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Application of the Natural Capital Protocol at Glensaugh Farm

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Please send us your comments and suggestions through the following link: (https://www.hutton.ac.uk/research/projects/GlensaughProtocolComments)

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Supplementary material contents

Main abbreviations

CICES	Common International Classification of Ecosystem Services
C / CO_2	Carbon / Carbon dioxide
CES	Crown Estate Scotland
CFT	Cool Farm Tool
ECN	Environmental Change Network
ES	Ecosystem services
ESC	Ecological Site Classification
GHG	Greenhouse gas
ha	hectare
JHI	The James Hutton Institute
kW / kWh	Kilowatt / kilowatt hour
NC	Natural capital
SEEA	System of Environmental and Economic Accounting
SEPA	Scottish Environment Protection Agency
t	ton (for metric ton)
UK	United Kingdom
WCC	Woodland Carbon Code

Executive summary

Aims and approach

1.01 The overall aim of this project is to evaluate the impacts and dependencies of past, actual, and potential changes in Glensaugh farm management strategies through a natural capital lens. More specifically this project analyses the potential and value of applying the Natural Capital Protocol (hereafter "the Protocol") to land-based business. In doing so, it explores how the Protocol can be applied and used to support and evaluate land-based business decision making in Scottish upland farms.

1.02 The application of the Protocol builds upon the Natural Capital Protocol and its sectoral guides for Forest products, Apparel and Food and Beverage developed by the Natural Capital Coalition, and the practical guide for land managers and advisers developed by the trial application of the Protocol to Crown Estates Scotland (CES). This project tests the application of the Protocol in a case study where long-term environmental and economic data sets are available. Our application goes further than the CES Protocol trials by developing a detailed assessment of time series data to estimate a set of quantitative and monetary indicators of changes in the dependencies and impacts of land-based business on natural capital.

1.03 The Protocol is applied to Glensaugh, one of the three Research farms belonging to the James Hutton Institute, which has a long legacy of research and data collection. The farm is located in the Grampian foothills of Aberdeenshire, covering close to thousand hectares. The primary land-based business at Glensaugh is commercial livestock (beef-cattle, sheep, and deer) farming, which is supported by an extensive grazing resource. Glensaugh is considered representative of Scottish upland sheep and beef-cattle farms.

1.04 The application of the Protocol uses data gathered at the farm level over the last 20 years. Those include data collected by the Environmental Change Network (ECN), farm accounts and reports that allow tracing back a group of site-specific indicators on land management and environmental performance. The analysis is complemented with a literature review and consultations with stakeholders and experts.

1.05 The natural capital assessment includes a retrospective analysis of management decisions on the farm covering the period 2002-2018. Over this period, Glensaugh has experienced changes in its land use and management, involving a shift in objectives from maximizing agricultural production to agriculture with increased environmental benefits. These changes include (in line with the industry trend) a reduction in livestock numbers and the use inputs, such as chemical fertilisers, but also a diversification of farm enterprises through investment in woodland expansion, renewable energy sources (mainly wind and solar energy), and rural tourism activities.

1.06 In addition, our assessment includes a prospective analysis of natural capital investment decisions aimed at enabling a transition to climate positive farming in Glensaugh. More specifically, this report applies the Protocol to measure and value natural capital impacts of woodland expansion investment in Glensaugh. Our analysis considers alternative native and non-native trees species, and analyzes their economic and environmental performance, while assessing the main trade-offs of carbon sequestration, timber, biodiversity conservation, and other ecosystem services.

Summary of results and key findings

Main natural capital dependencies: Traditional and diversified farm enterprises are dependent on natural capital and the range of ecosystem services that flow from them:

2.01 Livestock farming mainly depends on biomass from cultivated terrestrial plants in the form of swards and own-produced conserved winter feed (haylage and silage), which today cover about 89 percent of the farm's total livestock metabolic energy requirements. The hill sheep flock basically depends on extensive grazing resources, while between 30 to 50 percent of the low-ground sheep flock, beef-cattle, and deer energy requirements are covered by haylage and silage.

2.02 The farm's livestock, crop and forestry enterprises all depend on regulating services. In particular, the regulation of soil quality through decomposition and fixing processes that affect soil nutrient availability and biota, local climate regulation through the provision of shelter and shade by trees and woodlands to cattle, sheep and deer, pest and disease control to maintain cultivated plants and livestock production, and the maintenance of wild species and habitats that (as well as their biodiversity value) provide recreational opportunities for tourism, fishing and game shooting.

2.03 The land-based businesses of Glensaugh also depend on ecosystems that provide the basis for scientific research and for ecological knowledge and understanding to be built up over many generations, contributing to knowledge advancement, upland management culture and heritage.

Changes in natural capital state and condition: Table S1 shows a summary of main natural capital of Glensaugh farm, and trends in natural capital extent and condition over the period 2002-2018.

2.04 The most significant change in the extent of natural capital in Glensaugh is woodland expansion, which has reduced the area of both improved grasslands and semi-natural plant communities (i.e. acid grassland and dwarf shrub heath). More than 50 ha (accounting for 5.1 percent of the farm area) of new woodlands have been planted in the farm since 2002, using mainly a mix of native woodlands, with Scots pine as dominant species, and Larch, Ash, Hazel, Aspen, Holly and Juniper, as part of the species mix.

2.05 While most of the ecosystem assets have a moderate to good status, changes in crop and livestock management strategies and woodland expansion have improved the condition of overall natural capital in terms of their capacity to deliver ecosystem services.

2.06 There is evidence of a slight improvement in the water quality, substantiated by a reduction in the concentration of nitrates and phosphates in water and soils. There is also a traceable improvement in 'climate change regulation service', with net greenhouse gas emissions (GHG) having experienced a reduction greater than 20 percent since 2008. This reduction is mainly due to a decrease in livestock numbers, a decrease in fertiliser-induced emissions, and a partial substitution of fossil fuels and grid power by on-farm production of renewable energy.

Table S1 Glensaugh natural capital status and trends 2002-2018

Ecosystem asset (broad habitat)	Trends (2002-2018)		Current status
	Extent	Condition	
Enclosed farm: Temporary pasture (45.0 ha)	↘	→ ↗	Moderate
Enclosed farm: Permanent pasture (67.4 ha)	↗	→ ↗	Moderate
Agroforestry plot (10.2 ha)	→	→	Good
Seminatural grassland and dwarf shrub heath (640.2 ha)	↘	↗	Good
Blanket bog (grass and heather dominated) (131.7 ha)	→	↗	Good
Woodland (66.0 ha)			Good
Coniferous woodland (20.6 ha)	↗	↗	Good
Broadleaf woodland (11.6 ha)	↗	↗	Good
Mixed and other woodland areas (33.8 ha)	↗	↗	Good
Freshwaters (7.3 ha)	→	↗	Good

Where the following arrows indicate: "↗" improving/growing, "→" stable ; "↘" decreasing/shrinking. The Status colours indicate: Good; Moderate; Poor , which is defined according to the relative composite wildness index, ecological water conditions, and literature review (see sub-section 2.3.1).

Natural capital impacts: Table S2 summarizes the estimated impacts on natural capital of the main land use and management decisions in Glensaugh since 2002. Those impacts are framed in terms of the ecosystem services delivery.

2.07 Ecosystems assets (broad habitats) simultaneously generate multiple services, although it is generally not possible to manage those habitats to simultaneously maximize all services, and as a result, trade-offs can occur. In Glensaugh the consequence of woodland expansion on the maintenance of wild species associated with semi-natural plant communities where those plantations took place, and the protection of soil carbon stocks need to be carefully addressed.

2.08 The evidence of changes in biodiversity is inconclusive at the farm scale. Glensaugh is one of the terrestrial monitoring sites of the ECN which includes biodiversity surveys of the presence and abundance of butterflies, carabids, spittle bugs, bats, birds, and frogs. ECN data show variations in biodiversity over time, but no clear trends either in the number of individuals of specific invertebrate or vertebrate species counted or in the number of species identified.

2.09 The effect of woodland expansion on wild species diversity needs some further examination, as it would depend on the type of woodland planted and their management. The literature suggests that commercial tree plantations (i.e., oriented to timber production) established on semi-natural plant communities will affect the diversity of wild species associated with these habitats. But there are biodiversity trade-offs. For example, woodland expansion if properly done can provide new habitat and enhance habitat connectivity for species such as woodland birds. Existing woodlands in Glensaugh involve mainly native species that form relatively continuous and connected forest strips, which in principle is expected to enhance biodiversity conservation, while increasing timber and biomass production in the future. Currently three-quarter parts of woodlands in Glensaugh comprise trees with an age lower 10 years.

Table S2 Estimated changes in delivery of ecosystem services due to changes in land use and management

	Provisioning				Regulating & mantainance										Cultural			
	Cultivated plants & reared	Wild plants and animals (biomass)	Water supply (quantity)	Energy supply	Biological pest and disease	Global climate regulation	Local climate regulation	Control of erosion rates	Habitats and wild species	Pollination	Freshwater quality	Regulation of soil quality	Water flow /flood control	Wate water treatment	Aesthetic	Cultural and heritage	Knowledge systems Social	Recreation and ecotourism
Woodland expansion																		
Commercial plantation (timber)	↗ Moderate	↘ Low	→	↗ Moderate	↘ Low	↗ Moderate	↗ Moderate	↗ Low	↘ Moderate	↘ Moderate	↗ Moderate	↗ Moderate	↗ Moderate	↗ Moderate	→	↘ Low	Un-known	↗ Low
Seminatural woodland (amenity/conservation)	↗ Moderate	→	→	↗ Moderate	→	↗ Moderate	↗ Moderate	↗ Low	↗ Low	↘ Low	↗ Moderate	↗ Moderate	↗ Moderate	↗ Moderate	↗ Low	↗ Low	↗ Low	↗ Low
Agroforestry	↗ Moderate	→	→	↗ Moderate	→	↗ Moderate	↗ High	↗ Low	↗ Low	→	↗ Low	↗ Moderate	↗ Low	↗ Moderate	↘ Low		↗ Moderate	↗ Low
Grazing management																		
Rotational heather burning	↗ Moderate	→	→		Un-known	→		↘ Low	↘ Low	Un-known	↘ Moderate	↘ Low			↘ Moderate	↗ Moderate		↘ Low
Reduction in fertilizers & increased liming	↗ Moderate	↗ Moderate	→		Un-known	↘ Low		→		→	↗ Low	↗ Low	→		→		↗ Low	→
Livestock management																		
Reduction on livestock numbers	↘ Low	↗ Low			↗ Low	↗ Moderate		↗ Moderate	↗ Low		↗ Moderate	↗ Low						
Production of winter feed	↗ High	↘ Moderate	↘ Low	↘ Moderate	↘ Moderate	↘ Low		↘ Low	↘ Low		↗ Moderate	↘ Moderate		↘ Moderate	↘ Low		↗ Moderate	
Renewable energy production (solar, wind)				↗ High		↗ Moderate			→						↘ Low		↗ Moderate	↘ Low
New recreational services			↘ Low	↘ Low							↘ Low			↘ Low		↗ Moderate	↗ Moderate	↗ High

(Note: For more details see sub-sections 2.4.2 and A.2.3 at the Supplementary material)

Potential changes in ES delivery

		Not relevant	(blank)	Un-known	(grey)	Stable/neutral →
Improvement	High ↗	Moderate ↗		Low ↗		
Decline	Low ↘	Moderate ↘		High ↘		

2.10 Woodland expansion has improved the GHG emissions balance in Glensaugh over the last decade. The existing and newly planted woodlands were estimated to remove about 128 metric tonnes (t) of carbon dioxide (CO_2) from the atmosphere by 2018. This figure is expected to rise in the future considering that the early-years carbon sequestration balance includes initial soil carbon release due to assumed ground preparation practices (included in the models used).

2.11 GHG emissions from land-based business are still relatively large in Glensaugh, mainly due to livestock enteric fermentation and feed related GHG emissions, but also due to the consumption of fossil fuels, biomass burning and grid power consumption. There is some uncertainty regarding livestock farming GHG emissions in Glensaugh, as the two carbon auditing tools tested provide different results.

2.12 Changes in the management of crop, grassland, and livestock enterprises towards a reduction in inputs, and an increased dependency on grazing resources, has been translated into cost saving and increased efficiency. For instance, the ratio between net profits and GHG emissions by standard livestock unit has increased for all livestock enterprises (i.e., low-ground sheep, hill sheep, beef-cattle, and deer) in Glensaugh over the last 3 years, which suggests a combined increase in environmental and economic efficiency. Likewise, current grassland management fertilization costs represent (in real terms) less than a half of the costs recorded in 2006.

2.13 The adoption of new enterprises, mainly the production and use of renewable energy, has created new income and cost saving opportunities, while contributing to climate change mitigation through, amongst other things, the use of wind, solar and biomass renewable energy sources to contribute towards the farm heating and electricity demands.

Potential natural capital impacts due to woodland expansion

2.14 Further woodland expansion is planned on the farm involving up to 113 hectares in the short-term. Those woodland expansion plans have potential for increasing carbon dioxide sequestration by 700 to 1,500 t CO_2 per year over the next 20 years, depending on the species planted, and the point in time that planting takes place.

2.15 Special attention needs to be given to tree species and site selection, as well as to the temporal nature of the potential CO_2 sequestration due to the initial carbon release associated with soil disturbance, which in turn depends on ground preparation method and soil type.

2.17 Woodland expansion can create further opportunities for GHG emissions off-setting. There is a trade-off between carbon sequestration and potential biodiversity gains when non-native commercial species are planted instead of native woodlands. There is also an economic trade-off between commercial species and native woodland, as the minimum carbon payments required to make native woodland expansion profitable can be at least double the payments required when non-native fast-growing species are involved.

2.17 Woodland expansion seems also a more cost-effective alternative to improve the farm GHG balance than reducing livestock numbers, when the livestock revenues forgone are accounted for.

Risk and opportunities

3.01 Key natural capital related risks to the farm include:

- Climate change leading to an increased frequency of poor summers (higher rainfall and low soil temperature) which might reduce quality/quantity of harvested crops for winter-feed - that would compromise the livestock systems that depend on winter-feed (e.g., low-ground sheep flock and beef-cattle).
- Climate change leading to increased frequency of extreme weather events such as storms and droughts that can affect Glensaugh farm productivity and costs, through both damaging produced assets (e.g., infrastructure, livestock) and natural capital (woodlands, soils, wild species, water courses).
- Nutrients and pesticides leaching to watercourses from fertilizer and pesticide applications, with a potential soil enrichment downstream and proliferation of bracken (*Pteridium aquilinum*), affecting semi-natural plant communities and habitats.
- Loss of wild species diversity and soil biota due to increasing area of commercial non-native woodland plantations, bracken proliferation, and rotational heather burning.

3.02 Other key risk that are not necessarily connected to natural capital, but can have large effects on farm production decisions and farm resource use, include:

- Fluctuations in livestock and production input market prices.
- Uncertain effects of COVID-19 and Brexit on farming systems, agricultural policies, and upstream and downstream distribution chains.

3.03 Key natural capital related opportunities for Glensaugh include:

- Private funding for investment in GHG emissions mitigation, and other sustainable practices and technologies involving natural capital, aligned with the green recovery and climate change emergency policies.
- A shift in agricultural support towards payments for public goods with additional opportunities for public and private sector funding for farm-based environmental goods and services,
- Further diversification of farm activities with special attention to education/research and demonstration activities encompassing a transition to low carbon farming, recreational services, and renewable energies.
- Developing and demonstrating the value of a set of metrics to monitor the state and condition of natural capital over time.

Main recommendations to Glensaugh and other practitioners

4.01 In the particular case of Glensaugh, this work has demonstrated that natural capital assessment can be used to inform decision-making pertaining to land use and management strategies. For example, the results of the assessment suggest that diversified livestock enterprises can help to balance environmental and economic outcomes and farm financial resilience, while helping the farm enterprise respond better to climatic and price fluctuations. The substitution, for example, of beef-cattle and low-ground sheep enterprises by hill sheep can help GHG emissions reduction towards the transition to low carbon farming, but could have a negative impact on farm revenues, due to reduced livestock diversity and associated resilience to fluctuation of market prices.

4.02 Woodland expansion can create further opportunities for GHG emissions off-setting. More research is needed, however, to inform better site and species selection, by integrating other relevant variables such as access to roads and forest tracks, slope, sunlight and shade exposure, and economies of scale in forest management.

The potential effect of low soil-disturbing ground preparation techniques (e.g. manual turfing) on soil carbon release, and management costs, need to be studied in more detail.

4.03 In more general terms, the application of the Natural Capital Protocol proved to be useful as framework to guide a systematic assessment of natural capital impact and dependencies of Glensaugh farm. However, the application is data demanding (e.g. mapping resources, farm records, modelling), with the reliability and quality of the natural capital assessment being dependent on the availability and quality of information. Other land-based businesses applying natural capital assessment approaches need to evaluate the implications that the quality of the data and the scope of the approach could have in informing their decision-making.

4.04 The proliferation of carbon auditing tools, and standards such as the Woodland Carbon Code could assist the estimation of carbon balances at the whole farm or the land-based activity level. This could inadvertently put the emphasis of the natural capital assessment on carbon stocks and flows and their values, overlooking other important natural capital and ecosystem services impact indicators, for which quantification can be challenging due to information gaps. In this sense, it is critical to keep a larger number of natural capital impact indicators that are material to the farm business, or to wider society, even in qualitative terms, as a way to better balance multiple environmental goals beyond GHG reduction for climate change regulation (e.g. biodiversity conservation, enhancing water quality, reducing flood impacts, etc.).

Actions for consideration

5.01 Improving internal data and reporting:

- Development of natural capital accounts for the farm and integration into the Institute and farm reporting.
- Identification of priority direct or indirect indicators (set of metrics) to track changes in natural capital condition and impacts, such as soil organic matter and nutrients, soil pH, biodiversity index, GHG emissions, carbon stock and sequestration, water quality, and use of inputs (fertilisers, pesticides, fossil fuels).
- Analyse GHG emissions due to livestock farming in more detail, preferably using more sophisticated models (e.g. IPCC Tier 3 approaches), as different carbon auditing tools deliver divergent results, making the GHG livestock emissions more uncertain.

5.02 Funding and investment:

- Identify priorities and opportunities for maintaining and enhancing natural capital in Glensaugh.
- Integrate natural capital impact and dependency assessments in the feasibility analysis of potential investment projects in Glensaugh.

5.03 Working with stakeholders:

- Demonstrate the benefits of incorporating natural capital into land use decisions and research priorities.
- Raise awareness amongst stakeholders of the role of natural capital for maintaining healthy and resilient businesses, economies, and societies.

5.04 Roll-out of the Protocol: The experience gained with the application of the Protocol in Glensaugh suggests that this approach has potential to be beneficial for other farms and estates across Scotland. The Protocol could help them to evaluate and promote land use and management strategies that generate business opportunities, while also enhancing natural capital. To facilitate the Protocol roll-out we suggest:

- Assessment of the changes in the state and condition and impacts on natural capital over time. Creating a natural assets register would help in recording current extent and condition and changes over time of the natural capital base. Defining a set of key indicators (metrics) of impacts of land-based businesses on natural capital, along with the natural assets register, would help create the context for integrating natural capital into land management decisions and future public (government) payments.
- Exploring opportunities to mainstream natural capital assessment and reporting, including alternatives to tie natural capital reporting to other mandatory reporting processes (e.g. for pillar 2 payments, site conditions for Natura 2000, etc.)
- Using qualitative natural capital approaches for those impacts on natural capital and ecosystem services that are not easily measurable and monetarized, along with indicators of financial performance to inform land use and management decision-making. Accounting for wider business and societal cost and benefits can inform about the sustainability of investment alternatives.

1 Introduction

1.1 Background and motivation

Nature as capital or *natural capital* is a concept that is gaining traction in governmental and corporation's discourses (Helm, 2019; Schaefer et al., 2015). Though this term is widely used, natural capital can have different meanings depending on the perspective of the user or the use of the term (see Farrell and Stout, 2019:45-48). The two underpinning concepts of this term are nature (everything that occurs naturally, or it is not made by humans) and capital (stocks or assets), and both terms can have different connotation in academia, business, ecology or economics (*ibid,* p.46). From a more biophysical perspective natural capital can be referred to as "*the stocks of natural assets, which include geology, soil, air, water and all living things"* (SFNC, 2018). From a more economic perspective this concept has been introduced as an approach to economically value the contribution of nature to the provision of ecosystem services as key factors of human-wellbeing (Costanza and Daly, 1992; Turner and Daily, 2008). When both perspectives are combined, natural capital can be defined as "another term for the stock of renewable and non- renewable natural resources on earth (e.g., plants, animals, air, water, soils, minerals) that combine to yield a flow of benefits to people" (Natural Capital Coalition, 2016a: 2). Natural capital delivers a flow of *services*, frequently called Ecosystem Services (ES), which are considered as the benefits people obtain from ecosystems[1] (MEA, 2005).

A shift in interest from the flow of ecosystem services to natural capital stocks has become noticeable over the last few years in both scientific and policy discourses. Today, it is widely accepted that natural capital with enhanced resilience increases the ability to adapt in the face of change, and to provide ecosystem services in beneficial ways (Scheffer et al., 2015). Focusing only on ES provision seems insufficient and may not necessarily lead to more resilient and adapted environmental management options (for example if stocks are being depleted). Current provision of ecosystem services can be increased temporarily by depleting natural capital, such as by harvesting more fish or timber at the expense of depleting natural fish and timber stocks, when harvesting rates are wide higher than growth rates. This situation can also affect the provision of public goods, since focussing exclusively on the flow of services (e.g., water provision, climate regulation) can also be done at expense of the extent and condition (i.e. the ability of natural capital assets to maintain flows of services[2]) of the natural stocks that deliver those services. For example, enhancing the flow of climate regulation services through carbon sequestration can promote the use of non-native fast growing tree species, which can have a negative effect on biodiversity, but also on water resources (e.g., Nosetto et al., 2005; Chisholm, 2010). In contrast, enhancing the long term conservation of carbon stocks in tree biomass can favour native slow growing species which will retain carbon for longer periods of time, while enhancing the conservation of habitats and wild populations (Caparrós et al., 2010).

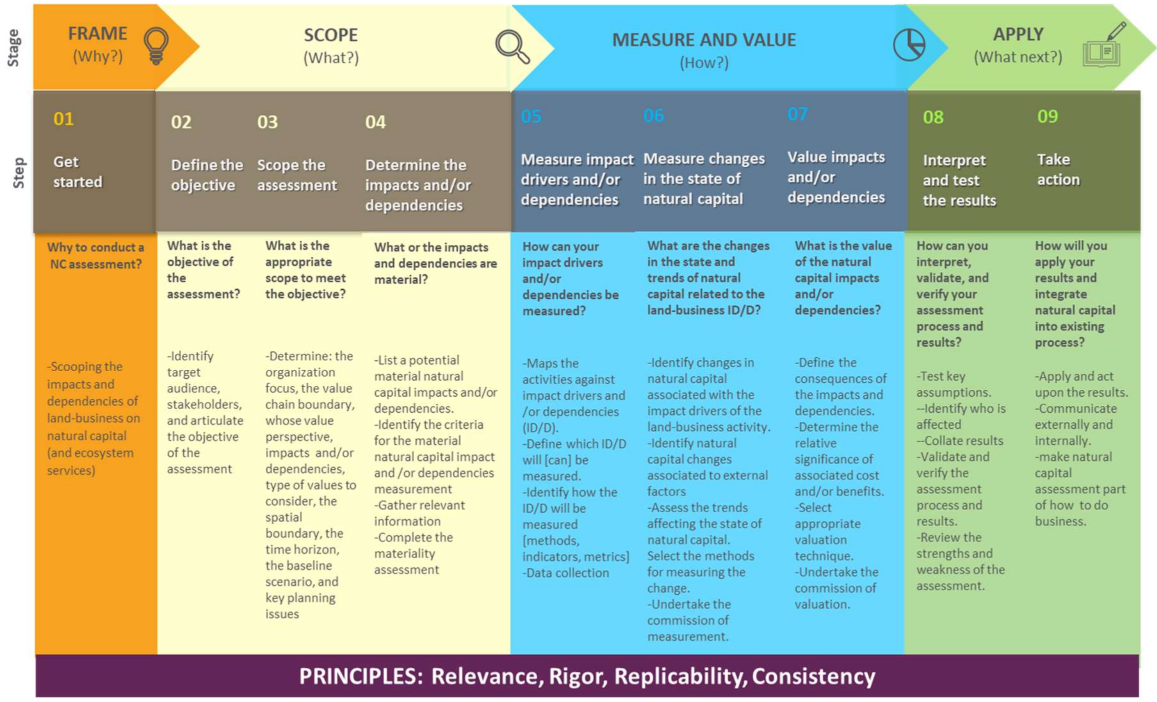
Consequently, natural capital assessment and accounting approaches are important additional tools for informing sustainable development (Guerry et al., 2015). Natural capital approaches involve understanding, measuring and assigning values to the contribution of natural capital to economic activity and ultimately to human well-being, and therefore represent a way of integrating nature into decision-making (Bolt et al., 2016). Both private and public sectors have been exploring how natural capital assessment may offer new approaches to decision-making focussed on more sustainable outcomes in both socio-economic and environmental terms. Today we can find two distinct branches of natural capital assessment frameworks, one related to business, and the other to national accounting. The branch of national accounting has yielded an internationally adopted framework, the System of Environmental and Economic Accounting (SEEA)(UNSD, 2014), while the business branch has led to different natural assessment and accounting frameworks, for example the Natural Capital Protocol (hereinafter "The Protocol").

The Protocol offers a standardised framework that describes a process for assisting companies to understand their links to natural capital and assess the magnitude of their dependencies and impacts on nature (Fig. 1). This framework brings together and builds on a number of existing approaches (tools, methods and conceptual

[1] Ecosystems when viewed as natural capital comprise a stock of potential ecosystem services (Barbier, 2011) that contribute to diverse human activities and life systems, and ultimately to human well-being (MEA, 2005; TEEB, 2010).

[2] The condition of natural capital can be defined by its ability to maintain flows of services, but also in terms of the quality or the underlying condition of natural capital (Natural Capital Committee, 2019)

frameworks) to help businesses integrate natural capital thinking into their business strategies and management (Natural Capital Coalition, 2016a; 2016b; 2016c; 2018). For land-based businesses, the direct dependency on natural capital, such as land, water, soil and ecosystems, and the services that flow from them is more evident. The impacts of agricultural systems on natural capital can be diverse, and operate at different spatial scales from local, to drainage systems, the catchment or even to regional or global levels for certain outcomes such as greenhouse gas (GHG) emissions. The Protocol proposes a series of steps and overarching questions that guide the identification, and when feasible, measurement and valuation of impacts, and finally the dependencies on natural capital.



Source: Adapted from the Natural Capital Protocol Guide (Natural Capital Coalition, 2016b)

Fig. 1 The Natural Capital Protocol Framework, Stages and Steps

A number of leading businesses have completed case studies, demonstrating the applicability of the Protocol to assess impacts and dependencies of the overall corporate activities or a specific project or product on natural capital. Materials, food, and clothing industries have contributed to the higher number of case studies of natural capital assessment in the private sector, with 84% of case studies on companies headquartered in either the USA or Europe (Pritchard and Horst, 2018). The Crown Estate Scotland (CES) partnered with the Scottish Forum on Natural Capital, the Scottish Environment Protection Agency (SEPA), Scottish Natural Heritage (SNH), the James Hutton Institute (JHI) and Scotland's Rural College (SRUC) to deliver the world's first trial of the Natural Capital Protocol for land-based businesses (Silcock et al., 2018). The trial included 2 tenant farms (Den and Ruthven) used for livestock farming and growing crops, and the Glenlivet Estate in Moray with a rich diversity of land-based business including forestry, recreational services, livestock farming, whisky distilling. Most recently the Protocol has been applied to a dairy farm also belonging to Crown Estates Scotland (Silcock and Russ, 2019). All the trials were applied to the farm and Estate boundaries covering changes in natural capital state and condition over the period 2007-2017 in the first three cases and from 2009-2019 in the dairy farm case study. Today there are a number of ongoing applications of the Protocol to different farming land-based businesses in Scotland, including the application presented in this report on Glensaugh farm[3].

[3] See: https://naturalcapitalscotland.com/article/testing-natural-capital-approaches-in-scottish-land-based-businesses/

Glensaugh is one of the three Research farms belonging to The James Hutton Institute, which has a long legacy of research and data collection. The application of the Protocol at Glensaugh evaluates the impacts and dependencies of past, actual, and potential changes in the farm management strategies through a natural capital lens. This project explores how the Protocol can be applied and used to support and evaluate land-based business decision-making in Scottish upland farms, including risks and opportunities associated with natural capital. Furthermore, this project tests the application of the Protocol in a case study where long-term environmental and economic data sets are available. In that way, this application goes further than the CES Protocol trials mentioned above, by developing a detailed assessment of time series data to estimate a set of quantitative and monetary indicators of changes in the dependencies and impacts of this land-based business on natural capital.

This document describes the methodological approaches, assessment criteria, outcomes obtained, and lessons learned from a comprehensive application of the Protocol to Glensaugh farm. This natural capital assessment includes a retrospective analysis of management decisions on the farm covering the period 2002-2018 (see Section 2). Over this period, Glensaugh has experienced changes in its land use and management, involving a shift in objectives from maximizing agricultural production to agriculture with increased environmental benefits (Dick et al., 2016). These changes include (in line with the industry trend) a reduction in livestock numbers and the use of inputs such as chemical fertilisers, but also a diversification of farm enterprises through investment in woodland expansion, renewable energy sources (mainly wind and solar energy), and rural tourism activities.

In addition, the natural capital assessment includes a prospective analysis of natural capital investment decisions aimed at enabling a transition to low carbon farming in the future, through woodland expansion in Glensaugh (see Section 3). Woodland expansion plans for Glensaugh respond to potential public and/or private funding opportunities for developing post-Brexit low-carbon farming initiatives that are expected to reward farmers who successfully reduce, save, store, and sequester carbon. This project also responds to the recognition of the role of woodland expansion in achieving the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019 and Scotland's Biodiversity Aichi targets for conserving biodiversity (Hollingsworth et al., 2020).

Both, the retrospective analysis of changes in dependencies and impacts of farm enterprises on natural capital, and the prospective woodland expansion natural capital assessment aim to inform the ongoing JHI initiative to transform Glensaugh into a climate positive farm. The latter initiative is part of the institutional response to the both the recently declared climate emergency and global biodiversity crisis (IPCC, 2020; IPBES, 2019).

The Protocol stages and steps formed the basis for the Glensaugh's natural capital assessment report (Fig.1). Sections 2 and 3 of this report are structured according to the Protocol stages and step, while next sub-sections 1.2 and 1.3 present the main characteristics of the Glensaugh case study and the methodological approach used, respectively. Section 4 concludes by discussing main findings and lessons learned from the Protocol application to Glensaugh farm.

1.2 Glensaugh case study

Glensaugh Research farm is located in the Grampian foothills in Aberdeenshire (Fig. 2.a), lying within an altitudinal range of 120 and 450 metres above sea level, with an average annual rainfall of 1,209 mm (±286mm). Glensaugh climate is relatively mild, with average temperature of 7.4^{o}C, and minimum and maximum temperatures of -0.16^{o}C and 17.1^{o} C, respectively[4]. This farm covers around one thousand hectares, mostly (almost 65 percent) dominated by semi-natural plant communities (grassland/moorland/heather), with 132 ha of heather moorland and heather/grass-dominated bogs, 45 ha of predominantly rotational grassland, 67 ha of permanent pastures, 10 ha covered by agroforestry plots and 66 ha of woodlands (Table 1). There are no Sites of Special Scientific Interest (SSSI) or other Designated sites on the farm. There is, however, a historical farmstead site (NO678795).

The farmland is varied in terms of its capability for agricultural production, with around 9% Land Capability for Agriculture (LCA) class 3.2 (capable of average production through yield of barley, oats and grass), 14% of LCAs

[4] Own estimation based on meteorological data of the Ecological Change Network (from January 2000 to December 2016) (available in http://www.ecn.ac.uk/)

4.1 and 4.2 (capable of producing a narrow range of crops primarily grassland with short arable breaks for forage crops), 35% LCAs 5.2 and 5.3 (capable of use as improved grassland), and the remaining 22% of LCAs 6.1 and 6.2 (capable of use as rough grazing with moderate quality of plants) (Figure Table and Figure A.5). According to the Land Capability for Forestry map (Table and Figure A.6), about 14% of Glensaugh has a moderate capacity for trees, and 43% a limited capacity for trees. The native woodland potential model (Towers et al., (2004) suggests a higher potential to grow trees, with 71% of Glensaugh land having the potential to grow native woodland, mainly upland Oak-Birch communities (37%), but also mixed and pure Scots pine woodlands (29%) (Table and Figure A.7).

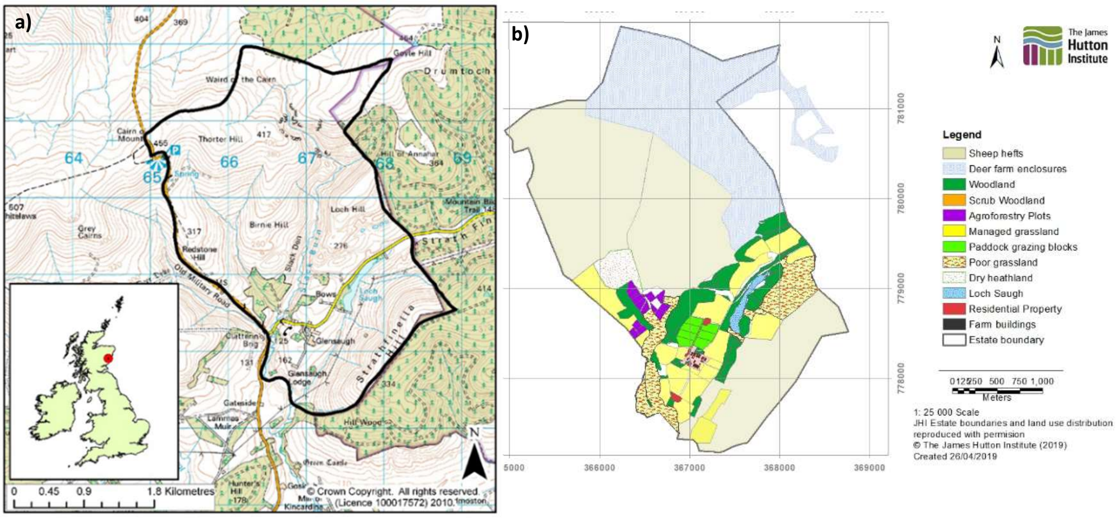


Fig. 2 Glensaugh (a) farm location and (b) land use distribution

Table 1 Land cover (broad habitats and constructed areas) in Glensaugh (year 2018)

Class	Area (hectares)	Percentage (%)
Enclosed farm	112.4	11.5
Improved grassland (permanent)	67.4	6.9
Improved grassland (temporary/rotational)	45.0	4.6
Semi-natural plant communities	771.9	79.3
Blanket bog (heather and grass dominated) (1)	131.7	13.5
Seminatural (un-improved) grassland and dwarf shrub heath (2)	640.2	65.8
Agroforestry plots(3)	10.2	1.0
Woodland	66.0	6.8
Conifers	20.6	2.1
Broadleaves	11.6	1.3
Mixed conifers/broadleaves	32.8	3.0
Other woodland areas	1.1	0.4
Freshwaters(1)	7.3	0.7
Loch Saugh	5.9	0.6
Other inland waters	1.4	0.1
Constructed areas	6.0	0.6
Roads and tracks	0.8	0.1
Residential areas	1.8	0.2
Farm buildings and other infrastructure	3.4	0.3
Total farm	**973.7**	**100**

Notes: (1) Bog and freshwater data as reported by the LCM (2007). No changes are assumed between 2007 and 2018; (2) Estimated data as a residual value after the different land cover areas are subtracted from the total farm area. This later area comprise mainly acid and dwarf shrub heath (dry heath) plant communities; (3) Trees planted in an area of improved grassland.
Source: *Own elaboration* using Glensaugh records and maps on land use data, and Morton et al. (2011).

