

LETTER • OPEN ACCESS

The carbon sequestration potential of Scottish native woodland

To cite this article: Tasmin I Fletcher *et al* 2021 *Environ. Res. Commun.* **3** 041003

View the [article online](#) for updates and enhancements.

Environmental Research Communications

LETTER



The carbon sequestration potential of Scottish native woodland

OPEN ACCESS

RECEIVED

15 December 2020

REVISED

24 March 2021

ACCEPTED FOR PUBLICATION

1 April 2021

PUBLISHED

16 April 2021

Original content from this work may be used under the terms of the [Creative Commons Attribution 4.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Tasmin I Fletcher¹ , Catherine E Scott¹ , Jeanette Hall² and Dominick V Spracklen¹ ¹ School of Earth and Environment, University of Leeds, Leeds, United Kingdom² NatureScot, Inverness, United KingdomE-mail: T.I.Fletcher@leeds.ac.uk**Keywords:** native woodland, natural regeneration, carbon sequestration**Abstract**

Woodland creation sequesters carbon and contributes to climate change mitigation. Most previous assessments of the carbon sequestration of new UK woodlands have focused on tree planting, little is known about the scale of the potential contribution from natural regeneration. We used a Potential for Native Woodland Model to make the first estimate of carbon sequestration by large-scale native woodland expansion through natural regeneration in Scotland. We estimate native woodland could expand to cover an additional 3.9 million hectares of the Scottish uplands removing an average of 6.96 million tons of CO₂ per year. This represents 35%–45% of the carbon removal target for UK woodlands that has been suggested by the UK Committee on Climate Change. Expanding woodlands to just 10% of this potential would double existing native woodland and could provide a multitude of benefits, including carbon removal equivalent to approximately 4% of this target. The next few decades are critical in terms of climate change mitigation, therefore further work is now required to improve these estimates and better constrain this potentially large contribution.

Introduction

Conservation and restoration of forests, wetlands and grasslands can provide one third of the actions needed to hold global temperature increase below 2 °C and prevent disastrous climate change (Griscom *et al* 2017). Many countries have included such natural climate solutions (also known as nature-based solutions) in their Nationally Determined Contributions submitted in support of the Paris Agreement on Climate (Grassi *et al* 2017). There is the potential for new woodland in the UK to sequester carbon and contribute to emission reduction targets (Valatin 2012). The UK Committee on Climate Change (UKCCC) has advised that to reach net-zero emissions by 2050, the UK must create 30,000–50,000 hectares of forest per year, sequestering 15–20 million tons of CO₂ per year (Mt CO₂ yr⁻¹) (UKCCC 2019).

In the UK, new woodland creation is achieved primarily by tree planting with much less focus on natural regeneration, which can also create new native woodlands (Spracklen *et al* 2013). Consequently, little is known about the carbon sequestration potential of woodland expansion through natural regeneration. O'Neill *et al* (2020) estimated that woodland creation on European sheep pasture was economically viable through natural regeneration for a carbon price of \$4 per ton of CO₂ (tCO₂) but required \$55/tCO₂ if woodland creation occurred through tree planting. A better understanding of the carbon removal potential of natural regeneration is therefore crucial to assess its role in climate change mitigation efforts.

Scotland has a large potential for woodland expansion, and the country accounted for 80% of new tree planting in the UK in 2019/2020 (Forestry Statistics 2020). Recent analysis by Sing and Aitkenhead (2020) provides an update to work commissioned by the Woodland Expansion Advisory Group (WEAG 2012, Sing *et al* 2013), estimating that 2.96 million hectares (Mha) of land are ecologically suitable for woodland expansion, with a further 0.54 Mha constrained to varying degrees by national designations and policies, showing that in total up to 45% of Scotland's land has the potential for woodland expansion.

Large areas of the Scottish uplands would be suitable for woodland expansion through natural regeneration, and this is the preferred method of expanding semi-natural and native woodland in the UK (Forestry

Table 1. Definition, area, percentage canopy cover and carbon sequestration values for NWM predicted woodland types.

