunity costs	- Timber revenue (only for unmanaged woodland)	- Greenhouse gas emissions reduction - Recreation
Crops and soils	- Net private costs (including capex and opex)	N/A	- Greenhouse gas emissions reduction - Air quality (NH_3)
Livestock	- Net private costs (including capex and opex)	N/A	- Greenhouse gas emissions reduction - Air quality (NH_3)

Option	Private costs	Private benefits	Social benefits
Waste and other	- Net private costs (including capex and opex)	N/A	- Greenhouse gas emissions reduction - Air quality (NH_3)

Source: Vivid Economics

4.3 Methods by option category

4.3.1 Forestry

Forestry includes the following options:

1. New planting of coniferous woodland
2. New planting of broadleaved woodland
3. New management of existing broadleaved woodland

Private costs

Capex for woodland options

Table 10 Woodland capital costs

Cost type	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Coniferous land acquisition costs	£12,340	£12,340	£12,340
Coniferous planting and establishment costs	£3,000	£4,500	£6,000
Coniferous financing costs	£5,960	£6,550	£7,130
Total coniferous capex	**£21,300**	**£23,390**	**£25,470**
Broadleaved land acquisition costs	£12,340	£12,340	£12,340
Broadleaved planting and establishment costs	£4,000	£6,000	£8,000
Broadleaved financing costs	£6,350	£7,130	£7,900
Total broadleaved capex	**£22,690**	**£25,470**	**£28,240**

Note: No capex is assumed for new management of existing broadleaved woodland.
Source: Vivid Economics; Redman, 2019; CEH, 2018; Savills, 2017

Land acquisition costs in the UK are £12,300 per hectare for new coniferous and broadleaved woodland planting. These costs are based on Savills data on UK agricultural land prices and CEH's assumption that woodland planting occurs on a mixture of permanent grassland and rough grazing land (CEH, 2018; Savills, 2017). The value is a weighted average of regional land prices for pastureland and country-specific planting rates for woodland. Regional land acquisition costs per hectare vary from £8,700 in Scotland to £17,300 in England for both types of woodland. This variation is explained by differences in productivity, and therefore the opportunity cost, of the pastureland that the woodland displaces.

Planting and establishment costs per hectare are £4,500 [£3,000 - £6,000] for new coniferous planting and £6,000 [£4,000 - £8,000] for new broadleaved planting. The planting and establishment costs of new woodland are taken from farm management data provided in the John Nix Pocketbook (Redman, 2019). Typical costs for woodland creation are dependent on several factors, notably whether and to what extent the site requires clearing, draining, weeding and fertilising. Lowland and upland sites typically cost different amounts. Planting and establishment costs for hardwoods, such as broadleaved woodland, are more dependent on the costs of fencing and other tree protection measures, resulting in a wider range of costs than for coniferous woodland. Like land acquisition, planting and establishment costs are spread over a repayment period of 20 years and not included for new management of existing broadleaved woodland.

Opex for woodland options

Table 11 Lifetime woodland operating costs

Cost type	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Coniferous maintenance costs	£1,820	£2,500	£2,730
Coniferous production costs	£70	£80	£100
Total coniferous opex	**£1,890**	**£2,580**	**£2,830**
Broadleaved maintenance costs	£1,820	£2,500	£3,260
Broadleaved production costs	£10	£10	£10
Total broadleaved opex	**£1,830**	**£2,510**	**£3,270**
Broadleaved management maintenance costs	£2,730	£4,550	£6,830
Broadleaved management production costs	£470	£720	£1,040
Total broadleaved management costs	**£3,200**	**£5,270**	**£7,870**

Source: Vivid Economics; Redman, 2019; CEH, 2018

Lifetime maintenance costs are £2,500 per ha for new coniferous and broadleaved woodland. Maintenance is necessary to preserve woodland health and to ensure maximum growth for production of timber and/or wood fuel. Here maintenance is assumed to cost £75 [£60 - £90] per hectare (ha), per year for both coniferous and broadleaved woodland. Once again a range is taken from the John Nix Pocketbook(Redman, 2019) which embodies varying extent and complexity of management. Contributing factors to higher maintenance costs include replacing fencing and tree protection, other pest management practices, fire prevention, management and consultation fees, and insurance premiums (Redman, 2019). The maintenance costs of new broadleaved planting are the same for new management of existing broadleaved woodland, except that a cost multiplier is introduced to account for a lower density woodland. The rationale behind this multiplier, set to 2 [1.5 – 2.5], is that existing broadleaved woodland is likely to be more extensive and fragmented. As such, maintaining the same area of existing woodland would cost more than an area of newly planted woodland. Maintenance costs for new broadleaved management total £150 [£90 - £225] per ha per year under our assumptions.

Lifetime production costs are roughly £2,500 per ha for new coniferous and broadleaved woodland. The cost of marking trees for thinning is £11 per ha [£9.75 - £13] for coniferous woodland and £5/ha [£4 - £6] for broadleaved woodland(Redman, 2019). Consistent with CEH assumptions, thinning begins 25 years after planting for coniferous woodland and 30 years after planting for broadleaved woodland(2018). We assume that thinning takes place in five-year increments. Felling and clearance occurs 59 and 92 years after planting for coniferous and broadleaved woodland, respectively. Felling and clearance costs are included for coniferous woodland at an additional£350/ha [£300 - £400], since these occur before 2100, which is the time horizon of the calculations. Cost ranges for thinning and felling/clearance are adapted from John Nix data(Redman, 2019). As was used for maintenance costs, production costs for new management of existing broadleaved woodland are subject to a woodland density multiplier which doubles costs in thinning and felling years. The rationale of the multiplier is the same: harvesting the same amount of wood products from a larger tract of land requires more time and resources. Production costs for broadleaved management are £10 [£8 - £12] in thinning years and £700 [£600 - £800] at the end of rotation.

