Journal of Environmental Management 306 (2022) 114486

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Biocapacity and cost-effectiveness benefits of increased peatland restoration in Scotland

Nicola Horsburgh [a,*], Andrew Tyler [a], Scot Mathieson [b], Mathis Wackernagel [c], David Lin [c]

[a] Biological and Environmental Sciences, School of Natural Sciences, University of Stirling, Stirling, FK9 4LA, United Kingdom
[b] Scottish Environment Protection Agency, Strathallan House, Castle Business Park, Stirling, FK9 4TZ, United Kingdom
[c] Global Footprint Network, 1528 Webster Street, Suite 11, Oakland, CA, 94612, USA

ARTICLE INFO

Keywords:
Peatland restoration
Biocapacity
Carbon footprint
Land use
Mitigation
Cost-effectiveness

ABSTRACT

Ecological Footprint and biocapacity accounting is a widely-used ecological accounting framework which tracks human demand against the biosphere's rate of regeneration. However, current national assessments do not yet include carbon-dense peatlands, hindering the evaluation of peatland biocapacity contributions. Also, the economic efficiency of peatland restoration is understudied and needed to inform land use decisions. We provide the first assessment of Scotland's biocapacity and add peatlands as a novel land type. We then project the biocapacity impacts in 2050 of current peatland restoration targets and various alternative management scenarios. Finally, we estimate the cost per tonne of greenhouse gas abated of various peatland restoration scenarios, and compare this with estimates of afforestation mitigation costs from the literature. Our results show that Scotland's per-person biocapacity exceeds the UK average by a factor of three. However, despite covering 25% of land area, peatland biocapacity increases Scotland's biocapacity total by only 2%, while the Carbon Footprint of degraded peatlands increases Scotland's ecological deficit by 40%. Current peatland restoration targets of the Scottish Government are estimated to reduce the national ecological deficit by only 9% in 2050. The cost-effectiveness of peatland restoration is context-dependent, and extremely cost-effective methods are applicable to peatland areas far exceeding current government restoration targets. Our findings provide land managers with evidence in favour of increased peatland restoration, both in terms of boosting biocapacity, and economic cost-effectiveness.

1. Introduction

A growing global population and the impacts of climate change is putting increasing pressure on the world's ecosystems (Costanza and Daly, 1992; CBD, 2005; Rockström et al., 2009; IPCC, 2014; IPBES, 2019; Wackernagel et al., 2019). Resulting resource scarcity threatens countries in the global North and South, but poses a particular risk to countries with below-average income (Wackernagel et al., 2021). To progress towards the United Nations Sustainable Development Goals for 2030, it is therefore important for countries to understand their demand for natural resources, and put that into the context of what is available globally. The Ecological Footprint and biocapacity provides an ecological accounting framework which compares our demand for natural resources and waste absorption (Ecological Footprint) with the biosphere's ability to provide these services (biocapacity) (Wackernagel and Rees, 1997). Results are reported in the National Footprint and Biocapacity Accounts (NFA) which calculate the Ecological Footprint and biocapacity for much of the world's countries annually. While the United Kingdom is included in the NFA, Scotland does not feature separately from the UK, leaving its relative resource intensity poorly understood. As per-person energy consumption in Scotland is comparable to the UK (UK Government, 2020b), we approximated Scotland's Ecological Footprint as the UK average of 4.2 global hectares per person [gha person^{-1}] (York University Ecological Footprint Initiative & Global Footprint Network, 2021). But, with abundant natural capital and a low population density, we hypothesised that Scotland may have more per-person biocapacity than the UK average of 1.1 gha person^{-1}, and hence Scottish biocapacity was estimated from first principles according to the methodology of Borucke et al. (2013).

The accounting framework considers six land types in the NFA: Crop Land, Grazing Land, Marine Fishing Grounds, Inland Fishing Grounds, Forests and Built-up Land. However, peatlands are not currently included in the NFA. These important wetland ecosystems are disproportionately large carbon stores, estimated to hold 30% of all soil

* Corresponding author.
E-mail address: nicola.horsburgh@stir.ac.uk (N. Horsburgh).

https://doi.org/10.1016/j.jenvman.2022.114486
Received 29 May 2021; Received in revised form 27 November 2021; Accepted 9 January 2022
Available online 20 January 2022

organic carbon in just 3% of the world's land area (Joosten, 2009; Hiederer and Köchy, 2011; Xu et al., 2018). Peatlands also provide clean drinking water, regulate flood peaks and support rare biodiversity (Bain et al., 2011). Near-natural peatlands are climate neutral and net-cooling (Evans et al., 2017), but degradation caused by draining, burning, conversion to agriculture and forestry (Li et al., 2018) has transformed peatlands into carbon sources with annual emissions of 1.91 (0.31–3.38) Gt CO_2e globally, predominantly as CO_2 (Leifeld and Menichetti, 2018), equating to nearly 6% of annual global fossil fuel emissions (IEA, 2020). Reduction of anthropogenic peatland emissions is thus important for climate targets, but these data are often under-reported or absent from greenhouse gas inventories (Bain et al., 2011) and are currently unaccounted for in the NFA.

Scotland provides an opportune case study. In Scotland, peatlands cover 1.9 million ha (25% of land area). Of this, 1.5 million ha are degraded, with associated CO_2 emissions of 5.7 Mt CO_2 yr^{-1} (Evans et al., 2017), equivalent to 14% of Scotland's reported annual GHG emissions (Scottish Government, 2018c). In recognition, the Scottish Government has committed to restore 250,000 ha of degraded peatlands by 2030 (Scottish Government, 2018a). Scotland's biocapacity could thus provide multiple insights, including the addition of peatlands to the accounting framework, the current biocapacity implications of peatland degradation, and the potential impact of peatland restoration targets on Scotland's future biocapacity.

Finally, as peatland restoration comes at a cost to the tax-payer and land manager, the economic efficiency of restoration is of interest. Recent studies of the net present value of peatland restoration strongly suggest that restoration benefits outweigh the costs (Glenk and Martin-Ortega, 2018; Moxey and Moran, 2014). However, specific evaluation of mitigation cost-effectiveness is lacking and would aid comparison with other land-use mitigation policies like afforestation. Here we present a range of cost-effectiveness outcomes for peatland restoration, based on the spectrum of capital and ongoing costs reported in the UK, and the latest peatland emission factors. We conclude with a discussion of land-use management implications.

2. Methods

2.1. Biocapacity accounting methodology

To provide an estimate of Scotland's biocapacity comparable with other national estimates in the National Footprint and Biocapacity Accounts of the Global Footprint Network (NFA), the methods of Borucke et al. (2013) and Lin et al. (2019) were followed. Biocapacity was calculated for the land types Crop Land, Grazing Land, Marine Fishing Grounds, Inland Fishing Grounds, Forests and Built-up Land; and then summed to find Scotland's total biocapacity, excluding peatlands.

$$BC_{Sco} = \sum_i A_{Sco,i} * YF_{Sco,i} * EQF_i \tag{1}$$

In Equation (1) BC_{Sco} is Scotland's total biocapacity and $A_{Sco,i}$ is the bioproductive land area of land type *i*. The bioproductive land area of Grazing Land, Inland Water, and Built-up Land was obtained from geospatial land classification systems; national statistics were used for Crop Land and Forest area; and Marine Fishing Grounds area was estimated via GIS.