Code	Definition	Area (ha)	Canopy cover %	Carbon sequestration (tC)
Sc5	Peatland with scattered trees/scrub	489,769	10	5,147,126
W4/Sc5/ W17/W18	W4 Birch (with open ground) + Peatland with scattered trees/scrub + W17/W18 Mosaic	381,898	29	11,639,093
W4/Sc5	W4 Birch (with open ground) + Peatland with scattered trees/scrub	278,264	23	6,726,012
W11	W11 Upland Oak-Birch with bluebell/wild hyacinth	257,519	80	21,650,743
U	Unsuitable for tree/scrub growth	196,623	0	0
W18/Sc5	W18 + Peatland with scattered trees/scrub Mosaic	196,184	56	11,442,739
W4	W4 Birch with purple moor grass & open ground	195,976	30	6,178,716
W18	W18 Scots Pine with heather	185,860	80	15,626,095
W18/W17	W18/W17	150,223	80	12,629,894
W7	W7 Alder-ash with yellow pimpernel	134,524	80	11,310,047
W17/ W18/W4	W17/W18 & W4 Birch (with open ground) Mosaic	126,844	63	8,331,513
Water	Inland Water	111,249	0	0
W4/ W17/W18	W4 Birch (with open ground) + W17/W18 Mosaic	106,998	48	5,341,270
Sc5/W4	Peatland with scattered trees/scrub Mosaic + W4 Birch with purple moor grass and open ground	106,539	17	1,903,401
Sc4	Scattered Birch/Willow	93,587	10	983,529
Sc7	Mixed montane scrub	91,135	30	2,873,285
Sc3	Birch/Willow	87,819	30	2,768,747
Sc5/W4/ W17/W18	Peatland with scattered trees/scrub + W4 Birch with purple moor grass and open ground + W17/W18 Mosaic	83,618	23	2,021,168
W11/W7	W11 + W7 Mosaic	75,356	80	6,335,520
W10	W10 Lowland mixed broadleaved with bluebell/wild hyacinth	74,393	80	6,254,573
W11/W17	W11/W17	67,116	80	5,642,711
Sc6	Basin Bog woodland/scrub	60,324	30	1,901,903
W17/W11	W17/W11	53,829	80	4,525,652
W17	W17 Upland Oak-Birch with bilberry/blaeberry	53,549	80	4,502,120
Sc5/W18	Peatland with scattered trees/scrub + W18 Mosaic	53,157	35	1,927,301
W18/W4	W18 + W4 Mosaic	51,370	63	3,374,138
W7/W4	W7 + W4 Mosaic	45,922	63	3,016,275
W17/W18	W17/W18	42,144	80	3,543,190
W9/W11	W9/W11	36,243	80	3,047,080
Sc1	Juniper	35,676	30	1,124,797
W9	W9 Upland mixed broadleaved with dog's mercury	28,753	80	2,417,361
Sc2	Scattered Juniper	28,224	10	296,611
W11/W7	W11/W7	26,202	80	2,202,894
W18/W4/Sc5	W18 + W4 + Peatland with scattered trees/scrub Mosaic	23,124	58	1,409,527
W7/W11	W7 + W11 Mosaic	20,426	80	1,717,310
W11/W9	W11/W9	18,962	80	1,594,217
W7/W10	W7/W10	18,591	80	1,563,033
W10/W8	W10/W8	16,885	80	1,419,600
Sc8	Scattered mixed montane scrub	16,309	10	171,391
BU	Built-up land	15,612	0	0
W7/W9	W7 + W9 Mosaic	13,223	80	1,111,727
W6	W6 Alder with stinging nettle	11,069	80	930,616
DR	Developed rural land	6,556	0	0
W10/W7	W10 + W7 Mosaic	6,254	80	525,822
W4/W18	W4 + W18 Mosaic	5,657	48	282,387
W17/W4	W17 + W4 Mosaic	5,470	63	359,260
W7/W11	W7/W11	5,040	80	423,722
W10/W16	W10/W16	3,894	80	327,424
W9/W7	W9 + W7 Mosaic	2,933	80	246,576
W4/a	W4 Birch with purple moor grass	2,820	80	237,063
W11/W4	W11 + W4 Mosaic	2,577	63	169,270
Sc6/W11	Basin Bog woodland/scrub + W11	2,283	48	113,971
W7/W17	W7 + W17 Mosaic	1,122	80	94,336
W8	W8 Lowland mixed broadleaved with dog's mercury	617	80	51,857
nodata	nodata	482	0	0
W19	W19 Juniper woodland with wood sorrel	390	80	32,775

Table 1. (Continued.)