The Highland Boundary Fault divides Glensaugh into two distinct geological zones. North of the fault the soils are of the Strichen Association developed on drifts derived from schistose rock: the brown forest soils and podzols of the lower slopes give way to peaty podzols and, on the highest ground, to peat. To the south of the fault the soils are developed on drifts derived from Old Red Sandstone: humus-iron podzols dominate the lower slopes and peaty podzols occur at higher elevations (Stutter et al., 2012). The two main water curses in Glensaugh are Cairn Burn and Birnie Burn, both affluent of the Devilly burn which is a river, in the River North Esk catchment of the Scotland river basin district. Part of Glensaugh lies inside a Nitrate Vulnerable Zone Strathmore and Fife (including Finavon). Likewise, part of Glensaugh (the west slope of Strathfinella Hill lies inside the Laurencekirk Potentially Vulnerable Area 07/01, whereas the main flooding sources in the Luther Water. See section A.1 at the Supplementary appendix for more details on Glensaugh soil and geology, land cover, and ecological characteristics.

Glensaugh is a typical upland livestock farming system with beef-cattle, sheep, and deer. The farm operates two distinctive livestock farming systems: (i) suckler cow herd, low ground sheep flock, and deer calves, which are systems that rely on conserved winter feed, and (ii) hill sheep flock and deer breeding stocks that rely on extensive grazing through the year. The overall system is based on the management of semi-natural grassland, rotational grassland, moorland, and permanent pastures that provide swards, haylage and silage to support livestock production. This management system also includes small scale rotational heather burning to maintain younger, more nutritious heather as part of the extensive grazing system. The predominantly rotational grassland is reseeded with perennial ryegrass and white clover mixtures every 7-10 years. This provides grazing for the crossbred ewe low-ground flock, swards for experimental work, silage for winter feeding and aftermath grazing for finishing lambs. Glensaugh carries about 420 Scottish Blackface (pure breed) and a similar number of crossbred ewes (mated with Texel and hybrid rams). In addition, the farm carries 50 Blue-Grey suckler cows (mated with Charolais and Limousine bulls), and 80 red deer breeding hinds. There is housing for 80 cows and calves, 500 ewes and 100 red deer calves, as set out in Table 2.

Table 2 Summary of land-based farm business and their characteristics in Glensaugh

<table>
<tr><th>Enterprise</th><th>Description</th></tr>
<tr><td>Beef-cattle</td><td>Blue-grey 50 suckler cows, grazing in the lowlands, and housed in winter, with a high dependency on own produced haylage and silage.</td></tr>
<tr><td>Sheep</td><td>420 Blackface ewes and gimmers, grazing in hill sheep heft (467 ha), with supplementary feed offered at times of severe stress; 430 cross breed sheep, grazing low ground areas, and dependant on haylage and silage for winter feeding. Replacement and finishing stock are silage and haylage fed in low-ground areas. There is housing for 500 ewes.</td></tr>
<tr><td>Deer</td><td>80 red deer hinds grazing in a deer farm fenced area close to 231 ha, mainly covering semi-natural grasslands, heather moorland, and blanket-bog. About 100 deer calves are temporarily housed and silage and haylage fed.</td></tr>
<tr><td>Winter feed (silage and haylage)</td><td rowspan="2">Temporary and permanent improved grasslands (112 ha) that are in part harvested to produce conserved winter feed in the form of silage and haylage. Those grasslands are also foraged by beef-cattle and low-ground sheep flocks during the summer. The ground is not ploughed, or ploughing is infrequent (e.g., for growing annual forage crops).</td></tr>
<tr><td>Grassland management</td></tr>
<tr><td>Agroforestry</td><td>Experimental parcels covering 10 ha planted with Scots pine, sycamore, and hybrid larch in 1988, used for sheep and beef-cattle grazing, and biomass provision for heating</td></tr>
<tr><td>Forestry</td><td>66 hectares of conifer, broadleaf and mixed forest, 50 ha of which have been planted in the last 10 years.</td></tr>
<tr><td>Renewable energy production</td><td>50 kW wind turbine commissioned in 2010, to provide electricity to the farm and the grid. 70 kW biomass boiler commissioned in 2011 (burns wood logs to heat Glensaugh Lodge and adjoining buildings in a mini district heating scheme), and 50kW solar panel array installed in 2014.</td></tr>
<tr><td>Recreation (fishing/shooting)</td><td>Fishing of brown trout in loch Saugh by a local angling association (who rent the fishing rights). Small-game shooting (grouse, partridge, pheasant, duck, and woodcock) by a hunter that rents the shooting rights. Occasionally wild red deer Stag are shot, to avoid breeding with the farm red deer herd.</td></tr>
<tr><td>Recreation (hostel, amenity)</td><td>One holiday cottage with a 50% occupancy rate over the year</td></tr>
<tr><td>Research/training/ demonstration</td><td>Visits of group of students from SRUC and University of Aberdeen and St. Andrews, 3 to 4 times a year, and about 2 demonstration activities a year</td></tr>
</table>

Forestry is an expanding activity in Glensaugh with about 50 ha of new woodlands being planted over the last 10 years (Figure A.2). Agroforestry plots were planted in Glensaugh in 1988, using Scots pine, hybrid larch and sycamore. Those plots are a source of biomass, and are also grazed by ewes between April and November, with lambs at foot in spring and early summer. A 50kW turbine as renewable energy production was commissioned in 2010 to meet part of Glensaugh' s electricity requirement. A 70kW biomass boiler was commissioned in 2011, displacing liquid petroleum gas (LPG) as a source of heating fuel, and a 50kW solar panel array was installed in 2014. Activities carried out by third parties on the farm include sporting (small game shooting, and fishing carried out by sporting tenants/licensees). Residential accommodation is available for recreational visitors, or researchers who are engaged in longer term research projects.

The farm is available as a platform for the JHI staff to conduct outdoor experiments from plot to field right up to landscape scale. As a research farm, it has an exceptional baseline of biophysical and economic data and monitoring stations. Glensaugh is one of the national terrestrial and freshwater monitoring sites of the UK Environmental Change Network (ECN), with a freshwater sampling point in Birnie Burn. The ECN involves routine monitoring for a number of indicators, such as vertebrate and invertebrate species abundance and presence, vegetation survey, meteorological data, and soil and data chemistry indicators since 1992 (Sier and Monteith, 2016). It is also a monitoring site for the Cosmic-ray soil moisture monitoring network (COSMOS-UK). In addition to previous data sets, the farm manager keeps a large and detailed set of physical and monetary records that have proven to be useful for evaluating the economic and environmental performance of livestock, crop, and renewable energy enterprises, and assessing their impacts and dependencies on natural capital

1.3 Methodological approach

Fig. 3 outlines the approach followed for the application of the Protocol to Glensaugh. The application of the Protocol follows, in general terms, the approach applied for the CES farms/Estate trial (Silcock et al., 2018). Our application goes beyond to the CES trial by developing a detailed assessment of time series data to estimate a set of quantitative and monetary indicators of changes in the dependencies and impacts of farm enterprises over time. Glensaugh's natural capital assessment was built on data collated using scientifically-sound methods over long periods of time. The dependencies and impacts of farming activities on natural capital in this farm were analysed considering available farm records, reports, scientific papers, interviews with the farm manager and other relevant stakeholders (i.e., members of the JHI senior management team and research staff using the farm for experimental and data collection purposes), along with other information layers, such as maps, data sets, statistics, regional and farm- level surveys, ECN data, as it is indicated in more detail in Sections 2 and 3 and the Supplementary material at the end of this report.

The objectives, scope, and the approach for applying the Protocol to Glensaugh have been initially defined in an inception face-to-face meeting with the farm manager at the farm site farm. The questionnaire (parts A and B) in sub-section A.4 of the supplementary material was used for this purpose. This questionnaire was sent to Glensaugh's management staff before the meeting with the farm manager. This questionnaire includes a series of open-ended questions and tables (e.g. Q11 matrix) that helped the identification of farm management priorities and main natural capital related risks and opportunities, which were useful for the definition of the natural capital assessment objectives and scope. Draft versions of the completed questionnaire have been sent to the farm manager after the interview for revision, with subsequent email exchanges until we reached a common understanding on the scope, objectives, and next steps for the Glensaugh's natural capital assessment. The agreed objectives and scope have been further discussed and validated with the JHI Director of Science and other staff coordinating farm management and research projects in Glensaugh.

In general terms, we agreed to test the Protocol to develop a retrospective analysis of changes in impacts and dependencies of traditional and diversified enterprises on natural capital, and carry out a prospective analysis of the potential natural capital impacts of further woodland expansion at Glensaugh. The main interest from a research standpoint were twofold: (i) to test the suitability of the Protocol to evaluate and inform land management decisions at the Glensaugh farm, and (ii) to analyse the Protocol potential to inform land-based business in Scotland more widely were. While the main practical interest for the Protocol application from the farm manager perspective was to inform further woodland expansion decision-making at Glensaugh. Considering data availability and quality it was agreed to consider the period 2002-2018 for the restrospective analysis.

The first inception meeting was also used to identify, in collaboration with the farm manager, the materiality of impacts and dependencies of each one of the Glensaugh's farm enterprises on natural capital and ecosystem services. The materiality here is understood as the relevance that the dependencies and impacts of farm activities on natural capital can have for the farm business and for the wider society. This relevance was assessed in qualitative terms (i.e., high, moderate, low or no relevance or unknown). The tables used to identify the materiality of impacts and dependencies of farm activities on natural capital are based on examples offered by the Natural Capital Protocol and its sectoral guides for the Food and Beverage, Apparel and Forestry sectors (Natural Capital Coalition, 2016a; 2016b; 2016c; 2018) (see section C of the questionnaire in sub-section A.4). The identification of the potential impacts on natural capital focused on resources use (land, water, energy) and outputs (e.g. emission, water pollution), while the qualitative assessment of dependency of farm enterprises on natural capital considered both the dependency of these enterprises on different ecosystems (broad habitats) and on ecosystems services. The inception meeting also helped to identify information sources and key JHI staff that could facilitated the access to this information.

Stage	Step	Tasks /Output	Approach	
			Meetings	Desk work
FRAME: Why?	1. Get started	-Introduction of the Protocol and its application land-based business -Gathered information about farm enterprises and management strategies	Inception meetings (steps 1–4)	
SCOPE: What?	2. Define the objective	Discussion/agreement of the objectives and potential benefits of the Protocol application for the farm business and beyond.		
	3. Scope the assessment	Discussion/agreement of the scope of the assessment to the farm boundaries, all farm enterprises, period 2002-2018 for the retrospective analysis		
	4. Determine the impacts and dependencies	Discussion/review of material impacts and dependencies of farm enterprises on natural capital (NC) NC asset register (extent and condition), and qualitative assessment of ecosystem services(ES) delivered by natural capital		Data collection, analysis, modelling, and validation (steps 4–9)
MEASURE AND VALUE: How?	5. Measure impact drivers and/or dependencies	Information gathering and analysis for the qualitative assessment for main NC and ES impacts and dependencies.	Consultation meetings/presentation (steps 5–8)	
	6. Measure changes in the state of natural capital	Dependency and impact pathways diagrams for main farm activities.		
	7. Value impacts and/or dependencies	Analysis of public and farm data set, maps, and models to quantify changes in NC and ES over the assessment period. Qualitative, quantitative and monetary assessment (when possible) of main impacts of woodland expansion project on NC and ES		
APPLY: What next?	8. Interpret and test the results	Identification of risk and opportunities associated with farm dependencies and impacts on natural capital Consultation process to review the NC assessment with Glensaugh farm management and research staff		
	9. Take action	Proposed action for consideration of the farm management staff		

Source: Adapted from Silcock et al. (2018).

Fig. 3 Steps and approach used for the application of the Protocol at Glensaugh farm

The Protocol application here accounted for a wide range of ecosystem services, including mainly provisioning services and regulating and maintenance services, though cultural services were also considered in qualitative terms. The classification of ecosystem services follows the categories of the Common International Classification of Ecosystem Services (CICES) version 5.1 (Haines-Young and Potschin, 2018) (see Table A.1 in the supplementary material).

The implementation of the Protocol at Glensaugh has implied an important deskwork for the collation of resources, and revision and analysis of diverse data sets, and modelling. This work included a further 3-day visit to the farm to collate farm records (e.g., old reports, livestock inventory data, land use records and maps). The deskwork also included the analysis of public data sets (e.g. maps and statistics), and, mainly, private data sets (e.g., farm accounts and detailed management records). During the implementation phase, additional meetings, and consultations (in person, by e-mail and over phone) with the farm manager and JHI research staff were necessary. Sections 2 and 3 and the supplementary material at the end of this report provide additional details on the data sets, criteria and methods involved in the identification, measurement and valuation of dependencies and impacts of current farm enterprises and the planned woodland expansion on natural capital.

Preliminary results and assessment methods have been discussed with the farm manager and different experts in and outside of the JHI. The preliminary results of the natural capital assessment have been presented at an Ecological Science Group seminar, and shared with a number of researchers to get feedback. The natural capital assessment at Glensaugh has been further connected to the JHI initiative to transform Glensaugh into a climate positive farm as indicated before. Accordingly, the Protocol application at Glensaugh puts especial attention to the quantification of changes in GHG footprint and per-unit GHG efficiency of production as result of changes in land use management in Glensaugh since 2002, and on the opportunities to yield carbon off-sets through woodland expansion. The climate positive farm initiative in Glensaugh goes beyond climate change mitigation objectives, as it also aims to improve biodiversity on the farm. Consistent with this, the Protocol application in this report also considers the likely natural capital and ecosystem services enhancement opportunities derived from a potential investment in woodland expansion in Glensaugh, including and analysis of trade-offs and synergies between carbon sequestration, timber production, biodiversity conservation, and other ecosystem services.

In the following section this report presents and discusses the results of the retrospective analysis of management decisions covering the period 2002-2018 (Section 2), and a prospective analysis of natural capital impacts of further woodland expansion in Glensaugh, covering a 50-year time horizon (Section 3).

2 Retrospective assessment of natural capital impact and dependencies

This section describes the methodological approaches, assessment criteria, outcomes obtained, and lessons learned from the Natural Capital Protocol application to Glensaugh to evaluate changes in farm management decisions covering the period 2002-2018. As indicated before, these changes include (in line with the industry trend) a reduction in livestock numbers and the use of inputs such as chemical fertilisers, but also a diversification of farm enterprises through investment in woodlands, renewable energy sources (mainly wind and solar energy), and rural tourism activities. In what follows, this section is structured according to the Protocol stages and step (Fig. 1)

2.1 Frame stage - Step 01: Get started

Step 01 is about why the Protocol is being undertaken, which provides the problem frame for the application of the further steps of the Protocol. The James Hutton Institute is one of the Scottish Government’s main research providers in environmental, crop and food science. The Institute was interested in using its research farm at Glensaugh to explore the applicability and scope of the Natural Capital Protocol framework to aid management of the research farm and inform land-based businesses in Scotland more widely. The application of the Protocol to Glensaugh responds to two main research questions: (i) What is the potential value added of applying the

Natural Capital Protocol framework? and (ii) How can natural capital approaches be used to support land-based business decision-making?

All of Glensaugh' s land-based enterprises depend on natural capital and the continuous supply of ecosystem services that flow from natural capital. Conducting a natural capital assessment in Glensaugh can help the identification, measurement, and valuation of the dependencies of the land-based businesses occurring in this farm on natural capital, and the ecosystem services that flow from the farm's natural capital. This assessment can also help to identify, measure and value the impact that business activities have on natural capital, and the risks and opportunities associated with natural capital management at the farm level.

2.2 Scope stage – Steps 02 and 03: Defining objective and scope of the natural capital assessment

Steps 02 and 03 are about defining what is (are) the main objective(s) for the natural capital assessment and what is its scope, in terms of the organization focus, the value chain boundary and whose is the value perspective from which impacts and dependencies on natural capital are to be considered. As indicated before, the objectives and scope of the Protocol application at Glensaugh have been defined and discussed through a series of meetings with the farm manager and members of the JHI's senior management and research staff. Those include:

2.2.1 Natural capital assessment objectives

The Protocol application at Glensaugh has two main objectives. The first objective is to evaluate the impacts and dependencies of recent land use changes and management decisions from a natural capital lens, and in a way that contributes to Glensaugh climate positive initiative. In this sense, the assessment aims to provide additional information layers on dependencies, impacts, risk and opportunities concerning natural capital to inform land-based business decisions, while supporting a transition to lower carbon farming systems, and enhancing the economic performance and resilience in terms of agricultural (livestock and crops) production and other enterprises in Glensaugh.

The second objective is to develop recommendations for refining the use of the Protocol in farming systems more widely[5]. In this later sense, Glensaugh application aims to contribute to the evaluation and synthesis of the lessons learned from the different natural capital assessment trial project for land-based business in Scotland developed by different organizations that form part of the 'Sustainable Land Management' working group of the Scottish Forum on Natural Capital. This later group includes members from local and Scottish government, land management and conservation, NGOs, business organisations, and academia. The overarching goal of this group, and to which the Glensaugh application aims to contribute, is to offer new and sustainable opportunities for land-based businesses in Scotland, built upon natural capital approaches, such as the Protocol[6].

2.2.2 Natural capital assessment scope

The agreed scope of the natural capital assessment for the retrospective analysis considers:

- The farm-wide natural capital assessment primarily refers to the land within the farm boundaries (Fig. 2) and farm enterprises (Table 2).
- The assessment covers the impact and dependencies of direct on-farm operations on natural capital and their changes over more than 15 years, from 2002 to 2018.
- The impacts and dependencies are assessed from the business and society perspectives. This latter when considering wider positive and negative externalities of farm operations.
- The assessment does not include the supply chain impacts and dependencies. However, risks and opportunities relating to the supply chain and elsewhere beyond the farm gate are considered where these are relevant.

[5] The desire of developing recommendation for applying the Protocol more widely, has favoured the use of open-access and relatively easy to use tool and data (e.g. the Woodland carbon code look-up tables, or the cool farm tool) for the assessment of specific impacts on natural capital or ecosystem services, as detailed latter.
[6] See: https://naturalcapitalscotland.com/article/testing-natural-capital-approaches-in-scottish-land-based-businesses/

Given the scope of the retrospective application of the Protocol at Glensaugh this work has involved a comprehensive natural capital assessment for the whole farm, considering key indicators of dependencies and impacts of farm business operations on natural capital. The assessment comprised an analysis of potential risks that can affect farm environmental and economic performance, as well as potential business opportunities to enhance natural capital

2.3 Scope stage - Step 04: Determine the impacts and/or dependencies

Step 04 is about determining impacts and dependencies on natural capital that are significant (material) for the business or wider society, for their further evaluation. The determination of the materiality of impacts and dependencies needs, in first place, a characterization of the farm's natural capital stocks (assets) and their relevance for the provision of ecosystem services, and then, determine the significance of the services delivered by natural capital for the farm business and wider society. Determining the materiality of natural capital impacts and dependencies for the farm business and society helped the identification of which dependencies and impacts are worth of a more detailed analysis. As indicated before, the materiality of natural capital impacts and dependencies have been determined in collaboration with the farm manager using the material presented in sub-section A.4.

2.3.1 Characterization of natural capital stocks, their state, condition, and trends

Glensaugh encompasses a series of broad habitats. Table 1 sets these out in the form of a natural capital asset register. The asset register shows the extent (in hectares) and condition of these habitats in Glensaugh and takes stock of changes observed since 2002. The extent of broad habitats in 2002 and 2018 is estimated using diverse sources, including farm reports and geo-referred maps that provide information on the area of improved permanent and temporary grassland, agroforestry plots and woodlands. Given the lack of more specific information, it is assumed that both the bog and freshwater habitats areas have not experienced changes in their extent over the period 2002-2018. The areas of these two habitats are in turn estimated using the 2007 Land Cover Map (LCM 2007) (Morton et al., 2011, Figure A.3), while the area of seminatural plant communities, which includes acidic grassland and dwarf shrub heath, is estimated as a residual value in view of changes in temporary and permanent improved grassland area and the woodland expansion experienced since 2002.

The most substantial change observed in the period 2002-2018 is an increase in the extent of woodland habitats through afforestation of improved grassland and semi-natural plant communities. The 2001/2002 annual Glensaugh report indicated that 144 hectares in Glensaugh were covered by temporary improved grassland. The apparent temporal shift between temporary to permanent grassland is not clear as it may just be an artefact of changes in definition of land cover classes from the data used here. Agroforestry plots have not changed in size in the period covered by the natural asset register.

Ecosystem condition can be defined as the overall quality of an ecosystem asset[7] in terms of its characteristics (Maes et al., 2020). The condition of ecosystems, along with their properties, provide the ecological basis for ecosystem service potential (La Notte et al., 2019). Ecosystem condition can convey, however, many different interpretations, that can be system-specific (e.g., conditions for grazing or water condition) or functional [e.g., habitat condition for supporting biodiversity] (Harwood et al., 2016). The literature suggests a set of generic and habitat-specific condition indicators (see Maes et al., 2020 for details). In agroecosystems those indicators could include water and soil pollutants, soil organic carbon, species-based indicators such as "wildness" of biota, or species richness, farming intensity or the occurrence of farmland birds, amongst others.

Changes in natural capital conditions reflected in the Glensaugh's natural capital asset register (Table 3) were qualitatively assessed in view of observed, modelled, or expected changes (considering literature review) for some of the agroecosystem indicators above referred, as it is detailed next. Trends in the condition of natural capital assets in Glensaugh are assessed by means of ECN data and publications using Glensaugh site

[7] In a broader sense, natural capital also encompasses *ecosystem assets*, which are defined from a natural capital accounting perspective as "spatial areas containing a combination of biotic and abiotic components and other characteristics that function together"(European Commission et al., 2014:162). In ecosystem accounting the term "ecosystem asset" is preferred to the term "ecosystem capital", as it is better aligned with the terminology used in the System of national accounts, and also conveys the ecosystem accounting intention of providing both physical and monetary terms (*ibid*, 162).

information, farm records, SEPA data on surface water condition, carbon sequestration and timber stock models, and wider literature review (see sub-section A.2.2 for further details on the natural capital condition assessment).

Table 3 Natural capital asset register (status and trend) in Glensaugh (2002-2018)

Asset (type of broad habitat)	Source (extent)	2002		2018		Trend	
		Extent	Condition	Extent	Condition	(extent)	(condition)
Enclosed farm		144.0		112.4		↘	→↗
Temporary improved grassland	*2001 farm*	*144.0*	*na*	*45.0*	*Stable/Improving*	↘	→↗
Permanent improved grassland	*report*			*67.4*	*Stable/Improving*	↗	→↗
Agroforestry plots[(1)]	Farm records	10.2	na	10.2	Stable	→	→
Seminatural grassland and dwarf shrub heath	*Estimated**	*659.9*	*na*	*640.2*	*Improving*	↘	↗
Blanket bog (heather and grass dominated)	*LCM (2007)*	131.7	*na*	131.7	*Improving*	→	↗
Woodland	*Farm records*	14.7		66.0		↗	↗
Coniferous seminatural woodland	*Farm records*	*6.2*	*na*	*6.2*	*Improving*	→	↗
Coniferous plantations	*Farm records*	*0.0*		*14.4*	*Mixed[(2)]*	↗	↘↗
Broadleaf seminatural woodland	*Farm records*	*0.4*	*na*	*0.4*	*Improving*	→	↗
Broadleaf plantations	*Farm records*	*0.0*		*11.2*	*Mixed[(2)]*	↗	↘↗
Mixed seminatural woodlands	*Farm records*	*8.2*	*na*	*8.2*	*Improving*	→	↗
Mixed plantations	*Farm records*	*0.0*		*24.6*	*Mixed[(2)]*	↗	↘↗
Other woodland areas	*Farm records*	*0.0*	*na*	*1.1*	*Improving*	↗	→
Freshwaters	*LCM (2007)*	7.3	*na*	7.3	*Improving*	→	↗

Extent and condition: "↗" improving/growing, "→" stable ; "↘" decreasing/shrinking; na (information not available).
[(1)] Sparse woodland planted in an area of improved grassland.
[(2)] Mixed effect of woodland expansion: medium-term improvement in global and local climate, and potential short-term negative effect on wild species diversity when commercial plantations are involved, and soil carbon loss.

The evidence on changes in the ability of habitats to deliver ecosystem services (i.e. condition) is mixed. Available farm-level evidence shows an increase in vegetation diversity in seminatural plant-communities and stable bogs (Morecroft et al., 2016), but a decrease in relevant invertebrate species such as carabids, usually associated with provision of pest control services (Brooks et al., 2012). Carbon sequestration models also suggest an increase in carbon stocks in Glensaugh woodland biomass, though the potential effect of conifer and broadleaf plantations on biodiversity is not clear. The literature suggests that seminatural plant communities and improved grassland can have a higher potential to provide wild plant and animal provisioning services and biological and pest control than dense conifer and woodland plantations (e.g., Burkhard et al., 2014; Smith and Dunford, 2018), but some of the farm plantations are not dense (in comparison with commercial plantations) in which case net biodiversity impacts will not necessarily be negative.

Where water quality is monitored (Birnie burn) the surface water quality has 'good chemical status' (e.g., nitrates concentrations lower than 25 mg/L and phosphates lower than 0.4 mg/L)[8]. Likewise, the Devily burn (ID 5708) which is part of the SEPA surface water quality monitoring sites, and to which Glensaugh watercourses are tributaries has a 'good water status' since 2008. Chemical conditions are those of a water with a high-quality class[9]. The overall hydro morphology of Devily burn is also considered to be in good condition, while biological elements oscillate from good to high conditions according to the Water Framework Directive (WFD) water body standards (European Parliament, 2000).

Overall, Glensaugh has an average score of 166 on the Relative Wildness index, with possible scores for this index ranging between 73 and 256[10]. Biodiversity on the farm includes a wide range of habitats and species that are surveyed frequently to record presence and abundance of different species. Breeding bird surveys include sea birds, owls and raptors, migrant and resident insectivores, and waterfowl. Bat surveys include presence and abundance of pipistrelles and myotid species. Other vertebrate species also surveyed include frogs. Invertebrate species surveys include carabid beetles, spittle bugs, moths, and butterflies. There are noticeable interannual

[8] There is no data available about ground water sources in Glensaugh
[9] For more information see: https://www.sepa.org.uk/environment/water/aquatic-classification/
[10] Relative Wildness' is a composite index based on four attributes naturalness of land cover, ruggedness, remoteness, and the lack of built modern artefacts. The scale is 1 to 256; the lower the score the less 'wild' the area (see sub-section A.2.2.1).

variations in the numbers of vertebrate species individuals counted of, while invertebrate species counted show a declining trend in the case of carabids (see subsection A.2.2).

Soil carbon stock was estimated as 198 thousand tonnes of carbon (tC) in 2007 (Natural Scotland, 2007). Carbon stock in the vegetation biomass has increased as results of woodland expansion since 2010 in Glensaugh. Soil carbon stock may have increased as a result of the newly planted woodlands soil debris carbon sequestration, and due to grassland improvements over the last 20 years. (see subsection A.2.4.2). Yet the effect of tree planting on net (soil) carbon gains in Scotland seem to be limited, especially when plantations involve organic soils (Friggens et al., 2020), low yielding trees and low-quality organo-mineral soils (Matthews et al., 2020).

2.3.2 *Characterization of the relevance of natural capital for ecosystem services delivery*

Broad habitats in Glensaugh provide multiple services of which farm productivity system relies. As indicated before, identifying the relevance of the habitats in the farm on the provision of ecosystem services helped with the assessment of the materiality of natural capital dependencies and impacts for the farm business and beyond. The relevance of different farm habitats for the delivery of ecosystem services have been discussed with the farm manager, and complemented by literature review and consultations with experts. Table 4 shows the results of this qualitative assessment.

Table 4 Ecosystem services provided by natural capital in Glensaugh

	Provisioning					Regulating & mantainance										Cultural			
	Cultivated plants	Reared animals	Wild plants and animals	Water supply	Energy supply	Biological pest and disease control	Air pollution removal	Global climate regulation	Local climate regulation	Control of erosion rates	Habitats and wild species	Pollination	Freshwater quality regul.	Regulation of soil quality	Water flow /flood control	Aesthetic	Cultural and heritage values	Knowledge systems and social relations	Recreation and ecotourism
Enclosed farm																			
Temporary improved grassland	High	High	Low			Medium	No relevance	Low	No relevance	Medium	Low	Medium	Low	High	No relevance	High	High	High	Low
Permanent improved grassland	High	High	Low			Medium	No relevance	Low	No relevance	Medium	Low	Medium	Low	High	No relevance	High	High	High	Low
Agroforestry plots(1)	Medium	Low	Low		High	Medium	Low	Medium	High	Medium	Medium	Medium	Low	High	No relevance	High	High	High	Medium
Seminatural-plant communities	No relevance	High	High			High	No relevance	No relevance	No relevance	Medium	High	High	Low	High	No relevance	High	High	High	High
Blanket bog	No relevance	Low	High			High	No relevance	No relevance	No relevance	Medium	High	High	Low	High	No relevance	High	High	High	High
Woodland																			
Coniferous seminatural woodland	Medium	No relevance	Low		High	Low	Low	High	High	Medium	High		Medium	High	Low	High	Medium	Medium	High
Coniferous plantations (new)	Low	No relevance	Low			Low	Low	High	High	Medium	Medium		Medium	High	Low	Medium	Medium	Medium	High
Broadleaf seminatural woodland	Medium	No relevance	Low		Low	Low	Low	High	High	Medium	High		Medium	High	Low	High	Medium	Medium	High
Broadleaf plantations (new)	Low	No relevance	Low			Low	Low	High	High	Medium	Medium		Medium	High	Low	High	Medium	Medium	High
Mixed seminatural woodlands	Medium	No relevance	Low		High	Low	Low	High	High	Medium	High		Medium	High	Low	High	Medium	Medium	High
Mixed plantations (new)	Low	No relevance	Low			Low	Low	High	High	Medium	Medium		Medium	High	Low	High	Medium	Medium	High
Other woodland areas	Medium	Low	High			Low	Low	High	High	Medium	High		Medium	High	Low	High	Medium	Medium	High
Freshwaters			High	High		Low		No relevance	High		High		High	No relevance	High	High	High	High	High

Relative importance : High Medium Low No relevance

A number of interesting messages emerged from Table 4. Provisioning services (mainly biomass from cultivated plants and reared animals) mainly depend on enclosed farm habitats (mainly improved grassland) and seminatural plant communities, while the provision of biomass from wild plants and animals (e.g. game species, fish) mainly depend on seminatural plant communities, bog and fresh water habitats. The relatively small extend of mature woodland and the relative young age of the new ones (Table 3) explain a low relevance of woodland habitats in the delivery of provisioning services, except for energy supply (biomass). The regulation of climate (at the local and global levels) has the highest relevance for woodland habitats, though these habitats are also considered key for regulating water quality and soil erosion control, and providing recreational opportunities. Higher cultural and heritage values are associated to habitats used for extensive livestock farming and game shooting, which are traditional upland farm activities, while forestry activity has been less relevant for Glensaugh, though it is gaining interest as part of the farm diversification strategies.

2.3.3 Determination of the materiality of impacts and dependencies on natural capital

Every enterprise at Glensaugh depends on natural capital and the ecosystem services it provides, and consequently, they can be affected by risks and opportunities associated with both impact and dependencies of farm operations on natural capital. Not all ecosystem services flowing from natural capital on the farm are significant from a farm business perspective. The relevance of provisioning services such as biomass from livestock and crops is more evident than regulating and cultural services from business perspective. Regulating and supporting services, such as local climate regulation, regulation of soil quality, and control of soil erosion, flood, or pest and diseases can have, nonetheless, an important effect on livestock, crops and timber production and their economic performance. Cultural services associated with physical or experiential interactions with the natural environment are relevant for the provision of recreational, education, and training opportunities. From a society standpoint, ecosystem services affecting the provision of public goods are of the greatest importance. These may include regulating services such as flood attenuation, water purification or global climate change regulation, but also cultural services associated with cultural landscape and biodiversity conservation. The latter services at Glensaugh are directly connected to scientific investigation and the creation of traditional ecological knowledge. In both cases, potential changes in extent and condition of natural capital affecting the provision of private and public goods carries operational, financial, legal, and/or reputational risks for the farming business.

The materiality of the natural capital impacts and dependencies by farm enterprise at Glensaugh was judged considering both the financial implications of natural capital dependencies and impacts for business, and the potential environmental and society impacts (e.g. global climate change and water quality regulation, or maintenance of wild species and habitats). The materiality assessment was discussed with the farm manager during the first visit to the farm, whereas the relevance of different broad habitats and ecosystem services for both business and society have been qualitatively assessed[11]. 0 shows a summary of the materiality matrix for both impacts and dependencies of farm activities on natural capital.

Table 5 Materiality matrix for main natural capital impact and dependencies of Glensaugh farm enterprises

Dependencies																Farm enterprise	**Impact drivers**							
Consumptive							**Non-consumptive**										**Outputs**							
Surface water	Groundwater	Forage	Fodder	Wood (biomass)	Fossil fuels	Renewable energy	Water Quality regulation	Flood control	Local climate reg	Global climate reg.	Biological pest cont.	Maint. ihabitas&sps.	Soil erosion cont	Cult&heritage val.	Knowledge system		GHG emissions	CO_2 sequestration	Water pollutants	Soil pollutants	Soil erosion*	Solid waste	Habitat conservation	Disturbance
o		o	o		o				o	o	o	o			o	Beef-cattle	o		o	o	o	o	o	
o		o	o		o				o	o	o	o			o	Hill sheep	o		o	o	o	o	o	
o		o	o		o				o	o	o	o			o	Low-ground sheep	o		o	o	o	o	o	
o		o	o		o				o	o	o	o			o	Deer	o		o	o	o	o	o	
o												o			o	Silage and haylage	o		o	o	o	o		
												o			o	Forestry		o	o	o		o		
												o			o	Agroforestry		o	o	o		o		
												o		o		Game shooting						o	o	o
o	o						o	o				o	o	o		Fishing						o	o	
	o			o		o						o		o		Tourism/recreation	o					o		
				o												Renewable energy						o		o
					o										o	Demonstration activities	o					o		
															o	Training/education activities	o					o		

Notes: **o** Impacts or dependencies that are material. Likely high materiality, Likely medium materiality, and Low materiality.
Source: *Own elaboration* based on the Natural Capital Protocol Sectoral Guides (Natural Capital Coalition, 2018, 2016c), and inception interview with Glensaugh farm manager.

Table 5 matrix provides a first approximation of the materiality of dependencies (consumptive or non-consumptive) and impact drivers (in terms of outputs) of farm enterprises on natural capital. Those impacts and dependencies with medium to high materiality have been further examined (deskwork phase), considering consultation with experts, data analysis and literature review.

[11] See Section A.4 in the Supplementary Appendix.

2.4 Measure and value stage – Steps 05-07: measure and value impacts and dependencies

This stage of the process focused on measuring and valuing the dependencies and impacts of specific land-based activities or farm operations on natural capital and ecosystem services in more detail. It started by mapping the specific activities that are dependent on, or give rise to impacts on ecosystem services, and the scientific evidence that either supports or contradicts the initial perceptions on the relevance of dependencies and impacts of farm enterprises on natural capital (0). The valuation of impacts and dependencies means more than just monetization. It refers to the process of estimating the relative importance, worth, or usefulness of natural capital to farms business and to people (society). Valuation can therefore be qualitative, quantitative or monetary or a combination of the three (Natural Capital Coalition, 2016a).

The dependencies and impacts of farm enterprises taking place in Glensaugh were initially valued in qualitative terms. For some of the most relevant dependencies and impacts, the assessments are supported by scientific evidence obtained from literature review, and for a set of impacts and dependencies the assessments are informed by a set of indicators directly collated in Glensaugh or modelled as discussed in the following sub-sections, and in more detail in section A.2 of the supplementary material of this report.

2.4.1 Dependencies on natural capital and ecosystem services

Dependencies on natural capital were valued in first place in qualitative terms considering the overall dependency of farm enterprises on broad habitats (Table 6), and dependencies in ecosystem services (Table 6).