Private Benefits

Table 12 Woodland lifetime private benefits

Revenue type	UK low estimate(£/ha)	UK medium estimate (£/ha)	UK high estimate (£/ha)
Coniferous wood fuel	£2,290	£2,510	£3,200
Coniferous timber	£2,810	£3,090	£3,930
Total coniferous private benefits	**£5,100**	**£5,600**	**£7,130**
Broadleaved wood fuel	£2,200	£2,430	£2,650
Broadleaved timber	£0	£0	£0
Total broadleaved private benefits	**£2,000**	**£2,430**	**£2,650**
Broadleaved management wood fuel	£2,240	£2,460	£2,680
Broadleaved management timber	£8,280	£8,280	£8,280
Total broadleaved management private benefits	**£10,520**	**£10,740**	**£10,960**

Note: Benefits in present value terms over the period of 2019-2100 and discounted using UK Government rates. Broadleaved timber revenues not included due to length of Beech rotation.

Source: Vivid Economics; Redman, 2019; CEH, 2018

Lifetime private benefits from wood fuel and timber production are £5,600 [£5,100 - £7,130] for new coniferous woodland and £2,430 [£2,000 - £2,650] for broadleaved woodland. For new management of existing broadleaved woodland, private benefits are £10,740 [£10,520 - £10,960]. Wood fuel and timber revenues are calculated using the respective yield classes of coniferous and broadleaved woodland as modelled by CEH(2018). Coniferous woodland is modelled as Sitka Spruce with yield class (YC) 12 for BAU, YC13 for MfLU (Net Zero), and YC14 for the HMU and TP scenarios. Cumulative production of coniferous woodland is anywhere between 708 and 826 m^3/ha, of which 40% is harvested from thinning every 5 years, and the remaining 60% by felling of the trees at the end of their cycle. New broadleaved woodland, modelled as Beech YC6, produces 552 m^3/ha over its rotation of which 40% is also harvested during thinning.[5] A 10% and 20% increase in cumulative production by 2050 is added under the MfLU scenario and HMU/TP scenarios, respectively. This increases cumulative production to 607 m^3 for the MfLU and 662 m^3/ha for the HMU and TP scenarios. Due to the long harvesting cycle of Beech, felling and clearance takes place after 2100, meaning that only thinning revenues are included in the analysis for new broadleaved woodland. Softwood timber is sold at a standing price of £32 per m^3 and hardwood timber for £25 per m^3 as per John Nix and Grown in Britain data(Grown in Britain, 2019; Redman, 2019). Timber revenues are included for new management of existing broadleaved woodland. These are assumed to take place in the year the woodland is brought under management. We assume new management is subject to the same scenario-dependent productivity increases as new planting by 2050. We also assume that the wood products of broadleaved woodland brought under new management is of the same quality as newly established commercial woodland.

Social Benefits

Table 13 Woodland lifetime social benefits

Social benefit	UK low estimate (£/ha)	UK medium estimate (£/ha)	UK high estimate (£/ha)
Coniferous carbon sequestration	£68,230	£89,490	£91,660
Coniferous recreation	£50,680	£50,680	£50,680
Coniferous physical health benefits	£9,510	£9,510	£9,510
Coniferous air filtration	£2,430	£2,430	£2,430
Coniferous flood management	£1,530	£1,530	£1,530
Total coniferous social benefits	**£132,380**	**£153,640**	**£155,810**
Rural broadleaved carbon sequestration	£67,320	£81,590	£82,090
Rural broadleaved recreation	£26,850	£26,850	£26,850
Rural broadleaved physical health benefits	£5,040	£5,040	£5,040
Rural broadleaved air filtration	£2,300	£2,300	£2,300
Rural broadleaved flood management	£1,530	£1,530	£1,530
Total rural broadleaved social benefits	**£103,050**	**£117,310**	**£118,820**
Peri-urban broadleaved carbon sequestration	£67,320	£81,590	£82,090

[5] We assume that thinning occurs in 5 year increments after the initial year of thinning.

Social benefit	UK low estimate (£/ha)	UK medium estimate (£/ha)	UK high estimate (£/ha)
Peri-urban broadleaved recreation	£66,620	£66,620	£66,620
Peri-urban broadleaved physical health benefits	£12,510	£12,510	£12,510
Peri-urban broadleaved air filtration	£6,000	£6,000	£6,000
Peri-urban broadleaved flood management	£1,530	£1,530	£1,530
Total peri-urban broadleaved social benefits	**£153, 980**	**£169,250**	**£169,750**

Note: Benefits in present value terms over the period of 2019-2100 and discounted using UK Government rates. No social benefits assumed for new management of existing broadleaved woodland.

Source: Vivid Economics; CEH, 2018; BEIS, 2019; Day & Smith, 2018; Forest Enterprise England, 2016.

The lifetime value of carbon sequestration is £89,490 [£68,231 - £91,662] per hectare for new coniferous woodland and £81,590 [£67,320 - £82,090] per hectare for new broadleaved woodland. Per hectare annual rates of carbon sequestration were calculated from CEH for new woodland planting. These rates vary substantially between low, medium and high ambition land use scenarios, embodying changes in the sequestration potential of new coniferous and broadleaved planting(CEH, 2018). The value of carbon sequestration is the product of per hectare, annual sequestration rates and the price for non-traded carbon in that year (as published by the Department for Business, Energy & Industrial Strategy (BEIS, 2019)

Lifetime recreation value is £50,675 per hectare for new coniferous woodland. For broadleaved woodland, lifetime recreation value varies depending on the location of planting, and thus varies between £26,850 for rural locations and £66,620 for peri-urban locations per hectare.[6] Recreation value is calculated in two steps. First, estimates of average annual visits for a new hectare of coniferous and broadleaved woodland are found using the ORVal ecosystem valuation tool created by the University of Exeter. It was assumed that new visits do not occur until 10 years after planting, and that annual visits increase linearly as forests become more mature(Giergiczny et al., 2015). It is estimated that a hectare of coniferous woodland typically generates 2,700 annual visits once it has reached maturity, assumed to be 59 years after planting. A hectare of mature broadleaved woodland generates 2,565 and 6,090 annual visits for rural and peri-urban locations, respectively, 92 years after planting. Second, annual visit numbers are then multiplied by a per visit willingness to pay (WTP) to UK woodland to arrive at the monetary value of recreation. A conservative value of £1.68/visit is used, which is the lower bound of a WTP range found by Forest Enterprise England (2016).