$YF_{Sco,i}$ is the Scottish yield factor, or relative national productivity of land type *i*. Yield factors were calculated by comparing each land type's primary production rate with the corresponding global average calculated in the NFA. Area and yield factor data of each land type is described in the Supplementary Material, and the calculation data is available in Supplementary Data.

EQF_i is the equivalence factor which relates the global average productivity of land type *i* to total world average productivity across all land types. Equivalence factors were obtained from the NFA, where they are calculated annually with the aid of a Global Agro-Ecological Zones model (York University Ecological Footprint Initiative & Global Footprint Network, 2021).

To estimate the biocapacity range, geospatial land areas were set to the upper and lower limits of reported classification accuracies, and the national productivity of Forests, Marine Fishing Grounds and Grazing Land were set to the extremes of reported confidence intervals. Crop area and yields are not reported with uncertainty estimates and could thus not contribute to the range estimate.

Benefits of this accounting methodology include that it is straight forward to implement with data that is readily available. The biggest limitation of this methodology is the reliance on global estimates of productivity for each of the land types, which is lacking for certain land types (like inland fishing grounds) and carries inherent uncertainty. However, one could argue that the Ecological Footprint and biocapacity estimates are produced consistently and can thus be compared to give a valuable indication of a country's relative resource intensity and how this changes from year to year. See Kitzes et al. (2009) for a further discussion of the limitations and research needs surrounding this framework.

2.2. Peatlands – a new biocapacity land type

To add peatlands as a new biocapacity land type, one could follow the NFA framework in Equation (1) and calculate a new yield factor for Scottish peatlands (which compares productivity of Scottish peatlands to global peatlands), and peatland equivalence factor (which compares the productivity of global peatlands to total world average productivity). However, this is challenging due to a paucity of data describing global peatlands. Instead, our approach used a direct comparison with an existing NFA land type: If one assumes that due to common climatic conditions Scottish peatlands have the same relative (national/global average) productivity as another unmanaged land type like Scottish broadleaf forests, then the existing YF and EQF of broadleaf forests can be scaled by the ratio of primary production (PP) of the two land types to derive a YF and EQF for peatlands, as shown in Equation (2). This can be substituted into Equation (1) to calculate the biocapacity of sequestering peatlands, as shown in Equation (3).

$$(YF^*EQF)_{peat} = \frac{PP_{peat}}{PP_{broadleaf}} * (YF^*EQF)_{broadleaf} \tag{2}$$

$$\begin{aligned} BC_{peat} &= A_{peat} * (YF^*EQF)_{peat} \\ &= A_{peat} * \frac{PP_{peat}}{PP_{broadleaf}} * (YF^*EQF)_{broadleaf} \end{aligned} \tag{3}$$

Values for PP_{peat}, $PP_{broadleaf}$ and A_{peat} are needed, while $(YF * EQF)_{broadleaf}$ is known from the Forest biocapacity calculation.

For PP_{peat} in Equation (3) we used results from a meta-analysis of peatland net ecosystem exchange (NEE), which measures net CO_2 flux of a system, reported as *emission factors* in the latest UK Peatland Greenhouse Gas Inventory (Evans et al., 2017). Emission factors are reported for different peatland types and conditions, which allows biocapacity to be calculated separately for different peatland classes, and then summed to estimate total peatland biocapacity. According to Evans et al. (2017), only rewetted and near-natural peatlands sequester CO_2 (indicated by negative emission factors), while all other peatland classes emit CO_2 and other greenhouse gases. Thus, to calculate peatland biocapacity, only intact sequestering peatlands were included, as damaged (emitting) peatlands, per definition of the accounting framework, must be counted as a Carbon Footprint (David Lin, personal communication; Lin et al., 2019).

For $PP_{broadleaf}$ we used results from UK broadleaf NEE studies (Broadmeadow and Matthews, 2003; Read et al., 2009; Thomas et al., 2011). The median of -2.7 t C ha^{-1} yr^{-1} was substituted for $PP_{broadleaf}$ which is comparable with other northern broadleaf forest studies listed in Thomas et al. (2011). The final unknown in Equation (3) A_{peat} is the area associated with each of the sequestering peatlands in Evans et al. (2017).

The biocapacity of each sequestering peatland category was then summed to estimate total peatland biocapacity:

$$BC_{peat\_total} = BC_{rewetted\_bog} + BC_{near\_natural\_bog} + BC_{near\_natural\_fen} \quad (4)$$

To revise the national biocapacity estimate to include peatlands, total peatland biocapacity was added to the previous national biocapacity total BC_{Sco1} calculated with Equation (1) to give BC_{Sco2}.

$$BC_{Sco2} = BC_{Sco1} + BC_{peat\_total} \quad (5)$$

The range of peatland biocapacity was calculated according to the 95% confidence intervals of peatland emission factors.

Peatland biocapacity is however only half the picture, as it does not capture the impacts of peatland degradation on Scotland's net biocapacity. To do this, the Carbon Footprint of degraded peatlands CF_{peat} associated with the 5.7 Mt CO_2 yr^{-1} of carbon dioxide emitted by damaged peatlands (Evans et al., 2017; CCC, 2019), was calculated according to standard NFA methodology (Borucke et al., 2013; Mancini et al., 2016). Subtracting the peatland Carbon Footprint from peatland biocapacity gives the net biocapacity of peatlands:

$$BC_{peat\_net} = BC_{peat\_total} - CF_{peat} \quad (6)$$

This indicates whether peatlands in their current condition are in a state of ecological reserve, with biocapacity exceeding the Carbon Footprint, or ecological deficit. To evaluate the impact of peatland emissions on national net biocapacity, the peatland Carbon Footprint was added to Scotland's previous Ecological Footprint of 4.2 gha person^{-1} to revise the estimate to

$$EF_{Sco2} = 4.2 + CF_{peat} \quad (7)$$

This revised Ecological Footprint was then subtracted from revised biocapacity to evaluate Scotland's revised net biocapacity.

$$BC_{Sco\_net} = BC_{Sco2} - EF_{Sco2} \quad (8)$$

Having added peatlands to the framework, it was possible to evaluate the impacts of different peatland management strategies on Scotland's future net biocapacity. Evans et al. (2017) compare current peatland restoration policy with alternative management scenarios in terms of restored peatland area and potential abatement by 2050. For each, this was translated into peatland biocapacity and Carbon Footprint using the above method, to explore how the net biocapacity of Scottish peatlands might change by 2050 and how this would affect the national balance. To focus on peatland impacts, it was assumed that the biocapacity and Ecological Footprint of the other land types remain unchanged to 2050.

2.3. Cost-effectiveness of peatland restoration

Decision makers often consider whether a policy is expected to deliver its objectives cost-effectively. For climate policy, the primary objective is to reduce greenhouse gas (GHG) emissions, and cost-effectiveness is therefore considered in terms of the average cost of saving each tonne of CO_2 equivalent. A simplified cost-effectiveness equation for peatland restoration which considers only GHG savings and restoration costs can be expressed as

$$CE = \frac{PV_c}{\sum_{y=1}^{y=N} C_y} \quad (9)$$

In Equation (9) CE is cost-effectiveness in £$(tCO_2e)^{-1}$, PV_c is the present value of restoration costs in £ ha^{-1}, C_y is the GHG abatement in year y in tCO_2e ha^{-1} and N is the policy time horizon (UK Government, 2019).