All livestock enterprises at Glensaugh depends on biomass from on-farm cultivated and seminatural plants in the form of swards and conserved winter feed (haylage and silage), which today cover about 89 percent of the farm's total livestock energy requirements (2018 data)[12]. Table 6 highlights the relevance of different broad habitats for each one of the livestock farm enterprises considered. For example, this assessment shows that hill sheep and deer enterprises are highly dependent on semi-natural plant community habitats, and moderately dependent on bog habitats. Beef-cattle farming is highly dependent on temporary and permanent grassland. The hill sheep flock's nutrition depends mainly on grazing (more than 90 percent of total flock energy requirements), while low ground sheep, beef-cattle and deer have a higher dependency on own-produced winter feed (from 34 to 50 percent of energy requirements, see Table 8). This latter dependency makes low-ground sheep flocks, deer, and beef-cattle farming systems more vulnerable to changes in climate conditions that affect production of winter feed (silage and haylage).

Silage and haylage basically depend on enclosed farm habitats (i.e. improved grasslands). Agroforestry plots provide shelter and shade to sheep flocks; hence they also 'depend' on this resource to some extent. Recreational activities, such as game shooting, have in contrast a low to moderate dependency on bog and seminatural habitats. Tourism and demonstration activities depend on the mix of habitats present in Glensaugh. Renewable energy production when biomass is involved depends on both woodlands and agroforestry plots.

Table 7 indicates, in qualitative terms, the consumptive and non-consumptive dependencies of Glensaugh activities on natural capital. This table highlights a high consumptive dependency of livestock farming and grassland management activities on surface water, plant materials (swards and feedstock), fossil fuel and renewable energy. Energy consumption is most important for animal winter housing (with requirements also for vehicle fuel used in husbandry activities). Tourism/recreation activities have a moderate dependency (by the farm, not by the tourists) on fossil fuel, but a higher dependency on renewable energy, mainly from biomass used for heating the holiday cottage. The dependency of the tourist/recreation activity on ground water is also relevant. Non-consumptive dependencies account for both regulating and cultural services. The qualitative assessment highlights the dependency of most farming activities on local climate regulation, biological and pest control and the maintenance of wild species populations and habitats. Decomposition and fixing processes affecting soil fertility (quality) and structure have an impact on forage, crops, and tree growth and yield. The dependency of farm activities on cultural services was identified as moderate to high. Livestock, crop, and

[12] Energy requirements are expressed in terms of the total metabolic energy (ME) requirements needed by type of livestock, to stay alive, grow, keep warm and move around (see sub-section A.2.3.2 for further details). The percentages refer to the energy requirements covered with own produced forage and feeding stock.

forestry farming relies on knowledge systems and cultural and heritage values associated with living systems, and human and social capitals that have been built over generations.

Table 6 Dependencies of farm enterprises on natural capital

	Enclosed farm		Agroforestry plots (improved grassland)	Seminatural plant communities	Woodland		Bog	Fresh waters
	Temporary improved grassland	Permanent improved grassland			Commercial plantation	Seminatural woodland		
Farm activities								
Beef-cattle	High	High	Not important	Low	Not important	Not important	Not important	Medium
Hill sheep	Low	Medium	High	High	Not important	Not important	Not important	Medium
Low-ground sheep	Medium	Medium	Not important	Low	Not important	Not important	Medium	Medium
Deer	Medium	Medium	Not important	High	Not important	Not important	Medium	Medium
Silage and haylage	High	High	Not important	Not important	Not important	Not important	Not important	Medium
Forestry	Not important	Not important	Not important	Not important	High	High	Not important	Medium
Agroforestry	Not important	High	High	Medium	Not important	Not important	Not important	Not important
Game shooting	Not important	Not important	Low	Low	Not important	Not important	High	Medium
Fishing	Not important	Not important	Not important	Not important	Not important	Not important	Not important	High
Tourism/recreation	Low	Low	Medium	Medium	Medium	Medium	High	Medium
Renewable energy (biomass)	Not important	Not important	Medium	Not important	Medium	Medium	Not important	Not important
Demonstration activities	High	High	Medium	Medium	Low	Low	Low	Not important
Training/education activities	Medium	Medium	Medium	Medium	Not important	Not important	Not important	Not important

Relative importance of dependencies on natural capital:
High Medium Low Not important

Table 7 Consumptive and non-consumptive dependencies matrix for Glensaugh enterprises

Farm enterprise	Dependencies of the farm on consumptive and non-consumptive good and services																		
	Consumptive (provisioning services)								**Non-consumptive (regulating & cultural services)**										
	Surface water	Groundwater	Rainwater	Forage (grazing)	Fodder (feedlot)	Wood fibre (biomass)	Fossil fuels	Renewable energy	Freshwater quality regulation (water)	Water flow/flood control	Local climate regulation	Global climate regulation	Biological pest /diseases control	Soil erosion control	Maintaining wild species & habitats	Soil quality regulation	Cultural and heritage values	Knowledge system, social relations	Nature-based recreation
Farm activities																			
Beef-cattle	High	Not important	Not important	High	High	Not important	High	High	High	Not important	Medium	Medium	Medium	Low	Medium	Medium	High	High	Not important
Hill sheep	High	Not important	Not important	High	Low	Not important	Low	Medium	Medium	Not important	High	Medium	High	Low	Medium	Medium	High	High	Not important
Low-ground sheep	High	Not important	Not important	High	High	Not important	High	High	Medium	Not important	Medium	Medium	Medium	Low	Medium	Medium	High	High	Not important
Deer	High	Not important	Not important	High	High	Not important	High	High	High	Not important	Medium	Medium	High	Low	Medium	Medium	High	High	Not important
Silage and haylage	High	Not important	High	Not important	Not important	Not important	High	High	Low	Not important	Low	Low	High	High	High	High	High	High	Not important
Forestry (commercial plantation)	High	Not important	High	Not important	Not important	Not important	High	Not important	Not important	Not important	Not important	Low	High	Low	High	High	Medium	Medium	Not important
Forestry (seminatural woodlands)	High	Not important	High	Not important	Not important	Not important	Medium	Not important	Not important	Not important	Not important	Low	High	Low	High	High	Medium	Medium	Not important
Agroforestry	High	Not important	High	Not important	Not important	Not important	High	Not important	Not important	Not important	Not important	Low	High	Low	High	High	Medium	Medium	Not important
Big-game shooting	Not important	Not important	Not important	Not important	Not important	Not important	Low	Not important	Not important	Not important	Not important	Low	Medium	Not important	High	Not important	High	High	High
Fishing	High	High	High	Not important	Not important	Not important	Not important	Not important	High	High	Not important	Low	High	High	High	Not important	High	High	High
Tourism/recreation	Not important	High	Not important	Not important	Not important	High	Low	High	High	Not important	Not important	Not important	Low	Low	Not important	Not important	High	High	High
Demonstration activities	Not important	Not important	Not important	Not important	Not important	Not important	Low	Not important	Not important	Not important	Not important	Not important	Low	Not important	Not important	Not important	Medium	High	Not important
Training/education activities	Not important	Not important	Not important	Not important	Not important	Not important	Low	Not important	Not important	Not important	Not important	Not important	Low	Not important	Not important	Not important	Medium	High	Not important

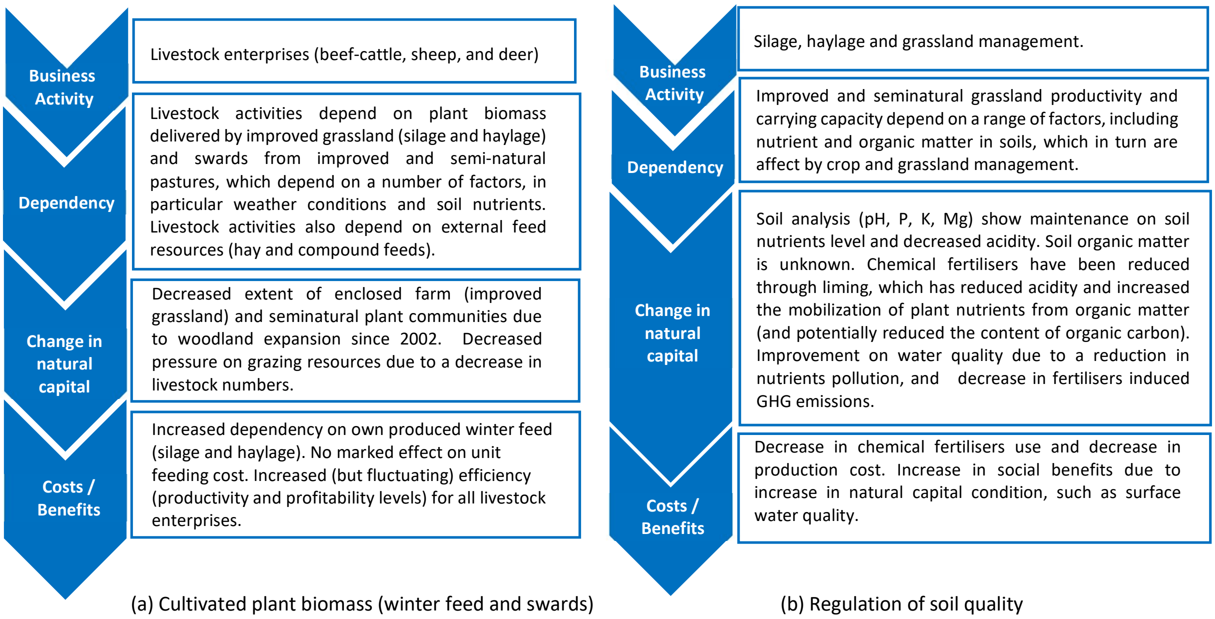
Relative importance of dependencies on natural capital:
High Medium Low Not important Unknown

Following the trial application on the Protocol to Crown Estate Scotland land business (Silcock et al., 2018), this assessment considers pathway diagrams for the most relevant consumptive and non-consumptive natural capital dependencies for extensive livestock enterprises, winter feed production, and forestry. All the three being land-use intensive business activities in Glensaugh.

Pathways of dependency on natural capital

Both hill and low-ground livestock farming systems rely on swards and on conserved winter feed (in this case own produced haylage and silage). The provision of both swards and winter feed resources depend on climate conditions, regulating services such as regulation of soil quality, water, local climate and biological and pest control, and cultural services associated with knowledge systems, cultural and heritage values. Pathways of dependency on natural capital are illustrated in Fig. 4.

Weather condition can have a significant effect on own winter feed production. In particular, a poor summer (i.e. high rain and low soil temperature) followed by a poor winter can place a severe strain on silage and haylage production systems. High summer rain, low soil temperatures and impaired plant growth can lead to poor livestock growth rates (see sub-section A.2.3.3). Systems which rely more on winter feed (cattle-beef, low ground sheep flock and deer calves) are particularly vulnerable to poor summer weather because both winter feed quantity and quality will be impaired. Likewise, prolonged drought periods (low rain) in the summer can also reduce forage productivity. Those animals which rely on extensive grazing (hill sheep flock) throughout the year will be less vulnerable, but will be at the mercy of winter storms unlike the livestock that are housed in winter. The strategy to cope with poor summer weather has been a gradual substitution of silage by hay (which is externally produced) and introducing silage preservatives and inoculants. Alternatives to reduce the reliance on winter feed are the substitution of suckler cows and of low ground crossbred by hill sheep ewes and gimmers.



(a) Cultivated plant biomass (winter feed and swards) (b) Regulation of soil quality

Source: Inspired by Russ and Silcock (2018)

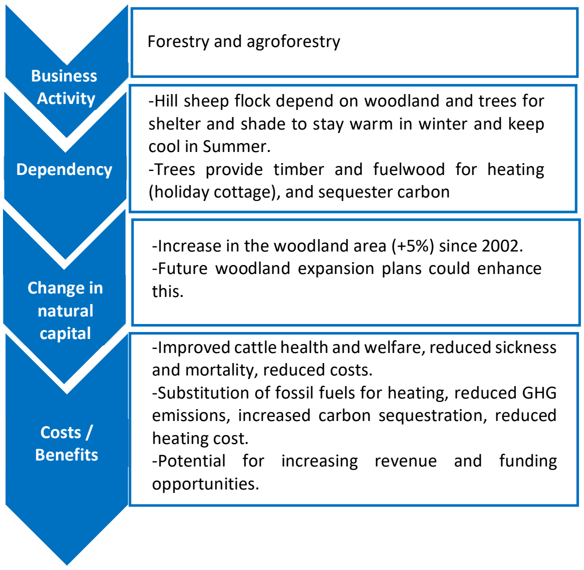
Fig. 4 Dependency pathways for (a) biomass from cultivated plants and (b) regulation of soil quality

Changes in land cover due to woodland expansion did not have an overall measurable effect on livestock productivity given the relative low stocking rates kept in Glensaugh (less than 0.29 SLU/ha in 2018) (see Table 8). Since 2006 the dependency on external feed resources has decreased, in particular for hill sheep enterprises, which has led to an increase in efficiency (measured as the net profits per standard livestock unit –SLU)[13], thought to be fluctuating, for all livestock enterprises. There is also an increased dependency on own produced conserved winter feed for all livestock species, except the hill sheep flock, which on the contrary depends mainly on semi-natural grazing resources. The fluctuating profitability levels for beef-cattle and low-ground sheep enterprises seem to be associated with poor summers (e.g. 2011-2012), but also with lower rainfall for the hill sheep and deer enterprises (e.g. 2013), presumably leading to decreased semi-natural sward production. For more details see sub-sections A.2.3.2 and A.2.3.3 of the Supplementary material of this report.

[13] Standard Livestock Units (SLU), equal to 1 for beef cows over 24 months of age, 0.15 for breeding ewes and gimmers and 0.30 for breeding hinds over 27 months (Scottish Government, 2019b: Annex A calculation of historic livestock units and stocking rates).

Winter feed and growing-season sward production can be affected by diverse environmental and management factors, including nutrient and organic matter in soils. Nutrient applications on the farm are based on measured requirement based on annual soil tests on pH, Phosphate (P), Potassium (K) and Magnesium (Mg) levels. Lime is applied when required, while P and K are applied through summer applications of dung and/ or slow release fertilizers to replace seasonal livestock offtake and to 'set up' the land for the following season (Fig. 4). For more details see sub-section A.2.3.3 of the Supplementary material of this report.

Local climate regulation provided by existing woodlands and trees (in both agroforestry and forestry systems) is relevant for hill sheep farming to protect flocks from windstorms during the winter and hot periods during the summer. Providing shelter for livestock can increase daily live weight gain (Raskin and Osborn, 2019), but also can have a positive effect on livestock health (e.g., reduced thermal stress), and reduce veterinary treatment costs (Van laer et al., 2014). Trees are additional source of revenues or cost savings through fuel wood and timber production, carbon sequestration and air pollution removal (Fig. 5). At Glensaugh, an average annual consumption of 4,454 kg of Propane gas has been substituted by biomass burning from agroforestry and woodland areas. This entails an average net decrease in GHG emission of 6.3 carbon dioxide equivalent tonnes (t CO_2e) per year, but only when carbon sequestration due to tree growth is higher than carbon release due to biomass burnt, as currently occurs in Glensaugh (see subsection A.2.4 for more details). Additional woodland expansion can enhance these business and cost saving opportunities.



Source: Inspired by Russ and Silcock (2018)

Box 1: Agroforestry plots in Glensaugh

Agroforestry research plots were planted at Glensaugh in 1988. Three tree species were selected and planted at different densities to compare their performance.
-Scots Pine (*Pinus sylvestris*) planted at a density of 400 trees per hectare.
-Hybrid Larch (*Larix eurolepis*) planted at a density of 100, 200 and 400 trees per hectare (lower densities have now been felled).
-Sycamore (*Acer pseudoplatanus*) planted at density of 100 and 400 trees per hectare.
-Control plots planted at conventional forestry densities of 2,500 trees per hectare.
-Commercial ewes, with lambs at foot in spring and early summer, are grazed in and around the trees between April and November.
-There was no measurable reduction in sheep output, although production of grass in closed canopy plots of larch and sycamore has subsequently declined. In addition, a new timber source had been created and a positive impact made on the landscape, and its biodiversity value.
- Suckler cows were introduced to the Scots Pine plot in 2008 to determine what benefits tree pasture will bring for the cattle and to identify any disadvantages to the trees.
Source: The James Hutton Institute webpage

Fig. 5 Dependency pathways for tree biomass and local climate change regulation

Livestock, forestry (and agroforestry), winter feed and grassland production activities also rely on biological pest and disease control ecosystem services (e.g., predatory, parasitism, herbivory or other biological mechanism that control crop and livestock pests and disease). Stocking rates are relatively low in Glensaugh hill, but higher in low-ground areas (see Table 8). Higher stocking densities can increase pest and disease spread among animals. Expenditures on livestock pest and disease prevention and control have slightly increased over the past year in Glensaugh, but the connection between increased medicine expenditures and a decrease in the use of biological pest and control services has not been studied on this farm.

Livestock, crop, and forestry activities depend on traditional ecological knowledge systems built up over many generations, and that are part of the Scottish upland cultural and heritage values. At Glensaugh, land and livestock management decisions are further supported by modern technologies, such as weather forecasting and soil testing. Weather forecasting allows the effects of bad storms on hill ewes to largely be avoided, as they are removed from the hill in advance of a bad storm. Soil testing guides nutrient application (dung and chemical fertilizers).

Forestry is a relatively young activity in Glensaugh, and current and future woodland expansion plans can benefit from experience of a neighbouring farm dedicated to forestry activity, and expertise from Scottish Forestry advice and extension services. Woodland expansion also provides potential business opportunities to offset farm GHG emissions, and potentially could be offered to third parties (see case study in Section 3 and subsection A.3 in the supplementary material).

Quantitative indicators of land-based business dependencies on natural capital

Table 8 offers a set of indicators of the dependency of Glensaugh enterprises on the farm's natural capital. The indicators illustrate trends in these dependencies within the period 2002-2018, or a number of years between this period in which information is available. The table shows average values and their variation over the accounting periods, and the value estimated or observed in 2018, as a reference for comparison purposes. These indicators are mainly referring to livestock, crops, and renewable energy enterprises.

Table 8 Estimated indicators of dependencies of Glensaugh enterprises on natural capital

Specific dependency	Enterprise	Quantitative indicators				
		Unit [1]	Period	Average value and variation over the period: Mean	SD	Value2018
Provision of biomass from cultivated plants: grazing and winter feed	Hill sheep	SLU/ha	2002-2018	0.14	0.02	0.16
		% ME grazing	2006-2018	71.89	20.11	93.42
		% ME winter feed	2006-2018	7.46	9.00	3.64
	Low ground sheep	SLU/ha	2002-2018	0.89	0.10	0.75
		% ME grazing	2006-2018	51.68	8.86	46.33
		% ME winter feed	2006-2018	30.44	10.41	45.50
	Beef-cattle	SLU/ha	2002-2018	0.53	0.06	0.45
		% ME grazing	2006-2018	56.62	11.90	51.57
		% ME winter feed	2006-2018	30.44	10.41	34.44
	Deer	SLU/ha	2002-2018	0.13	0.02	0.11
		% ME grazing	2006-2018	6.78	16.23	28.41
		% ME winter feed	2006-2018	24.50	8.16	50.49
	Total livestock	SLU/ha	2002-2018	0.32	0.02	0.29
		% ME grazing	2006-2018	58.8	6.66	53.49
		% ME winter feed	2006-2018	24.50	8.16	35.42
Provision of biomass: timber growth	Timber/biomass	m^3 /year	2002-2018	40.01	41.91	74.65
	Carbon sequestration (tree and soil debris)	t CO_2 / year	2002-2018	46.97	32.51	127.85
Provision (production) of renewable energy	Biomass[2]	m^3 /year	2012-2018	12.1	4.4	12.1
	Solar	kWh	2015-2018	4,410	586	4,992
	Wind	kWh	2013-2016	22,478	10.323	-
Soil quality regulation and other ecosystem services	Silage production	DM (g/kg)	2002-2018	295.00	58.71	343.00
		D-value (%)	2002-2018	65.92	4.92	68.70

Notes: [1] DM: dry matter; D-value: percentage of digestible organic matter; kWh: kilowatt hour, ME: metabolic energy, SD: standard deviation; SLU: standard livestock unit, t: metric ton. [2] Estimated considering the energy content in the propane gas substituted by biomass for heating, and BEIS (2019) conversion factors for biomass wood logs.

As indicated before, the percentage of total metabolic energy (ME) provided by Glensaugh' s grazing resources and own-produced crops varies for each one of the livestock enterprises. The average and standard deviation values presented in Table 8 give an idea of the variability observed within the periods considered. For instance, the dependencies of hill sheep and deer on grazing resources have been increasing since 2006. In 2018, most of the energy requirements of the hill flock was covered by grazing. The dependencies of beef-cattle, and low-ground sheep on grazing have not changed significantly since 2006. The dependency of deer enterprise and low-ground sheep on own produced winter feed has increased significantly since 2006. In 2018, this latter feed source covered close to half of the nutritional requirement of both livestock enterprises.

The nutritional quality of silage (and haylage) produced in Glensaugh depends on soil quality regulation and other ecosystems services (e.g. biological pest and disease control) and environmental and management factors. Silage quality in terms of the digestibility of organic matter has been relatively stable since 2002, with some noticeable improvement over the last 3 years (see sub-section A.2.3.3 for details). The dry matter content has shown improvements since 2002, which has in turn increased the metabolic energy content per unit of fresh silage provided at the feedlot.

Timber and biomass provision depend on the growth of tree biomass. Tree growth added about 75 additional cubic meters of timber/wood by 2018, which was translated into an estimated carbon uptake of 128 tons of CO_2, in tree biomass and soil debris. Woodland and the agroforestry plots are sources of biomass used in substitution of fossil fuels for some of the farm's heating. In 2018 the estimated biomass consumption for heating purposes was lower than the estimated timber growth, which indicates that the biomass use at Glensaugh can be considered sustainable.

Renewable wind and solar energy production also depend on natural capital (i.e. wind and sunshine as energy resources). The provision of solar energy was relatively stable over the last years, while more fluctuations were observed for the provision of wind energy (sub-section A.2.4.).

2.4.2 Impacts on natural capital and ecosystem services

The impact assessment either covers the whole period between 2002 and 2018 or a number of years within this period depending on data availability. Impacts were evaluated in qualitative terms and, where information is available, in quantitative (physical) and monetary terms. Qualitative impacts define expected effects of farm enterprises on natural capital or in the provision of ecosystem services. Table 9 highlights expected impacts of farm enterprises on natural assets compared to a hypothetical situation in which the land is not actively managed. Table 10 highlights the expected impacts of changes in farm management since 2002 on ecosystem services delivered by natural capital.

Table 9 Expected impacts of farm enterprises on natural capital

	Enclosed farm		Agroforestry plots (improved pasture)	Seminatural plant communities	Woodland		Bog	Fresh waters
	Temporary improved pasture	Permanent improved pasture			Commercial plantation	Seminatural woodland		
Farm activities								
Beef-cattle	Positive: Low	Positive: Low	Not important	Not important	Not important	Not important	Not important	Negative: Low
Low-ground sheep	Positive: Medium	Positive: Medium	Not important	Not important	Not important	Not important	Not important	Negative: Low
Hill sheep	Not important	Positive: Medium	Positive: Medium	Positive: Medium	Not important	Not important	Positive: Low	Not important
Deer	Positive: Low	Positive: Medium	Not important	Positive: Medium	Not important	Not important	Positive: Low	Not important
Silage and haylage	Negative: Low	Negative: Low	Not important	Not important	Not important	Not important	Not important	Negative: Low
Forestry	Not important	Not important	Not important	Negative: Low	Positive: High	Positive: High	Not important	Negative: Low
Agroforestry	Not important	Not important	Positive: High	Not important	Positive: Low	Not important	Not important	Not important
Game shooting	Not important	Not important	Positive: Low	Positive: High	Not important	Not important	Positive: Low	Not important
Fishing	Not important	Not important	Not important	Not important	Not important	Not important	Not important	Positive: Medium
Tourism/recreation	Not important	Not important	Not important	Not important	Not important	Not important	Not important	Not important
Demonstration activities	Not important	Not important	Not important	Not important	Not important	Not important	Not important	Not important
Training/education activities	Not important	Not important	Not important	Not important	Not important	Not important	Not important	Not important

Relative importance of impact on natural capital:

Positive: High, Medium, Low — Not important — Negative: Low, Moderate, High

The qualitative assessment is complemented with a quantitative assessment, based on a set of indicators that illustrate changes in impact levels over time (Table 11). The combined qualitative and quantitative impact assessment focuses on livestock grazing and winter feed, woodland expansion, investment in renewable energies, and recreational activities. The impacts of woodland expansion on natural capital in part rely on the type of plantations considered: commercial plantation, involving mainly conifers and oriented to timber production, and semi-natural woodland, involving mainly mixed native conifer and broadleaved species, and oriented to conservation and amenity.

Livestock management and forage production

Livestock numbers have been substantially reduced in Glensaugh since 2002, most markedly red deer hinds and low-ground ewes and gimmers (close to 50 percent reduction) numbers. The reduction in livestock numbers had in general a positive effect on natural capital (Table 9), and the ecosystem services flowing from broad habitats (Table 10), as discussed in more detail next, and summarised in Fig. 6 impacts pathway.

Table 10 Estimated changes in delivery of ecosystem services due to changes in the use of land and management

	Provisioning				Regulating & mantainance										Cultural			
	Cultivated plants & reared anim.	Wild plants and animals (biomass)	Water supply (quantity)	Energy supply	Biological pest and disease control	Global climate regulation	Local climate regulation	Control of erosion rates	Habitats and wild species	Pollination	Freshwater quality regulation	Regulation of soil quality	Water flow /flood control	Wate water treatment	Aesthetic	Cultural and heritage values	Knowledge systems Social relations	Recreation and ecotourism
Woodland expansion																		
Commercial plantation (timber)	↗ Moderate	↘ Low	→	↗ Moderate	↘ Low	↗ Moderate	↗ Moderate	↗ Low	↘ Moderate	↘ Moderate	↗ Moderate	↗ Moderate	↗ Moderate	↗ Moderate	→	↘ Low	Un-known	↗ Low
Seminatural woodland (amenity/conservation)	↗ Moderate	→	→	↗ Moderate	→	↗ Moderate	↗ Moderate	↗ Low	↗ Low	↘ Low	↗ Moderate	↗ Moderate	↗ Moderate	↗ Moderate	↗ Low	↗ Low	↗ Low	↗ Low
Agroforestry	↗ Moderate	→	→	↗ Moderate	→	↗ Moderate	↗ High	↗ Low	↗ Low	→	↗ Low	↗ Moderate	↗ Low	↗ Moderate	↘ Low	Not relevant	↗ Moderate	↗ Low
Grazing management																		
Rotational heather burning	↗ Moderate	→	→	Not relevant	Un-known	→	Not relevant	↘ Low	↘ Low	Un-known	↘ Moderate	↘ Low	Not relevant	Not relevant	↘ Moderate	↗ Moderate	Not relevant	↘ Low
Reduction in fertilizers & increased liming	↗ Moderate	↗ Moderate	→	Not relevant	Un-known	↘ Low	Not relevant	→	Not relevant	→	↗ Low	↗ Low	→	Not relevant	→	Not relevant	↗ Low	→
Livestock management																		
Reduction on livestock numbers	↘ Low	↗ Low	Not relevant	Not relevant	↗ Low	↗ Moderate	Not relevant	↗ Moderate	↗ Low	Not relevant	↗ Moderate	↗ Low	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Production of winter feed	↗ High	↘ Moderate	↘ Low	↘ Moderate	↘ Moderate	↘ Low	Not relevant	↘ Low	↘ Low	Not relevant	↗ Moderate	↘ Moderate	Not relevant	↘ Moderate	↘ Low	Not relevant	↗ Moderate	Not relevant
Renewable energy production (solar, wind)	Not relevant	Not relevant	Not relevant	↗ High	Not relevant	↗ Moderate	Not relevant	Not relevant	→	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	↘ Low	Not relevant	↗ Moderate	↘ Low
New recreational services	Not relevant	Not relevant	↘ Low	↘ Low	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	↘ Low	Not relevant	Not relevant	↘ Low	Not relevant	↗ Moderate	↗ Moderate	↗ High

Potential changes in ES delivery

Not relevant | Un-known | Stable/neutral →

Improvement: High ↗ | Moderate ↗ | Low ↗

Decline: Low ↘ | Moderate ↘ | High ↘

Source: *Own elaboration* based on farm records, ECN data, and literature review, including Burkhard et al., 2014, Smith and Dunford, 2018, scores, and expert's consultation.

Extensive livestock grazing, when low stocking densities are involved, can have a positive effect on wildlife, while improving pasture health and productivity (Schieltz and Rubenstein, 2016). Relatively low densities: (i) 0.16 Standard Livestock Unit (SLU) per hectare in the hill sheep heft); and (ii) 1.2 SLU/ha in the low-ground improved pastures (see Table 8 and sub-section A.2.3.1), suggest that grazing may have a positive effect on health and productivity of temporary and permanent improved grassland and seminatural grasslands productivity in Glensaugh.

Livestock production can also lead to soil erosion and promote fertilises use (to increase grass production), both of which can pollute water courses (Table 9-10). The latter is estimated to have a negative, but rather low, impact on freshwater quality in Glensaugh (see sub-section A.2.2.3). Animals grazing on herb-rich grassland have a more diverse diet which can give better natural protection from disease and pests and therefore they can potentially cut the need for pesticides, antibiotics and veterinary care (Clark et al., 2019)[14]. The quality of grass grown (and harvested) in Glensaugh seems to be improving, at least in terms of digestible organic matter, and dry matter content (see Table 8 and sub-section A.2.3.3).

[14] Expenses on veterinary inputs have experience slight increases since 2008, but its connection to changes in biological control of pest and diseases in this farm have not been studied in detail.

Winter feed production in Glensaugh is intrinsically linked to livestock enterprises, therefore its impacts are attributed to livestock management. Silage and more recently haylage production has slightly reduced Glensaugh' s dependency on external feed and has had an important contribution to low-ground sheep and suckler-cow diets (see Table 8 and sub-section A.2.3.2). The widespread switch from grazing to silage production, by reseeding grasslands, use of pesticides and chemical fertilisers, increased use of machinery, and in some cases enlargement and levelling of fields, and land drainage have caused significant environmental damage in some upland farms (Clark et al., 2019). Considering the former, the impacts from silage production on improved pastureland are considered from low to moderate at Glensaugh. Pasture and grassland management on the farm does not involve the use of heavy machinery. Chemical fertiliser application represents today about one fourth of the quantities applied in 2002, which has had positive impacts in relation to grassland management and winter feed production costs, GHG emissions and improvements in water quality (Table 11 and see sub-section A.2.3). The use of herbicides, fertiliser, machinery, or plastic to wrap silage and haylage[15] are considered to have a low to moderate impact overall on wildlife, climate, soil, and water related regulating services, among others (Table 10).

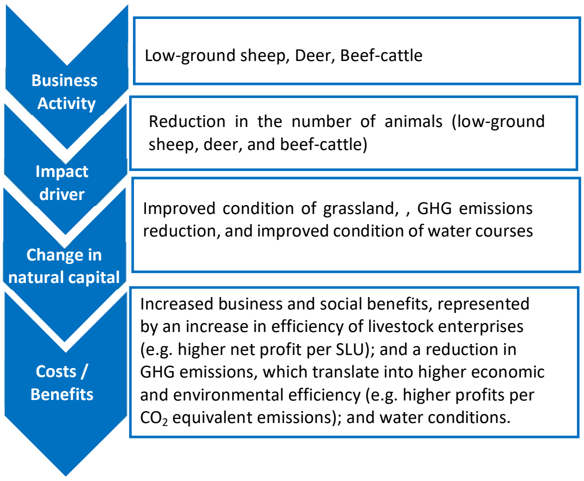


Fig. 6 Impact pathways for reduction in livestock numbers

Changes in livestock management and grassland fertilization strategies since 2002 have been translated into business and some social benefits, such as a reduction in GHG emissions and improvements in water quality (Fig. 6 and Table 11). GHG emissions from livestock and grassland fertilization have been gradually reduced by an average 3 percent per year since 2002. A reduction in livestock numbers, and management involving less fertilisers, and relatively more grazing, especially for hill sheep flocks, are behind Glensaugh' s GHG emission reduction figures, but also in an increase in profit levels by standard livestock unit. The combined decrease in GHG emissions and an increase in profit levels per livestock unit, was translated into improvements in combined environmental and economic efficiency, with higher profit levels per CO_2 equivalent emission (see Table 11 and sub-section 2.3.4).

There is uncertainty associated to livestock GHG emission estimation, as two tools applied (Cool Farm Tool (CFT) and the AgRE Calc tool) provided different emission estimates (see sub-section A.2.3.4)[16]. In what follows this report used the CFT online tool[17], as it allowed more flexibility in terms of the number of livestock species and years that could be considered. More research is, however, needed to analyse the reasons behind GHG emissions differences by the tools explored.

Nutrients leaching into watercourses from fertilisers have potential soil enrichment impacts downstream, down-slope and such enrichments can lead to proliferation of bracken (*Pteridium aquilinum*). The use of herbicides is frequent in Glensaugh to control bracken and some other weed species across the farm. The potential effect of herbicides on soil and water has not received much attention at Glensaugh, since pesticide concentrations are not monitored by ECN on Birnie burn, or by SEPA in the Devily burn. However, herbicide applications follow health and safety regulations, and as the water quality is in good to high overall condition in Devily burn, it is reasonable to expect that the environmental impact of pesticides is low.

[15] The use of plastic from silage wrap contributes to GHG emissions due to plastic production, and has adverse impact on ecosystems and human health due to the accumulation of plastic object and particles, when not properly recycled.
[16] Both the CFT and AgRE Calc are amongst the three recommended tools for farm-based carbon audits in Scotland (Leinonen et al., 2019).
[17] Available online: https://coolfarmtool.org/

Small scale rotational heather burning is part of the semi-natural vegetation (where heather-dominated) management strategies used at Glensaugh. The impact of these fires in terms of ecosystem services, habitats, and soil conditions depends particularly on the scale of the fires, their severity, and frequency. Controlled heather burning is deemed to have a positive effect on forage quality and productivity for livestock and grouse. Managed fires can also reduce heather canopy density and reduce fuel load. Heather burning gives rise to GHG emissions, but from some studies, the short to medium effect of managed burning seems to favour long-term carbon sequestration potential in moorlands, and minimise direct carbon losses by probably reducing the occurrence of more severe wildfires. This combination of potential effects may make the effect of small-scale moorland burning at Glensaugh neutral in the medium and long term (Table 10), but this is still a very contested subject with much that is still not well understood. The flipside of managed burning is that it can negatively affect water quality, soil micro biodiversity, above-ground biodiversity, and also have a negative visual and aesthetic impacts, which can be greater or lesser depending on the scale, severity and intensity of this practice (see Davies et al., 2016 for details).

Woodland management and woodland expansion

Existing woodlands in Glensaugh form relatively continuous and connected forest strips (see Fig. 2(b)). Most of existing woodlands in Glensaugh involve native conifer and mixed woodlands, which along with forest connectivity is expected to enhance biodiversity conservation. Woodlands have increased by 5% in extent over the last 10 years. Most of the new plantations are dominated by conifers, mainly Scots pine. The latter species accounts for more than two thirds of trees planted since 2012. All forest compartments, though dominated by Scots pine, include other native tree species, and into a lesser extent non-native tress (i.e. Larch). Sessile oak accounts for 13 percent of trees planted since 2012, larch a 10 percent of the planted trees. Other native tree species, such as Ash, Hazel, Aspen, Holly and Juniper together account for 8 percent of trees planted since 2012.

Woodland expansion impacts in Table 10 define two contrasting states: (i) A commercial oriented timber plantation, usually comprising mono-specific and fast-growing crops; (ii) A Seminatural woodland managed to enhance biodiversity conservation and amenity production. Woodland expansion in Glensaugh is somewhere in between these two contrasting states. Scots pine dominated woodlands are expected render revenues from timber and biomass production in the future. Income diversification through timber production is an important motivation for recent woodland expansion in Glensaugh. Nonetheless, the fact that woodland expansion basically is based on a mix of native species, instead of more productive timber species (e.g. Sitka spruce), highlights that woodland expansion in Glensaugh respond to broader objectives, such as biodiversity conservation.

Thought woodland expansion is usually deemed as a carbon offsetting activity, this offsetting potential needs to be carefully examined. For instance, woodland plantations taking place in areas dominated by organo-mineral and organic soils, and using moderate to high soil disturbing ground preparation techniques (e.g. light to heavy machinery), can lead to significant soil carbon stock losses rather than gains. Recent scientific literature highlights the limitation of woodland expansion to deliver net carbon gains in Scotland, in particular when organic (peaty) soils, low yielding tress or low quality soils are involved (Friggens et al., 2020; Matthews et al., 2020).