Lifetime physical health benefits due to higher levels of activity are estimated at £9,510 for coniferous woodland, £5,040 for rural broadleaved woodland, and £12,510 for peri-urban broadleaved woodland pe hectare. Physical health benefits rely on annual visit estimates taken from the Outdoor Recreation Valuation (ORVal) tool which is a recreational demand model produced by a team at the University of Exeter. This uses data from Natural England’s Monitor of Engagement with the Natural Environment dataset to estimate

[6] Implicit in the recreation value for new woodlands is the assumption that all new woodland created is publicly accessible, and that this does not change with the status of commercial management.

recreational visits made to natural areas in the UK. It also enables the user to predict the visits made to new spaces. This predict function was used to derive average annual visit numbers to new conifer and broadleaf woodlands. To do this we sampled one hectare sites across the UK and calculated average values. Using the same annual visits as for recreation, the number of unique visitors to woodlands is derived by dividing total number of annual visits to woodland by the median number of annual visits individuals make to natural environments in the UK.

The value of physical health benefits is expressed through a relative reduction in risk of all-cause mortality between regular visitors of greenspace such as woodlands and those who do not regularly visit greenspace. Premature death from all-cause mortality is slightly less likely for regular, low-activity (e.g. walking) visitors to greenspace. A monetary value for the reduction in risk is given a monetary value by using the Department for Transport's value of a prevented fatality of £2.2 million. In order to prevent an overestimate of physical health benefits, not all the value of exercise is attributed to the creation of the woodland. For example, some visitors who exercise in the woodland would have exercised in another environment if the woodland had not existed. A conservative assumption that only 10% of exercise is attributable to the creation of the woodland is made for physical health benefits.

Lifetime physical health benefits from air filtration are £2,430 per hectare for coniferous woodland, £2,300 per hectare for rural broadleaved woodland, and £6,000 per hectare for peri-urban broadleaved woodland. Data were obtained from additional processing of pollution-removal value data from a study conducted for the Office of National Statistics (Jones et al., 2017). The data for removal of $PM_{2.5}$ were used that contributes most air pollution-related health impacts in the UK. Health benefits were calculated for removal of $PM_{2.5}$ by coniferous trees and broadleaved woodland. The health benefits within each region in the UK were calculated using a population-weighted change in $PM_{2.5}$ concentration, estimating the resulting change in health outcomes using existing mortality and morbidity data for the following health impacts: respiratory hospital admissions, cardiovascular hospital admissions and loss of life years. It was assumed that pollution levels remain constant at current levels due to uncertainty about future emissions of particulate matter.

Lifetime flood management benefits are £220 for coniferous and rural broadleaved woodland, and £810 for peri-urban broadleaved woodland. Flood risk management benefits were obtained from a report by Broadmeadow et al., (2018), who use value of flood management through a replacement expenditure approach. Specifically, flood management benefits are ascertained by calculating how much water is held by all UK woodlands, and is valued by estimating how much it would cost to hold an equivalent amount of water in UK reservoirs. This UK wide value is then scaled down to a per hectare basis. There is a lack of good economic evidence on the value of flood management attributable to woodlands in the UK and this replacement expenditure approach likely is a lower bound on the benefits of improved flood management. Further work to quantify these impacts, particularly at local levels where benefits of water management are likely to be much larger, is needed to conduct robust assessments of benefits of woodland creation.

4.3.2 Bioenergy

Bioenergy includes the following options:

1. Miscanthus
2. Short rotation coppice (SRC)
3. Short rotation forestry (SRF)

Private Costs

Table 14 Bioenergy lifetime capital costs

Cost type	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Miscanthus land acquisition costs	£23,200	£23,200	£23,200
Miscanthus planting and establishment costs	£1,970	£3,420	£7,270
Miscanthus financing costs	£10,860	£11,410	£12,920
Total miscanthus capex	**£36,030**	**£38,030**	**£43,390**
SRC land acquisition costs	£16,700	£16,700	£16,700
SRC planting and establishment costs	£1,670	£2,220	£2,560
SRC financing costs	£6,930	£7,080	£7,160
Total SRC capex	**£25,300**	**£26,000**	**£26,420**
SRF land acquisition	£16,700	£16,700	£16,700
SRF planting and establishment	£5,500	£6,150	£6,800
SRF financing costs	£8,630	£10,370	£10,910
Total SRF capex	**£30,830**	**£33,220**	**£34,410**

Note: Costs in present value terms over the period of 2019-2050 and discounted using UK Government rates.
Source: Vivid Economics; Redman, 2019; CEH, 2018; Savills, 2017; Energy Technologies Institute, 2016

Land acquisition costs are £23,200 for miscanthus and £16,700 for SRC and SRF per hectare. Consistent with CEH scenario assumptions, miscanthus is assumed to displace cropland whereas SRC and SRF are assumed to displace a mix of permanent and temporary grassland (CEH, 2018). Savills data on UK agricultural land prices is used to determine the value of land for acquisition (Savills, 2017). The UK price shown in Table 14 is the average price of cropland across regions, weighted by regional planting rates. Per hectare costs for miscanthus vary from £23,860 for cropland in England to £19,540 for cropland in Scotland. SRC and SRF land acquisition costs similarly vary by region, from £20,040 in England to £10,020 in Scotland.

Lifetime planting and establishment per hectare costs are £3,420 [£1,970 - £7,270] for miscanthus, £2,220 [£1,670 - £2,560] for SRC, and £6,150 [£5,500 – £6,800] for SRF. Miscanthus and SRC are both replanted periodically, and thus incur planting and establishment costs every 20 years.[7] For miscanthus, the central estimate is taken from previous costings of farming pilots in the UK (Energy Technologies Institute, 2016). The low and high estimate are taken from expert opinion on planting techniques, with the lower bound using direct seeding method and the upper bound an in vitro method. SRC planting and establishment costs are similarly obtained from UK bioenergy experts and John Nix data (Redman, 2019). Planting and establishment costs for low-density (1 to 10 hectare) on-farm woodlands were also taken from John Nix data (Redman, 2019). The lower bound costs reflect planting density of 3 to 10 hectares, whereas the higher bound corresponds to SRF planted at a density of less than 3 hectares.