Code	Definition	Area (ha)	Canopy cover %	Carbon sequestration (tC)
W10/W7	W10/W7	385	80	32,356
W11/Sc6	W11 + basin bog woodland/scrub	380	63	24,990
W6/W11	W6 + W11 Mosaic	365	80	30,694
W4/W17	W4 + W17 Mosaic	315	48	15,749
W18/W11	W18 + W11 Mosaic	61	80	5,097
W7/Sc5	W7 + Peatland with scattered trees/scrub	2	56	94
TOTAL	—	3,878,170	—	189,576,370

Commission 1994). Advantages of natural regeneration over tree planting include best matching of species to site, structural heterogeneity of resulting woodlands, and conservation of local genetic stock (Peterken 1996). Additionally, natural regeneration does not involve the same level of ground disturbance as planting, which can lead to loss of carbon from the soil (Friggens *et al* 2020). Current land-use practices mean regeneration of native woodlands is often limited and a natural tree line (the physical limit above which trees cannot survive) is unable to establish across the majority of the country's uplands. Amongst other factors, the historic depletion of woodland has left long distances to seed sources in some areas and practices such as grazing by livestock (Speed *et al* 2010) and deer (Bunce *et al* 2014), and repeated muirburn (rotational burning of heather and grassland) suppress sapling growth. Modelling by Tanentzap *et al* (2013) found that deer browsing and ground vegetation cover were the main factors influencing birch regeneration, over seed availability.

Current research into woodland expansion rarely accounts for land that could support scrub-type woodland up to a naturally established tree line, and often excludes montane and other scrub habitats on highly exposed land. Montane scrub is severely depleted in Scotland, but benefits of this habitat include unique wildlife, slope stability, water runoff retention and reduced downstream flooding, and reduced windthrow of adjacent forest plantations (Scott 2000). Initial estimates of current climatic factors by Hale *et al* (1997, cited in Gilbert and Cosmo 2003, p.178) suggest that 609,400 hectares of land could support woodland above the commercial timberline, with a further 322,300 hectares unsuitable for tree growth but with potential for tall shrub species. Changes in climate may mean that this area increases in the future.

Here we make a first estimate of the potential carbon removal that would be achieved by large-scale expansion of native woodlands in the Scottish uplands through natural regeneration. First, we determined the land available for woodland to re-establish across Scotland if conditions allowed (i.e. if a seed source were present, existing vegetation allowed germination and seedling growth, and browsing was sufficiently low), up to its climatically determined extent. Next, we used this information to estimate the carbon removal and storage potential of this woodland. We specifically consider the potential across a range of ecosystems, including upland and montane habitats. Following preliminary calculations, we make recommendations as to how estimates could be improved and what further work would be required to achieve this.

Methodology

Our approach involved two components. First, we assessed the potential area of land in Scotland that could become new native woodland. Second, we assessed the carbon uptake and storage potential of this woodland.

Potential extent of native woodland

In the first step we defined the extent of potential woodland cover across Scotland and then determined the type of native woodland that is likely re-establish, given the right conditions.

To do this, we applied the Potential for Native Woodland Model (NWM), created by the Macaulay Institute and SNH (Towers *et al* 2004). The NWM was developed as a planning tool to aid expansion of native woodland across Scotland. Using national scale soil and landcover data, the NWM predicts potential National Vegetation Classification (NVC) woodland types that would be expected under current soil and vegetation conditions, down to a 1:50,000 scale. It should be noted that the potential for different woodland types is based on current conditions and is likely to vary with climate change.