Glensaugh has a mix of mineral and organo-mineral soils in the areas where woodland expansion has taken place, or is expected to take place (see sections A.2.4.2 and A.3). West's (2011) report, which is the reference used for the Woodland Carbon Code (WCC)[18] in the UK, indicates that ground preparation involving the use of machinery for ploughing (shallow turfing) and scarifying, can result in soil carbon release of up to 10 percent of initial carbon stock when trees are planted in organo-mineral soils. The latter percentage drops to 2 percent when trees are planted on mineral soils. Considering West (2001 and 2018) soil carbon release and sequestration look-up tables, and own carbon sequestration estimates based on the Forest Yield Model (Matthews et al., 2016), it is estimated that net annual carbon dioxide (CO_2) sequestration in tree biomass and soil debris had accrued 128 tonnes at Glensaugh by 2018 (Table 11) (see and sub-section A.2.4.2 for details). Carbon sequestration potential is expected to increase over the next years, partially offsetting GHG emissions from

[18] The Woodland Carbon Code is the voluntary standard for UK woodland creation projects to claim woodland expansion CO_2 sequestration. This standard involves independent validation and verification to provide assurance and clarity about the carbon savings in sustainably managed woodlands (more information: https://www.woodlandcarboncode.org.uk/)

livestock farming in Glensaugh. Further woodland expansion has the potential to fully offset these emissions and create further business opportunities.

In addition to the relevance of global climate change regulation services associated with forests carbon sequestration, woodland expansion has the potential of enhance multiple ecosystem services. For instance, planting improved pastures and semi-natural plant communities, such as acid grassland or dwarf shrub heath with coniferous and/or broadleaf trees would increase the provision of timber and fuelwood (biomass), while improving microclimatic regulation (both in winter and summer time), purifying water and air through the absorption of pollutants, and attenuating water flows and soil erosion (Table 10). But of course, it will also reduce the total area of grassland available for livestock grazing.

Woodland expansion can involve multiple trade-offs in the provision of ecosystem services. Plantations, and in particular mono-specific ones oriented to maximise timber production (i.e. using non-native fast growing species), can have a negative effect on ground vegetation cover when compared with semi-natural plant communities, but also on some animal species communities, such as carabids. Woodland expansion if properly done can enhance habitat connectivity for species such as woodland birds (Fleishman et al., 2014). Still the evidence on positive and negative effects of woodland expansion on wild plants and animals in the UK is limited and patchy (Burton et al., 2018). While there is no definitive relationship between tree age and biodiversity, there is evidence of an increase in biodiversity with stand age (Barsoum et al., 2016). Only a small proportion of Glensaugh woodlands are mature, while the vast majority of woodlands are younger than 10 years old. Hence, it is expected that the potential positive effect of woodland expansion on biodiversity would take some years yet to be reached.

Table 11 Estimated indicators of impacts of Glensaugh enterprises on natural capital

Specific impacts indicators	Enterprise	Quantitative and monetary indicators				
		Unit [1]	Period	Average value and variation over the period		Value 2018
				Mean	SD	
	Quantitative indicators (physical)					
GHG emissions[2]	Hill sheep	t CO_2 e/SLU	2006-2018	1.42	0.04	1.46
	Low ground sheep	t CO_2 e/SLU	2006-2018	1.50	0.14	1.39
	Beef-cattle	t CO_2 e/SLU	2006-2018	2.68	0.27	2.45
	Deer	t CO_2 e/SLU	2006-2018	1.32	0.08	1.44
	Total livestock	t CO_2 e	2002-2018	411.4	37.4	343.6
	Fertilizers & lime	t CO_2 e	2002-2018	69.6	48.7	28.5
	Biomass (heating)	t CO_2 e	2012-2018	10.8	4.9	10.8
	Electricity consumption	t CO_2 e	2010-2018	30.44	10.41	45.50
	Fossil fuel consumption	t CO_2 e	2002-2018	0.53	0.06	0.45
	Forestry (tree biomass & soil debris)	t CO_2 e	2002-2018	-46.97	-32.51	-127.85
	Improved grassland	t CO_2 e	2002-2018	-37.09	-	-37.09
Land use change	Grassland to forest	ha/year	2010-2018	7.15	4.35	6.8
Water pollution	Nitrate (as NO_3^- - N)	mg/l	2002-2015	0.15	0.08	-
	Phosphate (PO^{3-} - P)	µg/l	2002-2015	5.94	4.67	-
	Monetary indicators (in £, 2018 prices)					
Ratio profit/GHG emissions	Hill sheep	£/t CO_2 e	2006-2018	97.39	74.46	100.54
	Low ground sheep	£/t CO_2 e	2006-2018	123.44	47.07	187.74
	Beef-cattle	£/t CO_2 e	2006-2018	36.86	42.97	130.35
	Deer	£/t CO_2 e	2006-2018	47.5	59.44	121.79

Notes: [1] SD: standard deviation; SLU: standard livestock unit, t: metric ton.[2] Livestock GHG emissions are estimated using the Cool Farm Tool (Kayatz et al., 2019), including livestock enteric fermentation, manure management, feed production and fertilised induced GHG emissions (see sub-section A.2.3.4).

Woodlands can increase green water consumption[19] due to a higher evapotranspiration, with can be magnified with denser plantations. While less acknowledged, there is evidence suggesting that forest cover reduces water supply at the local small catchment level (Filoso et al., 2017), although the associated processes are complex

[19] Green water is the amount of water either intercepted by the vegetation, or enters the soil and it is absorbed by plants and evapotranspired back to the atmosphere.

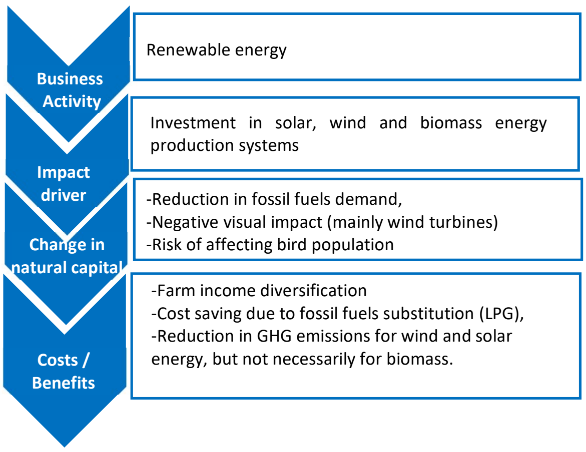
and change over time, and the magnitude and even sign of the effect of forest cover varies across catchments (Williams et al., 2012). Forests can also improve regulation of water supply as well as water quality. In humid and sub-humid areas, the effect of forest water consumption is not expected to be critical for the hydrological balance, though the projected increases of drier summers, and water shortages across much of Scotland may have a negative impact in forest growth (Gosling, 2014), and also on grass productivity[20].

Investment in renewable energy

Farm energy sources have been diversified since 2011 through a series of investments in solar, wind, and biomass energy (Table 2). Those investments have been translated into positive and negative outcomes as summarised in Fig. 7 impact pathway. Investment in renewable energy has diversified farm incomes (e.g. through sales of renewable energy to the grid), generated farm management cost savings (e.g., due to the substitution of Propane by biomass for heating purposes), but has also produced social benefits associated with a decrease in GHG emissions[21].

GHG emissions for electricity and heating energy have been declining at an average rate of 2 percent per year since 2008 in Glensaugh (see subsection A.2.4). Today, on-farm solar energy production is equivalent to 11 percent of current grid electricity consumption at Glensaugh. The wind turbine produced at Glensaugh was equivalent to circa 30 percent of grid electricity consumed between 2013 and 2016.

A potential negative impact of on-farm renewable energy, in particular wind turbines, is associated with perceived negative visual effect of these turbines. This in turn can also have an impact on recreation and tourism opportunities (Table 10). Wind turbines, if not properly located and designed can also have a negative impact on bird populations.



The role of biomass in Glensaugh' s decarbonization process is less clear. Burning wood logs obtained from forestry and agroforestry parcels would emit an important amount of CO_2 (i.e., 1.498 kg CO_2/kg of biomass), which would be only compensated if carbon dioxide uptake through tree biomass growth during the period would be equal to or higher than emissions from biomass burning. In Glensaugh woodland biomass growth (and carbon sequestration) is many times higher than the estimated biomass use and CO_2 emissions from wood log burning to generate heat for the Glensaugh lodge (see Table 8).

Fig. 7 Impact pathway for investment in renewable energy

Cultural services: Recreation, sports, and education

Investments in Glensaugh lodge holiday cottage, and waymarked footpaths over the last few years have increased recreational use opportunities in this farm, with about 100 visitors a year since 2015. Game shooting and fishing occur also in Glensaugh. Current access to recreation does not have a negative effect on livestock,

[20] Recent summer droughts (e.g. 2012/2013) had an effect on grass productivity which seems to affect those livestock enterprises depending more on grazing (hill sheep and deer) (see sub-section A.2.3.3).
[21] UK grid GHG emission have gradually reduced at an annual average rate of 8 percent since 2010 (BEIS, 2019), mainly due to an increase in renewable energy share.

agroforestry, and forestry enterprises. This activity nonetheless increases demands for water and energy, and services related to waste and water waste collection and treatment. Grouse, partridge, pheasant, duck, and woodcock are the main small game species shot in Glensaugh. Fishing takes place in Loch Saugh, and is managed by a local anglers' association. These leased-out recreational and sporting activities allow income diversification, but also secure a relatively constant flow of income that on average represents 10 percent of direct livestock profit from 2014-2018.

2.5 Apply stage – Steps 08: Interpretation and use of the results

This stage of the Protocol is about the interpretation and test of results. Similar to the CES Protocol trials (e.g., Russ and Silcock, 2018), the outcomes of the Protocol application were used to identify risk and opportunities associated to natural capital management. The analysis of farm records data, literature review, and modelling outcomes of this assessment enabled a better understanding of the potential implications of natural capital related risk and opportunities for Glensaugh farm.

Glensaugh natural capital assessment set the main focus on livestock, crop, and forestry activities, and to a lesser extent on renewable energy production and cultural services. This assessment put a strong emphasis on GHG emission reduction efforts, as a part of the Glensaugh climate positive farm initiative, and in response to Scottish net-zero carbon farming target. Thought, the potential effects of farm activities on water quality and biodiversity loss were also analysed in more detail and discussed, in view of ECN data and other information available. In the light of the outcomes of this assessment, a set of natural capital-, market-, and policy- related risk and opportunities have been identified. A number of natural capital risks and opportunities were identified and discussed with the farm manager. The risk and opportunity assessments also considered risk factors and opportunities related with global or national drivers that can affect land-based business across Scotland. The potential influence that these latter risk and opportunities can have for Glensaugh are also discussed.

2.5.1 Natural capital related risks

Climate change

Climate change can negatively affect the productivity and profitability of livestock enterprises. Animal and crop health can drop considerably due to an increased pressure of pests and diseases, heat and water stress, or winter storms, for example. Climate change is expected to result in increasing frequency and intensity of extreme rainfall events, but also increased summer drought risk (ASC, 2016). For example, models predict that up to 40-50 percent of prime agricultural land might experience moderate to severe drought risk by 2050 in Scotland (Brown et al., 2011).

For instance, a potential increase in the frequency of poor summers, characterised by higher rainfall and low soil temperature, could severely affect the productivity of livestock systems that depend on own produced winter-feed in Glensaugh, as the quality of this feed declines under poor summer conditions. Prolonged summer droughts along with higher temperatures and water stress, on the other hand, can also negatively affect grassland productivity and animal health (sub-section A.2.3.3).

An increase in the frequency and intensity of extreme climate events can affect all farm enterprises, from renewable energy production to recreational uses. This would demand climate change adaptation strategies, through more climate resilient production systems.

The risks posed by climate change are relevant, but also, they raise opportunities which are worth considering in designing adaptation strategies. Increases in temperature in spring and autumn can extend the grazing season, allowing for longer outdoor grazing, which in turn would reduce per-unit feeding cost (see sub-section A.2.3.3, e.g., hill sheep). A rise in temperature and CO_2 atmospheric concentration can increase crop and tree productivity through CO_2 fertilization, at least in the short to medium terms, as long as nutrient-limited soils, such as peat, are avoided (not planted). As a relatively high proportion (36%) of Scottish forests is on peat soils, hence the potential benefits of higher CO_2 concentrations for forestry may be minimal in existing forest (ASC, 2016). Investing in woodland expansion for carbon sequestration when tree species and soil are carefully selected can potentially increase carbon offsetting opportunities.

Habitats and wild populations

Woodland expansion on semi-natural plant communities (e.g. acid grassland and dwarf shrub heath), especially when involving non-native fast-growing species may reduce wild species diversity associated with open ground, but increase woodland-associated biodiversity. Likewise, some practices such as rotational heather burning in moorland and heather areas can affect both above-ground biodiversity and soil microbial communities, as well as hydrology. Woodland and seminatural habitats can be negatively affected by the expansion of invasive plants like bracken or Rhododendron. Non-native tree species such as Sitka spruce can also be considered as invasive species when native woodlands are encouraged, or there is need to protect semi-natural plant community habitats (e.g., Nygaard and Øyen, 2017). Sitka spruce is currently grown in several Glensaugh's neighbouring land holdings as commercial timber plantations. Biodiversity and habitat conservation concerns need to be included in woodland expansion and grassland management strategies in Glensaugh, such as using native woodland species, and/or maintaining a mosaic of habitats to favour a wider range of wild species.

Soil fertility and nutrients

Soil fertility is a limiting factor for agriculture in areas dominated by acidic soils, such as the pastures at Glensaugh. Occasional liming of permanent pastures of lower quality is one of the farm management strategies adopted at Glensaugh to increase grass productivity. Liming has in general a positive effect on the mobilization of nutrients from organic matter, but due to an increase in microbial activity it also increases CO_2 emissions (Smith et al., 2010). Ceasing liming as a means to reduce GHG emissions may negatively impact soil fertility, and hence sheep flock's productivity. There is a marked trade-off in the use of liming and chemical fertilisers, as liming has reduced the need for fertilisers in Glensaugh since 2002. This latter has been translated into a reduction in GHG emissions, some improvements in water quality, and a clear reduction in costs (see sub-section A.2.3.3).

However, nutrients, herbicides and other pesticides can all leach into watercourses. Nutrient leaching, in particular, can enrich downstream and down-slope soils, which can encourage bracken proliferation. Uncontrolled bracken expansion can quickly shade out and replace valuable habitats, and species-rich grazing areas. There are many other negative effects of bracken invasion, from making recreational access more difficult, harbouring ticks, to hampering tree regeneration, or even increasing fire hazards (SEARS, 2008). Bracken control demands further chemical (herbicides) and mechanical control measures, but these increase grassland management costs, and can affect soils and water quality due to compaction and pesticide leaching. Debates around the negative effect of herbicides on human health have placed widely used herbicides, such as *glyphosate*, under increasing public scrutiny. This demands development and use of safer, effective, and environmentally friendly products and weed control techniques.

2.5.2 Market and policy related risks

Fluctuations and volatility in livestock and input market prices have had large effects on net farming profits in the past, in particular, for deer and sheep enterprises. Brexit and more recently the coronavirus pandemic pose critical risks and enlarge uncertainties over the future of the Scottish agricultural sector. Both situations can have large effects on food and input supply chains and markets, but also affect future agricultural policies, payment schemes, and food supply systems.

In Scotland, as a consequence of Brexit, the European Union (EU) Common Agricultural Policy is gradually to be replaced by a domestic agricultural policy. Progressive simplification and improvements in existing schemes are expected from January 2021 to 2024, during which time potential new schemes for longer term rural policy will be piloted (Scottish Parliament, 2019). The effect of Brexit on Glensaugh's farm income is uncertain. This would depend upon payment levels and conditions under the Agricultural Bill replacing EU Basic payment schemes in Scotland, but also on whether the UK can negotiate favourable trade agreements with the EU and beyond. Scotland's lamb sector is more vulnerable to changes in trade agreements than beef, as its reliance on exports is greater than for beef, i.e. 26% of total lamb sales are exported, versus 6% for beef (Scottish Government, 2019a). Still, most UK lamb and beef sales depend on local market demands, and those demands are currently (and will be in future) affected by a most likely pandemic global economic recession.

Likewise, input prices and price volatility may rise, due to supply limitations and/or increased transportation and production costs. Phosphate fertilisers in Glensaugh are mainly imported (e.g., Gafsa phosphate products from Tunisia). Input markets can be significantly affected by changes in raw materials and energy prices. Raw material supply limitations can have cascade effects on input prices. Environmental policies may also affect input markets, for instance environmental taxes such as carbon tax on fossil fuel consumption or emission. Following the impact of COVID-19, green recovery strategies may include mechanisms such as setting or raising carbon prices for sectors of the economy which do not bear the full costs of emitting GHG. Carbon taxes are not actually applied to the agricultural sector directly, but this sector can be affected by changes in input prices due to carbon tax policies, if were to be adopted.

Improving productivity and efficiency is key for maintaining livestock enterprises' profitability and business resilience. At Glensaugh changes in livestock management, involving more precise management decisions based on meteorological data, soil, and winter-feed analysis, have reduced some livestock and grassland management costs, in particular for hill sheep flocks. Those changes also resulted in some environmental indicator improvements, such as reductions in total GHG emissions. Future agricultural policies in Scotland may adopt the principle of *public (government) payments for public goods*, which targets the delivery of public goods as part of farming income generation strategies. It is expected that net zero (carbon) aspiration will be also a relevant driver for farming systems transformation as discussed in the next sub-section.

Finally, changes in consumer preferences and behaviour regarding animal health and welfare, and climate sensitive production systems can drive changes in livestock markets, by reducing meat demand or alternatively demanding low carbon livestock products, or more sustainable production systems in general. A higher adaptation capacity to respond to new market and policy scenarios is critical. And a higher adaptation capacity is intrinsically attached to more resilient and enhanced natural capital. Glensaugh livestock farming systems do not seem to have critical negative impacts on natural capital conditions, given the relatively low stocking rates and the adoption of environmental-friendly practices (e.g. reduced use of agrochemicals) over the last 15 years. The latter can support and facilitate a transition to more sustainable farming that can respond to changes in Glensaugh marketing strategies.

2.5.3 Natural capital related opportunities

The other side of risks are the opportunities they convey. Natural capital management and investment can help transformation towards sustainable upland land management, and can align well with policies for delivering climate change goals, such as net-zero carbon farming. Natural capital investment can involve activities such as restoration of habitats, soils, and peatlands, and/or native woodland expansion. It can include green infrastructures, comprising features such as hedgerows, bioretention areas to capture and treat stormwater, and/or the integration of trees and/or shrubs with crops and livestock (agroforestry). A relevant feature of such investments is that they can simultaneously deliver multiple benefits, such as carbon sequestration, improvements in water retention, water quality or flood alleviation, biodiversity enhancement, and the provision of food, materials, and energy.

Evidence-based and spatially targeted natural capital investment and management seem key in developing sustainable, resilient, and efficient farm business strategies, as follows.

Enhancing resilience, environmental and economic efficiency

Soil analysis (for macro nutrients), combined with more precise inputs-application in grassland and livestock management have been proven to decrease production costs, while reducing environmental impacts and risks at Glensaugh over the last 15 years. Still there is room for further improvement, provided their cost-effectiveness. Improving soil quality by increasing organic matter and nutrients will benefit grass and winterfeed quality, and mitigate the effect of drought by enhancing water retention capacity. Extending mob grazing, which is a short-duration and high-intensity (stocking rate) grazing in a small area of pasture, can be used to improve soil health of Glensaugh[22] pastures and reduce frequency of re-seeding. This latter needs to be further examined considering initial investment requirements (e.g. fencing and securing livestock water provision), and the suitability of different livestock breeds to this practice. More extensive versions of mob grazing may involve green infrastructure such as hedgerows, as natural fences, which can generate some additional biodiversity benefits.

Income diversification may be critical for improving Glensaugh' s financial resilience. Non-farming activities represent further opportunities to improve farm profits by both saving costs and as new income sources. The contribution of non-farming activities, such as game shooting, tourism and recreation, forestry, and renewable energy production to direct net farm profits is still relatively low when compared to livestock, but they could potentially offer a fairly stable, and in some cases, increasing source of income.

Diversification seems also desirable in terms of livestock farming activities. Sheep enterprises have shown a good economic and environmental efficiency balance since 2010, whilst beef and deer enterprise improvements have been more significant over the last three years. Livestock enterprises are affected differently by fluctuations in climatic conditions (see sub-section A.2.3.3). Thus, a diversification in livestock enterprises may be also appropriate if the efforts to balance environmental and economic efficiency continue. Indeed, the relationships between net profits and GHG emissions have shown gradual improvements at Glensaugh over the last 10 years for all livestock species, which suggest higher efficiency (see sub-section A.2.3.4). The marginal benefits of increasing environmental and economic efficiency levels, and the trade-offs they may involve need to be further explored.

Continuing the diversification of land-based activities on the farm seems desirable, with special attention to education/research and demonstration activities involving a transition to low carbon energy sources, land uses, and technologies, with a good balance with other environmental goals, such as biodiversity conservation, and minimization of air, soil, and water pollution. Farm income diversification strategies should also give attention to opportunities accrued from the provision of public goods, such as increasing public recreational opportunities, animal welfare, and/or biodiversity conservation. Activities such as: (i) woodland expansion involving a careful selection of species and sites (e.g. native woodlands on mineral soils where there is greater potential for net carbon sequestration); or (ii) extensive livestock systems based mainly on grazing and breeds well adapted to upland farming conditions can potentially favour the delivery of public goods, while also supporting farm income and financial resilience. Likewise, agroforestry expansion can be seen as a potential way to combine both livestock and forestry without sacrificing livestock income. Diversification decisions need to balance environmental and economic efficiency, but also look at potential limitations concerning labour supply.

2.5.4 New agricultural and environmental policies and investment opportunities

Brexit opens up the possibility to better adapt (and simplify) agricultural policies to British farming conditions, but also to environmental policies and initiatives, that contribute to the goals of the UK Government 25-year environmental plan (HM Government, 2018). Brexit may represent an opportunity for a sustainable transformation in the agricultural and forestry sectors, but also brings risk to disrupt the food supply system.

The role of farms in a post–Brexit and post-COVID-19 situation is unclear. Future polices and markets can focus on farming systems producing cheap commodities that mainly benefit off-farm industries, or alternatively on enhancing food-security, or on reducing the environmental footprint of agriculture. The new food economy and the priorities set by the Scottish and UK governments are yet to be defined and tested. The Green Recovery strategies currently discussed by the Scottish and UK governments signal government intentions to lead the way to new social norms aimed at improving productivity while reducing emissions, and negative environmental footprints. The Scottish government needs yet to decide the extent to which they add food-security and self-sufficiency to their priorities.

Future public incentives are likely to be ruled by the 25 Year Environmental Plan's advice to link public payments to farmers for public goods. There is still an intense debate on the acceptance, interpretation and application of this principle (Bateman and Balmford, 2018). The new Agricultural Bill (under revision, and applicable in England)

[22] Rotational grazing is actually practiced on improved grasslands in Glensaugh.

for example foresees the provision of financial assistance [23] for supporting land, water and livestock management in ways that provide public goods, including the conservation of native livestock, promotion of animal health and welfare, and/or contribution to climate change mitigation and adaptation. It is not yet clear the role that the provision of public goods may have in the new Scottish agricultural policy, as Scotland has committed to retaining existing Common Agricultural Policy arrangements at least until 2024 after which new institutions are envisaged.

Other financial opportunities may arise through public funding as a source of natural capital investment, supported by current carbon offsetting initiatives such as the Woodland Carbon Code or the Peatland Code. Carbon offsetting though the WCC is a potential driver for investment in woodland expansion on the farm. This specific natural capital investment alternative is examined in detail later. Payments in relation to water quality or flood management do not seem to be a significant opportunity in Glensaugh. Water quality in Glensaugh is in good condition, and the farm is located in an area with a relatively low vulnerability to flood risk.

2.6 Apply stage – Steps 09: Take action

Actions for consideration

This stage is about how to apply the natural capital assessment outcomes to existing processes (e.g., business operating decisions, stakeholder awareness and engagement, business reporting). In light of the natural capital assessment outcomes and lessons learned during the process, four type of actions are proposed for consideration to Glensaugh decision-makers and JHI researchers.

Improving internal data and reporting: Glensaugh is a unique case study for the diversity of information available to conduct a comprehensive natural capital assessment study. However, data is relatively dispersed and there are some information gaps for assessing the condition of natural capital and the provision of specific ecosystem services, which include for example soil organic matter, and consumption of resources such as biomass for heating purposes, or ground water quality and consumption. Collecting this information can help improving natural capital condition and impact assessment in Glensaugh. Likewise, this assessment has identified the need of improving livestock farming GHG emissions (see sub-section A.2.3.4).

In more general terms, specific actions to improve internal data and reporting involve:

- Development of natural capital accounts for the farm and promote their integration into the James Hutton Institute and Glensaugh farm reporting.
- Identification of priority direct or indirect indicators (set of metrics) to track changes in natural capital condition and impacts, such as soil organic matter and nutrients, soil pH, biodiversity index, GHG emissions, carbon stock and sequestration, water quality, and use of inputs (fertilisers, pesticides, fossil fuels).
- Analyse GHG emissions due to livestock farming in more detail, preferably using more sophisticated models (e.g. IPCC Tier 3 approaches), as different carbon auditing tools deliver divergent results, making the GHG livestock emissions more uncertain.

Funding and investment: Integrating natural capital thinking into strategic land management decisions can also create further opportunities for funding investment aimed at enhancing natural capital resilience and its maintenance. Further actions for consideration encompass:

- Identify priorities and investment opportunities for maintaining and enhancing natural capital in Glensaugh.
- Integrate natural capital impacts and dependencies assessment in the feasibility analysis of potential investment projects at Glensaugh.

[23] Financial assistance many be given only in England by way of grant, loan or guarantee or in any other form.

Working with stakeholders: Raising the awareness of natural capital and ecosystem services amongst farm managers, the JHI staff and Board, local communities, and other stakeholders can help their engagement in the integration of natural capital into research priorities, demonstration and training activities, farm production systems and marketing**.** Specific actions for consideration include:

- Demonstrate the benefits of incorporating natural capital into land use decisions and research priorities.
- Raise awareness amongst stakeholders of the role of natural capital for maintaining healthy and resilient businesses, economies, and societies.

Roll-out of the Protocol: The experience gained with the application of the Protocol in Glensaugh suggests that this approach has potential to be beneficial for other farms and estates across Scotland. The Protocol could help to evaluate and promote land use and management strategies that generate business opportunities, while also enhancing natural capital. To facilitate the Protocol roll-out we suggest:

- Assessment of the changes in the state and condition and impacts on natural capital over time. Creating a natural assets register would help in recording current extent and condition and changes over time of the natural capital base. Defining a set of key indicators (metrics) of impacts of land-based businesses on natural capital, along with the natural assets register, would help create the context for integrating natural capital into land management decisions and future public (government) payments.
- Exploring opportunities to mainstream natural capital assessment and reporting, including alternatives to tie natural capital reporting to other mandatory reporting processes (e.g. for pillar 2 payments, site conditions for Natura 2000, etc.)
- Using qualitative natural capital approaches for those impacts on natural capital and ecosystem services that are not easily measurable and monetarized, along with indicators of financial performance to inform land use and management decision-making. Accounting for wider business and societal cost and benefits can inform about the sustainability of investment alternatives.

3 Prospective natural capital assessment of woodland expansion investment

As indicated before, the Protocol was applied to a practical natural capital investment example involving woodland expansion in Glensaugh. This application aimed at identifying, measuring, and valuing natural capital impacts and benefits to inform the design of the woodland expansion project in Glensaugh. This report explores the potential contribution of alternative woodland expansion options to the JHI climate positive farming initiative (JHI, 2019), which goes beyond climate change mitigation objectives, as it also aims to improve biodiversity on the farm. Accordingly, this prospective Protocol application also considers the likely natural capital and ecosystem services impacts and trade-offs between carbon sequestration, timber production, biodiversity conservation, and other ecosystem services. The two latter evaluated in qualitative terms.

In what follows, this section is structured following the Protocol stages and steps (Fig. 1).

3.1 Frame stage – Step 01: Get Started

The farm manager at Glensaugh has identified the opportunity to expand total woodland area with potential support from the Woodland Grant Scheme, and/or by issuing carbon credits through the Woodland Carbon Code, as a business diversification opportunity for Glensaugh. Woodlands currently cover about 7 percent of total Glensaugh land area, which is significatively lower than the mean of 18 percent of land covered by forest in Scotland as a whole. Doubling woodland area (from current 7 percent to 14 percent) is one of the strategies proposed by the project *Glensaugh: Scotland's climate-positive farm*, which aims to identify options to transform Glensaugh into an economically and environmentally sustainable farm that is climate positive and biodiversity rich. This natural capital assessment case study aims to inform the expected economic and environmental benefits and trade-offs, associated with different woodland expansion alternatives in Glensaugh.

3.2 Scope stage – Step 02 and 03: Defining the objective and scope of the natural capital assessment

This case study aims to analyse the potential of woodland expansion to sequester carbon and offset GHG emissions in Glensaugh, and the trade-offs and synergies involved with biodiversity conservation and the provision of other ecosystem services.

The analysis provides high level information on the financial cost and benefits of woodland expansion, along with natural capital (environmental) cost and benefits, mainly involving changes in carbon stocks in vegetation and soil. The case study considers woodland expansion with seven UK-native (Sessile oak, Birch, Scots pine) and non-native (Sitka spruce, Douglas fir, Larch (hybrid), Beech) forest species. For all those species, or combination of species, the case study analyses whether woodland expansion is an economically efficient pathway to offset the GHG emissions from the farm, and what are the main challenges involved.

The woodland expansion analysis considered the farm manager's preferences in terms of the potential areas for planting trees, as well as environmental restrictions to afforestation (e.g., avoiding peat soils), and economic restrictions, e.g. avoiding areas with higher opportunity cost , such as low-ground pastures which have a higher per hectare crop and livestock productivity and profitability. Glensaugh potential woodland expansion area covers about 113 ha of mainly improved and semi-natural grassland and other semi-natural plant communities. The currently planned woodland expansion could increase the total woodland area to a 18 percent of the total farm area.

According to the Native Woodland potential map (Towers et al., 2004) the planned woodland expansion area is suitable for growing native woodland plant communities, mainly Oak-Birch plant communities, but also mixed and pure Scots pine woodlands (Fig. 8). The suitability and potential productivity of Glensaugh land to growing a selection of native and non-native conifers and broadleaves is examined using the Ecological Site Classification (ESC) model (Pyatt et al., 2001)[24]. The ESC model defines species-specific yield class distribution: yield class is an index used in the UK to indicate the potential productivity of even-aged tree stands[25]. The ESC model suggests a low potential timber productivity for native woodlands, while the potential is higher for non-native species, such as Sitka spruce (Fig. 9).

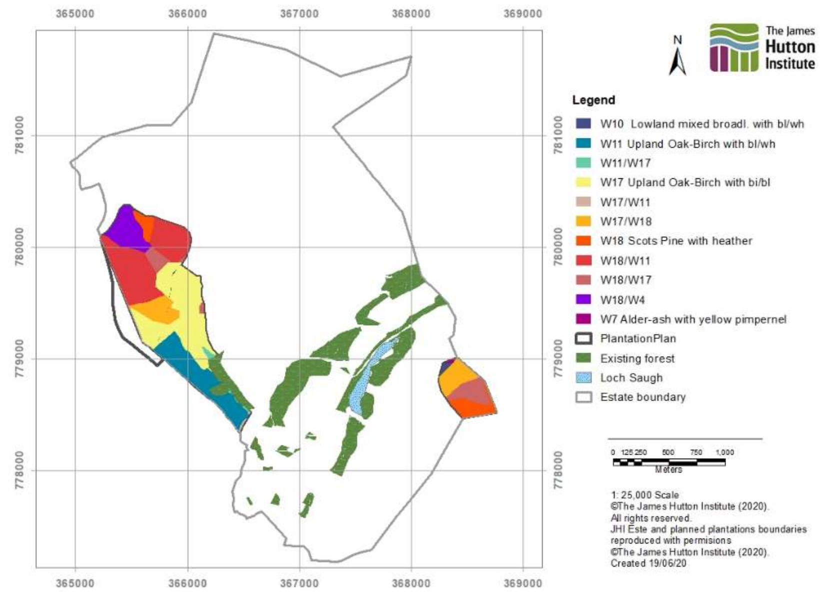


Fig. 8 Planned woodland expansion area, existing forest, and native woodland potential

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

[25] The yield class is based on the maximum mean annual increment of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a standard management prescription (Matthews et al., 2016).

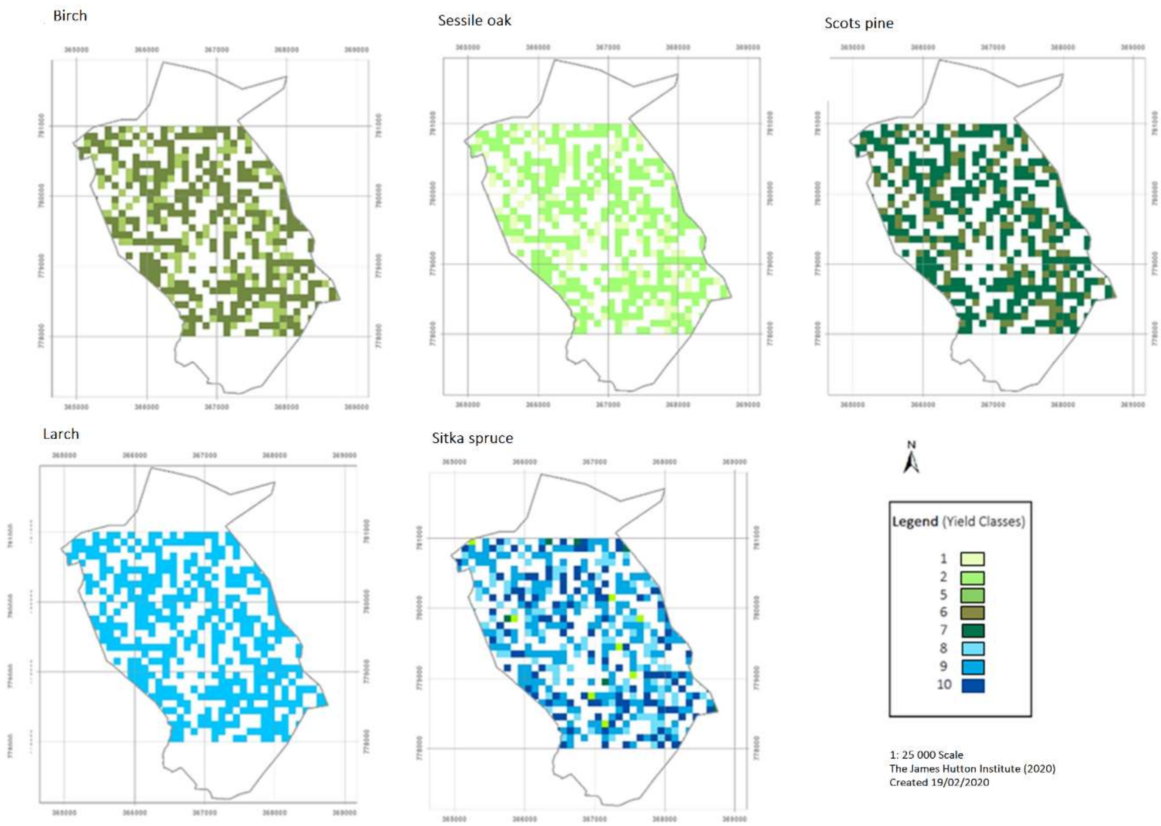


Fig. 9 Yield class distributions by species according to the Ecological Site Classification model

3.3 Scope stage – Steps 04 Determine impacts and dependencies

Forest growth strongly depend on soil conditions (e.g., nutrient availability and limitation), but also on water availability. The conservation of current open-ground biodiversity and local ecosystems is relevant to provide regulating services such as pollination, biological pest, and disease control, but woodland expansion has the potential to lead to multiple material impacts on ecosystem services, as follows. Planting improved grasslands with coniferous and/or broadleaf trees would increase the provision of timber and fuelwood, and carbon sequestration (in particular when mineral soils are involved[26]), while improving microclimatic regulation (both in winter and summer time), purifying water and air through the absorption of pollutants, attenuating water flows, and reducing soil erosion. Woodland expansion can also potentially enhance recreation value, as well as its use for mushroom picking and foraging.