To find the present value of peatland restoration costs PV_c it is necessary to consider one-off capital costs of works expenditure and land purchase, and ongoing costs related to monitoring, maintenance and opportunity costs of displaced land use activities (Glenk and Martin-Ortega, 2018; Moran et al., 2013; Moxey and Moran, 2014). Capital costs were assigned to year 1. Ongoing costs were assigned to years 2 to N. To convert ongoing costs to a comparable present value an annual discount rate of 3.5% (years 1–30) and 3% (thereafter) was used, as recommended by the UK Treasury's Green Book (UK Government, 2020a). Costs were then summed to estimate the present value of restoration cost across the time horizon N. Holden et al. (2008) report a median project cost of £1600 ha^{-1} (including works expenditure, land purchase, monitoring and maintenance), with the capital costs of gully blocking (range: £250 ha^{-1} to £750 ha^{-1}) and forestry removal (range: £1000 ha^{-1} to £10,000 ha^{-1}) at either end of the cost spectrum. Opportunity costs are reported to vary between £13 ha^{-1} yr^{-1} and £370 ha^{-1} yr^{-1} (Holden et al., 2008). To create a range of restoration cost scenarios, it was noted that high opportunity costs associated with restoring peatlands under productive lowland practices like forestry and agriculture are generally linked with high capital costs, while low opportunity costs associated with less productive practices like upland grazing are often linked with lower capital costs like gully blocking (Moxey and Moran, 2014). Thus, the following four scenarios were chosen to illustrate the range of cost-effectiveness outcomes one might expect for various cost options and displaced activities. While costs are unlikely to exceed either end of the spectrum, factors like site accessibility and level of degradation can have large cost implications. These values are therefore not intended to replace more rigorous site-specific analyses.

A. Gully blocking: Low capital (£250 ha^{-1}) + low opportunity cost (£13 ha^{-1} yr^{-1})
B. Low average: Median capital (£1600 ha^{-1}) + low opportunity cost (£25 ha^{-1} yr^{-1})
C. High average: Median capital (£1600 ha^{-1}) + mean opportunity cost (£192 ha^{-1} yr^{-1})
D. Reflooding grassland: Moderate capital (£2000 ha^{-1}) + high opportunity cost (£370 ha^{-1} yr^{-1})
E. Forestry removal: High capital (£10,000 ha^{-1}) + high opportunity cost (£370 ha^{-1} yr^{-1})

Two time horizons were evaluated: $N = 30$ years, to align with 2050 policy targets, and $N = 60$ years, to match conventional silviculture rotation lengths and enable comparison with afforestation cost-effectiveness estimates.

For the GHG reduction C_y in Equation (9) it was assumed that for the first decade after restoration peatlands behave like rewetted peatlands, and thereafter return to near-natural peatlands (Lees et al., 2019). Accordingly, GHG emission factors from Evans et al. (2017) were used to find the GHG emission differential between "Rewetted bog" and the starting condition ("Modified eroded bog" for (A), (B) and (C), "Intensive grassland" for (D) and "Forest" for (E)). This was multiplied by ten to find the GHG reduction after the first decade. Similarly, the GHG differential between "Near-natural bog" and the starting condition and was multiplied by 20 and 50 respectively to find the GHG reduction for the remainder of the time horizon. The two results were summed to yield the total GHG reduction for each time horizon. As an example, the GHG differential of scenario (A) for the 60-year time horizon is shown below. Refer to Supplementary Data for data and calculation details, including confidence intervals surrounding these estimates. Negative change implies an emissions reduction, and all greenhouse gases are considered, to follow the method used by the UK Government and allow comparison with other land use policies.

$$\begin{aligned}\Delta GHG &= 10\left(EF_{rewetted} - EF_{modified}\right) + 50\left(EF_{near\_nat} - EF_{modified}\right)\\ &= 10(0.81 - 4.85) + 50(0.01 - 4.85)\\ &= -40.4 - 242\\ &= -282.4\ tCO_2e\ ha^{-1}\end{aligned}$$

For each restoration scenario (A-E), the present value of restoration costs and GHG differential were substituted into Equation (9) to calculate mitigation cost-effectiveness. This was compared with the non-traded cost comparator (NTCC), defined as the weighted average discounted price of the non-traded cost of carbon over the period of interest. Restoration delivered below the NTCC benchmark is seen as cost-effective (UK Government, 2019). While one should strictly calculate a separate NTCC for each time horizon, only the 30-year period (2018–2047) was considered as there is significant uncertainty regarding the non-traded price of carbon after 2050. Rounded to the nearest pound, the NTCC for all the above restoration scenarios is £66 per tCO_2e.

3. Results

3.1. Scotland's biocapacity

Scotland's 2018 biocapacity, excluding peatlands, is estimated at 19,024,085 (17,695,273–20,721,018) global hectares, or 3.5 (3.3–3.8) gha person^{-1} when scaled by Scotland's population estimate of 5,438,100 (National Records of Scotland, 2018). This is over three times the UK biocapacity of 1.1 gha person^{-1} and more than double the global average biocapacity of 1.6 gha person^{-1} (York University Ecological Footprint Initiative & Global Footprint Network, 2021). The yield factor calculation is outlined in Table 1, followed by the biocapacity calculation in Table 2. Fig. 1 shows that Forests and Marine Fishing Grounds are currently the largest contributors to Scottish biocapacity.

Assuming Scotland has an Ecological Footprint equal to the UK average of 4.2 gha person^{-1}, Scotland's biocapacity advantage leads to a modest ecological deficit of 0.7 gha person^{-1}, significantly smaller than the UK deficit of 3.1 gha person^{-1} and world average deficit of 1.2 gha person^{-1}.

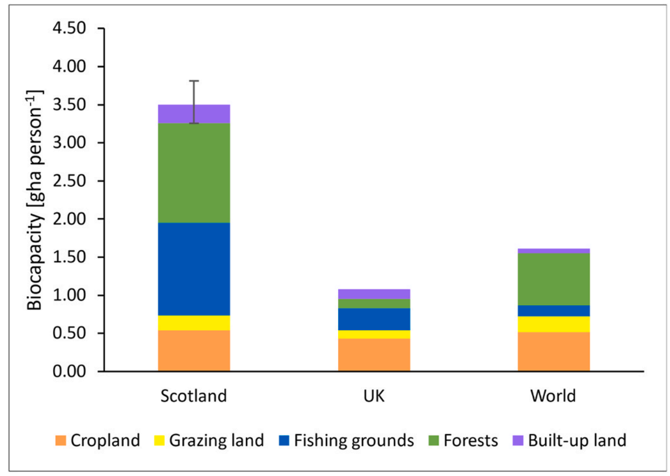

Fig. 1. Land type contributions to biocapacity. Error bar = Scotland's estimated biocapacity range: 3.3 to 3.8 gha person^{-1}. UK and World biocapacity for 2017 (York University Ecological Footprint Initiative & Global Footprint Network, 2021). Excludes peatlands.