Opex for bioenergy options

Table 15 Bioenergy lifetime private costs

Cost type	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Miscanthus maintenance costs	£990	£990	£990
Miscanthus production costs	£9,070	£10,670	£12,280
Total miscanthus opex	**£10,060**	**£11,660**	**£13,270**
SRC maintenance costs	£990	£990	£990
SRC production costs	£14,950	£17,590	£20,220
Total SRC opex	**£15,940**	**£18,580**	**£21,210**
SRF maintenance costs	£1,780	£2,970	£4,450
SRF production costs	£180	£290	£410
Total SRF opex	**£1,960**	**£3,260**	**£4,860**

Note: Costs in present value terms over the period of 2019-2100 and discounted using UK Government rates. Costs reflect yield assumptions for the Multifunctional Land Use scenario (miscanthus 14 odt/ha/year; SRC 15 odt//ha/cycle year).

Source: Vivid Economics; Redman, 2019; CEH, 2018; Savills, 2017; Energy Technologies Institute, 2016

Lifetime maintenance costs are uniform for miscanthus and SRC at £990, while they amount to £2,970 [£1,780 - £4,450] per hectare for SRF. Maintenance costs for miscanthus and SRC are minimal at £50/ha/yr, reflecting only the use of herbicides. These costs were taken from Energy Technologies Institute data (Energy Technologies Institute, 2016). SRF maintenance costs closely resemble the costs of new management for existing broadleaved woodland. Specifically, maintenance costs range are £150 [£90 - £225] per hectare per year.

Lifetime production costs per hectare are £11,670 [£9,070 - £12,280] for miscanthus, £17,590 [£14,950 - £20,220] for SRC, and £290 [£180 - £410] for SRF. Harvest costs include the costs for cutting, baling and carting. For Miscanthus, UK bioenergy experts were consulted to arrive at a price of £41 [£35 - £47] per odt.

[7]We assume that financing costs only apply to the first cycle of planting. Subsequent planting periods are therefore paid out of pocket with biomass revenues.

Accordingly, an annual harvest that produces 15 odt/ha implies productions costs of £615 [£525 - £705] for that year. SRC production costs were taken from John Nix data (Redman, 2019). The production costs are higher at £66 [£56 - £76] per odt, occurring every harvest year which take place in three-year increments. A hectare of SRC that yields 45 odt per harvest implies production costs of £2,970 [£2,530 - £3,420]. Because production costs are contingent on the tonnage odt of biomass produced, these will change according to the land use scenario chosen. Low ambition scenarios show lower production since the yield assumptions are lower. The opposite is true for high ambition scenarios: higher yield assumptions imply higher production and thus higher production costs. Consistent with CEH assumptions, there is no thinning for SRF implying that all productions costs are from felling and clearance in 26-year rotations. Productions costs in these years are £350 [£300 - £400] multiplied by the low planting density cost multiplier of 2[1.5 – 2.5].

Private Benefits

Table 16 Bioenergy lifetime private benefits

Revenue type	UK low ambition (£/ha)	UK medium ambition (£/ha)	UK high ambition (£/ha)
Miscanthus bioenergy	£15,190	£18,230	£24,300
SRC bioenergy	£14,920	£18,650	£24,870
SRF bioenergy	£2,680	£2,680	£2,680

Note: Benefits in present value terms over the period of 2019-2050 and discounted using UK Government rates
Source: Vivid Economics; CEH, 2018

The lifetime private market benefits per hectare from biomass production are £18,230 [£15,190 - £24,300] for miscanthus, £18,650 [£14,920 - £24,870] for SRC, and £2,680 for SRF. Bioenergy revenues for miscanthus and SRC are the product of odt/ha scenario-dependent yield assumptions and the price of bioenergy. The baseline yield assumption for miscanthus is 12.5odt/ha/year. This increases to 15 for the Net Zero scenario and to 20 for the High Mitigation Uptake and Technology Push scenarios. The baseline yield assumption for SRC is 12odt/ha/year, or, 35 odt/ha/harvest year. This increases to 15 (45) for the Multifunctional Land Use scenario and to 20 (60) for the High Mitigation Uptake and Technology Push scenarios. A price of £70/odt is assumed for biofuel produced from both miscanthus and SRC. For SRF, we use poplar yield class 12 to model private benefits (CEH, 2018). A hectare of SRF produces 312 m^3 of wood over its 26-year rotation. Consistent with the methods employed for forestry options, the standing price for SRF is used to determine private market benefits: £21 per m^3 based on UK hardwood timber price indexes for the year of 2018 (Grown in Britain, 2019).

Social Benefits

Table 17 Bioenergy lifetime social benefits

Social benefit	UK low ambition (£/ha)	UK medium ambition (£/ha)	UK high ambition (£/ha)
Miscanthus carbon sequestration	N/A	£90,750	£90,750
SRC carbon sequestration	N/A	-£132,230	-£132,230
SRF carbon sequestration	N/A	£2,620	£12,080

Note: Benefits in present value terms over the period of 2019-2050 and discounted using UK Government rates. Carbon sequestration for low ambition scenarios not modelled by CEH. Values in red indicate net social costs.

Source: Vivid Economics; CEH, 2018

While Miscanthus and SRF have net social benefits through carbon sequestration, emissions from SRC planting equate to £132,230 in costs over its lifetime per hectare. Bioenergy sequestration rates for BAU scenario were not modelled by CEH, and therefore are not included in our analysis. Furthermore, a rescaling of the CEH's sequestration rates were carried out for miscanthus and SRC. A uniform sequestration per ha over time was assumed for medium and high ambitions scenarios for these two options. While miscanthus sequesters £90,750 per hectare over its lifetime under medium and high ambition scenarios, conversion of land to SRC adds emissions to the atmosphere and thus represents a social cost of £132,230 per hectare over its lifetime. The original sequestration rates for SRF modelled by CEH were kept in our analysis. Consistent with their modelling, the per hectare sequestration pathway for SRF does differ substantially between medium (£2,620) and high (£12,080) ambition scenarios. As for all land use options, the value of carbon sequestration is the summation of annual sequestration rates and the price for non-traded carbon for that year.