On the flipside, woodland expansion can reduce the provision of ecosystem services. For instance, mono-specific tree plantations can have a negative effect on ground vegetation cover when compared to semi-natural plant communities, and can potentially affect some animal species communities, such as carabids. There is evidence that forest biodiversity increases with stand age, and that woodland expansion if properly done can enhance habitat connectivity for species such as woodland birds. Still the evidence on positive and negative effects of woodland expansion in the UK on wild plant and animal communities is limited and patchy (Burton et al., 2018). Woodlands can also increase water consumption though higher evapotranspiration rates than grasslands, which can be more relevant in semi-arid or arid areas, than in Scotland. However the associated forest-water processes are complex and change over time (Williams et al., 2012).

The impacts of woodland expansion on natural capital will be contingent to the management practices adopted.

[26] The additionality of woodland expansion in terms of net carbon sequestration (i.e., gross CO_2 sequestration minus soil carbon emissions due to ground preparation) is expected to be higher in areas with mineral soils, and higher tree growth productivity potential (Matthews et al., 2020).

Table 12 highlights potential impacts that woodland expansion can have in the delivery of ecosystem services, considering different stages of woodland expansion, from pre-establishment, establishment, management and harvesting, and considering contrasting management practices or strategies.

Table 12 Potential impact of woodland expansion features on ecosystem services delivery

	Provisioning				Regulating & maintenance									Cultural services			
	Cultivated plants and reared animals	Wild plants and animals (biomass)	Water supply	Energy supply	Pest and disease control	Global climate regulation	Local climate regulation	Control of erosion rates	Habitats and wild species	Pollination	Freshwater quality regulation	Regulation of soil quality	Water flow /flood control	Aesthetic	Cultural and heritage values	Knowledge systems Social relations	Recreation and ecotourism
Ground preparation mechanised		↘ Moderate decline				↘ High decline		↘ Moderate decline	↘ Moderate decline		↘ Low decline	↘ Low decline	↘ Low decline	↘ Moderate decline			↘ Moderate decline
Ground preparation by hand						→ Neutral		→ Neutral	→ Neutral		→ Neutral	→ Neutral	→ Neutral	→ Neutral			→ Neutral
Planting woodland amenity/conservation	↗ Moderate improvement	↗ Low improvement	→ Neutral	↗ Low improvement		↗ Moderate improvement	↗ Moderate improvement	↗ Low improvement	↗ Low improvement		↗ Moderate improvement	↗ Moderate improvement	↗ Moderate improvement	↗ Low improvement			↗ Low improvement
Planting commercial species	↗ High improvement	↘ Moderate decline	→ Neutral	↗ Moderate improvement	↘ Low decline	↗ High improvement	↗ Moderate improvement	↗ Low improvement	↘ Low decline		↗ Moderate improvement	↗ Moderate improvement	↗ Moderate improvement	↗ Moderate improvement	↗ Moderate improvement		↗ Low improvement
Fertilising soils	↗ High improvement	↗ Low improvement				↘ Moderate decline			↘ Moderate decline		↘ Moderate decline						
Controlling pest and diseases (pesticides)		↘ High decline			↘ High decline						↘ Moderate decline						
Controlling pest and diseases (biological)		→ Neutral			↗ Low improvement												
Harvesting – selective logging	↗ Moderate improvement	→ Neutral				↘ Low decline	→ Neutral	→ Neutral			→ Neutral			→ Neutral			→ Neutral
Harvesting – clear cutting	↗ High improvement	↘ Low decline				↘ Low decline	↘ Low decline	↘ Moderate decline			↘ Moderate decline			↘ High decline			↘ High decline

High improvement ↗ | Moderate improvement ↗ | Low improvement ↗ | Neutral →
Unknown/not relevant | Low decline ↘ | Moderate decline ↘ | High decline ↘

Source: Own elaboration, adapted from the Natural Capital Coalition (2018:42-44) forest products sector guide.

The selection of species and specific practices can have differential impacts on natural capital and ecosystem services delivery. Less intensive (e.g. manual) ground preparation can greatly reduce soil carbon losses when compared with more disturbing ground preparation techniques, such as ploughing, which also would increase GHG emissions. Fertilization and chemical pesticides used on the young trees can affect ground and surface water quality, while pesticides when not selective can affect wider groups of plants and animals (and human health). Non-native species can be more productive and sequester more carbon than native species (in particular the slow growing ones) (Matthews et al., 2020), but also consume more water and arguably may support lower biodiversity than many of the native tree species.

Forest harvesting can increase soil erosion leading to deteriorating water quality, in particular in sloping areas. Practices such as selective thinning define current forestry operations in Glensaugh. Using continuous cover forestry systems based on selective thinning is deemed better protect soil from erosion and nutrients loss when compared to clear-cut forestry (Reynolds, 2004; Weis et al., 2006). Selective thinning can reduce negative effects of clear-cutting, but will also increase timber harvesting and management costs.

3.4 Measure and value stage – Step 05: Measure of impacts drivers of woodland expansion

3.4.1 Timber and biomass production

The main impact driver for timber and woodland production is the suitability and productivity of land to grow tree species. The suitability is affected among others by soil and climate characteristics and conditions. Soil moisture, nutrient availability, and soil all affect the ecological suitability for growth of different tree species. Aspects of climate such as warmth (temperature) and wetness (rainfall) are the most significant factors used to define climatic zones for tree species choice. Continentality and windiness can also influence the conditions for tree growth at a site and therefore timber production as well (Pyatt et al., 2001). Climate change is also a significant driver of tree growth due to an expected increase in temperature (extending the growing season) and CO_2 atmospheric concentrations (CO_2 fertilization). This latter can have a positive effect on tree growth in areas when there are no soil nutrients limitation problems

Timber production potential varies within species and yield classes. Timber growth potential estimations for Glensaugh are based on timber production tables taken from the Forest Yield model by species, forest stand age and yield class, which have been applied to the predicted yield classes for Glensaugh using the Ecological Site Classification model (see sub-section A.3 for details). The yield classes predicted by the ESC depend on climatic zones, windiness, continentality and soil characteristics (Pyatt et al., 2001). As indicated before, this model suggests a very low potential to grow broadleaved species for timber, in particular oaks, when compared with other native (Birch and Scots pine) and non-native species. Timber growth and yield potential, according to ESC estimates, is significatively higher for non-native conifer species such as larch and Sitka spruce, than for any native species (Fig. 10).

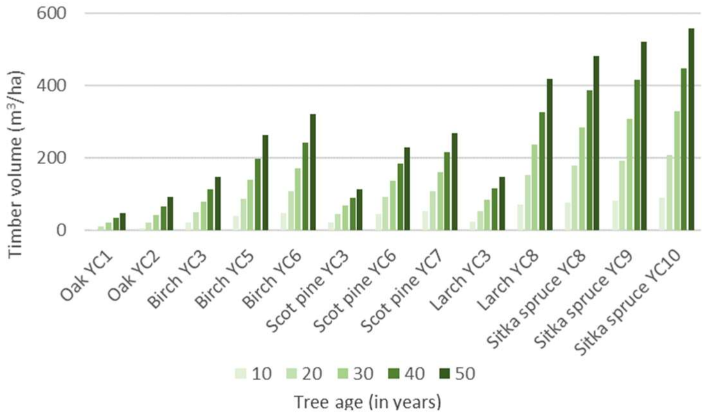


Fig. 10 Timber production potential by species and yield class

3.4.2 Climate change regulation

The main impact drivers for carbon sequestration (global climate change regulation service) by trees are the same as for growing timber, as carbon sequestration depends on tree biomass growth[27]. Soil attributes along with forest management characteristics influence in turn GHG emissions from forestry. For instance, woodland plantations taking place in areas dominated by organo-mineral and organic soils, and using moderate to high soil disturbing ground preparation techniques, can lead to important soil carbon stock losses (West, 2011).

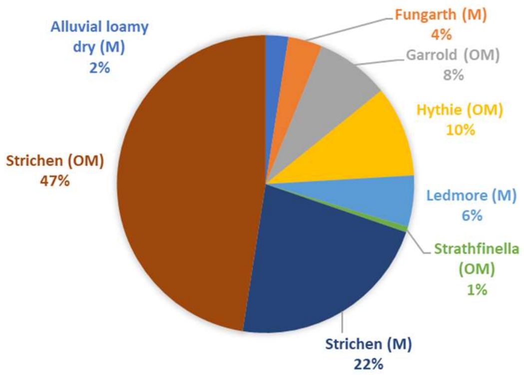
Glensaugh has a mix of mineral and organo-mineral soils in the areas where woodland expansion is planned (Fig. 11). West (2011), which is the reference used for the Woodland Carbon Code[28] in the UK, indicates that ground preparation involving the use of machinery for ploughing (shallow turfing) and scarifying, can result in soil carbon release of up to 10 percent of the initial soil carbon stock, if trees are planted in organo-mineral soil, or 2 percent when trees are planted on mineral soils. Initial soil carbon release would average 39.30 t CO_2 per hectare when ground preparation techniques used imply a moderate soil disturbance. These emissions can be reduced by half when ground preparation techniques used encompasses low soil disturbance, such as hand turfing and mounding. Even though low soil disturbance ground preparation would imply GHG emission savings, labour can be a limiting factor as this is more labour-intensive than mechanical ploughing. Carbon sequestration balance accounts for soil carbon emissions in this case study assuming a moderate ground preparation intensity, but low disturbance figures are also calculated (Fig. 11).

Carbon sequestration due to tree biomass growth is estimated based on non-linear timber growth functions, and expansion factors that relate timber volume with total carbon stock in aboveground and root tree biomass (see sub-section A.3.1 for details). Non-thinning models are assumed, and the forest rotation length for each species is defined by optimizing timber and /or carbon benefits for every 100 m x 100 m grid cells (Fig. 9). Carbon

[27] Estimated carbon sequestration depends on timber growth. Expansion factors that relate timber volume with total carbon stock in aboveground and root tree biomass are considered (see sub-section A.3.1 for details).

[28] The Woodland Carbon Code (WCC) is the voluntary standard for UK woodland creation projects to claim woodland expansion carbon dioxide sequestration. This standard involves independent validation and verification to provide assurance and clarity about the carbon savings in sustainably managed woodlands (see: https://www.woodlandcarboncode.org.uk/)

sequestration in soil debris accounts for the estimates provided by West (2018) WCC look-up tables (see sub-section A.3). Though we suggest to look at the WCC soil carbon sequestration results with caution, as a recent studies suggests that the effect of tree planting in soils with a high organic content would have limited net soil carbon gains in Scotland (Friggens et al., 2020).



Soil type	Estimated carbon stock t C/ha (0-30 cm)	Soil carbon release ($t\ CO_2$/ha) Moderate disturbance (10%)	Soil carbon release ($t\ CO_2$/ha) Low disturbance (2%)
Alluvial loamy dry (M)	108.22	18.44	6.24
Fungarth (M)	130.81	9.59	0.00
Garrold (OM)	160.08	58.70	29.35
Hythie (OM)	204.49	74.98	37.49
Ledmore (M)	102.94	7.55	0.00
Strathfinella (OM)	85.73	31.43	15.72
Strichen (M)	133.65	9.80	0.00
Strichen (OM)	135.33	49.62	24.81
Weighted average	**140.83**	**39.30**	**18.10**

Notes: Mineral soils (M); organo-mineral soils (OM).
Source Baggaley et al. (in revision).

Fig. 11 Soil type distribution in the woodland expansion planned area

Total carbon sequestration in tree biomass, and soils is estimated for three contrasting woodland expansion scenarios. Those include: (i) timber/biomass production, (ii) climate change mitigation through maximizing carbon sequestration, and (iii) carbon sequestration and biodiversity enhancement with woodland plantations being constrained to native tree species.

Fig. 12 shows the estimated carbon sequestration potential for the three different scenarios in Glensaugh, compared to average GHG emissions from land-based businesses (mainly from livestock production). This figure shows total carbon sequestration potential assuming that 113 hectares of seminatural plant communities and improved grasslands are planted with trees at the same time (in 2020). In this case, it is estimated that there will be an initial carbon emission of up to 4 thousand tonnes of CO_2 due to ground preparation. It is also estimated that carbon sequestration in tree biomass and soil debris can fully offset GHG emissions from all other farm activities in a period of 10 years, even when only native woodlands are planted. Woodland expansion can create further business opportunities in the carbon offsetting market, especially when faster growing species such as Larch or Sitka spruce are planted.

a) Carbon sequestration potential by woodland expansion scenario b) Species distribution by woodland expansion

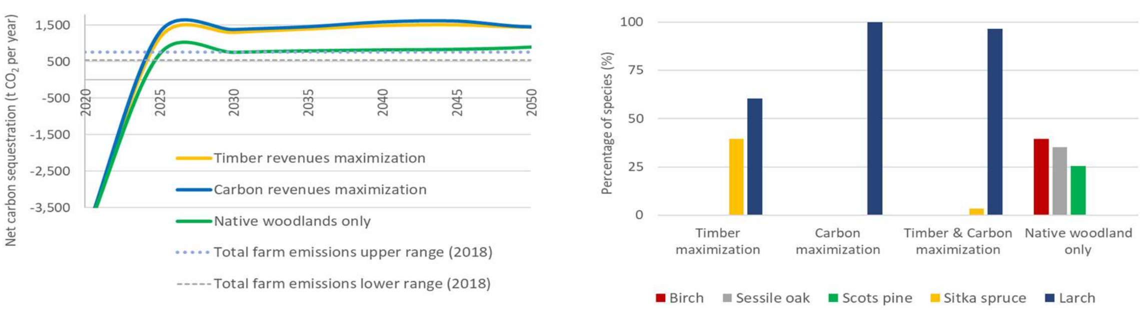


Fig. 12 Net carbon sequestration and species distribution by woodland expansion scenario

It is also estimated that a minimum area of 105 hectares of native woodland (89 percent of planted area) would need to be planted to offset current GHG emissions from Glensaugh activities over the next 10 years (i.e. 'native woodland only' scenario). This area declines to 60 hectares for the 'carbon revenues maximization' scenario, and to 65 hectares for the 'timber maximization' scenario. The results for the 'timber maximization' scenario suggest that planting 40 percent of the area with Sitka spruce, and 60 percent with Larch would maximize timber revenues. When only carbon and both timber and carbon revenues are considered, then planting all or most of the area with Larch is predicted to maximise benefits from carbon sequestration. The difference in predicted benefits between Larch and Sitka spruce is not significant, and planting either of these species or a mix of them would render higher timber and carbon benefits than the other species tested.

3.4.3 Other potential impacts of woodland expansion

Planting woodlands can provide shelter for livestock on the farm, particularly for hill sheep during the winter to protect them from cold and rain which can affect sheep condition. Keeping sheep in good condition is key to maintain their productivity. The effect of woodland expansion on hill sheep condition may not be very relevant at the early stages of the project, in particular if the area is fenced to avoid livestock browsing damage. Trees on-farm systems can enhance productivity and resilience of livestock enterprises when forest patches are incorporated within the grazing areas (England et al., 2020). Hence, new woodland area may only provide the ecosystem service of shelter in areas of trees planted close to or within areas of grassland[29].

Changes in habitats (from grassland to woodlands) can have a positive impact on water and soil quality, which would be more relevant if tree plantations are spatially targeted to absorb diffuse pollutants from agriculture. The role of forests in controlling water flow patterns and maintaining water quality by filtering sediments, nutrients and other contaminants from runoff is well stablished (Creed et al., 2016). Changing the land use from arable or improved grassland to woodlands would be expected to be mainly positive in terms of water quality in Scotland, though some small negative responses would be expected with changes from seminatural habitats with low management intensity to coniferous woodlands (Dunn et al. 2015). Addition of fertilizers and the atmospheric N and sulphur deposition can result in increased soil and water acidification and diffuse pollution (ibid). Despite the previous, the impact of planned plantations on water quality is not expected to be significant at Glensaugh, given that its water courses are in good chemical condition. Woodland expansion can also have a moderate effect on soil quality and soil erosion control. More research is needed to analyse whether the type of woodlands (e.g. conifers versus broadleaved) or selection of species may impact local climate, and water quality regulation services.

In the longer-term woodland expansion can have a positive effect on biodiversity, in particular when native woodlands are involved. Woodland expansion involving native species can enhance habitat connectivity for species such as woodland birds, and in can help support populations of endangered species that depend on woodland habitats (Woodland Trust, 2012).

3.5 Measure and value stage – Steps 06: Measure changes in the state and trend of natural capital

The expected impacts of woodland expansion on the condition of natural capital are mixed. Woodland expansion would result in changes in natural capital state and condition, due to the change in the use of land (i.e., from semi-natural plant communities and improved grasslands to forest), but also due to a reduction in the land available for livestock production. Table 13 shows the predicted impact of woodland expansion on the farm's natural capital asset register. Almost two thirds of woodland expansion would take place on dwarf shrub heath and acid grassland, and about one third on improved grassland[30]. The condition of those broad habitats in 2018 was categorised as stable and improving in some cases (Table 3), and it is expected to keep stable for the remaining semi-natural and improved grassland. Woodland expansion may have mixed effects, with a decrease in soil carbon and changes in wild species diversity, with shifts from dominance by open ground species changes to dominance by woodland species.

Woodland expansion encompasses a variety of benefits that can be translated into business opportunities for income diversification, and benefits for the wider society. Woodland expansion also conveys economic and

[29] An expansion of agroforestry system may provide better shelter services during winter, but also summer days.
[30] According to the Land Cover Map (2007)

environmental trade-offs when compared to maintaining livestock enterprises as the main use of land. A reduction in land available for livestock production, if the current stocking rates are maintained, would imply a decrease in dependency on grazing grass but increased dependency on stored or bought-in feed if the remaining pasture area is not sufficient to feed the stock, and hence this could raise GHG emissions. Stocking densities in Glensaugh sheep heft where the woodlands are to be planned are relatively low (0.16 SLU/ha), and if the planned 113 hectares were planted, the stocking density would increase by 32 percent (0.22 SLU/ha). Relatively poor upland grassland can support stocking rates between 0.2 and 0.4 SLU/ha (Chapman, 2017), which suggests that setting 113 ha of land aside from grazing may not have an important effect on hill sheep productivity and costs. A larger woodland expansion could compromise the financial resilience of hill sheep enterprise.

Table 13 Woodland expansion case study impact on the natural capital asset register

Asset (type of broad habitat)	Current status (2018)		Potential status (2024)		Trend	
	Extent	Condition	Extent	Condition	(extent)	(condition)
Enclosed farm	112.4		70.4			
Improved grassland	*112.4*	*Stable/Improving*	*70.4*	*Stable*	↘	→
Seminatural-plant communities	*659.9*		*567.9*			
Dwarf shrub heath (dry heath)	*282.3*	*Improving*	*224.3*	*Stable*	↘	→
Acid grassland	*181.2*	*Improving*	*147.2*	*Stable*	↘	→
Other	*196.4*		*196.4*		→	→ ↗
Woodland(1)	66.0		173.0	Mixed	↗	↘ ↗

Extent and condition: "↗" improving/growing, "→" stable ; "↘" decreasing/shrinking.

(2) Mixed effect of woodland expansion: medium-term improvement in global and local climate, and potential short-term negative effect on wild species diversity, and soil carbon loss.

3.6 Measure and value Stage – Step 07: Value impacts

Woodland expansion would demand an initial investment between £0.71 to £0.82 million for planting, fencing, and maintaining 113 hectares of new woodlands (Table 14). Planting and maintenance costs are expected to be higher for native broadleaved and mixed woodlands than for fast growing conifers. The considerable woodland expansion investment, along with the time that trees would need to reach diameters of commercial interest, make woodland expansion economically unprofitable at Glensaugh, when only the benefits of timber and/or biomass are accounted for. Assuming an average 3 percent real discount rate, the present discounted value of net benefits from timber/biomass are significatively lower than the present discounted value of the cost of woodland plantation, maintenance, and fencing costs. This situation could potentially change if new plantations benefit from additional incentives, such as grants for woodland expansion, or payments for carbon sequestration, for example.

The current Scottish government forest grant scheme supports[31] the creation of new woodlands. If grant payments are approved for Glensaugh, from the models used here, they can potentially make woodland expansion profitable for fast growing species such as Sitka spruce and Larch plantations. For instance, additional payments lower than £0.5 per t CO_2 would render Larch and Sitka plantation profitable at Glensaugh, generating benefits higher than investment costs in present value terms. If no woodland expansion subsidies are granted, payments between £7 to £27 per carbon ton (t CO_2) sequestered over a period of 50 years can create incentives to woodland expansion using native woodland species, such as Birch, Sessile oak, and Scots pine. The threshold carbon prices would also depend on price level associated to timber revenues[32], and those are significatively lower for non-native conifer plantations, such as Sitka or Larch (Table 15).

Threshold carbon prices are in the range of WCC prices paid in the UK (i.e., £3 to £15 tCO_2) for species such as Birch and Scots pine. Estimated carbon prices are also in line with threshold prices estimated by Haw (2017) for broadleaved woodlands managed for timber and for game and biodiversity. Most of natural capital accounting approaches in Scotland (e.g., Dickie et al., 2019; Office for National Statistics, 2020) use central non-traded carbon value to price carbon sequestration (BEIS, 2019). Non-traded carbon values represent estimated abatement cost per tonne of carbon for non-traded sector emissions (such as forestry). Considering low to

[31] For more details see: https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/forestry-grant-scheme/

[32]The analysis consider a range of timber prices (from low to high) for conifers and broadleaves (see sub-section A.3.3).

central non-traded carbon values as the social value of carbon abatement, and an average 3 percent discount rate, the present value of carbon mitigation over a period of 50 years using native species would be worth between £ 1.3 to £ 2.7 million. These values would rise to £ 2.5 million and £ 5.3 million for low and central non-trade carbon prices, respectively, when non-native forest species that jointly maximize timber and carbon (i.e. Sitka spruce and Larch) are considered (Table 14).

Table 14 Cost and benefits for alternative woodland expansion alternatives (in 000 £, 2018 prices)

Woodland expansion alternative	Net present values (50-years, real discount rate 3%)						
	Investment (Cost)			Timber stock value	Carbon sequestration values		
	Plantation and maintenance(1)	Fencing	Total		Non-trade price		WCC price (£ 6 t CO_2)
					low	central	
Native woodland only	-505.4	-318.23	-823.6	132.9	1,288.4	2,665.3	123.3
Timber and carbon maximization	-389.6	-318.23	-707.9	288.9	2,568.6	5,340.5	233.2

Notes: (1) Planting cost include ground preparation, plants and planting cost, and the present value of maintenance cost over 20 years.

The lowest band of the non-traded carbon price (£34.6 tCO_2) estimated by BEIS (2019a) for 2018 is between 2 to 12 times higher than WCC prices paid in the UK. Payments for carbon sequestration in emerging voluntary markets such as the Woodland Carbon Code seem not likely to achieve values akin to the non-traded carbon ones. Therefore, planning woodland expansion for carbon trading on such carbon price expectations (non-traded prices) does not seem realistic. Our study suggest that payments for carbon around £ 11.6 per t CO_2 could generate enough incentives for using exclusively native woodlands according to their potential (Fig. 8) for the Glensaugh woodland expansion project. If the creation of new woodlands is supported by the current grant scheme, WCC carbon credits can create additional incentive, at competitive prices (lower than £ 5 per t CO_2) for supporting woodland expansion using exclusively native tree species (Table 15).

Table 15 Threshold prices for carbon sequestration over 50-years (£ tCO_2)

	Timber price scenario (2018 prices) and moderate soil disturbance (no grants included)			Additional payments to WE grant [1]
Tree species	Low	Average	High	Central
Birch	8.41	7.78	6.87	1.24
Douglas Fir	11.37	10.70	9.93	3.57
Larch	4.89	3.75	2.55	0.32
Scots pine	10.30	9.36	8.34	2.43
Sessile oak	27.96	19.80	19.77	9.01
Sitka spruce	5.86	2.93	1.90	0.27
Native woodland potential mix [2]	15.12	11.63	10.96	4.55

Notes: [1] Additional payments in case maximum woodland expansion grants are granted. Note that WCC payments can be conceived as additional payments to current woodland expansion grant. [2] Native woodland mix according to Fig. 8 .

Livestock enterprises' profit, per t CO_2 equivalent GHG emissions, averages £37 per t CO_2 for beef cattle, £97 per t CO_2 for hill sheep , and £123 per t CO_2 for low-ground sheep (see Table 11 and sub-section A.3.3.4). These average values can be seen as the opportunity cost of cutting one ton of CO_2 by reducing the number of animals (by one standard livestock unit-SLU[33]). The effect of reducing stocking rates on profits is not necessarily linear, and as indicated before it seems that there is still room for reducing the farm area available for livestock grazing (e.g. hill sheep heft) without necessarily reducing livestock profitability. As previously mentioned, further woodland expansion (beyond 18 percent of the farm area covered by woodlands) may start to produce an opportunity cost for hill sheep farming. Reducing hill sheep stocking rate (in one SLU) is estimated to involve an opportunity cost of £97 (±55.1) per t CO_2 equivalent, which is about 8 times higher than the carbon payments required for planting native woodlands at Glensaugh (Table 15).

[33] As indicated before a standard livestock unit equals to one beef-cow, or 6.7 breeding ewes and gimmers.

There is insufficient information to estimate the monetary value of other material impacts of woodland expansion, such as potential improvements in water quality regulation, soil quality and erosion control, and wild species diversity. Native woodlands are expected to increase biodiversity services, while water and soil quality and erosion control may be similar between native and non-native species. This indicates a potential trade-off between carbon sequestration and biodiversity services. Considering average WCC payments for carbon sequestration (i.e., £ 6 per tCO_2), planting fast-growing non-native woodlands would deliver a carbon sequestration value that is £938 higher per hectare when compared to native woodlands[34]. The latter value can be seen as the opportunity cost associated with the potential improvement in wild species biodiversity if the farm managers decide to use native woodlands for the Glensaugh woodland expansion project instead of non-native species that in principle are expected to significantly increase carbon offsetting opportunities.

3.7 Apply Stage – Step 08: Interpret and test results

An upfront investment in woodland expansion of between £0.71 and £0.82 million by 2020 can yield a considerable social return in terms of carbon, even at the lowest estimated range of non-traded carbon values and the only native woodland scenario (i.e., £1.3 million) though carbon emissions mitigation over a 50-year period (Table 14). The latter represents a (social) benefit-cost ratio of 1.6:1 over 50 years.

The results of this study suggest that carbon payments around £ 12 per t CO_2 can create incentives for using native woodland species in the species mix. Native woodland plantations are expected to enhance wild species diversity when compared to non-native woodlands, while yielding a wide range of other market and non-market benefits that were not possible to quantify and value at this stage. Nonetheless, native woodland expansion would require higher support levels than planting more profitable species, such as non-native conifers (i.e. Sitka spruce or larch).

A potential strategy to increase opportunities associated with carbon offset and timber markets at Glensaugh is planting a mix of native and non-native species. For example, planting more productive species (usually non-native) in areas with higher suitability for growing timber and easier access to roads to facilitate future tree harvesting and timber transportation. Likewise, planting non-native species in areas with more difficult access, and designing new plantations in a way that they favour habitat connectivity. Additional research is needed for designing economically efficient and environmentally beneficial woodland species selection, and management strategies, considering decision elements such as access to roads, plots slope and orientation, economies of scale in terms of management and harvesting costs, and the effect of all these variables on forest growth and forestry costs.

3.8 Apply Stage – Step 09: Take action

There is need to measure and value other impacts from the woodland expansion project. These include the potential costs and opportunities for adopting low soil disturbance ground preparation practices to reduce soil carbon release. There is an opportunity to monitor soil carbon release and sequestration in new plantations to track progress and improve our understanding on soil carbon dynamics in different types of forest plantations, as well as surveying changes in wild species presence and abundance, as part of Glensaugh climate positive farm research and demonstration strategies.

[34] For comparative purposes, those values are estimated as the net present values of an infinite sequence of forest rotations, and considering only carbon payments as the only forest revenue.

4 Key finding and recommendations

4.1 Potential value added of applying the Protocol to evaluate land-based business

In general terms, analysing land-based business from natural capital lens allows for a more comprehensive perspective of farm activities. For instance, defining the pathways that connect specific farm enterprises or activities with changes on natural capital and their associated costs/benefits for the business provides a better understanding of the relevance that natural capital and ecosystem services have for land-based business. The Protocol offers a systematic framework to identify and value natural capital impact and dependencies for specific farm enterprises, products, or processes. However, the application is data demanding (e.g. mapping resources, farm records, modelling), with the reliability and quality of the natural capital assessment being dependent on the availability and quality of information. Other land-based businesses applying natural capital assessment approaches need to evaluate the implications that the quality of the data and the scope of the approach could have in informing their decision-making.

Achieving environmental targets such as net zero carbon emissions on-farm would demand increased efforts to reduce farming GHG emissions and making sure they are balanced by carbon sequestration. The proliferation of carbon auditing tools, and standards such as the Woodland Carbon Code could assist the estimation of carbon balances at the whole farm or the land-based activity level. This however could inadvertently put the emphasis on carbon stocks and flows and their values, overlooking other important natural capital and ecosystem services impact indicators, for which quantification can be challenging due to information gaps. In this sense, contemplating a natural capital approach for evaluating GHG emission reduction efforts is critical to keep a larger number of natural capital impact indicators that are material to the farm business, or to wider society, even in qualitative terms, as a way to better balance multiple environmental goals beyond climate change regulation, such as biodiversity conservation, enhancing water quality, or reducing flood impacts.

4.2 Natural capital assessment for supporting decision making

In the particular case of Glensaugh, this work has demonstrated that natural capital assessment can be used to inform decision-making pertaining to land use and management strategies. The analysis of time series data, along with scientific literature review, and the modelling outcomes used for the retrospective natural capital assessment enabled a better understanding of the potential implications of natural capital related risk and opportunities for Glensaugh. For example, the results of the Glensaugh assessment suggested that diversified livestock enterprises can help to better balance environmental and economic outcomes and farm financial resilience, while helping the farm enterprise respond better to climatic and price fluctuations. The substitution, for example, of beef-cattle and low-ground sheep enterprises by hill sheep can help GHG emissions reduction towards the transition to low carbon farming, but could have a negative impact on farm revenues and the farm resilience to fluctuation of market prices. These latter results give a different and potentially richer perspective than the simpler idea of substituting beef-cattle by sheep.

The prospective natural capital assessment applied to evaluate potential natural capital impacts of woodland expansion at Glensaugh suggested that this latter investment expansion can create further opportunities for GHG emissions off-setting. The assessment provides a general idea of the potential benefits and trade-offs involved by two alternative woodland expansion objectives: (i) timber& carbon maximization, and (ii) biodiversity enhancement through native woodlands expansion. Natural capital accounts can help the identification of priorities and opportunities for natural capital investment. Glensaugh natural capital assessment further addressed the potential of private and public funding opportunities, connected to the Woodland Carbon Code and woodland expansion grants in Scotland, respectively.

The woodland expansion economic assessment used a relatively detailed and spatially granulated forest growth and economic decision model. However, refining the latter model by integrating other relevant variables such as access to roads and forest tracks, terrain slope, sunlight and shade exposure, economies of scale in forest management, non-market values associated to biodiversity conservation, soil erosion control or water quality regulation can better inform site and species selection, and the design of the woodland expansion project. This highlights the importance of data availability and quality to better inform decision making. Nevertheless, producing information is costly, and decision-makers need to balance the benefits of improving information and the costs involved. The qualitative assessment of natural capital impacts beyond timber and carbon sequestration, such as potential effects of woodland expansion on water quality regulation, soil quality and erosion control, or wild species diversity informs about potential trade-offs when only native woodland or fast-growing non-native species are used.

4.3 Main recommendations to practitioners

Disseminating the results of this assessment can contribute to stakeholder engagement (e.g., upland farmers, local community, researchers, private investors, extension officers, etc.) to raise awareness of the need to enhance natural capital resilience for providing ecosystem services in many beneficial ways, and adapting in the face of environmental and socio-economic changes. The experience gained with the application of the Protocol in Glensaugh suggests that this approach has potential to be beneficial for other farms and estates across Scotland. The Protocol could help to evaluate and promote land use and management strategies that generate business opportunities, while also enhancing natural capital. Some specific actions to facilitate roll-out of the Protocol are discussed next.

Developing and integrating natural capital accounts into farm or estate reports enable the integration of natural capital thinking into land use and investment decisions and management priorities. Natural capital asset registers at the farm or estate levels are useful to record current in the extent and condition and changes over time of the on-farm natural capital base.

Defining a set of key indicators (metrics) of impacts of land-based businesses on natural capital, along with the natural capital assets register, would help create the context for integrating natural capital into land management decisions and future public (government) payments. Examples of those indicators include soil organic matter and nutrients, soil pH, biodiversity index, GHG emissions, carbon stock and sequestration, water quality, and use of inputs (fertilisers, pesticides, fossil fuels, supplementary feedstuff). Some of these indicators require additional data treatment and modelling. The methods and criteria proposed in this report (see supplementary material) can help future natural capital assessments in Glensaugh and other upland farms in Scotland. Connecting natural capital assessment and reporting to other mandatory reporting processes (e.g. for pillar 2 payments, site conditions for Natura 2000, etc.) could also help a wider adoption of natural capital assessment approaches such as the protocol. The challenges and opportunities for tiding natural capital reporting to the former mandatory reporting processes need to be further examined.

Glensaugh application highlights the convenience of combining qualitative natural capital approaches for those impacts on natural capital and ecosystem services that are not easily measurable and monetarized, along with indicators of financial performance to inform land use and management decision-making. Accounting for wider business and societal cost and benefits can inform about the sustainability of investment alternatives, at the time help to identify marketing and funding opportunities.

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SUPPLEMENTARY MATERIAL

A.1 Characteristics of Glensaugh farm

Glensaugh covers around thousand hectares, most of them (almost 50 percent) dominated by semi-natural plant communities (grassland/moorland/heather), 45 ha of predominantly rotational grassland, 67 ha of permanent pastures, 10 ha covered by agroforestry plots and 66 ha with woodlands (Table A.1 and Figure A.1).

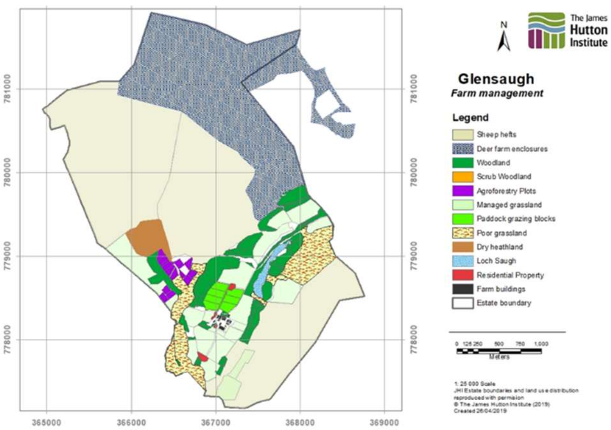
On the alluvial soils of the valley bottom the semi-natural vegetation is dominated by species-rich Agrostis-Festuca grassland. This gives way to species-poor Agrostis-Festuca on the lower slopes, with bracken (*Pteridium aquilinum*) also present. The higher slopes are dry heather (*Calluna vulgaris*) moor, with blaeberry (*Vaccinium myrtillus*), wavy hair grass (*Deschampsia flexuosa*) and bell heather (*Erica cinerea*) locally important. On the deeper peats at the highest altitude, cross-leaved heather (*Erica tetralix*) and cotton sedge (*Eriophorum vaginatum*) become co-dominant (Stutter et al., 2012). The two main water curses in Glensaugh are Cairn Burn and Birnie Burn, both affluent of the Devilly burn which is a river, in the River North Esk catchment of the Scotland river basin district. Part of Glensaugh lies inside a Nitrate Vulnerable Zone Strathmore and Fife (including Finavon). Likewise, part of Glensaugh the west slope of Strath Finella Hill lies inside the Laurencekirk Potentially Vulnerable Area 07/01, whereas the main flooding sources in the Luther Water.