3.2. Peatland biocapacity and Carbon Footprint

Using Equations (3) and (4), the biocapacity of Scottish peatlands is currently estimated at 0.07 (0.03–0.09) gha person^{-1}, equivalent to 2% of Scotland's total biocapacity (Table 3). The spatial distribution of Scotland's biocapacity, including peatlands, is shown in Fig. 2, with land type contributions colour coded according to magnitude. The minor contribution of peatlands is illustrated by light grey areas, largely north

Table 1
Yield factor calculation. Scottish yields describing primary production for each land type (this study), are scaled by world average yields (York University Ecological Footprint Initiative & Global Footprint Network, 2021) to obtain Scottish yield factors. Grazing land is split into improved and unimproved grazing, and Forests are split into coniferous and broadleaf forests. NPP = net primary production, NAI = net annual increment, wha = world hectare.

Land Use Type	Yield Description	Scottish Yield	World Yield	Yield Factor
[-]	[-]	[t ha^{-1}]	[t wha^{-1}]	[wha ha^{-1}]
Crop land	Crop yields [t ha^{-1} yr^{-1}]	8.18	4.00	2.04
Grazing (impr)	Above ground NPP [t DM ha^{-1} yr^{-1}]	10.00	6.19	1.62
Grazing (unimpr)		3.00	6.19	0.48
Marine	Phytoplankton NPP [mgC m^{-2} day^{-1}]	356.16	503.84	0.71
Inland water	All inland water equally productive	–	–	1
Forests (conif)	NAI [m^3 ubs ha^{-1} yr^{-1}]	8.53	1.82	4.69
Forests (broad)		2.73	1.82	1.50
Built-up land	Equivalent to Crop Land	–	–	2.04

Table 2
Scotland's biocapacity in 2018. Land areas from Corine Land Cover (2018) (Grazing land, Inland water, Built-up land); geospatial marine boundaries (Marine fishing grounds); and national statistics (Crop land, Forests). Grazing land is split into improved and unimproved grazing, and Forests are split into coniferous and broadleaf forests. YF = yield factor (this study), EQF = equivalence factor (York University Ecological Footprint Initiative & Global Footprint Network, 2021), wha = world hectare, gha = global hectare.

Land Use Type	Area	YF	EQF	Biocapacity	Biocapacity
[-]	[ha]	[wha ha^{-1}]	[gha wha^{-1}]	[gha]	[gha person^{-1}]
Crop land	573,850	2.04	2.50	2,933,952	0.54
Grazing (impr)	1,212,891	1.62	0.46	899,786	0.17
Grazing (unimpr)	757,485	0.48	0.46	168,583	0.03
Marine	25,143,100	0.71	0.37	6,565,386	1.21
Inland water	121,055	1.00	0.37	44,716	0.01
Forests (conif)	1,064,000	4.69	1.28	6,384,108	1.17
Forests(broad)	380,000	1.50	1.28	728,692	0.13
Built-up land	254,044	2.04	2.50	1,298,864	0.24
TOTAL				19,024,085	3.50

Table 3
Peatland biocapacity of Scotland in 2018, comprising of near-natural and re-wetted peatlands. Note: Peatland area data is for 2013, the most recent area estimates in the UK Peatland GHG Inventory (Evans et al., 2017), thus assuming no significant change in peatland area from 2013 to 2018. PP = primary production (Net Ecosystem Exchange), gha = global hectare, BC = biocapacity.

Peatland	Area	PP_{peat}/PP_{broad}	$(YF*EQF)_{broad}$	Peatland BC	Peatland BC
[-]	[ha]	[-]	[gha ha^{-1}]	[gha]	[gha $person^{-1}$]
Nr-nat	490,497	−1.0/-2.7=0.37	1.92	348,951	0.064
Re-wet	20,415	−0.6/-2.7=0.22	1.92	8714	0.002
TOTAL				357,665	0.07

of 56.0°N and west of 3.0°W.

Using the standard methodology of Borucke et al. (2013) and Mancini et al. (2016), the Carbon Footprint associated with 5.7 Mt CO_2 yr^{-1} of carbon dioxide emissions by degraded peatlands (Evans et al., 2017) is 0.34 gha $person^{-1}$. Note: This study considers only CO_2 emissions in the Carbon Footprint to align with current NFA methodology. Substituting peatland biocapacity and Carbon Footprint into Equation (6) leads to a substantial peatland ecological deficit of 0.07–0.34 = 0.27 gha $person^{-1}$, which increases Scotland's deficit by 38%, from 0.70 to 0.97 gha $person^{-1}$ according to Equation (8), as shown in Table 4.

Table 4 also compares the future net biocapacity of peatlands and Scotland for a range of alternative management pathways presented by Evans et al. (2017), illustrated in Fig. 3.

The Central scenario, following current government restoration targets of 250,000 ha by 2030, could reduce the peatland deficit to 0.20 gha $person^{-1}$ (−27%), leading to a 7% decrease in national deficit by 2050 (Table 4). The Low scenario represents policy aspirations to cease peat extraction, restore 25% of lowland peat and 50% of upland peat.