4.3.3 Agroforestry

Agroforestry includes the following options:

Agroforestry includes the following options:

1. Silvoarable agroforestry (agroforestry on cropland)
2. Silvopastoral agroforestry (agroforestry on pastureland)
3. Hedgerow expansion

Adhering to the planting details specified by CEH(2018),silvoarable agroforestry and silvopastoral agroforestry occupy 18% of a hectare of cropland and 10% of a hectare of pastureland. The costs of these options are scaled in proportion with the amount of trees typically planted on a single hectare. For hedgerows, estimates represent the costs and benefits associated with planting a 100m row of hedgerows on the side of a field.

Private costs

Capex for agroforestry options

Table 18 Agroforestry capital costs

Cost type	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Silvoarable planting and establishment costs	£920	£1,220	£1,530
Silvoarable financing costs	£360	£480	£590
Total silvoarable capex	**£1,280**	**£1,700**	**£2,120**
Silvopastoral planting and establishment costs	£510	£680	£850
Silvopastoral financing costs	£200	£260	£330
Total silvopastoral capex	**£710**	**£940**	**£1,180**
Hedges planting and establishment costs	£360	£1,800	£3,200
Total hedgerow capex	**£360**	**£1,800**	**£3,200**

Note: Costs in present value terms over the period of 2019-2050 and discounted using UK Government rates.
Source: Vivid Economics; CEH, 2018; Redman, 2019; DEFRA, 2019

Planting and establishment costs per hectare are £1,220 [£920 – £1,530] for silvoarable agroforestry, £680 [£510 - £850] for silvopastoral agroforestry, and £1,930 [£360 - £3,200] for hedgerow expansion. Capex for silvoarable and silvopastoral agroforestry are taken from John Nix data for on-farm woodlands with planting density under three hectares(Redman, 2019). The cost for establishing a woodland of this density, £6,800, is then multiplied by the percentage of agricultural land that the option displaces: 18% for silvoarable and 10% for silvopastoral. Planting and establishment costs for hedgerows may include costs for laying, coppicing, gaping-up, casting up, and binding and staking, depending on the sophistication of the hedge. Costs for these activities were taken from DEFRA's Country Side Stewardship scheme for hedgerows and boundaries (DEFRA, 2019b). Because not all hedges will require complex management, a range of costs for hedgerows is incorporated, using John Nix data (Redman, 2019).

Table 19 Agroforestry operating expenditure

Cost type	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Silvoarable maintenance costs	£1,650	£1,820	£1,920

Cost type	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Silvoarable production costs	£0	£0	£0
Total silvoarable opex	**£1,650**	**£1,820**	**£1,920**
Silvopastoral maintenance costs	£1,650	£1,840	£1,940
Silvopastoral production costs	£5	£6	£8
Total silvopastoral opex	**£1,660**	**£1,850**	**£1,950**
Hedgerow maintenance costs	£130	£130	£130
Total hedgerow opex	**£130**	**£130**	**£130**

Note: Costs in present value terms over the period of 2019-2050 and discounted using UK Government rates.
Source: Vivid Economics; Redman, 2019; CEH, 2018; Burgess et al., 2003; Barr et al., 2000

Lifetime maintenance costs per hectare are £1,820 [£1,650 - £1,920] for silvoarable agroforestry, £1,840 [£1,650 - £1,940] for silvopastoral agroforestry, and £130 for hedgerows. As for woodland, maintenance costs for agroforestry options include removal of dead trees, replacing fencing and tree protection, and pest management practices (Redman, 2019). However, maintenance costs for silvoarable and silvopastoral agroforestry is predominantly made up of pruning costs, necessary to prevent foliage from intercepting sunlight needed by the crops and grassland surrounding the trees. Using data from Burgess et al. (2003), a single pruning schedule is assumed for silvoarable and silvopastoral agroforestry, where pruning takes place in years 2, 4, 7, and 9 after planting. The cumulative pruning costs over these five years amount to £1,120 to £1,140. Maintenance costs for hedgerows are calculated on a per metre basis using productivity data for hedgerow management and average hourly wages for contractors from Barr et al.(2000) and Redman (2019).

Production costs are only modelled for silvopastoral agroforestry, which amount to £6 [£5 - £8] over the lifetime of the option. Silvopastoral agroforestry assumed species is Sycamore yield class 6 with a 44 year rotation length and first year of thinning 20 years into the rotation (CEH, 2018). Agroforestry options are evaluated over 2019 to 2050, production costs only accrue from three cycles of thinning in years 25, 30, and 35. As for silvoarable agroforestry, species Poplar yield class 12 with a rotation length of 35 years and no thinning regime is assumed. All production costs take place past 2050 and are not modelled. CEH also assumes that trimmings from hedgerows are used as biofuel. Maintenance costs include the production costs for collecting hedgerow trimmings, since the hedge trimmings are expected to be removed from a location whether for biomass use or otherwise.

Private Benefits

Table 20 Agroforestry private benefits

Revenue type	UK low ambition (£/ha)	UK medium ambition (£/ha)	UK high ambition (£/ha)
Silvoarable biofuel	£0	£0	£0
Silvopastoral biofuel	£70	£70	£70
Hedgerow biofuel	£6	£6	£6

Note: Benefits in present value terms over the period of 2019-2050 and discounted using UK Government rates.
Source: Vivid Economics; CEH, 2018

Lifetime private benefits from biomass production are £56 for silvopastoral agroforestry and £6 for hedgerows. For silvopastoral agroforestry, the cumulative production of a hectare of sycamore over its rotation is 264 m^3, of which 40% is assumed to be harvested from thinning. Three cycles of thinning occur between 2019 and 2050, with production of 64 m^3, priced at £26 m^3as per 2018 hardwood timber price indexes (Grown in Britain, 2019). Harvesting of silvoarable agroforestry occurs after 2050 and is not included in the analysis. A hedgerow is assumed to be composed of several unproductive tree species. We use Beech as representative and hedgerow private benefits mirror the harvesting schedule of new broadleaved planting, downsized to the smaller scale. As is apparent in Table 20, the private benefits for agroforestry options are small when evaluated on a sub-hectare scale.