The Highland Boundary Fault divides Glensaugh into two distinct geological zones. North of the fault the soils are of the Strichen Association developed on drifts derived from schistose rock. The brown forest soils and podzols of the lower slopes give way to peaty podzols and, on the highest ground, to peat. To the south of the fault the soils are developed on drifts derived from Old Red Sandstone: humus-iron podzols dominate the lower slopes and peaty podzols occur at higher elevations (see Figure A.4)[35]. Glensaugh soils comprise hill peat (>50 cm) on upper, gentle slopes covered by *Sphagnum sp*. and *Eriophorum vaginatum* (hair's tail cotton grass). Peaty podzols on intermediate slopes (average organic horizon depth 25 cm) have developed in thin glacial till vegetated by *Calluna vulgaris* (heather), *Vaccinium myrtillus* (blaeberry), *Deschampsia flexuosa* (wavy hairgrass) and Nardus stricta (mat-grass). Freely drained humus-iron podzols (average organic horizons depth 15 cm), and peaty gleys occupy flatter areas bordering the water streams (Stutter et al., 2012)

A.1.1 Land cover and land uses

Table and Figure A.1 Glensaugh: land use distribution (year 2018)

Class	Area (hectares)	Percentage (%)
Woodland	66.0	6.78
Conifers	20.6	2.11
Broadleaves	11.6	1.19
Mixed conifers/broadleaves	32.8	3.36
Other woodlands (scrubs, designated open area)	1.1	0.11
Sheep hefts	467.0	47.96
Deer Farm Inside the farm boundaries	232.0	23.82
Dwarf shrub heath (out of the sheep hefts)	16.1	1.65
Managed grassland	112.4	11.54
Permanent grass	67.4	6.92
Rotational grass	33.4	3.43
Paddock grazing blocks	11.6	1.19
Poor grassland	54.5	5.6
Agroforestry plots	10.2	1.04
Freshwaters	7.6	0.78
Other land cover	2.0	0.21
Constructed areas	6.0	0.62
Total farm	**973.7**	**100**
Deer Farm (out of the farm boundaries)	**33.07**	
Total	**1,006.80**	



Source: *Own elaboration* using Glensaugh land use data.

[35] All Tables and Figures with an "A" preceding an Arabic number can be found in the supplementary material at the end of this report.

Table and Figure A.2 Glensaugh' s woodland

Class	Area (hectare)	Percentage (%)
Conifers	20.79	31.50
Norway spruce	0.92	1.40
Sitka spruce	0.19	0.29
Scots pine	6.05	9.17
European larch	0.67	1.01
Scots pine / European larch	12.76	19.32
Mixed conifers	0.20	0.31
Broadleaves	12.33	18.67
Beech	0.12	0.18
Sessile Oak	0.46	0.70
Mixed broadleaves	11.74	17.78
Mixed plantations	29.25	44.31
Mixed conifers/broadleaves (& scrubs)	27.64	41.87
Mixed Sitka/broadleaves	1.61	2.44
Others	3.64	5.52
Designated open ground	2.63	3.98
Other lands	1.01	1.53
Total	**66.02**	**100.00**

Source: *Own elaboration* and Glensaugh forest plantation records.

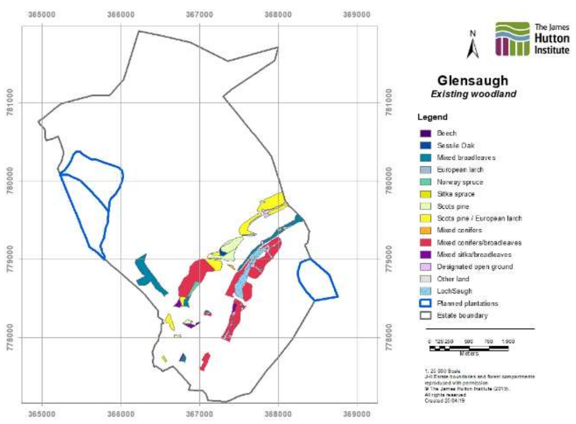
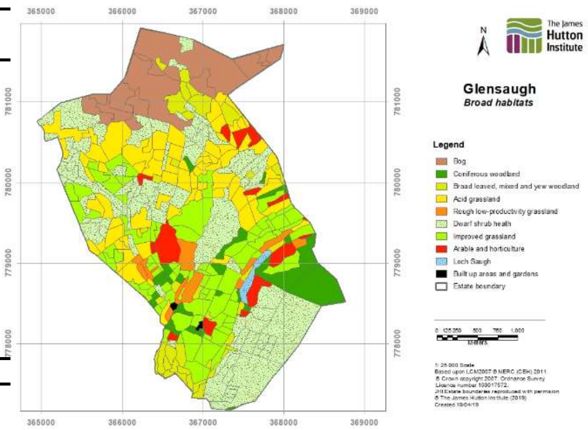


Table and Figure A.3 Glensaugh: Broad habitats – Land Cover Map Scotland (LCM) 2007

Broad habitat Group	Sub-group	Area (hectares)	Percentage (%)
Woodland	Coniferous woodland	63.00	6.47
	Broad leaved	57.11	5.87
Dwarf shrub heath	Heather and dwarf shrub	155.88	16.01
	Heather grass	126.46	12.99
Bog	Bog, grass dominated	23.54	2.42
	Bog, heather dominated	108.13	11.10
Acid grassland	Acid grassland	181.16	18.60
Rough grassland	Rough grassland	26.52	2.72
Improved grassland	Improved	184.79	18.98
Arable and horticulture	Arable unknown	39.86	4.09
Built up areas	Suburban	0.69	0.07
	Urban industrial	0.71	0.07
Freshwater	Loch Saugh	5.86	0.60
Total		**973.72**	**100.00**

Source: Own elaboration using Morton, D., Rowland, C., Wood, C., Meek, L., Marston, C., Smith, G., Simpson, I.C. (2011) Final report for LCM2007 - the new UK land cover map. CS Technical report No. 11/07 NERC/Centre for Ecology and Hydrology 112pp. (CEH project number: C03259)

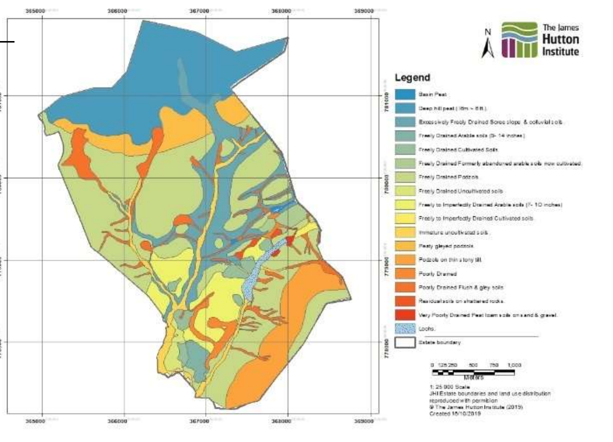


A.1.2 Soil classification map

Table and Figure A.4 Glensaugh' s soil map

Series	Phase	Percentage (of farm area)
Anniegathel	Poorly Drained	1.44
Basin Peat	Basin Peat	0.13
Blanket Peat	Deep hill peat (l6m).	18.92
Corby	Freely Drained Cultivated Soils.	1.80
Corby	Freely Drained Uncultivated soils	0.81
Fungarth	Freely Drained Arable soils (9- 14 inches).	0.97
Fungarth	Freely to Imperfectly Drained Arable soils	6.09
Gaerlie	Peaty gleyed podzols.	5.23
Garrold	Podzols on thin stony till.	7.35
Hythie	Poorly Drained Flush & gley soils	4.36
Ledmore	Poorly Drained Flush & gley soils	1.74
Strathfinella	Freely Drained Podzols.	7.94
Strichen	Excessively Freely Drained Scree slope	11.00
Strichen	Freely Drained Formerly abandoned arable soils now cultivated.	0.97
Strichen	Freely Drained Podzols.	25.78
Strichen	Residual soils on shattered rocks.	0.26
Undifferentiated Alluvium	Freely to Imperfectly Drained Cultivated soils.	0.26
Undifferentiated	Immature uncultivated soils.	3.96
Alluvium	Very Poorly Drained Peat loam soils	0.18
Other	Lochs and water bodies	0.79
		100.00

Source: own elaboration using the Glensaugh soil map (part of farm records and maps)



A.1.3 Land capability and potential maps

Table and Figure A.5 Glensaugh' s land capability for agriculture (partial cover 1:50,000)

Code	Description	Area (hectares)	Percentage (%)
3.2	Land capable of average production though high yields of barley, oats and grass can be obtained. Grass leys are common	85.22	8.75
4.1	Land capable of producing a narrow range of crops, primarily grassland with short arable breaks of forage crops and cereal	6.33	0.65
4.2	Land capable of producing a narrow range of crops, primarily on grassland with short arable breaks of forage crops	129.74	13.32
5.2	Land capable of use as improved grassland. Few problems with pasture establishment but may be difficult to maintain	123.31	12.66
5.3	Land capable of use as improved grassland. Pasture deteriorates quickly	222.32	22.83
6.1	Land capable of use as rough grazing with a high proportion of palatable plants	10.04	1.03
6.2	Land capable of use as rough grazing with moderate quality plants	204.86	21.04
6.3	Land capable of use as rough grazing with low quality plants	186.04	19.11
	Loch Saugh	5.87	0.60
Total		**973.73**	**100.00**

Source: Own elaboration using the Scottish map of land capability for agriculture (partial cover) 1: 50,000 (Soil Survey of Scotland Staff, 1984-87) Land Capability for Agriculture maps of Scotland at a scale of 1:50 000. Macaulay Institute for Soil Research, Aberdeen.

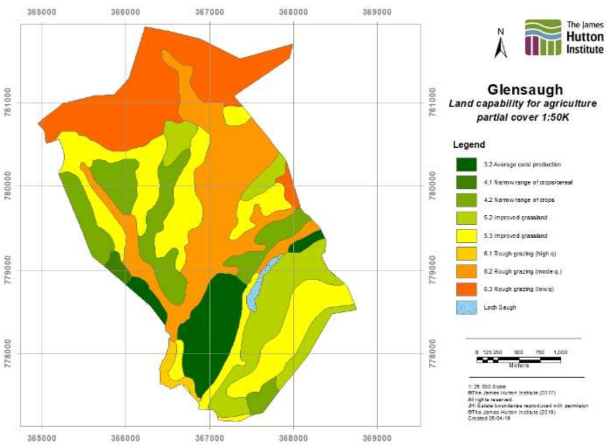


Table and Figure A.6 Glensaugh' s land capability for forestry

Class	Land capability for forestry	Area (hectares)	Percentage (%)
4	Moderate flexibility for trees	132.96	13.65
5	Limited flexibility for trees	416.51	42.77
6	Very limited flexibility for trees	170.00	17.46
7	Land unsuitable for trees	237.68	24.41
18	Loch Saugh	5.87	0.60
	Other (not defined)	10.71	1.10
	Total	**973.73**	**100.00**

Source: Own elaboration using The Macaulay Land Use Research Institute (1989). Land capability classification for Forestry. Aberdeen.

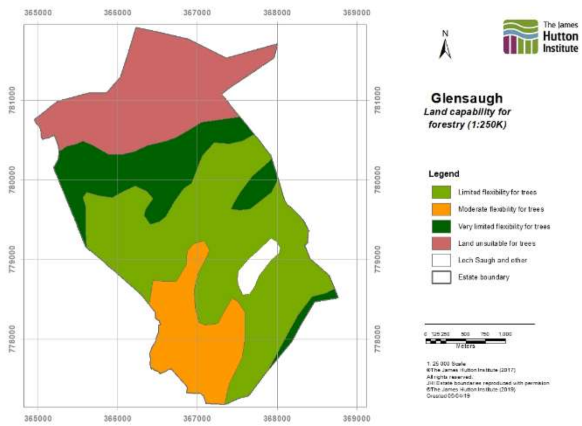
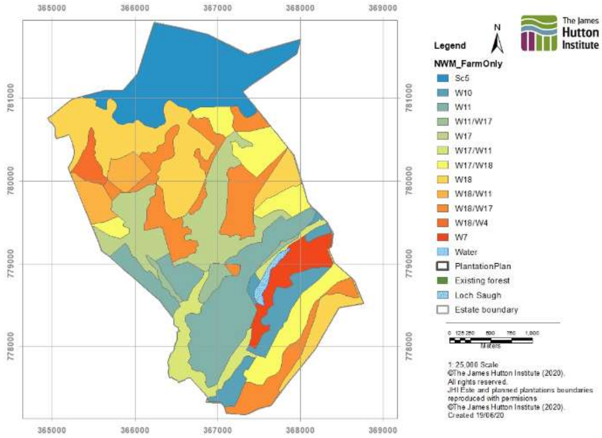


Table and Figure A.7 Glensaugh’ s Native woodland potential

Class	Code	Area (hectare)	Percentage (%)
Peatland with scattered trees/scrub		153.69	15.78
Lowland mixed broadleaved with bluebell/wild hyacinth	W10	47.85	4.91
Upland Oak-Birch with bluebell/wild hyacinth	W11	130.30	13.38
Upland Oak-Birch with bluebell/wild hyacinth and bilberry/blaeberry	W11/W17	15.36	1.58
Upland Oak-Birch with bilberry/blaeberry	W17	110.29	11.33
Upland Oak-Birch with bilberry/blaeberry and bluebell/wild hyacinth	W17/W11	43.51	4.47
Upland Oak-Birch with bilberry/blaeberry and Scots Pine with heather	W17/W18	95.85	9.84
Mosaic of Scots Pine with heather and Upland Oak-Birch with bluebell/wild hyacinth	W18+W11 Mosaic	33.32	3.42
Mosaic of Scots Pine with heather and Birch woodland with purple moor grass	W18+W4 Mosaic	12.37	1.27
Scots Pine with heather	W18	157.03	16.13
Scots Pine with heather and Upland Oak-Birch with bluebell/wild hyacinth	W18/W17	131.45	13.50
Alder-ash with yellow pimpernel	W7	36.84	3.78
Loch Saugh		5.87	0.60
Total		**973.73**	**100.00**

Source: Own elaboration using the Scottish Native woodland potential map developed by the Macaulay Institute (The Macaulay Land Use Research Institute) and SNH (Scottish Natural Heritage) (2004). Scottish Native woodland potential map, recently updated to cover all Glensaugh areas (http://nar.hutton.ac.uk/dataset/spatial-datasets-for-glensaugh-research-farm)

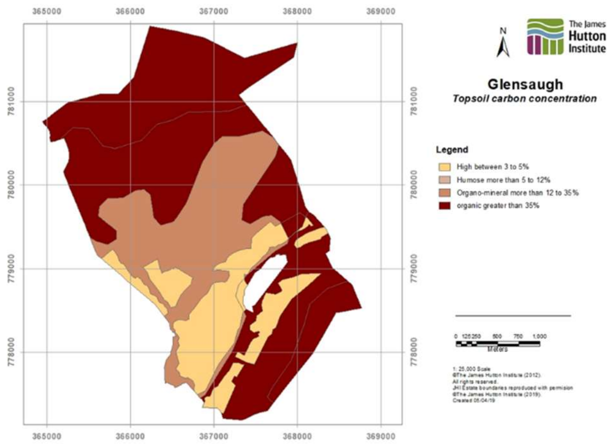


A.1.4 Soil carbon maps

Table and Figure A.8 Glensaugh’ s Topsoil carbon concentration

Class	Area (hectares)	Percentage (%)
High - more than 3 to 5 %	163.61	16.80
Humose - more than 5 to 12 %	0.00	0.00
Organo-mineral - more than 12 to 35 %	229.99	23.62
Organic - greater than 35 %	565.14	58.04
Others: Loch Saugh	5.87	0.60
Others: not defined	9.12	0.94
Total	**973.73**	**100.00**

Source: Own elaboration using Lilly, A., Baggaley, N. & Donnelly, D. (2012). Map of soil organic carbon in topsoils of Scotland. Map prepared for EU project GS-SOIL - Assessment and strategic development of INSPIRE compliant Geodata-Services for European Soil Data. ECP-2008-GEO-31800'



A.1.5 Soil degradation risk maps

Table and Figure A.9 Glensaugh' s Soil Erosion risk

General description of soils, slopes and water abortion capacity				Risk class	Area (hectares)	Percentage (%)
Soil type	Risk	Slope type	Water absorption capacity			
Mineral soils					252.87	25.97
Coarse,	Low	Almost level to moderate	High to low	L3	3.1	0.32
medium	Moderate	Almost level to moderate	High to low	M1	30.79	3.16
and fine		Almost level to steep	High to low	M2	59.61	6.12
texture		Gentle to steep	High to low	M3	65.07	6.68
	High	Moderate to steep	High to low	H1	77.39	7.95
		Moderately steep to steep	Moderate to low	H2	16.91	1.74
Organic soils					702.14	72.12
Soils	Low	Almost level to gentle	High to low	Lii	3.48	0.36
with		Almost level to moderate	High to low	Liii	8.2	0.84
peaty	Moderate	Gentle to moderately steep	High to low	Mi	57.14	5.87
surface		Moderate to steep	High to low	Mii	186.23	19.13
layers		Moderately steep to steep	High to low	Miii	242.14	24.87
		Steep	High to low	Miv	24.52	2.52
	High	Peat soil on all slopes	High to low	H	180.43	18.53
Loch Saugh					5.87	0.60
Not defined					12.85	1.32
					973.73	**100.00**

Source: Own elaboration using Lilly and Baggaley (2018). Soil erosion risk map of Scotland (partial cover). James Hutton Institute, Aberdeen.

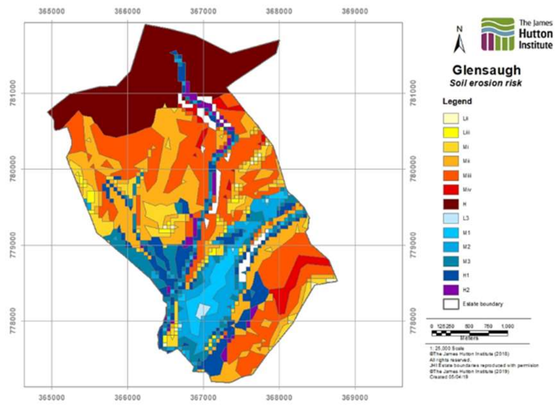


Table and Figure A.10 Glensaugh' s Runoff risk

Description	Area (hectares)	Percentage (%)
Low runoff risk	80.79	8.30
Moderate runoff risk	415.37	42.66
High runoff risk	471.69	48.44
Loch Saugh	5.87	0.60
Total	**973.73**	**100**

Source: Own elaboration using Lilly and Baggaley (2018). Runoff risk map of Scotland (partial cover). James Hutton Institute, Aberdeen.

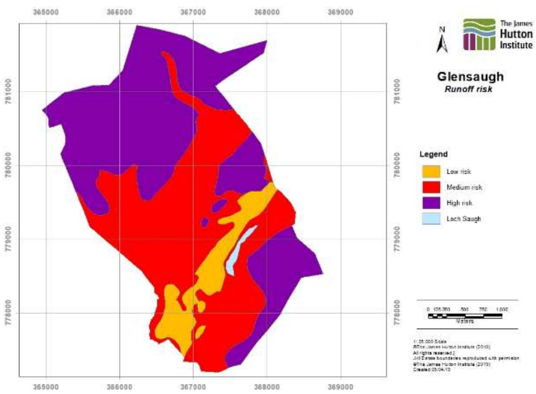
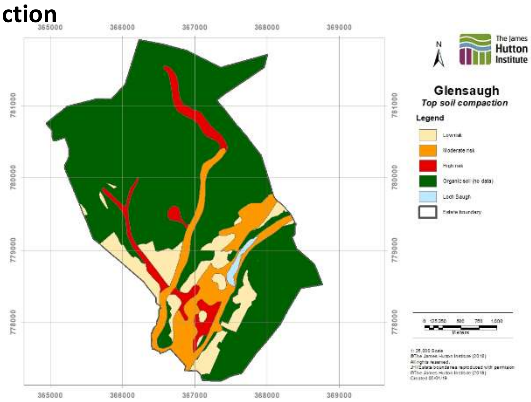


Table and Figure A.11 Glensaugh' s Risk of topsoil compaction

Description	SLP class	Area (hectares)	Percentage (%)
Low risk of topsoil compaction	L	98.37	10.10
Moderate risk of topsoil compaction	I1	107.90	11.08
High risk of topsoil compaction	H1	51.61	5.30
Organic soils (no data)		709.98	72.91
Loch Saugh	Other	5.87	0.60
Total		**973.73**	**100.00**

Source: Own elaboration using Lilly, A. and Baggaley N.J. (2018). Topsoil compaction risk map of Scotland (partial cover). James Hutton Institute, Aberdeen.



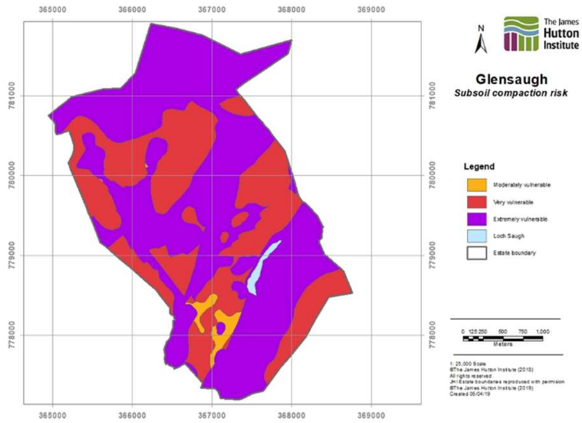


Table and Figure A.12 Glensaugh' s Risk of subsoil compaction

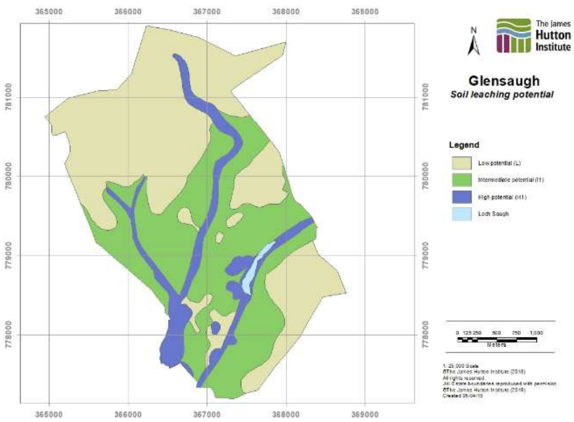
Description	Area (hectares)	Percentage (%)
Moderately vulnerable to subsoil compaction	16.21	1.66
Very vulnerable to subsoil compaction	340.67	34.99
Extremely vulnerable to subsoil compaction	610.97	62.75
Loch Saugh	5.87	0.60
Total	**973.73**	**100.00**

Source: Own elaboration using Lilly, A. and Baggaley N.J. (2018). Subsoil compaction risk map of Scotland (partial cover). James Hutton Institute, Aberdeen.

Table and Figure A.13 Glensaugh' s Soil leaching potential

Description	SLP class	Area (hectares)	Percentage (%)
Low SLP Deep soils with low permeability due to medium to fine textured subsoils or thick organic surface layers that can absorb or prevent contaminants from infiltrating	L	492.66	50.59
Intermediate SLP: Deep, permeable, medium textured soils that can possibly transmit a wide range of pollutants	I1	370.81	38.08
High SLP: Soils with little ability to retain potential pollutants because they are either shallow or allow flow directly to rock, gravel, or shallow groundwater	H1	104.39	10.72
Loch Saugh	Other	5.87	0.60
Total		**973.73**	**100**

Source: Own elaboration using Lilly, A. and Baggaley N.J. (2018). Soil leaching potential map of Scotland (partial cover). James Hutton Institute, Aberdeen



A.2 Methodological appendix and material

A.2.1 Ecosystem services classification

This study uses the Common International Classification of Ecosystem Services (CICES), that groups ecosystem services into three main categories: provisioning, regulating and maintenance, and cultural services, while making a distinction between biotic and abiotic services. The CICES classification uses the Millennium Ecosystem Assessment (MEA) description of ecosystem services as a starting point, while refining the definitions and classification of ecosystem function, services, and benefits to people to enable a consistent economic valuation. The MEA framework recognises four categories of ecosystem services: (1) *provisioning services*, such as biomass for nutrition, materials or energy, or water; (2) *regulating services* that affect climate, water quality, floods, disease or waste; (3) *cultural services* that provide recreational, aesthetic and spiritual benefits; and (4) *supporting services* that operate alongside more basic ecological structures and processes and are necessary for the maintenance of all other ecosystem services, such as soil formation, photosynthesis, or nutrient cycling. Supporting services are recognised as the underpinning structures and processes that ultimately give rise to ecosystem services, and therefore are not recognised explicitly in the context of CICES or in this report.

Table A.1 Classification of ecosystem services according to the Common International Classification of Ecosystem Services

Section	Division	Group	Class
Provisioning (Biotic)	Biomass	Cultivated terrestrial plants for nutrition, materials or energy	-Cultivated terrestrial plants (including fungi, algae) grown for nutrition
			-Cultivated terrestrial plants (including fungi, algae) grown as a source of energy
			-Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials
		Reared animals for nutrition, materials, or energy	-Animals reared for nutritional purposes,
			-Animals reared to provide energy (including mechanical)
			-Fibres and other materials from reared animals for direct use or processing (excluding genetic materials)
		Wild plants (terrestrial and aquatic) for nutrition, materials, or energy	-Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition
			-Wild plants (terrestrial and aquatic, including fungi, algae) used as energy sources;
			-Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)
		Wild animals (terrestrial and aquatic) for nutrition, materials or energy	-Wild animals (terrestrial and aquatic) used for nutritional purposes
			-Wild animals (terrestrial and aquatic) used as a source of energy;
			-Fibres and other materials from wild animals for direct use or processing (excluding genetic materials)
	Genetic material from all biota (including seed, spore or gamete production).	Genetic material from plants, algae or fungi	-Seeds, spores, and other plant materials collected for maintaining or establishing a population. -Higher and lower plants (whole organisms) used to breed new strains or varieties; Individual genes extracted from higher and lower plants for the design and construction of new biological entities
		Genetic material from animals	-Animal material collected for the purposes of maintaining or establishing a population. -Wild animals (whole organisms) used to breed new strains or varieties. -Individual genes extracted from organisms for the design and construction of new biological entities
	Water	Surface water used for nutrition, materials, or energy	-Surface water for drinking, or used as a material (non-drinking purposes) or as an energy source
			-Surface water used as an energy source
		Ground water for used for nutrition, materials, or energy	-Ground (and subsurface) water for drinking, used as a material (non-drinking purposes)
			-Ground (and subsurface) water used as an energy source
Regulation & Maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems	Mediation of wastes or toxic substances of anthropogenic origin by living processes	-Bioremediation by micro-organisms, algae, plants, and animals
			-Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals
		Mediation of nuisances of anthropogenic origin	-Smell reduction -Noise attenuation - Visual screening
			-Control of erosion rates

Section	Division	Group	Class
			-Buffering and attenuation of mass movement
	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	-Hydrological cycle and water flow regulation (Including flood control, and coastal protection)
			-Wind protection -Fire protection
		Lifecycle maintenance habitat and gene pool protection	-Pollination (or 'gamete' dispersal in a marine context)
			-Maintaining nursery populations and habitats (Including gene pool protection)
			-Seed dispersal
Regulation & Maintenance (Biotic)		Pest and disease control	-Pest control (including invasive species) -Disease control
		Regulation of soil quality	-Weathering processes and their effect on soil quality
			-Decomposition and fixing processes and their effect on soil quality
	Regulation of physical, chemical, biological conditions	Water conditions	-Regulation of the chemical condition of freshwaters by living processes
			-Regulation of the chemical condition of salt waters by living processes
		Atmospheric composition and conditions	-Regulation of chemical composition of atmosphere and oceans
			-Regulation of temperature and humidity, including ventilation and transpiration
Cultural (biotic)	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	Physical and experiential interactions with natural environment	-Characteristics of living systems that that enable activities promoting health, recuperation, or enjoyment through active or immersive interactions
			-Characteristics of living systems that enable activities promoting health, recuperation, or enjoyment through passive or observational interactions
		Intellectual and representative interactions with natural environment	-Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge
			-Characteristics of living systems that enable education and training
			-Characteristics of living systems that are resonant in terms of culture or heritage
			-Characteristics of living systems that enable aesthetic experiences
	Indirect, remote, often indoor interactions with living systems that do not require presence in the environmental setting	Spiritual, symbolic, and other interactions with natural environment	-Elements of living systems that have symbolic meaning
			-Elements of living systems that have sacred or religious meaning
			-Elements of living systems used for entertainment or representation
		Other biotic characteristics that have a non-use value	-Characteristics or features of living systems that have an existence value
			-Characteristics or features of living systems that have an option or bequest value

Notes: *Genetic material from all biota (including seed, spore, or gamete production).
Source: Based on CICES V5.1 Spread sheets[36].

A.2.2 Natural capital condition

As indicated in the main text, the condition of natural capital can be defined by its ability to maintain flows of services, but also in terms of the quality or the underlying condition of natural capital (Natural Capital Committee, 2019). Habitat condition (quality) and properties provide the ecological basis for ecosystem service potential (La Notte et al., 2019). The properties refer to the structures and processes of an ecosystems, such as soil types, slope gradient, climate conditions, or position within a watershed; while conditions refer to the integrity and health status of an ecosystem (Burkhard and Maes, 2017).

The literature suggests that ecosystem condition indicators in agroecosystems include the nitrogen balance, soil organic carbon, the share of High Nature Value farmland and organic farming, farming intensity and the occurrence of farmland birds. Conservation status of habitats and species (e.g. butterflies, pollinators) is a particularly important indicator to measure the condition of grasslands (Maes et al., 2018). Changes in natural capital conditions reflected in the natural asset register (Table 3) consider observed, modelled, or expected changes (considering literature review) for some of the agroecosystem indicators above referred, as it is detailed next.

A.2.2.1 Relative wildness index

Relative Wildness is a composite index based on four attributes naturalness of land cover, ruggedness, remoteness, and the lack of built modern artefacts. The scale is 1 to 256; the lower the score the less 'wild' the area. In Scotland, this data is provided by the Scottish Natural Heritage (SNH). Glensaugh area has a weighted

[36] Available online at https://cices.eu/resources/ (last accessed 12/14/2018).

average score of 166 on the Relative Wildness index, with scores ranging from 73 and 256. Fig. A.14 shows that wilder areas are linked to the blanked bog area, while the area of managed grassland and woodland expansion exhibit lower wildness index.

A.2.2.2 Biodiversity surveys

As indicated before, habitat condition can be valued in terms of indicators such as abundance and diversity of species. The evidence on changes in biodiversity richness is mixed for Glensaugh. On one side, ECN data suggest a decline in the abundance of relevant invertebrate species (e.g. carabids, butterflies) and relative increase in bats and birds. In terms of diversity we observe variability in the number of species identified by the annual ECN biodiversity survey (Fig. A.15). In general, there is an overall decline in carabid beetles across the ECN sites in the UK, which also applies to Glensaugh (Brooks et al., 2012). The decline in carabids has been more noticeable in bogs and heather moors than in grasslands (Pozsgai and Littlewood, 2014). Carabid beetles are important component of ecosystems. They are particularly important in agriculture because they help control pests and weeds. This result suggest a decline in pest control services, which are important for crop production.

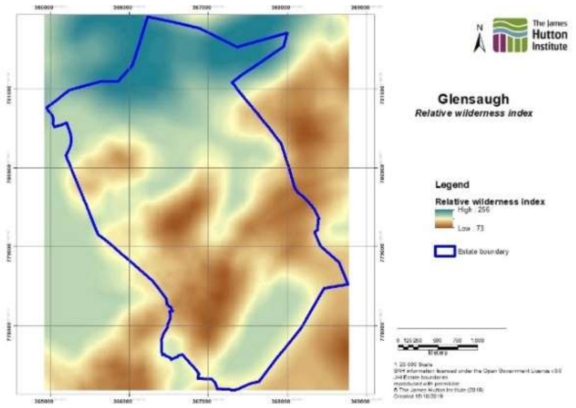
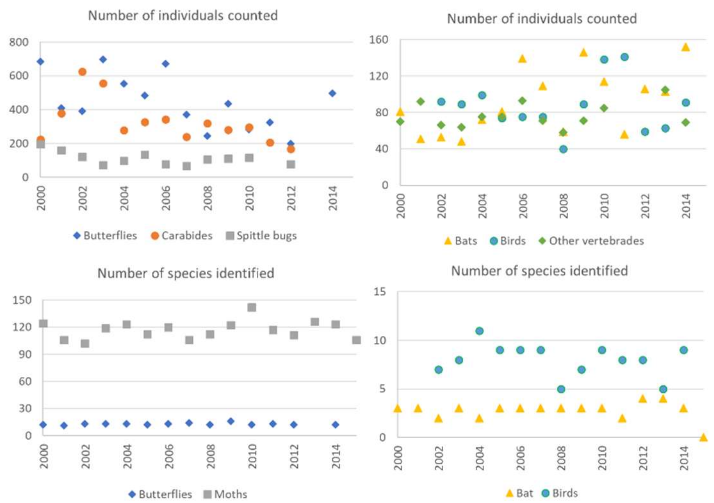


Fig A.14 Relative wildness index (composite value)

There is also evidence of increases in vegetation richness across UK ECN sites in connection to a large reduction of acidic deposition in recent decades, and recent weather pattern with wetter summers. Changes in site management are also likely to have influenced trends at certain sites, particularly with respect to agricultural practices (Rose et al., 2016). ECN data also suggest that the communities associated with low disturbance levels and low agricultural inputs, particularly moorland (upland grass and heath) and bog communities (from which Glensaugh is one of the four sites evaluated), are most stable (Morecroft et al., 2016).

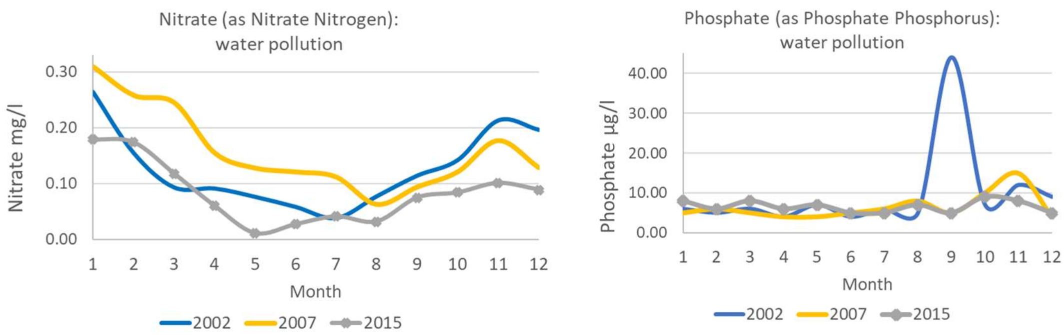


Source: Own elaboration based on ECN invertebrate and vertebrate species survey.

Fig A.15 Abundance and diversity of invertebrate and vertebrate species in Glensaugh

A.2.2.3 Freshwater resources condition

ECN water monitoring data from the Birnie burn site show a slight reduction in both nitrate and phosphate concentrations since 2002 (Fig. A.16). There is also a slight increase in water pH, and a slight decrease in dissolved organic carbon (DOC). Decreasing concentrations of DOC in surface waters might be expected to be accompanied by lower losses of carbon from waters to the atmosphere in the form of CO_2 and methane following microbiological and physical degradation of dissolved organic matter. Rotational heathland burning (that is practiced with a frequency close of 10 to 15 years in Glensaugh) and planting forest on grazed or seminatural plant communities with organic soils could also increase DOC loss and export (Natural Scotland, 2007), and hence also contribute indirectly to GHG emissions. The extent of these losses is difficult to quantify but is a potentially important policy parameter with respect to national carbon accounting (Monteith et al., 2007).



Source: Own elaboration based on ECN Birnie burn monitoring data

Fig A.16 Changes in nitrate and phosphate concentration in water Birnie Burn

The main watercourses in Glensaugh (Cairn burn and Birnie burn) are tributaries of the Devilly burn which is a river (ID: 5708) in the River North Esk catchment of the Scotland river basin district. The overall condition of this river is good, as well as the water quality, water flow and levels and physical conditions[37].