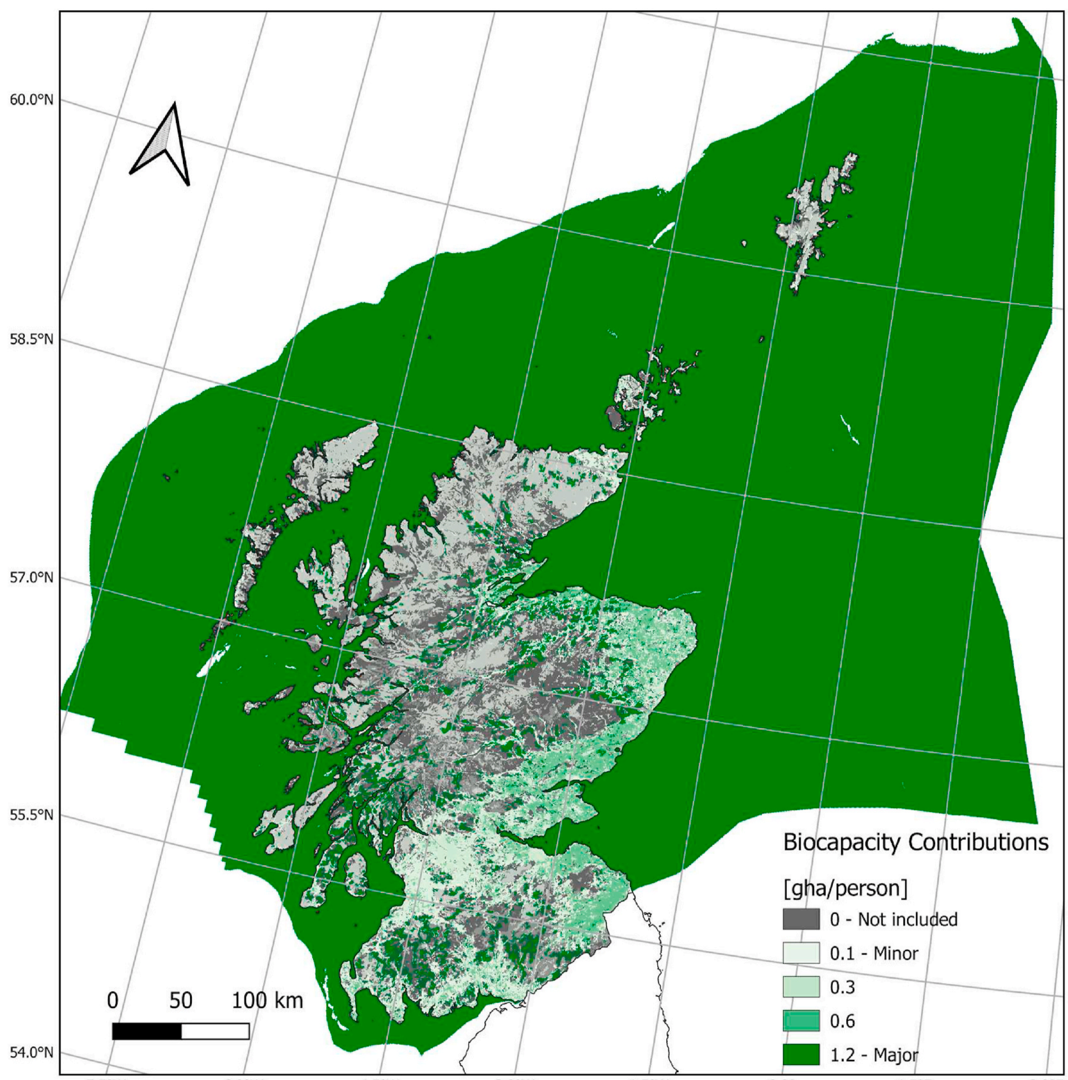

Fig. 2. The contribution of different land types to Scotland's biocapacity. Peatland biocapacity of 0.07 gha $person^{-1}$ appears light grey, largely north of 56.0°N and west of 3.0°W, illustrating the minor contribution of peatlands to the national total. Major contributions are from Marine and Forest land types (dark green), followed by Crop land. Datum: EPSG 3035, ETRS/LAEA-extended; Land cover: Corine Land Cover 2018; Boundary: GADM database v3.4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
The projected impact of different management scenarios on future peatland and national net biocapacity (negative indicates deficit). Percentage change in net biocapacity compared to 2018 "With peatlands" net biocapacity. Note: It is assumed Scotland's 2018 deficit of 0.70 gha person^{-1} for other land types remains constant to 2050. BC=Biocapacity, CF=Carbon Footprint.

Scenario	Year	Peatland BC	Peatland CF	Peatland net BC	Scotland's net BC
[-]	[-]	[gha person^{-1}]	[gha person^{-1}]	[gha person^{-1}]	[gha person^{-1}]
Without peatlands	2018	–	–	–	−0.70
With peatlands	2018	0.07	0.34	−0.27	−0.97
Central	2050	0.10	0.30	−0.20 (−27%)	−0.90 (−7%)
Low	2050	0.12	0.28	−0.16 (−41%)	−0.86 (−11%)
Stretch	2050	0.14	0.22	−0.09 (−68%)	−0.79 (−19%)
High	2050	0.08	0.32	−0.24 (−13%)	−0.94 (−3%)
Pragmatic	2050	0.20	0.30	−0.10 (−63%)	−0.80 (−17%)

This could decrease the peatland deficit to 0.16 gha person^{-1} (−41%) leading to an 11% decrease in national deficit (Table 4). The Stretch scenario exceeds current policy aspirations and funding by restoring 50% of lowland peat, 75% of upland peat and 50% of afforested peat. This large-scale peatland restoration effort could reduce the peatland deficit to 0.09 gha person^{-1} (−68%), leading to a 19% decrease in national deficit (Table 4). The High scenario restores 250,000 ha by 2030, but allows simultaneous degradation of 25% of near-natural peatlands by conversion to forest and extensive grassland. This results in little change from the status quo, and provides a warning against perverse land-use policies. Finally, the Pragmatic scenario represents restoration of all peatlands out-with forests and agriculture (75% of Scotland's peatlands). While not addressing afforested peat, this is still an ambitious effort in peatland restoration which could reduce the peatland deficit to 0.10 gha person^{-1} (−63%), leading to a 17% decrease in national deficit by 2050 (Table 4).

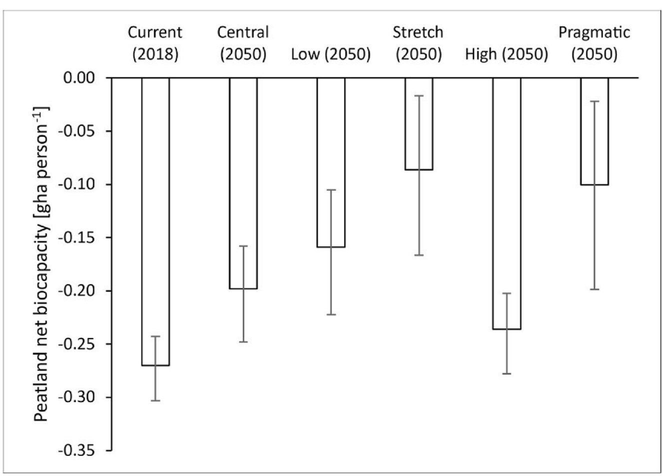

Fig. 3. Current and future peatland net biocapacity according to different management scenarios. Error bars represent 95% CI of emission factors.

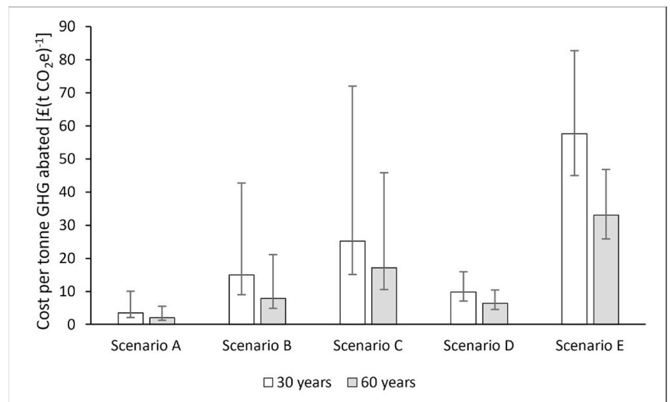

Fig. 4. Estimated mitigation cost-effectiveness of peatland restoration. Scenarios: A = low capital + low ongoing (drain blocking), B = median capital + low ongoing, C = median capital + ave ongoing, D = moderate capital + high ongoing (reflooding grassland), E = high capital + high ongoing (forestry removal). Error bars represent 95% Confidence Interval of CO_2 emission reduction estimates, with CO_2 the largest contributor to total greenhouse gas emissions.

These comparisons show that current restoration policy in the Central scenario is not ambitious enough to address the peatland deficit. It is only the Stretch and Pragmatic scenarios, currently beyond all policy aspirations, which have the potential to reduce the peatland (and national) deficit significantly by 2050.

3.3. Cost-effectiveness estimates of peatland restoration

The mitigation cost-effectiveness spectrum of peatland restoration is summarised in Table 5. There is a large range in the cost-effectiveness

Table 5
Estimated mitigation cost-effectiveness spectrum of peatland restoration. Scenarios: A = low capital + low ongoing (drain blocking), B = median capital + low ongoing, C = median capital + ave ongoing, D = moderate capital + high ongoing (reflooding grassland), E = high capital + high ongoing (forestry removal). PV = present value, CE = cost-effectiveness. CI = confidence interval. Costs from Holden et al. (2008).