The NWM encompasses 5.3 Mha, approximately two thirds of the country, covering upland mainland Scotland but excluding the central and eastern lowlands, where modified soils mean that it is more difficult to predict appropriate native woodland types. Current woodland is not accounted for in the NWM, therefore areas of existing woodland, determined using the 2018 National Forest Inventory (NFI) Woodland Map Scotland,

were removed from the analysis. All areas categorised as woodland in the NFI were excluded, except for those classed as ‘failed’ areas of plantation, where woodland is not currently present.

The outputs of the NWM are categorized into 58 woodland types. Inland water, built-up land, developed rural land and land unsuitable for tree/scrub growth are also identified. The woodland types may be single or interchangeable NVC classes, and in some cases mosaics of different NVC classes are predicted. The full range of NWM outputs is shown in table 1.

Carbon storage calculations

Canopy cover

Due to the complexity of interaction between vegetation, soil and climate, canopy cover in naturally regenerating woodland can vary widely and it is likely that a mosaic of denser and more sparsely wooded areas would occur naturally across the landscape. It is therefore important to account for this in calculations of carbon sequestration in native woodlands.

To determine the percentage canopy cover for the woodland types predicted by the NWM, each component part of the woodland types was assigned a canopy cover value, as given in Towers *et al* (2004). Although woodland in the UK is defined as land under stands of trees with a canopy cover of at least 20% (Forestry Statistics 2020), the NWM incorporates areas with canopy cover as low as 10% in order to include the potential for open woodland and scattered trees/scrub.

Types W4a, W6-W11 and W16-W19 were assigned 80% canopy cover; W4 (with open ground) and Sc1, Sc3, Sc6 and Sc7 were assigned 30% canopy cover; and Sc2, Sc4, Sc5 and Sc8 were assigned 10% canopy cover. Inferring mosaic composition proportions from the NWM, we then calculated the percentage canopy cover for each of the woodland types predicted by the NWM. Values for canopy cover are shown in table 1.