<u>Social Benefits</u>

Table 21 Agroforestry social benefits

Social benefit	UK low ambition (£/ha)	UK medium ambition (£/ha)	UK high ambition (£/ha)
Silvoarable carbon sequestration	N/A	N/A	£4,900
Silvopastoral carbon sequestration	N/A	N/A	£1,900
Hedgerow carbon sequestration	N/A	N/A	£350

Note: Benefits in present value terms over the period of 2019-2050 and discounted using UK Government rates. Per hectare benefits are shown in brackets. Carbon sequestration for agroforestry only modelled for high ambition scenarios by CEH.
Source: Vivid Economics; CEH, 2018

Lifetime social benefits have been limited to carbon sequestration, due to availability of data, for agroforestry options under high ambition scenarios, equal to £4,900 for silvoarable agroforestry, £1,900 for silvopasotral agroforestry, and £350 for hedgerow expansion per hectare. The figures are the annual sequestration rates for agroforestry from CEH (2018). The non-traded price of carbon is used to determine the value of carbon sequestration for these three options. Other potential non-market impacts of agroforestry, such as on-farm biodiversity, improvements in water quality from reduced nitrate leaching into water courses, improved soil structure and fertility from litter fall, have not been quantified.

4.3.4 Peatlands

Peatlands includes the following options:

1. Restoration of upland peatland
2. Restoration of lowland peatland
3. Restoration of woodland to bog

Private Costs

Using data on England's biodiversity strategy indicators for peatlands (DEFRA, 2019c), the conditions of upland peat, lowland peat, and woodland bog are shown in Table 22. A weighted average of the three peatland conditions (i.e. the percentages of the peatland belonging to the near natural, drained, or eroding categories) creates a representative hectare for upland peat, lowland to peat, and woodland to bog. Various activities to restore peatland activities are shown in Table 23.

Table 22 The state of UK Peatlands

Option	% in near natural condition	% in drained condition	% in eroded condition
Upland peatland	17%	71%	12%
Lowland peatland	35%	45%	20%
Woodland to bog	26%	58%	16%

Note: England's biodiversity strategy indicators only cover a fraction of UK's peatlands. It is assumed that two thirds of non SSSI under HLS, CS or FC protection are in near natural condition, and that the remaining one third of non SSSI under HLS, CS or FC protection are in eroding condition.

Source: Vivid Economics and CEH; DEFRA, 2019b

Table 23 Restoration activities by peatland type and condition

Option	Near natural condition	Drained condition	Eroded condition
Upland peatland	- Peat damming	- Peat damming - Hag reprofiling	- Peat damming - Hag reprofiling - Revegetating with sphagnum spp. plug plants
Lowland peatland	- Peat damming	- Peat damming - Revegetating with sphagnum spp. Plug plants	- Peat damming - Revegetating with sphagnum spp. plug plants - Plastic piling - Scrub removal
Woodland to bog	- Plastic piling - Forestry removal	- Plastic piling - Forestry removal - Brash crushing	- Plastic piling - Forestry removal - Brash crushing - Scrub removal

Source: Vivid Economics and CEH

Using upland peat as an example, the restoration costs for peatlands are thus calculated as:

$$Restoration\ Costs_{upland}\ (\textbf{Eq. 3})$$

$$= \left(\%_{near\ natural} * \frac{£}{ha_{peat\ damming}}\right)$$

$$+ \left(\%_{drained} * \left(\frac{£}{ha_{peat\ damming}} + \frac{£}{ha_{hag\ reprofiling}}\right)\right)$$

$$+ \left(\%_{eroding} * \left(\frac{£}{ha_{peat\ damming}} + \frac{£}{ha_{hag\ reprofiling}} + \frac{£}{ha_{revegetation}}\right)\right)$$

, where $\frac{£}{ha_x}$ corresponds to the cost of restoration activity *x*. Referring to past restoration costs of peatlands in the UK found in Glenk & Martin-Ortega (2018) and Okumah et al. (2019), we apply a low, median and high cost to each restoration activity in order to coincide with the cost scenarios used in our analysis. For example, upland restoration costs under a low-cost scenario would be calculated as:

$$Restoration\ Costs_{upland,low}\ (\textbf{Eq. 4})$$

$$= \left(\%_{near\ natural} * \frac{£}{ha_{peat\ damming,low}}\right)$$

$$+ \left(\%_{drained} * \left(\frac{£}{ha_{peat\ damming,low}} + \frac{£}{ha_{hag\ reprofiling,low}}\right)\right)$$

$$+ \left(\%_{eroding} * \left(\frac{£}{ha_{peat\ damming,low}} + \frac{£}{ha_{hag\ reprofiling,low}} + \frac{£}{ha_{scrub\ removal,low}}\right)\right)$$

, where $\frac{£}{ha_{x,low}}$ is the cost of restoration activity *x* under a low-cost scenario. In this way, we calculate what it would cost to restore an average ha of peatland in the UK based on the assumed state of peatlands:

$$Restoration\ Costs_{upland,low}$$

$$= (0.17 * £103) + \left(0.71 * (£103 + £950)\right) + \left(0.12 * (£103 + £950 + £470)\right)$$

$$= (£17) + (£748) + (£182)$$

$$\boxed{= £\mathbf{947}}$$

The range of costs for each type of restoration activity is given below in Table 24.

Table 24 Restoration activities costs for low, central, and high cost scenarios

Restoration Activity	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Peat damming	£103	£105	£447
Hag reprofiling	£950	£1,000	£1,140
Revegetating with sphagnum spp. plug plants	£470	£800	£1,210
Plastic piling	£70	£370	£890
Scrub removal	£2,500	£2,500	£2,500
Forestry removal	£3,000	£3,000	£3,000
Brash crushing	£130	£900	£1,660

Note: Low, median, and high cost estimates not available for forestry removal and scrub removal.
Source: Vivid Economics; Glenk & Martin-Ortega, 2018; Okumah et al., 2019

Capital expenditure by peatland type is shown in Table 25. On average, woodland to bog is the most capital-intensive restoration at over £6,000 per hectare. This is followed by lowland restoration at over £2,500 per hectare and upland peatland restoration costs of close to £1,500.