–			30-year horizon			60-year horizon		
–	Capital incl. monitoring	Opp. costs	PV of costs	GHG reduction (95% CI)	CE (95% CI)	PV of costs	GHG reduction (95% CI)	CE (95% CI)
	[£ ha^{-1}]	[£ ha^{-1} yr^{-1}]	[£ ha^{-1}]	[tCO_2e ha^{-1}]	[£(t CO_2e)$^{-1}$]	[£ ha^{-1}]	[tCO_2e ha^{-1}]	[£(t CO_2e)$^{-1}$]
A	250	13	484	137 (48; 228)	**4 (2; 10)**	578	282 (105; 461)	**2 (1; 5)**
B	1600	25	2051	137 (48; 228)	**15 (9; 43)**	2232	282 (105; 461)	**8 (5; 21)**
C	1600	192	3454	137 (48; 228)	**25 (15; 72)**	4838	282 (105; 461)	**17 (10; 46)**
D	2000	370	8673	888 (542; 1238)	**10 (7; 16)**	11,347	1785 (1093; 2482)	**6 (5; 10)**
E	10,000	370	16,673	289 (202; 370)	**58 (45; 83)**	19,347	586 (413; 746)	**33 (26; 47)**

results, with an order of magnitude difference between the least and most expensive restoration options. All restoration options deliver GHG savings at a lower cost than the non-traded cost comparator (NTCC) of £66 per tCO_2e, and thus represent cost-effective GHG mitigation.

Fig. 4 illustrates peatland restoration cost-effectiveness. Note that the average cost per unit of greenhouse gas abated reduces when mitigation is considered over 60 years.

4. Discussion

4.1. Scotland's biocapacity

Scotland's biocapacity estimate of 3.5 global hectares per person supports the hypothesis that Scotland has more biocapacity per person than the UK average. While this is partly due to Scotland's lower population density, Fig. 1 shows that the main advantage comes from the large contribution of Marine Fishing Grounds and Forests to the Scottish total. The wealth of marine biocapacity stems from Scotland's shelf sea area, which is almost half the size of the entire UK shelf sea. While marine net primary production (NPP) is lower in cooler Scottish waters, this is not enough to offset the area gains. The largest biocapacity advantage, however, exists in forestry, where 10.1 million of the 14.9 million m^3 coniferous net annual increment (NAI) in Great Britain is produced in Scotland (Forestry Commission, 2016), leading to a per person forest biocapacity in Scotland of more than ten times the UK average. If Scotland has an Ecological Footprint equal to the UK average of 4.2 gha $person^{-1}$, Scotland's biocapacity advantage leads to a modest ecological deficit of 0.7 gha $person^{-1}$, less than a quarter of the UK's deficit. However, decarbonisation targets in the current Climate Change Plan (Scottish Government, 2018a) are being updated to reflect the ambition to reach net-zero greenhouse gas emissions by 2045 (as opposed to 2050 for the rest of the UK), and may result in a smaller Scottish Ecological Footprint than the UK average. A separate assessment of Scotland's Ecological Footprint would therefore be a useful addition to this study and would provide a better estimate of Scotland's ecological deficit.

4.2. Peatland biocapacity and Carbon Footprint

Peatlands make a modest 2% contribution to Scotland's biocapacity, despite covering 25% of land area. This is because peatland biocapacity only considers CO_2-sequestering peatlands, which limits the calculation to c.500,000 of the 1.9 million ha of Scottish peatlands. Peatland biocapacity is also influenced by primary production rate, which is low due to slow-growing peat-forming species (Li et al., 2018). The combination of small eligible land area and low primary production rate is thus responsible for the low biocapacity of Scottish peatlands. Another aspect of the peatland calculation which merits discussion is the choice of broadleaf primary production value with which to compare peatland primary production. While the value of -2.7 t C ha^{-1} yr^{-1} for $PP_{broadleaf}$ is highly aggregate, the sensitivity of national biocapacity to variations in $PP_{broadleaf}$ is low (0.02, see Supplementary Data), suggesting that conclusions about peatland contributions are not reliant on the precision of this estimate. We are aware of one study in the literature which also estimates wetland biocapacity. Siche et al. (2010) uses Emergy Net Primary Production to estimate wetland biocapacity in Peru, and while the methodology is not directly comparable, their study also finds wetland biocapacity to be low compared to other land types, at 0.16 gha $person^{-1}$ (1.1% of Peru's total biocapacity).

The substantial Scottish peatland Carbon Footprint of 0.34 gha $person^{-1}$ is directly proportional to the estimated CO_2 emissions reported in the 2017 UK Peatland GHG Inventory. Although based on the best available data, there is uncertainty surrounding this emissions estimate, derived from uncertainty in emission factors, the extent of peatlands, assignment to peatland condition classes, and changes in peatland condition. While uncertainty in emission factors is captured by 95% confidence intervals, other sources cannot be quantified at present (Evans et al., 2017). More CO_2 flux studies and advances in peatland mapping will reduce this uncertainty, and improve the estimated peatland Carbon Footprint and biocapacity.

4.3. The need for increased peatland restoration

Considering the large Carbon Footprint of damaged peatlands, and the risk of accelerated peatland degradation due to climate change (Alexandrov et al., 2016; Tarnocai, 2006), it follows that the main motive for restoration is to protect this significant carbon store and halt any further degradation. Here we argue that present restoration targets will not achieve this. Current policy aims to restore only 250,000 ha (17%) of the 1.5 million ha of degraded peatlands by 2030, which would leave more than 1.2 million ha (60%) of Scotland's peatlands in a degraded condition by 2050, even if all targets are met. In biocapacity terms, this is illustrated by a mere 27% (9%) reduction of the 2050 peatland (national) deficit for the Central scenario. Current targets therefore lack the ambition required to address peatland emissions and the resulting ecological deficit. The High scenario also warns that degradation of just 25% of remaining near-natural peatlands in parallel with restoring 250,000 ha could eliminate nearly all restoration benefits by 2050. This emphasises the urgent need to protect our remaining near-natural peatlands from destructive land-use practices like draining, burning and afforestation.

4.4. Cost-effectiveness considerations

The case for increased restoration is strengthened by the finding that peatland restoration provides cost-effective mitigation across a spectrum of restoration costs. Projects with low capital and ongoing costs such as drain blocking and gully blocking (Scenario A) are extremely cost-effective at £2 per tCO_2e over 60 years (Table 5), and represent low-hanging fruit by which to ease the mitigation burden on other sectors. Surprisingly, despite the high restoration cost of peat under agricultural grassland (Scenario D), it has emerged as a highly cost-effective option at £6 per tCO_2e over 60 years, due to the large emissions savings to be gained from restoration. This suggests that in cases where land-use change is considered on agricultural grassland with underlying peat, for instance in areas with declining productivity, peatland restoration could offer significant and cost-effective carbon benefits.

The average project with median restoration cost and ongoing cost (Scenario C) yields average cost-effectiveness of £17 per tCO_2e over 60 years. Here, ongoing costs of £192 ha^{-1} are the largest contributor to overall restoration cost. Should ongoing costs be reduced to £25 ha^{-1} for the same capital cost (Scenario B), the cost-effectiveness improves significantly to £8 per tCO_2e, thus illustrating that ongoing costs play an important role in the efficiency of peatland restoration.