A.2.2.4 Soil carbon stock

The ECOSSE project includes Glensaugh as one of the sites mapped and sampled in Scotland to estimate soil carbon stock and emissions. This project reports a total soil carbon stock of 197.99 Kt C measured for 0 to 15 cm for the organic horizon only. The results of this project also suggest that there is rapid capture of plant derived C in soil microbial biomass, and a slow turnover of C in acid soils, in particular blanket peat. Those results also suggest that peat is a source of methane emissions, while peaty podzols (Fig. A.4) act as carbon sink in Glensaugh (Natural Scotland, 2007).

Chapman et al. (2013) suggest no detectable changes in overall total soil carbon stock in Scotland from 1978 and 2009. The evidence regarding changes in soil carbon stock is limited in hill lands of Scotland, but it is likely that land use changes will result in a reduction of soil carbon (Pakeman et al., 2018). Both studies indicate that an exception would be the potential increase in forestry and woodland, when appropriate species, sites and management techniques are considered. In principle, it is expected that there will be some soil carbon increase in newly planted woodlands at Glensaugh. Net carbon gains on woodland need to be carefully considered, in view of potential GHG emissions due to soil disturbance during ground preparation, which are significantly higher when mechanical ground preparation techniques and organo-mineral soils are concerned (West, 2018).

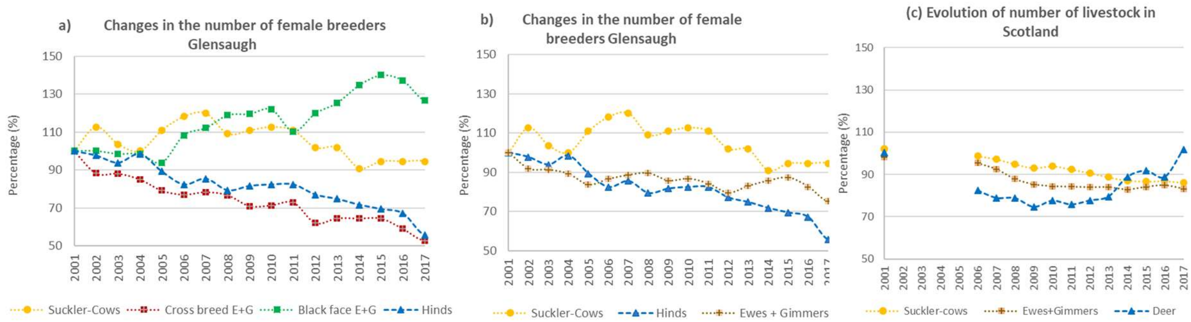
[37] According to the SEPA water environmental hug: https://www.sepa.org.uk/data-visualisation/water-environment-hub/

A.2.3 Trend in the dependency and impacts of livestock farming systems on natural capital

A.2.3.1 Drivers of impacts and dependencies of livestock farming on natural capital

The stocking rate is a main driver of the dependency of livestock farming on natural capital and the ecosystem services that flow from them, such as the biomass form cultivated and wild plants. Stocking rates, and livestock feeding systems (e.g. extensive grazing, intensive livestock production) are impacts drivers as they can add pressure on regulating services such as freshwater quality regulation, soil erosion control or global climate change regulation.

An important change in Glensaugh farming management over the last two decades is the reduction of livestock numbers, in consonance to livestock numbers reduction observed in Scotland. At Glensaugh this has affected mainly deer farming but also sheep enterprises in general, with a slightly higher reduction in the number of animals than the Scottish average (Fig. A.17). The number of Black Face ewes and gimmers (E+G), which is the main Hill flock breed in Glensaugh has increased in about 30%, whilst the number of other breeds has slightly decrease since 2001[38].



Source : Own elaboration based on (a,b) Glensaugh Reports (various years); (c) Scottish Government: Final Results of the June 2016 Agricultural Census

Fig A.17 Evolution of livestock numbers in Glensaugh and Scotland (2002-2018)

Managed grassland area has experienced a decrease since 2002 due to woodland expansion. This has not had a direct effect on livestock productivity as the stocking rates of Glensaugh are kept relatively low on average (Table A.2). Improved grassland keep higher stocking rates, of about 1.2 LU/ha, than sheep heft and deer farm.

Table A.2 Changes in livestock stocking rates per species in Glensaugh

Livestock species	Description of the managed area	Area (in hectares)		Livestock numbers				Stoking rate (SLU/ha)	
				N. female breeders[(1)]		Livestock Units (LU)[(2)]			
		2002	2018	2002	2018	2002	2018	2002	2018
Beef cattle and Low-ground sheep	Improved grassland	144.0	112.4	66 762	51 561	66.0 114.3	51.0 84.2	1.25	1.20
Hill sheep	Sheep heft	485.0	467.0	310	508	46.5	76.2	0.10	0.16
Deer	Deer farm	232.0	232.0	128	83	38.4	24.9	0.17	0.11
Total		**861.0**	**811.4**			**265.2**	**236.3**	**0.31**	**0.29**

Notes: [(1)] Number of female breeders on 31 October. [(2)] Livestock units following the Less Favoured Area Support Scheme (LFASS) guidance (Scottish Government, 2019)[39], which indicates 1 LU for beef cow over 24 months of age; 0.15 LU for breeding ewes and gimmers; and 0.3 LU for breeding female hinds (over 27 months).

[38] Changes are estimated considering 2001 livestock census, information for livestock census is annually available from 2006 to 2017.

[39] More information: https://www.ruralpayments.org/publicsite/futures/topics/all-schemes/lfass/less-favoured-area-support-scheme-full-guidance

A.2.3.2 Livestock metabolic energy requirements and dependencies on external and own resources

There are multiple dependencies of livestock farming on natural capital are multiple, and most direct is the biomass from cultivated and wild plants used as grass and feedstock. The extent of the dependency on own and externally produced resources (from both grazing and feedstuff provided at the feedlot) is estimated as a share of the total metabolic energy requirement by livestock type and year. Total energy requirement by livestock enterprise are quantified monthly in view of farm livestock census records, and energy requirement factors by livestock species, age, sex, and breeder condition (e.g., pregnancy, lactation) taken from the specialised literature (Table A.3).

The contribution of own and external resources to livestock energy requirements are in turn estimated using monthly farm records on the amount of feedstuff (straw, hay, silage, haylage and compound feed) provided at the feedlot, and their proximate composition. The amount of feedstock supplemented by livestock enterprise is systematically recorded and verified since 2006, therefore the analysis of changes in the dependency on own natural capital (i.e., broad habitats and water) cover the period 2006-2018. Typical metabolic energy and dry matter contents for straw[40], hay and compound feed are taken from literature, while silage and haylage contents depend on the annual winter feed quality analysis undertaken at Glensaugh (Table A.4). The metabolic energy from grazing is then estimated as a residual value between the total metabolic energy requirements and the energy from supplemented feedstuff.

Table A.3 Energy requirements by species, age, and type

Class	Daily energy requirements (in MJ/ Metabolic energy -ME)			
	Beef-cattle[(a)]		Deer[(b)]	
	MJ/ME day	Observations	MJ/ME day	Observations
Breeding livestock	86.3	Medium size suckler cow/heifers (500-575 kg)	20.8	Hinds
	101.4	Bulls/bullocks	29.3	Stags
Progeny	10.5	Suckled calves	6.1	Calves
Store/fat stock			17.1	Hinds
			17.7	Stags
	Uphill sheep[(c)]		Lowland sheep[(c)]	
	MJ/ME day	Observations	MJ/ME day	Observations
Breeding livestock	7.9	Black face ewes and gimmers (50-60 kg)	10.9	Cross breed ewes and gimmers (70 kg)
	9.9	Tups	9.9	Tups
Progeny	7.4	Lambs	7.4	Lambs
Store/fat stock	11.7	All types	11.7	All types

Source: Individual energy requirements based on [(a)] Mark Hilton (1995) Nutritional Requirements of Beef Cattle. DVM, DABVP, Veterinary Clinical Sciences, School of Veterinary Medicine, Purdue University; [(b)] Hackman, T.J. (2010). A System for Predicting Energy and Protein Requirements. Wiley-Liss, Inc. DOI 10.1002/zoo.20332; [(c)] AHDB (2016) Feeding the ewe. A manual for consultants , vets, and producers. Agriculture and Horticulture Development Board (AHDB). All female breeders' requirement account for pregnancy and lactation energy requirements.

Table A.4 Metabolic energy and dry mater content by feedstuff

Class	Metabolic energy content (MJ/kg DM)	Dry matter (DM, in g/kg)	Metabolic energy fresh weight (MJ/kg)
Straw (barley) (typical value)[(a)]	6.50	860	5.59
Grass hay (typical value)[(a)]	8.60	870	7.31
Compound feed (typical value)[(a)]	12.65	870	11.01
Silage and haylage (average value)[(b)]	10.87 (0.56)	318 (40.2)	3.45 (0.41)

Source: *Own elaboration* based on: (a) Cottrill et al. (2009). A review of the energy, protein and phosphorus requirements of beef cattle and sheep. Defra Project WQ 0133, and (b) Quality analysis period (2006-2018 for silage pit) that are transferred to haylage bales produced in Glensaugh, standard deviation provided in parenthesis.

[40] It estimated that half of straw is used for bedding in case of beef-cattle, while the other half is consumed as feedstock.

Fig A.18 shows the (a) estimated total energy requirements by livestock type and year (2006-2018), and (b,c) the share of energy requirements covered with own and external resources by livestock enterprise. The dependency on own produced feedstock foraging and grazing has been gradually increased over the last years, covering today almost 60 percent of total energy requirements. Grazing is especially relevant for hill sheep flocks, while low-ground livestock (beef-cattle and sheep) and deer enterprises have a higher dependency on winter feed, and feedstuff externally produced. A higher dependency on external resources can be a risk factor in situations such as the current restriction imposed due to COVID-19 pandemic. On the other hand, a higher dependency on own produced feed can increase pressures on farm natural capital (e.g., changes in land use and management intensity, or water resources). At Glensaugh, current stocking rates do not seem to drive increased pressures on the farm's natural capital as result of an increase in the dependency on own produced resources.

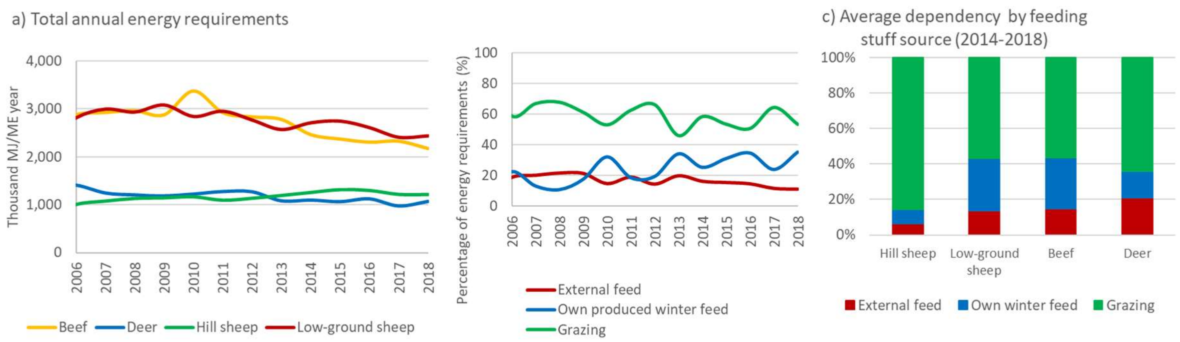
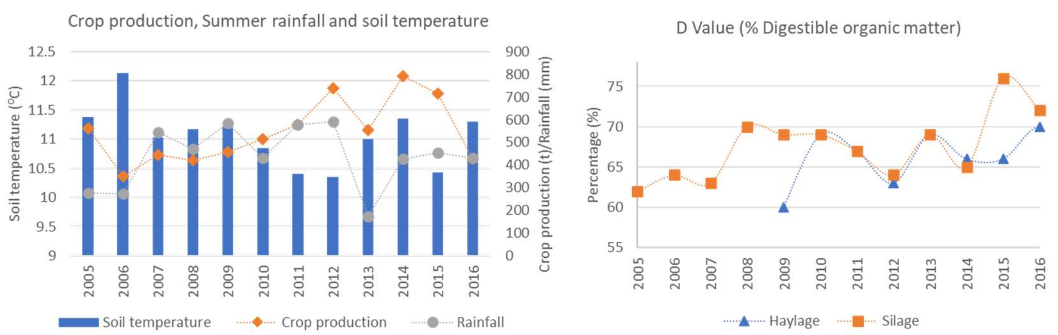


Fig A.18 Total energy requirements and average contribution of own and external feedstock

A.2.3.3 Trends in crop productivity and management

Livestock activities rely on plant biomass obtained from enclosed farm habitats, mainly improved grassland, and paddocks to produce silage and haylage, as well as swards from improved and seminatural grasslands. Conserved feed and swards productivity depend on a number of environmental and management factors and their interactions, in particular weather conditions. Haylage and silage production show some fluctuations that seem to be connected with low summer precipitations and high soil temperatures (Fig. A.19(a)). The quality of silage and haylage (here measured as the percentage of digestible organic matter or digestibility) is negatively affected by the opposite conditions: rainy and cold summers (Fig. A.19(b))[41]. This latter situation in Glensaugh is coped by the substitution of silage (and haylage) by hay.



(a) Total winter feed production and summer weather conditions

(b) Winter feed quality by type of feed

Source: Own elaboration based on ECN meteorological data and farm records on crop production and winter feed quality.

Fig A.19 Winter feed production and quality and summer weather conditions in Glensaugh (2005-2016)

[41] Note that digestibility of 70 percent and higher is considered good, and these indicates drops to less than 65 percent in 2012, which is considered a particularly poor summer.

A.2.3.4 Effect of crops productivity and quality on livestock enterprises profitability

Changes in conserved winter feed and grass productivity and quality can affect livestock growing rates, but also production costs through increases in the demand of external feeding resources (see Figs. A.20(b)). Fig. A.20 shows the variation of: (a) unit supplementary feeding costs by livestock enterprise; (b) unit price (or production cost) for external and own produced resources per unit of metabolic energy (ME MJ); and (c) net operating margin[42] by livestock enterprise cost. All Fig. A.20's charts are estimated at 2018 prices for comparability purposes. Fluctuations in the dependency and unit cost (price) on feedstuff produced externally, and also in dependency and production costs of own-produced winter feed (by metabolic energy unit, also for comparative purposes) have a negative impact on livestock enterprises unit feeding cost and profits.

Hill sheep flock, which mainly depends on grazed grass, and on own-produced winter feed for lamb finishing[43], shows the lowest unit feeding cost per standard livestock unit. When livestock productivity is concerned, deer exhibits the lowest profits by a comparable standard livestock unit. Sheep enterprises (hill and flock) are in general more efficient (more productive per standard livestock unit). All livestock enterprises show a broader range of fluctuation in profits per livestock unit. In part, fluctuations in livestock profitability are connected to variations in livestock prices, but also variations on the dependency on external feedstock and winter feed, among other management and ecological factors affecting livestock production, benefits, and costs. Beef-cattle enterprise (suckler cows) profits per SLU depict a noticeable increase since 2012.

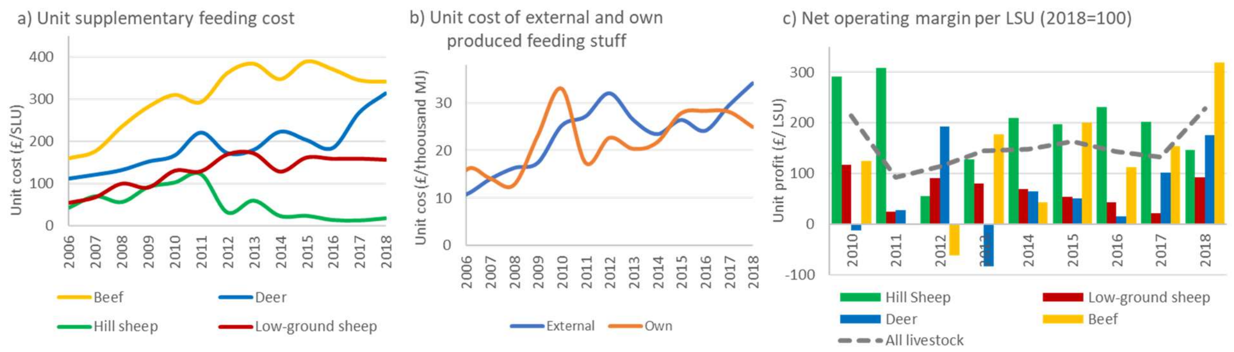


Fig A.20 Unit feeding cost and net profits by livestock enterprise in Glensaugh (2006-2018, 2018 prices)

A higher dependency on own-produced resources can increase the pressure on natural capital, through land use changes, ground and surface waters, or soils, in ways that can generate changes in the state and condition of natural capital. The main land use change observed in Glensaugh is woodland expansion (see sub-section A.2.4.1), and there is no clear evidence of natural capital condition deterioration due to an increase on the dependency on own-produced feedstuff.

On the contrary, despite the climatic fluctuations, a gradual increase in forage crop productivity and quality has been observed over the last few years (Fig. A.19), along with a marked reduction in the use of fertilisers. Indeed, chemical fertiliser application represents today about one fourth of the quantities applied by 2002, and this has been translated into saving in grassland management costs (Fig A.21). This reduction in fertilisers use has been accompanied by occasional liming in permanent pastures of lower quality, which are further managed as low input sheep pasture. Liming has in general a positive effect on the mobilization of nutrients from organic matter, but due to an increase in the microbial activity it also increases CO_2 emissions (Smith et al., 2010). GHG fertilising and liming induced emission have also experienced a decrease since 2002 (> 150%), which also affects off-farm fertilisers production emissions, and grassland management costs. For instance, fertilization and liming cost over the period 2006-2008 are more than 2.5 times higher (in real terms) than average costs observed in the period 2016-2018 (Fig. A.21.b).

[42] Representing the margin each enterprise makes after paying for variable costs of production, such as wages and raw materials, but before paying interests or taxes.

[43] Note that energy attributed to lamb finishing is distributed between the hill and low-ground flocks considering the number of black face (+cheviot) and crossbreed ewes and gimmers, that grass in hill and low-ground areas respectively.

Table A.5 shows the correlation matrix between pair of variables including summer rainfall and soil temperature, crops production and quality (in terms of their digestibility) and livestock enterprises profitability. In general summer rainfall has a strong negative correlation with haylage quality and in a lesser extent with silage quality. Higher summer rainfall have a strong negative correlation with beef profitability. Higher soil temperature level during the summer affect negatively to hill flock profits and crop productivity (forage harvest to produce winter conserved feed). Silage and haylage quality (here measures in terms of their digestibility) have a strong positive correlation with beef-cattle profits as the enterprise with a higher dependency on winter feed.

Table A.5 Correlation matrix between climate, crop productivity and quality and livestock enterprises profitability (data for 2006-2016)

	Summer rainfall	*Summer soil temp*	*D-Value Silage*	*D-Value Haylage*	*Profits Hill Sheep*	*Profits LG sheep*	*Profits Beef*	*Profits Deer*	*Crop pro-duction*
Summer Rain fall (jun-Sep)	1.00								
Soil T (Jun-Sep)	**-0.50**	1.00							
D-Value Silage	-0.11	-0.27	1.00						
D-Value Haylage	**-0.64**	0.10	0.28	1.00					
Profits Hill Sheep	0.18	**-0.39**	**0.46**	**0.38**	1.00				
Profits Low-ground sheep	-0.19	-0.23	0.18	0.05	0.29	1.00			
Profits Beef	**-0.63**	0.13	**0.64**	**0.50**	0.17	0.12	1.00		
Profits Deer	**0.36**	-0.27	-0.20	**-0.36**	-0.05	0.17	-0.55	1.00	
Crops production	0.19	**-0.59**	0.05	-0.20	**0.31**	**0.38**	-0.14	**0.57**	1

A.2.3.5 Trends in the use of fertilisers

The use of herbicides has been common in Glensaugh, with an average 20 ha of land treated every year since 2002. The quantity of products used depict relevant variations (Fig. A.22). Available water and soil pollution does not include pesticides. Good to high over water condition in Devily burn (to which Glensaugh water courses are affluent) would suggest that the impact is small.

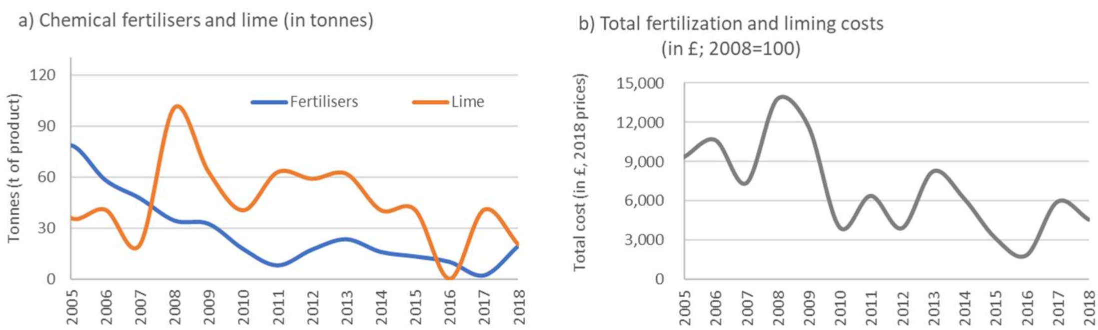


Fig A.21 Use of chemical fertilisers and liming in Glensaugh (2005-2018, 2018 prices)

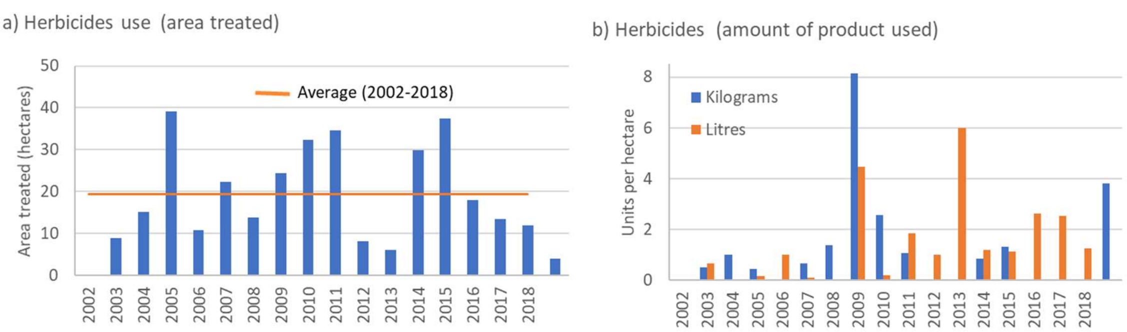


Fig A.22 Use of chemical fertilisers and liming in Glensaugh (2005-2018, 2018 prices)

A.2.3.6 Livestock farming GHG emissions and changes in economic-environmental efficiency

Changes in livestock numbers, and livestock and grassland management, have both had a significant effect on Glensaugh greenhouse gas emissions. Livestock emissions are estimated using the Cool Farm Tool (CFT), which is a greenhouse gas (GHG) calculator, intended for product-level calculations of outputting emissions for individual products produced on-farm (Kayatz et al., 2019). In addition, and for comparative purposes, we use the AgRE Calc tool to estimate livestock activity (beef and sheep) GHG emissions[44]. As indicated before, both CFT and AgRE Calc are amongst the three recommended tools for farm-based carbon audits in Scotland (Leinonen et al., 2019).

Table A.6 Information needed to estimate GHG emissions in the Cool Farm Tool (period 2002-2018)

Concept	Unit	Beef	Hill sheep	Low-ground sheep[(a)]	Deer[(b)]
Number of breeders	heads	51-75	350-508	445-596	72-135
Female breeder's life weight	kg	550			
Number of juvenile animals	heads	31-48	108-187		68-110
Age at first calf	months	26			
Grazing period (breeders)	Days/hours	165/24(45)	(100)	(75)	(100)
Meat calves/juvenile	(percentage)	130/24	(50)		(50)
Grazing type	Type	confined pasture	open grazing	confined pasture	open grazing
Grazing plots quality	qualitative	high	medium	medium	medium
Average dry matter head intake	DM kg/head &day	13.30-17.54	0.63-0.98	0.67-1.50	0.75-2.01
Compound feed (off-farm)	*DM kg/head &day*	*0.21-0.38*	*0.00-0.11*	*0.03-0.27*	*0.10-0.48*
Hay (off-farm)	*DM kg/head &day*	*0.00-0.23*	*0.00-0.25*	*0.00-0.35*	*0.00-1.93*
Grass-silage/haylage (own)	*DM kg/head &day*	*2.19-5.05*	*0.00-0.13*	*0.18-0.61*	*0.08-1.07*
In-farm grazing [(d)]	*DM kg/head &day*	*3.41-8.02*	*0.24-0.82*	*0.39-0.59*	*0.53-1.17*
Straw (feeding stuff & bedding)	t	312-481	2-36	50-100	50-103
Manure management (deep bedding – no mixing)					
Female breeder/adults	percentage/days	45/164		4/14	
Calves/juveniles	percentage/days	15/30	30/120		50/210

Notes: : [(a)] Low ground flock, including feeding and energy demand for replacement animals; while finishing lambs are attributed according the number of hill and low ground ewes and gimmers [(b)] Deer GHG are estimated considering Other livestock sheep options. [(c)] Estimated as a residual value of total energy requirements and the energy content in supplementary feed, and a dry matter (DM) content of 200 g/kg and a metabolic energy content of 11.2 MJ/kg in grass from grazing (Cottrill et al., 2009).

Source: *Own elaboration* based on Glensaugh farm records and consultation with the farm manager.

GHG emission were estimated by livestock enterprise, considering average livestock numbers over the year, dry matter (DM) intake, proportion of the time animals are grazing outdoors and housed, and annual dependency on different supplementary feeding stuff, and bedding and manure management from 2002 to 2018[45] (Table A.6).

CFT and AgRE Cal estimate GHG emission (in CO_2 equivalent units) attributable to enteric fermentation, feed production, grazing (only in case of beef-cattle in case of CFT and for sheep and beef in case of AgRE Calc) and manure management. AgRE Calc estimates in general higher GHG emissions. Table A.7 shows differences in emission estimation by sources for beef and sheep enterprises. For example, estimated feed emission are higher in CFT, while enteric fermentation and grazing estimated by AgRE Calc is significantly higher than CFT estimates. Emission are estimated using the CFT free online tools as it allows for more flexibility in accounting for more livestock species and years. More research is needed to analyse the reason behind GHG emissions differences by these two tools. AgRE Cal estimation are considered as an upper emissions threshold.

According to CFT estimations (including deer), enteric fermentation accounts for 70 percent of livestock GHG emissions, with manure management and feed production accounting for more than 14 and 12 percent of emission, respectively. Beef-cattle enterprise account for about 40 percent of total livestock emissions, with hill

[44] AgRE Calc covers all main agriculture production systems in Scotland, and different to CFT it allows for a whole farm emissions estimation, while CFT estimates emission for single livestock enterprises. For a detailed analysis of the advantage and disadvantages of both carbon auditing tool see Leinonen et al. (2019).

[45] Estimated livestock GHG emission considering the periods 2002, 2004, 2006,2008, 2010, 2012, 2014, 2016 and 2018 for the CFT application , and year 2018 for AgRE Calc.

and low-ground flocks being responsible together for about half of livestock GHG emissions, and deer farming a 10 percent (Fig. A.23(a)).

Table A.7 Estimated GHG emissions using AgRE Calc and CFC for beef and sheep enterprises (year 2018)

Emission source	AgRE Calc (emissions in kg CO_2 eq)			CFT (emissions in kg CO_2 eq)			Difference
	Beef	Sheep	Total	Beef	Sheep	Total	
Feed	12,362	13,740	26,102	27,870	2,261	30,131	-4,029
Bedding	59,256	10,406	69,662			0	69,662
Manure (manure management)	22,250	4,783	27,033	29,400	2,490	31,890	-4,857
Enteric fermentation	112,986	196,254	309,240	58,660	177,970	236,630	72,610
Grazing	35,142	57,965	93,107	9,070		9,070	84,037
Grassland management						33,520	-33,520
Total	241,996	283,148	525,144	125,000	182,721	341,241	183,903

The emission by standard livestock unit show a different picture of Glensaugh livestock farming emission, in that case considering only the number of breeding and replacement animals. Deer and Black face hill flock show on average the lowest GHG emission per SLU with variation across the periods, depending on the share of feed and grazing. Low-ground flocks (including finish and replacement animals) have a similar per SLU emissions than hill flock (Table A.8), and as expected beef-cattle GHG emission by SLU almost double the emission from other ruminant species raised in Glensaugh (Fig. A.23).

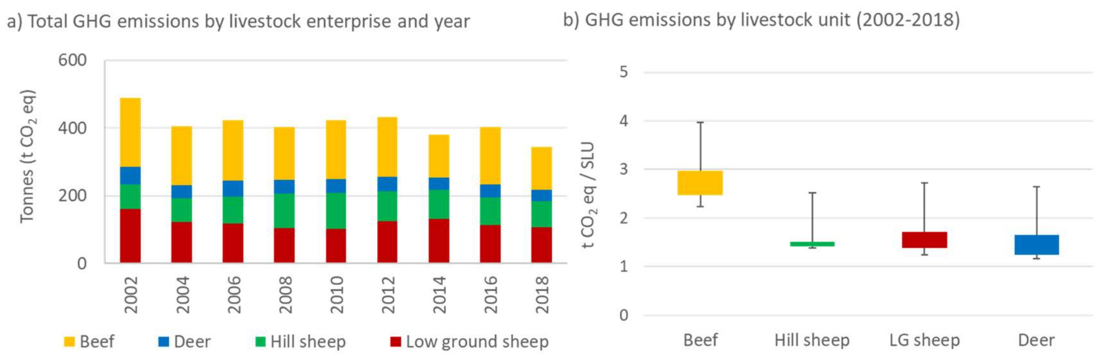


Fig A.23 Livestock farming total and unit GHG emissions by enterprise and year (2002-2018)

Table A.8 Combined environmental and economic efficiency (profit and GHG emissions ratio by standard livestock unit by livestock enterprise and year, 2018 prices)

Year	Net profits (net operating margin £/SLU)				GHG emissions (t CO_2 e/SLU)				Ratio profit/emissions (£/tCO_2e)			
	Beef	Hill flock	LG-flock	Deer	Beef	Hill flock	LG-flock	Deer	Beef	Hill flock	LG-flock	Deer
2,006	84.38	-10.49	84.93	46.70	2.58	1.48	1.33	1.37	32.66	-7.10	63.77	34.08
2,008	38.36	38.64	133.21	-25.85	2.46	1.37	1.45	1.23	15.56	28.16	91.88	-20.94
2,010	124.14	291.13	301.06	-12.50	2.68	1.37	1.54	1.19	46.31	211.74	195.58	-10.47
2,012	-61.03	55.41	225.77	192.79	3.02	1.41	1.76	1.32	-20.22	39.34	128.40	145.86
2,014	43.00	209.35	181.55	64.90	2.43	1.42	1.63	1.28	17.72	147.09	111.16	50.77
2,016	112.29	231.84	120.53	15.93	3.15	1.43	1.41	1.39	35.59	161.96	85.56	11.44
2,018	319.48	146.65	260.45	175.50	2.45	1.46	1.39	1.44	130.35	100.54	187.74	121.79
Mean	**94.37**	**137.50**	**186.79**	**65.35**	**2.68**	**1.42**	**1.50**	**1.32**	**36.86**	**97.39**	**123.44**	**47.50**
SD	108.17	104.31	73.35	80.66	0.27	0.04	0.14	0.08	42.97	74.46	47.07	59.44

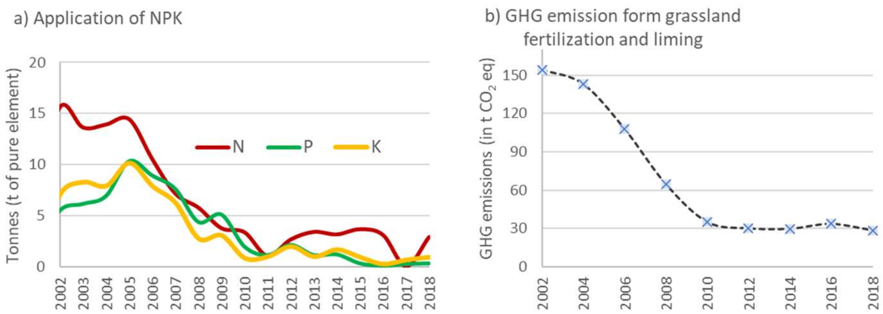
Notes: LG stands for low ground.
Source: *Own elaboration* using farm records data and the online Cool Farm Tool.

An interesting indicator to analyse the combined environmental and economic efficiency of livestock enterprises is the ratio between net margin (profits) and GHG emission by standard livestock unit (Table A.8). Low-ground and hill sheep are the enterprises that show the highest economic/environmental efficiency, which on average are three times more efficient that beef-cattle (suckler cows) and deer enterprises. It is also important to mention that the profit-GHG emission ratios have been increasing over the last years for all livestock enterprises, which suggest higher efficiency. This seems to be related with increases in the quality of own-produced winter stock (Fig. A.19(b)), and its likely negative effects on unit feeding cost and enteric fermentation emissions. Still net profits greatly depend on local livestock and input market conditions, which explain the fluctuations on net profits, and hence on the environmental economic efficiency of these livestock enterprises.

A.2.3.7 GHG emissions due to grassland management

Other livestock -related emission come from grassland fertilization. These were also estimated using the online Cool Farm Tool (Kayatz et al., 2019). The farm manager at Glensaugh has kept detailed records on grass and cropland management since 2002. These include information on the area (plot), time and quantity of fertilizers (including liming) applied in Glensaugh. As there are many different types of fertilizers, for estimating fertilization induced GHG emissions, the application of NPK as pure elements was estimated (Fig. A.24(a), considering the composition of each product applied. In accordance to the drastic reduction in the use of fertilizers (Fig. A.21), fertilization induced GHG emissions have experienced a significant reduction since 2020 (Fig. A.24(b)). Fertiliser induced emissions account for carbon dioxide and nitrous oxide as estimated using the CFT.

Small size rotational heather burning is also practiced in Glensaugh, with a rotation length close to 15 years. While heather burning improves swards edibility (e.g. to favour grouse breeding), it can negatively affect soils and moss. The benefits and disbenefits of using controlled fires in moorland management is still disputed, and clearly depend upon how trade-offs are made between ecosystem services and the spatial and temporal scales of concern (Davies et al., 2016). There are no specific records on the size and location of the parcels burnt to provide estimates of GHG emissions from burning.



Source: *Own elaboration* based on Glensaugh farm records and the online Cool Farm Tool

Fig A.24 Fertilizers application and GHG emissions (2002-2018)

A.2.4 Changes in dependencies and impacts of other land-based business on natural capital

Livestock farming and associated grass and cropland management are the main Glensaugh farming activities. Forestry is gaining relevance due to the recent woodland expansion undertaken in the farm, and the plan for further increases in woodland area as part of the net zero farming strategies (see sub-section A.2.4.2 and section A.3). Revenues from forestry (and agroforestry) are yet not significant, as most of woodlands are relatively young. Old woodlands and agroforestry plots thinning are sources of the biomass used in a boiler to provide heating. This is the main source of heating for the Glensaugh lodge. The use of biomass in substitution of fossil fuels has been translated in both GHG emissions and cost savings as detailed next. Electricity consumption depends on the grid, and the wind turbine also provide electricity to the grid. GHG emission from electricity consumption were also estimated (sub-section A.2.4.2).

A.2.4.1 Fossil fuel, heating, and electricity consumption GHG emissions

Glensaugh farm records account for three different fossil fuels: heating oil, propane (formerly used for Glensaugh lodge heating) , and diesel used for machinery and vehicles. GHG emission from burning heating oil, propane and diesel are taken from the UK Government GHG Conversion Factors report (BEIS, 2018; BEIS, 2019). Table A.9 shows the main GHG emissions and energy conversion factors associated to fossil fuels and biomass consumption for different purposes, and average annual energy sources consumption. This table include also solar and wind energy production. No emission are directly attributed to these latter sources of energy.