Table 25 Peatland capital expenditures

Cost type	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Upland peatland restoration costs	£950	£1,030	£1,540
Upland peatland financing costs	£370	£400	£590
Total upland peatland cost	**£1,320**	**£1,430**	**£2,130**
Lowland peatland restoration costs	£1,560	£1,910	£2,750
Lowland peatland financing costs	£610	£740	£1,070
Total lowland peatland cost	**£2,170**	**£2,650**	**£3,820**
Woodland to bog restoration costs	£3,560	£4,420	£5,510
Woodland to bog financing costs	£1,280	£1,720	£2,140
Total woodland to bog cost	**£4,930**	**£6,140**	**£7,650**

Note: Costs in present value terms over the period of 2019-2100 and discounted using UK Government rates.
Source: Vivid Economics; CEH, 2018; DEFRA, 2019b; Glenk & Martin-Ortega, 2018; Okumah et al., 2019

Table 26 Peatland operational expenditures

Cost type	UK low estimate (£/ha)	UK central estimate (£/ha)	UK high estimate (£/ha)
Upland peatland recurring costs	£590	£2,936	£4,410
Lowland peatland recurring costs	£730	£2,936	£11,743
Woodland to bog recurring costs	£730	£2,936	£11,743

Note: Costs in present value terms over the period of 2019-2100 and discounted using UK Government rates.
Source: Vivid Economics; CEH, 2018; Glenk & Martin-Ortega, 2018; Moxey& Moran, 2014; Moxey, 2016

Adopting a median annual recurring cost of £100 for all three peatland options, the central estimate of lifetime opex is uniformly £2,936 per hectare. Recurring costs covers the monitoring, management and opportunity costs associated with the restoration of peatland. The cost of the central estimate includes monitoring, management costs, and foregone income from the prior use of the land (Glenk & Martin-Ortega, 2018). For upland peatland restoration, the annual recurring costs range from £20/ha to £140/ha (Moxey, 2016). The lower bound reflects the minimum of monitoring and management costs and land with no profitable prior use. The upper bound reflects high monitoring and management costs and/or that the land had profitable prior use for livestock grazing and grouse management. Lifetime recurring costs for upland peat therefore range from £590 to £4,410 per hectare. We adopt a wider range of recurring costs for lowland peatland and woodland to bog of £25/ha to £400/ha, as used by Moxey & Moran (2014). Raising the lower and upper bound is justifiable since some lowland peat and bog have been converted to profitable enterprises, such as horticultural production and commercial woodland management. Accordingly, lifetime recurring costs range from £730 per hectare, when restoration takes place on marginal land that requires little monitoring or management costs, to £11,743 per hectare, when restoration takes place on highly productive agricultural land.

Private Benefits

Peatland restoration only creates private market benefits for the restoration of woodland to bog when the woodland is not being commercially managed. There are no private benefits when the woodland is being commercially managed prior to restoration, the reason for this being that new revenues only occur when the woodland is not already harvested for timber. Hence, the wood harvested from restoration is included as a private market benefit only when the woodland is in an unmanaged state. In such instances we assume the revenues from timber are £8,280 per hectare, equivalent to revenues from felling and clearance of broadleaved woodland.

Social Benefits

Table 27 Peatland social benefits

Social benefit	UK low ambition (£/ha)	UK medium ambition (£/ha)	UK high ambition (£/ha)
Upland peatland carbon sequestration	N/A	£14,620	£19,450
Upland peatland recreation value	£3,110	£3,110	£3,110
Total upland peatland social benefits	**N/A**	**£17,730**	**£22,560**
Lowland peatland carbon sequestration	£189,600	£189,600	£189,600
Lowland peatland recreation value	£3,110	£3,110	£3,110
Total lowland peatland social benefits	**£192,710**	**£192,710**	**£192,710**
Woodland to bog carbon sequestration	N/A	£14,330	£19,450
Woodland to bog recreation value	£3,110	£3,110	£3,110
Total woodland to bog social benefits	**N/A**	**£17,440**	**£22,560**

Note: Benefits in present value terms over the period of 2019-2100 and discounted using UK Government rates. Carbon sequestration for low ambition scenarios not modelled.

Source: Vivid Economics; CEH, 2018

The lifetime social benefits are £17,730 [£22,560] for upland peatland restoration, £189,600 for lowland peatland restoration and £17,440 [£22,560] for restoration of woodland to bog. Annual net sequestration between restored and unrestored peatland is calculated to remain consistent with CEH scenario sequestration rates (CEH, 2018). An earlier version of this model assumed that greenhouse gas emissions savings from restoration were uniform across upland and lowland sites. This assumption was revised following the publication of the CCC Land Use (2020) report after it was acknowledged that restoration of lowland peat, involving conversion of grassland and cropland, confers large GHG emissions savings per hectare relative to upland sites. The previous assumption was that avoided GHG emissions were 3tCO_2e per hectare per year for upland and lowland areas. The annual per hectare emissions factors used for lowland peatland restoration are now 39tCO_2e for cropland restored and 30tCO_2e for grassland restored, which is consistent with the values used to inform the CCC's Net Zero (2019) advice. Accordingly, the lifetime value of GHG emissions savings has increased substantially from £15,340 to £189,600 per hectare for lowland peat restoration. The benefits of GHG removals are supplemented by an average annual recreation value of £103, taken from previous work done at Vivid Economics, analogous to lifetime benefits of £3,110 per hectare.

4.3.5 Agricultural practices and technology (AP&T)

AP&T are grouped into the following three categories:

1. Crops and soils
2. Livestock
3. Waste and other

Each category of agricultural practices and technologies is made up of several options. The options grouped under each category are shown below.