Carbon sequestration

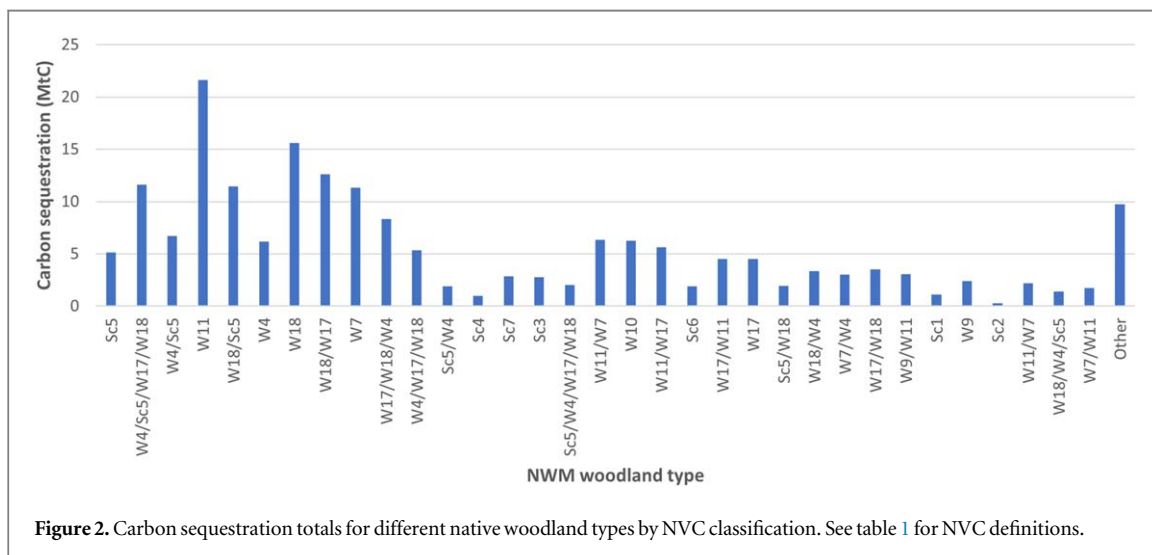
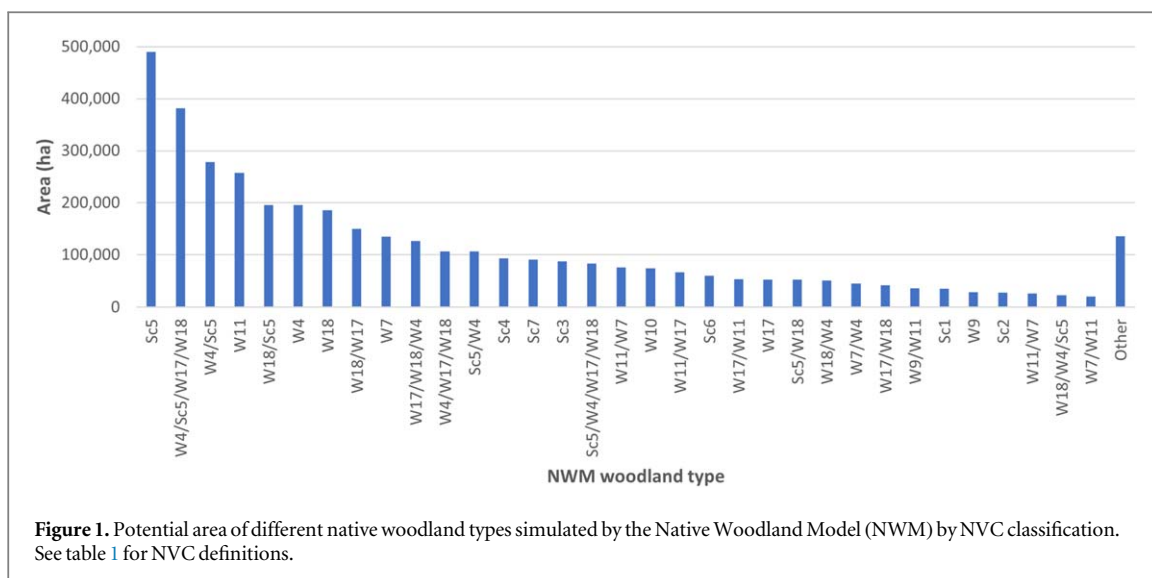
We estimated carbon sequestration based on data from a study by the Scottish Forest Alliance (SFA), which modelled above-ground carbon sequestration at 12 native woodland sites across Scotland (Perks *et al* 2010). Established through a combination of planting and natural regeneration, these sites were predominantly upland, with nutrient poor soils, focusing on NVC types W17 (upland oak/birch with bilberry), W18 (Scots pine with heather), W11 (upland oak/birch with bluebell/wild hyacinth), W7 (alder/ash with yellow pimpernel), W9b (upland ash with birch/rowan/aspen) and W4 (birch with purple moor grass). An average carbon sequestration total of 84 tons of carbon per hectare (tC ha^{-1}) for mature woodland (based on total values given in table 1 of Perks *et al* 2010) after 100 years was calculated. This included tree biomass in the stemwood, crownwood, foliage and large roots, as well as thinnings and timber products removed from site during management. Carbon gains were estimated separately for each species. This value is broadly in line with other studies of carbon sequestration in UK native woodlands, which average around 135 tC ha^{-1} (Patenaude *et al* 2003, Butt *et al* 2009, Morison *et al* 2012, Hale 2015, Hale *et al* 2019).

We assumed this value represented an 80% canopy cover mature woodland. To provide carbon sequestration for different woodland types predicted by the NWM, we used the canopy cover for each woodland type to scale carbon sequestration. That is, for Sc2 woodland with canopy cover of 10% we scaled by 10% over 80% giving a carbon sequestration of 10.5 tC ha^{-1} ($84 \text{ tC ha}^{-1} \times 10/80$). To calculate average annual sequestration rates, we assumed that mature woodlands take 100 years to develop and, as a simplification, that carbon uptake is linear over this period. In reality, carbon uptake will be slow during the early years of regeneration but would also peak at higher values than the average rate we calculate here.