The time horizon considered also has a large impact on the cost-effectiveness outcome, as average costs per tonne CO_2e abated in the 60-year horizon are between 30% and 50% lower than in the 30-year horizon. Longer time horizons are particularly appropriate for peatland restoration. Near-natural peatlands can continue to grow and sequester carbon for thousands of years (Levy and Gray, 2015), while emissions from damaged peatlands will continue for as long as the peat remains drained and there is peat left to oxidise (Joosten and Couwenberg, 2009). Further, peatlands offer a strong net-cooling effect over longer time horizons, due to the long atmospheric lifespan of carbon dioxide (Evans et al., 2017). This indefinite benefit (burden) of near-natural (degraded) peatlands demonstrates the need for appropriate time horizons in policy evaluation, as short 20- or 30-year horizons do not capture true restoration benefits.

The 60-year horizon was chosen to match conventional silviculture rotation lengths, allowing a broad comparison with afforestation cost-effectiveness estimates in the literature, which ranges from -£7 to £41 per tCO_2e sequestered (Read et al., 2009; Valatin and Price, 2014). As shown in Table 5, we estimate average peatland restoration cost-effectiveness to range from £2 to £33 per tCO_2e abated, suggesting broadly comparable mitigation cost-effectiveness between peatland restoration and afforestation. However, for peatland restoration the top end estimate of £33 per tCO_2e pertaining to forestry removal on peat, only applies to 24% of Scotland's degraded peatlands. 64% of Scotland's degraded peatlands are drained, modified or eroded out-with forestry or agriculture (Evans et al., 2017), and could be restored via more cost-effective techniques described by Scenarios A to D, in the range of £2 to £17 per tCO_2e. These low-cost options could be applied to a peatland area far exceeding the government's current restoration target of 250,000 ha, with the benefit of significant carbon savings. This suggests that current peatland restoration policy is not fully exploiting the potential benefits of this efficient mitigation strategy. Should the co-benefits of restoration, like the reduced treatment of drinking water (Martin-Ortega et al., 2014) and flood risk reduction (Shuttleworth et al., 2019) be included in the cost-benefit analysis, the cost-effectiveness of peatland restoration will increase further.

The range of capital and ongoing costs used in this study refers to a 2008 report on peatland restoration costs in the UK. Although a comprehensive report spanning 72 projects and 412 sites, there is uncertainty linked to changes in costs and reporting methods. In comparison, a 2017 report on peatland restoration in Western Europe between 1993 and 2015 funded by the EU-LIFE programme (Andersen et al., 2017) found UK restoration costs averaged €1200 ha^{-1} (approximately £1000 ha^{-1}) including works expenditure, land purchase and monitoring, and excluding opportunity costs. Also, Matthews et al. (2012) report an average restoration capital cost of £1280 ha^{-1} across 58 lowland raised bogs in Scotland between 1994 and 2011. These values are lower than the median project cost of £1600 ha^{-1} used in this study (including works expenditure, land purchase and monitoring) which suggests that the cost-effectiveness estimates provided here are likely to be conservative.

5. Conclusion

Due to a lower population density and abundant natural capital, particularly in coniferous forests and marine fishing grounds, Scotland's per-person biocapacity is over three times larger, and its ecological deficit is over four times smaller, than that of the UK. However, this biocapacity advantage is being eroded by peatland degradation, with the Carbon Footprint of CO_2 emissions from degraded peatlands increasing Scotland's ecological deficit by 40%. Biocapacity implications were evaluated for different peatland restoration scenarios presented in the literature, and it is was found that only restoration targets which far exceed current government targets can offer meaningful biocapacity benefits by 2050. The cost per tonne of greenhouse gas abated of peatland restoration is found to be broadly comparable with that of afforestation, and peatland restoration is found to be cost-effective across a spectrum of capital and ongoing costs. The specific cost-effectiveness of peatland restoration strongly depends on the restoration approach and current land use, and extremely cost-effective restoration options are available for peatland areas which far exceed the current restoration targets of the Scottish Government. Peatland restoration can provide significant and economically efficient greenhouse gas mitigation, and should be increased dramatically to protect this important carbon store and make meaningful progress towards reducing emissions in the land use sector.

Author contribution

Nicola Horsburgh: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization Andrew Tyler: Conceptualization, Writing – review & editing, Supervision, Project administration Scot Mathieson: Conceptualization, Writing – review & editing, Supervision Mathis Wackernagel: Conceptualization, Methodology, Resources, Writing – review & editing David Lin: Methodology, Writing – review & editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Thank you to the two anonymous reviewers, whose comments and suggestions greatly improved the manuscript. We also thank the Scottish Government Agricultural Census Analysis team for providing vital statistics for the calculation.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.114486.

References

Alexandrov, G.A., Brovkin, V.A., Kleinen, T., 2016. The influence of climate on peatland extent in western siberia since the last glacial maximum. Sci. Rep. 6 (1), 1–6.
Andersen, R., Farrell, C., Graf, M., Muller, F., Calvar, E., Frankard, P., Caporn, S., Anderson, P., 2017. An overview of the progress and challenges of peatland restoration in Western Europe. Restor. Ecol. 25 (2), 271–282.
Bain, C.G., Bonn, A., Stoneman, R., Chapman, S., Coupar, A., Evans, M., Gearey, B., Howat, M., Joosten, H., Keenleyside, C., 2011. IUCN UK Commission of Inquiry on Peatlands. IUCN UK Peatland Programme. Available. www.iucn-uk-peatlandprogramme.org.
Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J.C., Wackernagel, M., Galli, A., 2013. Accounting for demand and supply of the biosphere's regenerative capacity: the National Footprint Accounts' underlying methodology and framework. Ecol. Indicat. 24, 518–533.
Broadmeadow, M., Matthews, R., 2003. Forests, Carbon and Climate Change: the UK Contribution.
CBD, 2005. *Millennium Ecosystem Assessment.* Ecosystems and Human Well-Being: Biodiversity Synthesis. World Resources Institute, Washington DC.
CCC, 2019. UK Committee on Climate Change: Net Zero Technical Report.
Costanza, R., Daly, H.E., 1992. Natural capital and sustainable development. Conserv. Biol. 6 (1), 37–46.
Evans, C., Artz, R., Moxley, J., Renou-Wilson, F., 2017. Implementation of an Emissions Inventory for UK Peatlands.
Forestry Commission, 2016. 25-year Forecast of Softwood Timber Availability. National Forest Inventory, 231 Corstorphine Road, Edinburgh, EH12 7AT. Available. www.forestry.gov.uk/forecast.
Glenk, K., Martin-Ortega, J., 2018. The economics of peatland restoration. J. Environ. Econ. Pol. 7 (4), 345–362.
Hiederer, R., Köchy, M., 2011. Global soil organic carbon estimates and the harmonized world soil database. European Commission Joint Res. Centre, Inst. Environ. Sustain. EUR 79 (25225), 10–2788.
Holden, J., Walker, J., Evans, M.G., Worrall, F., Bonn, A., 2008. *A Compendium of UK Peat Restoration and Management Projects.* SP0556. Report to Defra, London.
IEA, 2020. Data and Statistics. International Energy Agency. Available. https://www.iea.org/.
IPBES Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Guèze, M., Agard, J., Arneth, A., Balvanera, P., Brauman, K.A., Butchart, S.H.M., Chan, K.M.A., Garibaldi, L.A., Ichii, K., Liu, J., Subramanian, S.M., Midgley, G.F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Chowdhury, R. R., Shin, Y.J., Visseren-Hamakers, I.J., Willis, K.J., Zayas, C.N., 2019. Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.3553579. Available.
IPCC, 2014. Climate Change 2014 - Synthesis Report.
Joosten, H., 2009. The Global Peatland CO_2 Picture: Peatland Status and Drainage Related Emissions in All Countries of the World.
Joosten, H., Couwenberg, J., 2009. Are emission reductions from peatlands MRV-able? Wetlands Int.
Kitzes, J., Galli, A., Bagliani, M., Barrett, J., Dige, G., Ede, S., Erb, K., Giljum, S., Haberl, H., Hails, C., 2009. A research agenda for improving national Ecological Footprint accounts. Ecol. Econ. 68 (7), 1991–2007.
Lees, K.J., Quaife, T., Artz, R.R.E., Khomik, M., Sottocornola, M., Kiely, G., Hambley, G., Hill, T., Saunders, M., Cowie, N.R., 2019. A model of gross primary productivity