Table 28 Grouping of agricultural practices and technology options

Category	Agri-mitigation measure
Crops and soils	- Autumn to spring manure application - Manure planning - Use grass clover crops instead of N2 fertiliser - Controlled release fertilisers - Loosen soil compaction - Precision farming crops - Crops with enhanced NUE - Triticale
Livestock	- Beef breeding - Breeding current - Breeding genomics - Breeding low methane - Use probiotics in animal diets - Measures to improve livestock nutrition - Use nitrate as feed additive - Measures to improve cattle health - Measures to improve sheep health - 3NOP - High sugar grasses - Nitrate add - Livestock reductions
Waste and other	- AD maize - AD pig poultry maize - Slurry acid

Source: Vivid Economics and CCC

Private Costs

Table 29 AP&T option costs per year

Category	Practice or technology	UK estimate	Share of total category implementation in the UK (%)
Crops and Soils	Autumn to spring manure application (£/ha)	-£1,217	2%
	Manure planning (£/ha)	-£48	7%
	Use grass clover crops instead of N2 fertiliser (£/ha)	-£113	19%
	Controlled release fertilisers (£/ha)	£434	24%
	Loosen soil compaction (£/ha)	£7	7%
	Precision Farming Crops (£/ha)	-£482	21%
	Crops with enhanced NUE (£/ha)	N/A	19%
	Triticale (£/ha)	N/A	1%
Livestock	Beef breeding (£/head)	-£233	2%
	Breeding current (£/head)	-£9,459	2%
	Breeding genomics (£/head)	-£2,288	4%
	Breeding low methane (£/head)	- £4,418	3%
	Use probiotics in animal diets (£/head)	- £126	15%
	Measures to improve livestock nutrition (£/head)	-£11	19%
	Measures to improve cattle health (£/head)	-£96	13%
	Measures to improve sheep health (£/head)	£13	32%
	3NOP (£/head)	£1,178	8%
	High sugar grasses (£/head)	-£2,160	1%
	Nitrate add (£/head)	£736	2%
Waste and other	AD maize (£/plant)	-£68 million	< 1%
	AD pig poultry maize (£/plant)	-£24.4 million	< 1%
	Slurry acid (£/ha)	£202	~ 100%

Note: Costs in present value terms over the period of 2019-2050 and discounted using UK Government rates. Values in red indicate negative private costs i.e. net private benefits.

Source: Vivid Economics; CEH, 2018; CCC data

Table 30 AP&T category average private cost, weighted by share of total deployment

Social benefit	UK estimate
Crops and Soils (£/ha)	-£58
Livestock (£/head)	-£322
Waste and other (£/plant)	-£1,184

Note: Benefits in present value terms over the period of 2019-2050 and discounted using UK Government rates. Values in red indicate negative private costs i.e. net private benefits.

Source: Vivid Economics

The net private costs for the three AP&T categories are -£58 for crops and soils per hectare, -£322 per livestock head, and -£1,184 for waste and other. The cost data for these calculations were provided by the CCC, in the form of annualised net private costs per ha or livestock head, already discounted to 2050. Each AP&T measure was multiplied by the time period of assessment (31 years) to arrive at a lifetime £/ha or head cost estimate. To create an average net private cost for each of the three AP&T categories (soils and crops, livestock, and waste and other), each measure was weighted by its corresponding share of total deployment among all the options for that group.[8] Using 'waste and other' as an example, this calculation is similar to the method used for calculating the restoration costs for peatland options:

$$Costs_{waste\,\&\,other} = \left(\%_{of\ waste\,\&\,other} * \frac{£}{ha_{AD\ Maize}}\right) + \left(\%_{of\ waste\,\&\,other} * \left(\frac{£}{ha_{AD\ Maize}} + \frac{£}{ha_{AD\ Pig\ Poultry\ Maize}}\right)\right) + \left(\%_{of\ waste\,\&\,other} * \left(\frac{£}{ha_{AD\ Maize}} + \frac{£}{ha_{AD\ Pig\ Poultry\ Maize}} + \frac{£}{ha_{Slurry\ Acid}}\right)\right)$$

<u>Private Benefits</u>

Private benefits are not explicitly modelled in our analysis since net private costs are intended to reflect these.

<u>Social Benefits</u>

[8]Note: Net private costs for the crops with enhanced NUE, triticale and livestock reductions measures were not provided. As such, these two measures were not included in our calculation of average net private costs for the Crops & Soils and Livestock agri-mitigation options.

Table 31 Social benefits for AP&T, weighted by share of total deployment

Social benefit	UK estimate (£/ha or livestock head)
Crops and Soils carbon emissions avoided (£/ha)	£165
Crops and soils removal of airborne ammonia avoided (£/ha)	£208
Total crops and soils social benefits (£/ha)	**£373**
Livestock carbon emissions avoided (£/head)	£136
Livestock removal of airborne ammonia avoided (£/head)	£3[9]
Total livestock social benefits (£/head)	**£139**
Waste and other carbon emissions avoided (£/plant)	£207
Waste and other removal of airborne ammonia avoided (£/plant)	£556
Total waste and other social benefits (£/plant)	**£763**

Source: Vivid Economics; CCC data; CEH, 2018; Defra, 2019a

The lifetime value of greenhouse gas emissions reductions is£165 for crops and soils, £136 for livestock, and £207 for waste and other. The per hectare values of emissions reduction were calculated using the annual rates for agri-mitigation calculated by the CCC. These rates were multiplied by the price of non-traded carbon in that year to arrive at cumulative benefits from 2019-2050 for each measure. The total lifetime value of emissions avoided or sequestered was divided through by the cumulative deployment by 2050 to arrive at an average per hectare estimate. An average of the three categories (soils and crops, livestock, and waste and other) was obtained by weighting each measure by its corresponding share of total deployment among all the measures for that category.

The lifetime value of ammonia emissions avoided are £208 for crops and soils, £3 for livestock, and £556 for waste and other. The value of ammonia removal from air by AP&T were estimated using tNH3/ha or per head removed for every applicable option. These were multiplied by the annual cumulative deployment to provide an estimate of the yearly pollution removed relative to a baseline where AP&T are not deployed. Accordingly, tonnes of ammonia removed increased linearly with the annual increase in deployment. The lifetime cumulative ammonia was then divided by the cumulative deployment of each option to arrive at a per hectare estimate. Lifetime tonnes of ammonia avoided were monetised using DEFRA's Air Quality Damage Cost Guidance, which provides a national average of the health damages avoided from every tonne, equal to £6,046 (DEFRA, 2019a). Finally, a weighted average is created for each AP&T category.

[9]Note: The £/head benefits of NH3 reductions from livestock reductions could not be calculated due to insufficient data on costs and annual reduction rates.

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