Results

There is potential for new native woodlands across 3.9 Mha, roughly 74% of the area of our analysis. Figure 1 shows the potential woodland area for the main NWM types. The woodland type covering the largest area is peatland with scattered trees/scrub (Sc5), which covers just under 490,000 ha. The NVC woodland type covering the greatest area is W11 (upland oak/birch woodland with bluebell/wild hyacinth), which is predicted to cover nearly 258,000 ha. Other NWM types which cover significant areas as part of woodland mosaics include W4 (birch with open ground), W17 (upland oak/birch with bilberry) and W18 (Scots pine with heather). Open woodland and scattered trees/scrub (canopy cover $\leq 30\%$) accounts for 1.9 Mha, roughly 50% of the total woodland area.

Figure 2 reports carbon sequestration by the different woodland types and shown in detail in table 1. Total carbon sequestration is dominated by W11 (11% of total carbon sequestered), W18 (8%) and W18/W17 mosaic (7%). Scattered trees and scrub on peatlands cover the largest area, equivalent to 12% of total native woodland cover but only contribute 3% of carbon storage due to the low canopy cover and low assumed carbon storage per area. Open woodlands (canopy cover $\leq 30\%$) account for 50% of woodland area, but only 22% of total carbon sequestered.

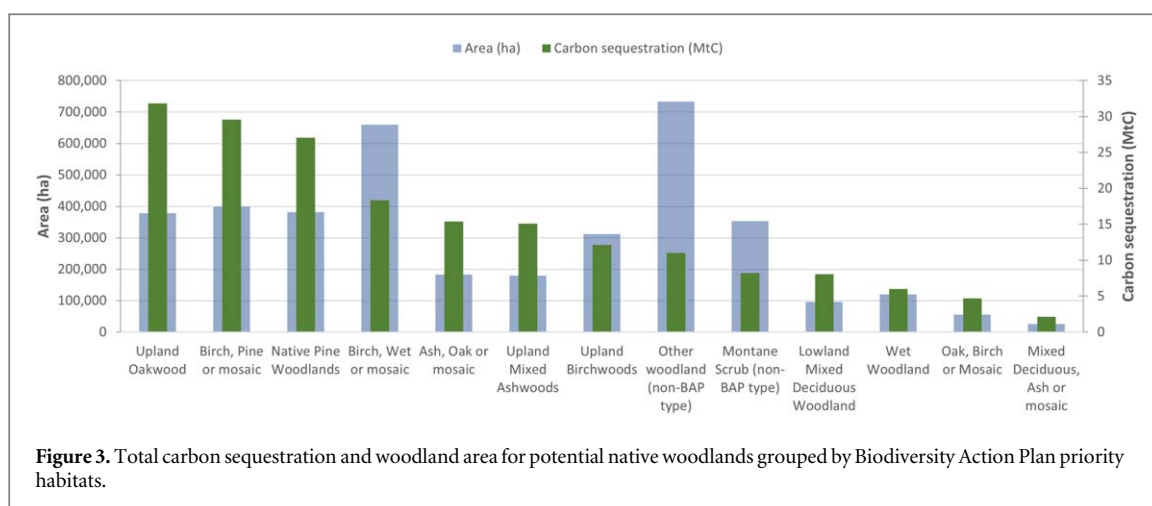


Montane habitats, defined by the NWM as types Sc1, Sc2, Sc3, Sc4, Sc7 and Sc8, cover a total of 353,000 ha (9% of the model area) and collectively sequestered 8.22 Mt C, or 4% of the total for all native woodland.

Total carbon sequestration potential across all NWM predicted model outputs is 190 Mt C (table 1), which equates to 696 Mt CO₂. Based on the broad assumptions that a woodland takes 100 years to mature and that uptake of carbon is linear during that time, our calculations suggest an average carbon sequestration potential of 1.90 Mt C yr⁻¹, which equates to 6.96 Mt CO₂ yr⁻¹.