based on satellite data suggests formerly afforested peatlands undergoing restoration regain full photosynthesis capacity after five to ten years. J. Environ. Manag. 246, 594–604.
Leifeld, J., Menichetti, L., 2018. The underappreciated potential of peatlands in global climate change mitigation strategies. Nat. Commun. 9 (1), 1–7.
Levy, P.E., Gray, A., 2015. Greenhouse gas balance of a semi-natural peatbog in northern Scotland. Environ. Res. Lett. 10 (9), 94019.
Li, C., Grayson, R., Holden, J., Li, P., 2018. Erosion in peatlands: recent research progress and future directions. Earth Sci. Rev. 185, 870–886.
Lin, D., Hanscom, L., Martindill, J., Borucke, M., Cohen, L., Galli, A., Lazarus, E., Zokai, G., Iha, K., Eaton, D., Wackernagel, M., 2019. Working Guidebook to the National Footprint Accounts. Global Footprint Network, Oakland. Available. https://www.footprintnetwork.org/content/uploads/2019/05/National_Footprint_Accounts_Guidebook_2019.pdf.
Mancini, M.S., Galli, A., Niccolucci, V., Lin, D., Bastianoni, S., Wackernagel, M., Marchettini, N., 2016. Ecological footprint: refining the carbon footprint calculation. Ecol. Indicat. 61, 390–403.
Martin-Ortega, J., Allott, T.E.H., Glenk, K., Schaafsma, M., 2014. Valuing Water Quality Improvements from Peatland Restoration: Evidence and Challenges, vol. 9. Ecosystem Services, pp. 34–43.
Matthews, P., Hughes, J., Dowse, G., 2012. The State of Scotland's Lowland Raised Bogs in 2012: Interim Findings from a Survey of 58 Scottish Lowland Raised Bogs and Analysis of Change since 1994/95. Scottish Wildlife Trust, Edinburgh, pp. 1–60.
Moran, D., Wreford, A., Evans, A., Fox, N., Glenk, K., Hutchings, M., McCracken, D., McVittie, A., Mitchell, M., Moxey, A., 2013. *Assessing The Preparedness of England's Natural Resources for a Changing Climate: Assessing The Type and Level of Adaptation Action Required to Address Climate Risks in the 'vulnerability Hotspots', Report To the Adaptation Sub Committee, Committee On Climate Change.* Adaptation Sub-committee Progress Report. Committee on Climate Change, London, UK, pp. 1–192.
Moxey, A., Moran, D., 2014. UK peatland restoration: some economic arithmetic. Sci. Total Environ. 484, 114–120.
National Records of Scotland, 2018. Scotland's population 2018 - the registrar general's annual review of demographic trends. Available. https://www.nrscotland.gov.uk/files//statistics/rgar/2018/index.html.
Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C., Snowdon, P., 2009. Combating Climate Change: a Role for UK Forests. An Assessment of the Potential of the UK's Trees and Woodlands to Mitigate and Adapt to Climate Change. The Stationery Office Limited, pp. 1–24.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, I.F.S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., 2009. Planetary boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14 (2), 32 [online]. http://www.ecologyandsociety.org/vol14/iss2/art32/.
Scottish Government, 2018a. Climate Change Plan, Third Report on Proposals and Policies 2018-2032. Edinburgh: Available. http://www.gov.scot/Publications/2018/02/8867.
Scottish Government, 2018c. Scottish Greenhouse Gas Emissions 2018.
Shuttleworth, E.L., Evans, M.G., Pilkington, M., Spencer, T., Walker, J., Milledge, D., Allott, T.E.H., 2019. Restoration of blanket peat moorland delays stormflow from hillslopes and reduces peak discharge. J. Hydrol. X 2, 100006.
Siche, R., Agostinho, F., Ortega, E., 2010. Emergy net primary production (ENPP) as basis for calculation of ecological footprint. Ecol. Indicat. 10 (2), 475–483.
Tarnocai, C., 2006. The effect of climate change on carbon in Canadian peatlands. Global Planet. Change 53 (4), 222–232.
Thomas, M.V., Malhi, Y., Fenn, K.M., Fisher, J.B., Morecroft, M.D., Lloyd, C.R., Taylor, M.E., McNeil, D.D., 2011. Carbon dioxide fluxes over an ancient broadleaved deciduous woodland in southern England. Biogeosciences 8 (6), 1595.
UK Government, 2019. Valuation of Energy Use and Greenhouse Gas - Supplementary Guidance to the HM Treasury Green Book on Appraisal and Evaluation in Central Government.
UK Government, 2020a. The Green Book (2020). HM Treasury. Available. https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent/the-green-book-2020.
UK Government, 2020b. Total Final Energy Consumption at Regional and Local Authority Level: 2005 to 2018. Available. https://www.gov.uk/government/statistics/total-final-energy-consumption-at-regional-and-local-authority-level-2005-to-2018.
Valatin, G., Price, C., 2014. How Cost-Effective Is Forestry for Climate Change Mitigation? *Challenges And Opportunities For the World's Forests In the 21st Century.* Springer, pp. 297–339.
Wackernagel, M., Hanscom, L., Jayasinghe, P., Lin, D., Murthy, A., Neill, E., Raven, P., 2021. The importance of resource security for poverty eradication. Nat. Sustain. 1–8.
Wackernagel, M., Lin, D., Evans, M., Hanscom, L., Raven, P., 2019. Defying the Footprint Oracle: implications of country resource trends. Sustainability 11 (7), 2164.
Wackernagel, M., Rees, W.E., 1997. Perceptual and structural barriers to investing in natural capital: economics from an ecological footprint perspective. Ecol. Econ. 20 (1), 3–24.
Xu, J., Morris, P.J., Liu, J., Holden, J., 2018. PEATMAP: refining estimates of global peatland distribution based on a meta-analysis. Catena 160, 134–140.
York University Ecological Footprint Initiative & Global Footprint Network, 2021. National Footprint and Biocapacity Accounts, 2021 Edition. Produced for the Footprint Data Foundation and distributed by Global Footprint Network. Available. https://data.footprintnetwork.org/.