Specific farm records on the use of wood biomass are not kept. Therefore, biomass use emissions are estimated indirectly, accounting for the average propane consumption before the acquisition of the biomass boiler, and the equivalent amount of biomass needed to produce a similar amount of heating energy. The amount of biomass needed to produce an equivalent heating energy of 29.4 MWh (4,454 l*6.6kWh/l) is estimated in 7.2 (±2.6) metric tonnes (about 12.1 (± 4.4) m^3) of wood annually[46]. As discussed in more detail in sub-section A.2.4.2, current timber growth in existing woodland accrued about 75 m^3/year in 2018, which is growing as most of woodland plantations are younger than 10 years old. Current biomass use is lower to biomass growth, which provides further opportunities to commercialise timber and carbon offsets.

Table A.9 Energy consumption and GHG emission for fossil fuels and biomass use

Energy source	Unit	Main use	Caloric value (kWh/unit)[b]	GHG emissions factor (in kg CO_2eq/unit)	Annual consumption (in total units)[c]	Annual GHG emissions (in t CO_2 eq)
Propane (LPG)	litre	heating	6.60	1.519	4,454 (2.036)	6.77 (3.09)
Heating oil[a]	kg	heating	11.13	3.178	2,030(858)	6.45(2.73)
Red diesel	litre	machinery, vehicles	9.96	2.594	6,444 (1,592)	16.72(4.13)
Grid electricity[d]	kWh	various		0.428(0.080)	75,941 (28,465)	34.13(17.02)
Biomass (wood logs)[e]	kg	heating	4.08	1.498	7.200 (3,300)*	10.78(4.93)
Solar energy	kWh	various on-site and grid export			4,410(586)	-
Wind energy	kWh	grid export			22,478(10,323)	-

Notes: [a] Heating oil emissions are based on fuel oil caloric values and GHG emission conversion factors. [b] Caloric values are estimated by relating CO_2 equivalent emission by unit (litre or kg) of fuel consumed and the CO_2 equivalent emission by kWh. [c] Average consumption from 2008-2018 for heating oil, 2006-2011 for propane, 2006-2018 for red diesel, 2010-2018 for grid electricity consumption, 2015-2018 for solar energy, 2013-2016 for wind energy, and estimated values in case of biomass(*). Inputs consumption is taken from Farm Plan software used in Glensaugh. Standard deviation in parenthesis. [d] Electricity emission factors vary year to year, and those consider emission from electricity in the UK grid, which estimation accounts for all energy sources used for producing electricity in the UK including grid losses. [e] Biomass emissions account for total biomass burning emissions, without assuming that CO_2 emissions are compensated by carbon sequestration through tree growth. *Annual biomass consumption is and estimated rather than a recorded figure.

Source: *Own elaboration* based on BEIS, DEFRA (2018 and 2019) GHG conversion factors and Glensaugh farm records.

Total biomass GHG emission are accounted for. In particular, direct CO_2, and CH_4 and N_2O emissions associated to wood logs burning. CO_2 emission are labelled as *outside of the scope* of UK GHG emission conversion factors, as following the IPCC rules for reporting energy sector emissions, it is assumed that biomass energy will be produced at a zero carbon cost as the fuel source absorbs itself an equivalent during the growth phase than the amount of CO_2 released due to burning. The time that carbon is released and is sequestered matters in terms of global warming effects. Therefore, burning biomass can only be sustainable if the annual emission due to biomass burning plus any other emission due to biomass preparation and transportation need to be smaller or at most equal to the annual carbon uptake through biomass growth.

A.2.4.2 Net carbon sequestration through land use change

The GHG balance associated with changes in the use of land are mainly due to woodland expansion, but also due to existing forest and grassland management. At Glensaugh 23 hectares improved grassland are estimated

[46] An average wood density of 0.593 tonnes per cubic meter is considered (Table A.9).

to add about 37 tCO_2[47] per year to the GHG balance. The criteria and methods used to estimate changes in tree biomass and soil carbon due to recent woodland plantations on the farm is explained in detail in sub-section A.3. Estimations of carbon sequestration due to tree biomass growth are based on timber volume growth models, carbon stock conversion factors, and suitability models of tree species growth and yield. Soil carbon emissions and sequestration is estimated considering Glensaugh carbon soil carbon stock estimations, and WCC look up tables as detailed in sub-section A.2.3. All those models and factors are applied to estimate net carbon sequestration in existing woodlands and new woodland plantations over the period 2002-2018 (Table A.10).

Initial social carbon release depend upon the type of soil (mineral or organo-mineral), the soil carbon stock, and the ground preparation and plantation techniques. An initial average carbon release of 23.4 t CO_2/ha is considered for planted woodlands from 2010 to 2017[48], which represent estimated average soil carbon losses in the top 30 cm of soil when plantations took place on improved pastures (67%) or seminatural plant communities (33%), over both organic and mineral soil, and using forestry ploughing (shallow turfing) and scarifying as the main ground preparation practice. In 2018, 4 out of the 6.8 hectares planted this year used manual ground preparation techniques. In that case initial soil carbon emissions are estimated in 14.9 t CO_2/ha

Table A.10 Woodland plantations by year and species (in hectares)

Species	Yield class[(1)]	Existing forest (2009)	New woodland plantation by year								
			2010	2011	2012	2013	2014	2017	2018	2019	Total
Beech	2	-			0.12						0.12
E. larch	-	-						0.67			0.67
Mixed broad-leaves	Oak-Birch	0.35	0.67	0.35				8.84		1.24	11.1
Mixed conifers/broadleaves	Oak /Scots pine	3.74	11.77	0.58		6.88	4.67				23.9
Mixed Sitka/ spruce broadleaves	Sitka/Oak-Birch	1.61									-
Norway spruce	6	0.92									-
Scots pine	7	0.93			3.5			1.62			5.12
Scots pine / E. larch	7	4.14						3.08	5.54		8.62
Sessile Oak	2				0.46						0.46
Sitka spruce	8	0.19									-
Designated open ground	-	-							0.62		0.62
Other woodland	-	2.82						0.05	0.64		0.69
Total		11.88	12.44	0.94	4.09	6.88	4.67	14.25	6.8	1.24	51.3

Note: [(1)] Dominant Yield Class in the area of woodland plantations according to the Ecological Site Classification (ESC) decision support system (Pyatt et al., 2001)

Figure A.25 shows estimated changes in net carbon sequestration and carbon stock due to land use changes since 2002. For the results presented next, it is important to note that woodland plantation involving organo-mineral soils and the use of mechanical ploughing for ground preparation is expected to induce to soil carbon release. Consequently, recent woodland expansion may have implied a large amount of soil carbon release in Glensaugh soil (with a large part of organ mineral ones), even if low to moderate soil disturbance ground preparation techniques are used. It is estimated that soil carbon emission were nonetheless offset by carbon uptake in tree biomass growth.

Woodland expansion has increased carbon stock tree biomass and soils. It is estimated that woodland expansion have increased vegetation and soil carbon stock by 138 tons of carbon (~500 t CO_2). Net carbon sequestration as result of woodland expansion efforts accounted for about 128 tCO_2 in 2018, which is equivalent to an annual sequestration of 1.9 tCO_2/ha of woodland. This sequestration rate is expected to rise in the coming years, as shown in subsection A.3, which analyses the carbon sequestration potential associated to woodland expansion in Glensaugh.

[47] Smith et al. (2007) suggest that converting lands where arable rotation is practiced to improved grasslands can add 1.6 tCO_2 per hectare over a period of 20 to 30 since land use change takes place (quoted by Rees et al., (2018)).
[48] Considering soil types in the area of existing woodlands in Glensaugh (Figure A.2).

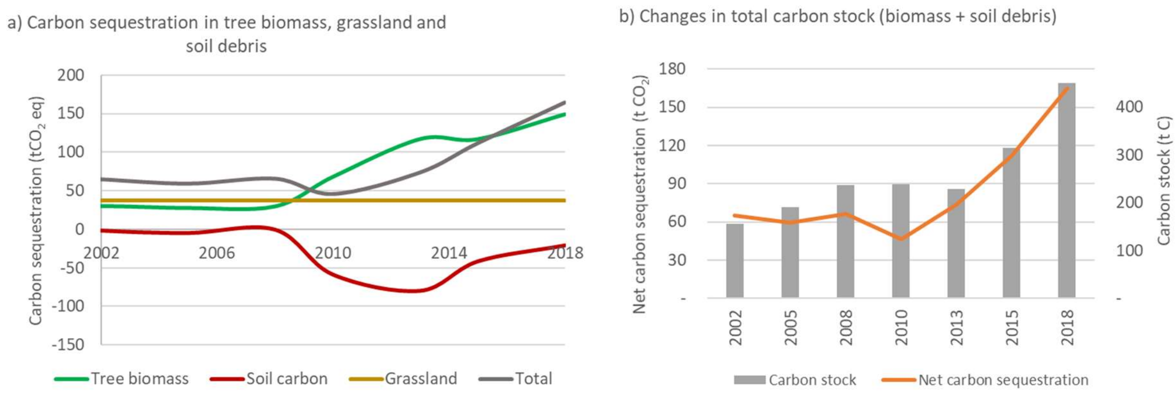


Fig A.25 Changes in net annual carbon sequestration and carbon stock in tree biomass and soil due to land use changes (2002-2018)

A.2.4.3 Total GHG emission and carbon offsets

GHG emissions range between 500 to 700 CO_2 equivalent carbon dioxide tonnes in 2018[49], without considering emissions offsets due to carbon sequestration. Livestock farming and grazing management contribute more than 70 percent of total farm GHG emissions, with energy consumption (fossil fuel, biomass, and grid electricity) responsible for about 25 percent of Glensaugh carbon (equivalent) footprint. Emissions due to energy use may be even higher than estimated, as red diesel consumption figures may need to be revised[50].

Glensaugh GHG emissions have been decreasing at an average annual rate of 2 percent since 2010 (see Fig. A.26). This latter reduction rate is higher than the 1.4% of GHG emission reduction estimated for the Agriculture and related land use sector in Scotland in the period 2010-2016[51]. Glensaugh' s emission reduction is the result of a combined effect of decreases in livestock numbers and fertiliser use, as well as, due to a decrease in heating energy, electricity, red diesel consumption which has been more relevant over the last three years. Solar panels produce an energy equivalent to 11 percent of total grid electricity consumption, while a wind turbine produced an energy equivalent to 30 percent of the grid energy consumed between 2013 and 2016, though this energy was mainly exported to the grid.

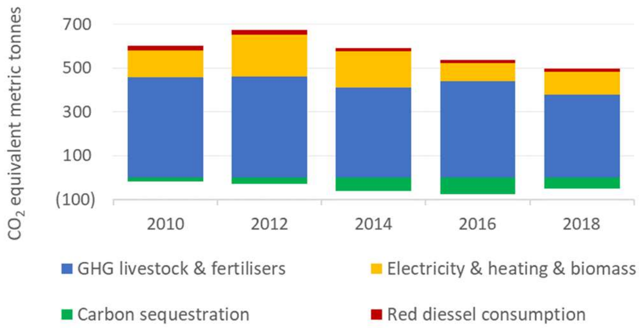


Fig A.26 Net GHG emissions by source and year

[49] The upper range correspond to the AgER Calc estimations and the lower to CFT GHG livestock emission estimations.
[50] It is not clear if fuel consumption is fully recorder in the farm management software (e.g. FarmPlan) used in Glensaugh.
[51] GHG annual reduction rate estimated using data from the Scottish Greenhouse Gas Emission Inventory 2016 (https://www.gov.scot/publications/scottish-greenhouse-gas-emissions-2016/) .

Carbon sequestration from woodland expansion offset about one third of total farm GHG emissions (estimations for 2018). Woodland expansion shows a big potential to offset these emissions, as shown in next sub-section, though it would also involve significant investment levels (see section 3 in the main report). Estimated emissions and carbon sequestration may be underestimated, as other emissions due to grassland management (i.e., rotational heather burn), soil carbon release or sequestration in semi-natural vegetation, or additional carbon sequestration in the agroforestry plots are not accounted for.

A.3 Woodland carbon stock and flows

Carbon stock and flows are estimated for both existing woodlands (Table A.8) and for the planned woodland expansion area (Fig. 7). These stock and flows differ by tree species, soil class and initial land cover on the planted areas (improved grassland or seminatural plant communities). Woodland carbon stock and flows account for expected changes in tree biomass and soils (accounting only for the first 30 cm of soils). None of the carbon stock and flow figures are derived from Glensaugh site measures. Tree growth is estimated using species specific timber volume models, while carbon stock considering carbon conversion factors. Net carbon sequestration would depend on changes on carbon stock, which are also affected by changes in the number of trees due to management. Changes in soil carbon stock are based on West (2011) criteria, and carbon stock estimated specific for Glensaugh, as detailed below.

A.3.1 Estimation of timber growth and associated carbon sequestration

Tree biomass carbon stock and CO_2 sequestration estimations are based on timber production tables taken from the Forest Yield model by species, forest stand age and yield class (Matthews et al., 2016)[52]. Timber growth function are estimated by forest species as nonlinear functions that depend on yield class and age (Table A.11)[53]. Tree biomass carbon stock estimates further account for expansion factors that relates timber volume with total carbon stock in aboveground and root tree biomass (Table A.12).

Table A.11 Timber volume nonlinear functions and regression parameters by species

Function:	$v = K \cdot (t \cdot YC)^b \cdot e^{-at}$							
Variables	European larch		Beech		Scots pine		Douglas fir	
K	0.6836	***	0.6475	***	0.6952	***	0.7365	***
	(0.0858)		(0.0445)		(0.0677)		(0.0769)	
b	1.0585	***	1.0596	***	1.0249	***	1.0050	***
	(0.0223)		(0.011)		(0.0154)		(0.0159)	
a	-1.54E-03	**	-3.71E-04	**	9.72E-04	*	1.23E-04	
	(4.97E-04)		(1.42E-04)		(4.54E-04)		(3.41E-04)	
R^2	0.990		0.990		0.972		0.974	
N obs.	320		600		601		720	
Function:	$v = K \cdot (t^2 \cdot YC)^b \cdot e^{at}$						$v = K \cdot (t \cdot YC)^b \cdot e^{at^2}$	
Variables	Sitka spruce		All Oak species		Norway spruce		All Birch species	
K			0.0418	***			0.5222	***
			(0.0020)				(0.0442)	
b	0.6607	***	0.9696	***	1.0585	***	1.1090	***
	(0.0007)		(0.0052)		(0.0223)		(0.014)	
a	7.35E-03	***	1.12E-02	***	-1.54E-03	***	-3.86E-05	***
	(8.21E-05)		(1.16E-04)		(4.97E-04)		(2.77E-06)	
R^2	0.966		0.999		0.990		0.995	
N obs.	1,800		450		320		240	

Notes: *p < 0.1, ** p < 0.01; *** p < 0.001. Robust standard error in parenthesis.
Source: *Own elaboration* based on Annual Forest Yield Model production tables. Estimations based on yield tables for the yield classes (YC) available in the FTM by species (Matthews et al., 2016).

[52] Yield Class (YC) is an index used in the UK of the potential productivity of even-aged stands of trees. It is based on the maximum mean annual increment of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a standard management prescription (Matthews et al., 2016).
[53] Standing timber estimates consider plantation spacings ranging from 1.7 to 2.5 m.

These timber volume models and carbon stock conversion factors are applied to both existing (Table A.10) and planned forests, in view of predicted yield classes according to the Ecological Site Classification (ESC) decision support system (Pyatt et al., 2001) (see Fig. 8 in the main text). It is important to note that exponential timber function tends to overestimate carbon sequestration at the early tree growth stages when compared to the Woodland Carbon Code look up table values (West, 2018). These functions predict timber growth well when compared to the FYM tables. Following WCC rules, a maximum of 80 percent of carbon sequestration estimates are accounted for as potential carbon offset credits.

Table A.12 Biomass to carbon conversion parameters for forest species in Great Britain

Species	Density of timber (ρ) in t m^{-3} (MC 12%[(a)])	Carbon content (ϕ) in tC t^{-1} of timber [(b)]	Timber to above ground biomass expansion factor[(c)]	Root ratio (Mroot/Maboveground)[(c)]	Expansion factor from timber to total biomass [(c)]	Conversion from standing timber to carbon (c_t) (tCO_2 m^{-3})
Beech*	0.689	0.46	2.226		2.226	2.587
Oak	0.689	0.46	2.226		2.226	2.587
Birch (SAB)	0.673	0.46	2.226		2.226	2.527
Mixed broadleaves (SAB)	0.673	0.46	2.226		2.226	2.527
Douglas fir	0.497	0.42	2.230	0.260	2.490	1.906
European larch	0.545	0.42	2.226	0.360	2.586	2.170
Hybrid larch	0.465	0.42	2.226	0.360	2.586	1.852
Norway spruce	0.400	0.42	2.226	0.250	2.476	1.525
Sitka spruce	0.384	0.42	2.230	0.410	2.640	1.561
Scots pine	0.513	0.42	2.230	0.300	2.530	1.999
Mixed broadleaves/ conifers (MBC)**	0.593	0.44	2.228	0.150	2.378	2.275

Notes: The conversion factor from standing timber volume to carbon biomass (c_t) (tonnes of carbon dioxide per cubic metre of timber) is estimated as c_t= ρ *ϕ *EF*Ķ. The density of timber is estimated assuming a relative humidity (RH) of 65%, which gives an equilibrium moisture content (MC) at 20°C of approximately 12%[(a)]. The carbon content refers to oven dry wood[(b)], and to convert to carbon timber weight is multiplied by ϕ, EF and Ķ, which are the carbon content in dry biomass, the expansion factor that indicates the total volume of wood in relation to the standing timber volume[(b)], and the ratio of molecular weight to convert C to CO_2, respectively. *Beech density equals to oak. ** Mixed broadleaves/conifers considers the average between Scots pine and Birch (SAB: Sycamore-Ash-Birch)).
Source: Own elaboration based on (a) Morison et al. (2012); (b) Milne and Brown (1997) and (c) Levy et al. (2012).

A.3.2 Changes in soil carbon stock due to woodland expansion

Carbon sequestration and release in woodland soil debris is estimated using the Woodland Carbon Code (WCC) look up tables (West, 2018). Whereas the WCC data are not available for the yield classes predicted by the ESC (e.g. odd numbers and lower yield classes) the yield class is round down to the nearest even number of the WCC look up tables (Table A.13). Net soil carbon gains due to woodland expansion need to be carefully considered, in view of potential GHG emissions due to soil disturbance during ground preparation, which are significantly higher when mechanical ground preparation techniques and organo-mineral soils are concerned (West, 2018).

Soil carbon stock was estimated for Glensaugh (area of planned plantations (see Fig. A.28 and Table A.14). Those consider different carbon stock figures for soil series and type of soils (organo-mineral or mineral). In case of planned forest, soil carbon stock are estimated for the ESC six-digit grid, and potential CO_2 release is estimated at the grid level, and assuming forestry ploughing (shallow turfing) and scarifying as the most likely ground preparation practice. West (2011) indicates that this latter ground preparation practice is expected to release up to 20 percent of soil carbon stock in organo-mineral soil and 5 percent in mineral soils. This percentages can increase of decrease with more and less intrusive soil preparation techniques (Table A.13). Soil carbon release estimations in Glensaugh consider a moderate intensity ground preparation consisting in forestry ploughing (shallow turfing) and scarifying, and hand turfing and mounding. Under these conditions, we expect a 10 percent of initial carbon stock release when plantations take place in organo-mineral soils and 2 percent in mineral soils (see Table 4).

Table A.13. Estimated carbon sequestration and release in soil debris by species and yield class (in t CO_2/ha and year)

Max age	Oak	Birch	Beech	Scots pine		Douglas fir	Sitka spruce		Larch	Norway spruce
	YC4	YC4	YC4	YC4	YC8	YC8	YC6	YC10	YC 6	YC 6
5	0.29	0.34	0.29	0.07	0.12	1.20	0.14	0.16	0.67	0.14
10	0.338	0.34	0.36	0.09	0.15	1.48	0.18	0.20	0.83	0.17
15	0.35	1.12	0.36	0.09	0.15	1.49	0.18	0.20	0.83	0.17
20	0.35	0.82	0.36	0.09	0.15	1.75	0.18	0.20	0.83	0.17
25	0.35	0.33	0.36	0.09	0.15	3.12	0.18	0.53	2.42	0.17
30	0.35	0.21	0.36	0.09	0.56	4.65	2.77	1.76	1.57	0.17
35	3.426	0.15	1.055	0.09	1.62	-0.76	1.22	0.35	-0.72	2.81
40	3.426	1.32	1.75	0.09	0.10	2.50	1.15	0.93	0.82	0.08
45	0.938	4.75	0.69	2.13	0.99	1.99	0.92	0.69	-0.01	1.91
50	0.666	1.02	0.07	0.47	1.92	1.14	0.42	-0.03	-0.5	2.16
55	0.102	-0.26	-0.41	0.645	2.49	-0.05	-0.51	3.09	-0.33	1.01
60	-0.422	-0.25	-1.28	0.435	0.70	-0.40	-0.50	1.84	-0.44	-0.18
65	-0.736	-1.02	-1.32	0.19	0.21	-0.76	0.89	0.71	-0.27	-0.62
70	-0.758	-0.69	-0.744	0.107	-0.25	-0.82	0.49	-0.44	-0.498	-0.58
75	-0.49	-0.49	-0.52	-0.085	-0.31	-0.88	0.00	-0.69	-0.25	-0.52
80	-0.386		-1.02	0.45	-0.54	-0.81	-0.22	-0.73	-0.24	-0.47

Notes: Soil debris carbon sequestration and release by species and yield class (YC) is estimated considering information for the closer YC available in the Woodland Carbon Code (WCC) look up tables which yield classes are indicated in the second row (West, 2018). Following the WCC, only 80 percent of soil carbon sequestration is accounted for. For YC lower than the minimum YC recorder in the WCC look up tables, we consider changes in soil carbon debris of those minimum yield classes. Carbon emission do not account for soil carbon emission due initial ground preparation.

Table A.14 Soil carbon stock by soil class, land cover and soil type and estimated initial carbon release due to low to high ground preparation intensity in Glensaugh

Soil series name	Land Cover	Soil type[(1)]	Soil carbon Stock (t C/ ha)			Initial carbon release due to ground preparation technique		
			Mean	Min	Max	Low intensity [(2)]	Moderate intensity [(3)]	High intensity [(4)]
Alluvial	Dwarf shrub heath	M	108.2	98.8	117.6	0.0	7.9	19.8
Loamy dry	Improved grassland	M	108.2	98.8	117.6	0.0	7.9	19.8
Fungarth	Acid grassland	M	130.8	117.6	144.0	0.0	9.6	24.0
	Improved grassland	M	130.8	117.6	144.0	0.0	9.6	24.0
Garrold	Coniferous woodland	OM	160.1	0.0	0.0	29.3	58.7	117.4
	Dwarf shrub heath	OM	160.1	0.0	0.0	29.3	58.7	117.4
Hythie	Dwarf shrub heath	OM	204.5	195.9	213.0	37.5	75.0	150.0
	Improved grassland	OM	204.5	195.9	213.0	37.5	75.0	150.0
Ledmore	Coniferous woodland	M	102.9	0.0	0.0	0.0	7.5	18.9
Strathfinella	Coniferous woodland	OM	85.7	73.7	97.8	15.7	31.4	62.9
Strichen	Acid grassland	OM	134.0	128.9	139.1	24.6	49.1	98.3
	Coniferous woodland	OM	136.2	131.9	140.4	25.0	49.9	99.9
	Dwarf shrub heath	OM	136.2	131.9	140.4	25.0	49.9	99.9
	Improved grassland	M	133.6	128.4	138.9	0.0	9.8	24.5

Notes: [(1)] OM: organo-mineral, M: mineral. [(2)] Low intensity ground preparation consisting in hand turfing and mounding. This ground preparation technique is expected to affect a 5 percent of initial carbon stock release when plantations take place in organo-mineral soils and 0 percent in mineral soils. [(3)] Moderate intensity ground preparation consisting in forestry ploughing (shallow turfing) and scarifying, and hand turfing and mounding. This ground preparation technique is expected to affect a 10 percent of initial carbon stock release when plantations take place in organo-mineral soils and 2 percent in mineral soils. [(4)] High intensity ground preparation consisting in turfing or tine, using double or single throw mouldboard plough (deep plough). This ground preparation technique is expected to affect a 20 percent of initial carbon stock release when plantations take place in organo-mineral soils and 5 percent in mineral soils (West, 2018).

A.3.3 Timber and carbon prices and management costs

Timber stumpage prices for conifers and woodland plantations and management cost are taken from the ERAMMP Forest research project [54] and updated to 2018 using the timber price index[55] and UK GDP deflator,

[54] Saraev (2019). ERAMMP – economic analysis. Forest Research (unpublished).

[55] Estimated by Forest Research: https://www.forestresearch.gov.uk/tools-and-resources/statistics/statistics-by-topic/timber-statistics/timber-price-indices/

respectively. Stumpage timber prices for broadleaves are obtained from British hardwoods data. Carbon prices correspond to the range of prices reported by the WCC projects (Haw, 2017) (Table A.15).

Table A.15 Unit prices and cost associated to woodland management

Class	Unit	Unit value (£/unit)		
		Low	Central	High
Coniferous standing timber price (over bark)	m^3	16.99	33.98	50.97
Broadleaves standing timber price (over bark)	m^3	33.98	67.96	101.94
Carbon sequestration	t CO_2	3.00	6.00	15.00
Ground preparation and planting cost (conifers)	ha	2,560.00	2,785.00	5,080.00
Ground preparation and planting cost (broadleaf)	ha	3,160.00	4,180.00	5,680.00
Annual maintenance cost (annual cost, for 20 years)	ha	56.18	56.18	56.18
Deer fencing	ha	2,804.43	2,804.43	2,804.43

A.4 Questionnaire to define the objectives and scope of the Protocol implementation at Glensaugh

A.4.1. Questionnaire for defining the objective and scope of the natural capital assessment in farming systems in Scotland

Name of the participant	

Relationship to the farm	

Farm		Place and date:	

A. GENERAL QUESTIONS BEFORE APPLYING THE NATURAL CAPITAL PROTOCOL (NCP)

I have some questions to guide the initial exploration for the NCP application at the [__________] farm

1. How familiar were you with the natural capital protocol before we start the contact regarding this project?

☐ Not familiar at all

☐ I was aware of the Crown Estate Scotland trial application

☐ I was aware of the NCP before this application

Comments:

2. How familiar are you with the concepts of ecosystem services and natural capital?

☐ Not familiar at all

☐ I know the concepts, but I am not totally familiar on the meaning of the concepts

☐ I am familiar with the concepts

Comments:

3. What do you think are the main natural capital depletion risks in the farm? (if there is any)

This can include risk for an activity, the business, risk for society:

4. What do you think are the main environmental impacts of the farm activities on natural capital?

5. What information do you use for decision making?

6. Do you think that a natural capital assessment can help your decision making?

☐ YES (go to 7) ☐ NO (*) ☐ Not sure/I do not know (go to 7)

*If no please indicate the reasons, and if you want to continue with this questionnaire.

Comments (if any):

7. What kind of information on natural capital could help your decision-making in [__________] farm?

8. What kind of decisions do you think a natural capital assessment can help with in [__________] farm?

9. What could be in your opinion the main practical applications for the NCP in [__________] farm?

10. What is (are) the main the main objectives for the farm business (management)?

B. DEFINING THE OBJECTIVES AND SCOPE OF THE NATURAL CAPITAL ASSESSMENT IN [_________] FARM

Next, I will start with the overarching questions for the application of the NCP. Considering what we discussed before, I ask you to share your vision regarding the following questions.

The main idea is to define together the objectives and scope of the natural assessment at the [__________] farm. Please note that we can go back to any point of this questionnaire, and in the following weeks, to make any correction or clarification as needed.

Framing the natural capital assessment

11. Can you define the degree of relevance (where 1 is not relevant at all, 3 moderate and 5 very relevant) of the following aspects for a natural capital assessment at the [_______] farm? Please mark with and X, provide more details and please indicate if there are other aspects that are relevant for the natural capital assessment

Aspect	**1 (—)**	**2 (–)**	**3 (0)**	**4 (+)**	**5 (++)**	**Comments**
-Improving the farm productivity (yields)						
-Improving the farm income						
-Reducing production costs						
-Reducing the use of external inputs						
-Reducing the use of energy						
-Improve risk assessment and management						
-Improving farm long-term resilience						
-Finding potential funding opportunities						
-Farm income diversification						
-Adoption of innovative farming practices/technologies						
-Enhancing biodiversity conservation						
- Reducing the risk of natural hazards						
-Improving specific environmental indicators (specify)						
-Maintaining/improving relationships with: Farming community						
: Local area community						
: Science community						
-Maintaining/improving the farm reputation						
Other (specify)						

12. Why to conduct a natural capital assessment in [__________] farm?

Scope of the natural capital assessment

13. What should be the objective(s) of the natural capital assessment in [__________] farm?

14. What are the main stakeholders that should be considered in the natural capital assessment in [__________] farm?

15. What are the value chain aspects that the natural capital assessment should be considered? (*considering the information that would be relevant for the farm management and decision making*)

16. What should be the spatial boundary of the natural capital assessment? [Define using a map if possible]

17. What is the time horizon that should (could) be considered and why?

18. What should be the baseline scenario to which refer (for comparative purposes) the natural capital assessment results? (i.e., the starting point or benchmark against which changes in natural capital attributed to your business' activities can be compared (for example before and after any relevant investment or management change undertaken at the farm)

19. What are the key current (and/or) future planning issues that should be considered by the natural capital assessment?

C. POTENTIAL IMPACTS AND/OR DEPENDENCIES ON NATURAL CAPITAL IN [_________] FARM

20. Can you indicate the activities that are carried on in the farm by land cover or habitat?

Table A.4.1 Matrix of land cover and enterprises

Land cover/Broad habitat	Area (hectares)	Enterprises in the farm (indicate the share of land used)																
		Intensive farming	Extensive farming	Organic farming	Intensive livestock farming	Extensive livestock farming	Intensive forestry	Low intensity forestry	Small game shooting	Big-game shooting	Fishing	Energy production	Beverage & food industry	Wild-life conservation active.	Recreation / tourism	Demonstration farm activities	Training/education activities	Others (specify)
Enclosed farm																		
Arable land																		
Orchards																		
Fallow land																		
Temporary pasture (improved grassland)																		
Permanent pasture (improved grassland)																		
Hedgerows																		
Buffer strips																		
Field margins																		
Other ecological focus areas (EFA)																		
Semi-natural plat grassland																		
Acid grassland																		
Calcareous grassland																		
Meadows																		
Coastal and Floodplain grazing Marsh																		
Woodland and forests																		
Coniferous seminatural woodlands																		
Coniferous plantations																		
Broadleaved seminatural woodlands																		
Broadleaved plantations																		
Mixed seminatural woodlands																		
Mixed broadleaved/coniferous plantations																		
Other habitats																		
Bogs (raised and blanket)																		
Heathland																		
Moorland																		
Others (specify):																		
Freshwater																		
Other land cover (specify)																		

Comments:

21. Please identify and indicate the relevance level of natural capital dependencies for the following farm activities? The dependencies consider consumptive and non-consumptive good and services

Table A.4.2 Dependency matrix (initial identification of dependencies and their relevance)

To discuss with relevant stakeholders. Indicate the relevance of the dependency: H: highly relevance, M: moderate, L: low relevance, N: no relevance, U: unknown.

Enterprises	Dependencies of the farm on consumptive and non-consumptive good and services																			
	Consumptive										Non-consumptive									
	Surface water	Groundwater	Rainwater	Animal food	Timber/Wood /fibre	Animal materials	Plant materials	Fossil fuels	Renewable energy (except photosynthesis)	Other	Filtration toxic substances (water)	Water flow regulation & Flood attenuation	Pollination	Biological pest /diseases control	Maintaining nursery populations & habitats	Buffering and attenuation of mass movement (falls, slides, flows)	Decomposition and fixing processes	Information from nature (knowledge)	Nature-based recreation/tourism	Other
Farm activities																				
Extensive crop systems																				
Intensive crop systems																				
Organic farming																				
Intensive forestry																				
Low intensity forestry																				
Extensive livestock farming																				
Intensive livestock farming																				
Deer rearing																				
Small game shooting																				
Big-game shooting																				
Fishing																				
Energy production																				
Peat extraction																				
Beverage & food industry																				
Wild-life conservation activities																				
Recreation/Tourism																				
Demonstration activities																				
Training/education activities																				
Others (specify)																				

Comments on dependencies:

22. Please identify the impacts on natural capital by different farm activities and indicate the relevance level of the impacts and how strong is the available evidence on the level of the impacts?

Table A.4.3 Impact driver's matrix (initial identification of potential impacts)

To discuss with relevant stakeholders. Indicate the relevance of the impact driver: H: highly relevance, M: moderate, L: low relevance, N: no relevance, U: unknown.

Enterprises	Impact drivers													
	Inputs					Output								
	Water use	Terrestrial ecosystem use	Freshwater ecosystem use	Wildlife	Energy	GHG emissions	Non-GHG air pollutants	Water pollutants	Soil pollutants	Soil erosion	Solid waste	Disturbances	Air pollution filtration	Carbon sequestration
Arable crops (irrigated)														
Arable crops (rainfed)														
Organic farming														
Intensive forestry														
Low intensity forestry														
Extensive livestock farming														
Intensive livestock farming														
Deer rearing														
Small game shooting														
Big-game shooting														
Fishing														
Energy production														
Peat extraction														
Beverage & food industry														
Wild-life conservation activities														
Recreation/Tourism														
Demonstration activities														
Training/education activities														
Others (specify)														

Comments on impacts:

23. Identify the criteria, data availability for the measuring dependencies and/or impacts of the land-based business on natural capital.

Information availability on land-based business inputs and outputs

Business input/ output	Impact driver category	Potential metrics (measurable impact drivers)	Availability		Comments (including the contact person, format of data, period covered, frequency)
			YES	NO	
Input	Water use	Volume of surface and ground water consumed (water abstraction)			
	Terrestrial ecosystem uses	Area of terrestrial habitat used by type (broad habitats) Considering more details on the type of crop and grasslands			
	Freshwater ecosystem use	Area (length) of freshwater habitat used by type (e.g., wetland, lakes, ponds, rivers, aquifers, etc.)			
	Game and wildlife	Number of wild fish caught by species			
		Number of wild mammals caught by species			
		Number of wild birds caught by species			
	Wild plants and fungi	Volume of wild plants and fungi extracted			
	Other resources use	Volume of mineral extracted			
		Volume of peat extracted			
	Others:				
Output	GHG emission	Mass of the carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), Hydrofluorocarbons (HFCs) and perfluorocarbons (PFC)			
	Non-GHG air pollutants	Mass of the particulate matter ($PM_{2.5}$) and coarse particulate matter (PM_{10}), Volatile Organic Compounds (VOCs), mono-nitrogen oxides (NOx), Sulphur dioxide SO_2, carbon monoxide (CO)			
	Water pollutants	Mass discharged to receiving water body of nutrients (nitrates and phosphates), or other substance (pesticides), faecal indicator organisms, etc.			
	Soil pollutants	Mass of water matter discharged and retained in soil over a given period			
	Soil erosion	Mass of soil loss, or mass of sediment deposition			
	Solid waste	Mass of solid waste by type: domestic waste, building materials, plastic, silage, animal feed, animal health products, seeds, agrochemicals (concentrates), machinery waste (oil, batteries, tyres, machine), cardboard cores, etc.			
	Disturbances	Visual disturbances (such as number of wind turbines, area occupied by solar panels or landfills)			
	Biodiversity effects	Bird populations (survey)			
		Insect populations (survey)			
		Other (specify)			
	Others:				

24. Other relevant information and data available at the farm level to construct a natural asset register, and to characterise and/or measure the state (current situation such as the stock of resources at the assessment period) and condition (quality of natural assets).

Data set/Information	Observations	Contact person
Habitat and Land cover maps	Indicate years:	
Forest inventory	Indicate years	
Biodiversity surveys	Indicate type of species and years	
Ecosystem services maps (models)	Indicate ES and type of models DB is not aware of	
Soil nutrients test	(years and location)	
Sediments	(years)	
Soil carbon	(years)	
Production data (crops, livestock, wood)	(type of information available and years)	
Others:		

25. Is there any other comments or questions you'd like to discuss about this process?

Comments (if any)

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