Discussion

If native woodlands expanded to the potential estimated by the NWM, they would cover an additional 50% of Scotland’s land area, making a major contribution to Biodiversity Action Plan priority habitats (figure 3). Woodlands composed of native species currently cover only 5.8% of Scotland (Forestry Statistics 2020), with semi-natural woodland covering only 4% of Scotland (Bunce *et al* 2014). Allowing native woodlands to expand to an additional 10% of their potential area (0.4 Mha) would therefore represent a doubling of native woodlands in Scotland. Such an expansion would also make a substantial contribution towards existing plans for woodland expansion from 18% to 25% of land area by 2050 (Thomas *et al* 2015). Forestry Strategy 2019–2029 calls for an increase in the annual woodland creation target from 10,000 to 15,000 ha per year by 2025, including 3000–5000 ha of native woodland (The Scottish Government 2019). To achieve expansion to 10% of their potential area by 2050 would involve creation of 13,000 ha of native woodland per year. Although this rate is comparable to that set for overall planting targets, natural regeneration requires fewer resources than planting, allowing greater



scope for large scale woodland expansion. Consequently, natural regeneration may augment planting targets as a method of woodland establishment in areas where it is appropriate and feasible.

A large fraction of the potential native woodland would consist of open woodland and scattered trees rather than closed canopy woodland. The average canopy cover of the potential woodlands is 60%. The definition of woodland in the UK is land under stands of trees with a canopy cover of at least 20% (Forestry Statistics 2020). About one fifth of the potential woodland (0.7 Mha) in our study has a canopy cover less than this and so would not be classified as woodland under this definition. Only one third of the woodlands (1.2 Mha) consists of closed canopy cover woodlands ($\geq 80\%$ canopy cover) and half of the woodland area (1.9 Mha) consists of open woodland and scattered trees ($\leq 30\%$ canopy cover). The low canopy cover and open character of the native woodland created through natural regeneration may reduce any potential negative impact of large-scale woodland expansion on open landscape character or biodiversity, for example by softening the edges of more dense woodland and increasing edge habitats (Bunce *et al* 2014). Forest plantations can have negative impacts on open-ground breeding birds (Wilson *et al* 2014), but less is known about the impacts of scattered native trees.

Previous analysis focusing on woodland expansion by tree planting has suggested around 3.5 Mha of land is available across the whole of Scotland (Sing and Aitkenhead 2020). In the context of natural regeneration, we estimate 3.9 Mha are available across two thirds of the same modelled area. Under the UK Forestry Standard (Forestry Commission 2017), areas of peatland and other low productivity land are deemed inappropriate for tree planting due to net carbon losses from deep peat and poor timber yields on certain soils or climate conditions. In contrast, allowing woodland to expand naturally means that trees are likely to establish in such areas, although they may be sporadic, stunted and the timber of little economic value. By removing these areas from their analysis, Sing and Aitkenhead calculated 1.23 Mha to be unsuitable for woodland creation, compared with only 0.2 Mha across two thirds of the same area by the NWM. This is reflected in the high proportions of low canopy cover woodland and scrub predicted by the NWM, that may grow on poor quality or exposed land.

We estimate that 3.9 Mha of native woodland could be established in the Scottish uplands with a potential carbon sequestration of 696 Mt CO₂ over a 100 year period, equivalent to an average removal of 6.96 Mt CO₂ yr⁻¹. This carbon sequestration is equivalent to 35%–45% of the carbon removal targets through woodland creation suggested by the UKCCC for achieving net-zero emissions in the UK. Under an assumed afforestation rate of 10,000 ha per annum, Scottish forests would remove less than 4 Mt CO₂ yr⁻¹ between now and 2050 (UKCCC 2020). Expansion of native woodlands to 10% of their potential across the Scottish uplands could result in an additional 0.7 Mt CO₂ yr⁻¹ removal, demonstrating the substantial opportunity for increased native woodlands to contribute to carbon removal. Carbon removal is dominated by W11 and W18 which together account for 20% of potential carbon uptake. Prioritising actions to areas that support these woodland types (oak and Scots pine woodlands, figure 3) would maximise carbon uptake per woodland area (tC ha⁻¹) of new woodlands. Overall, our analysis shows large-scale expansion of native woodlands through natural regeneration has significant potential to deliver climate mitigation in Scotland. Future work is required to assess the potential for native woodland creation in upland areas across the UK.

Limitations and recommendations

Our analysis contains a range of simplistic assumptions. The amount of carbon stored in a woodland is highly variable, and will depend on factors such as species composition, soil, and former land use (Ostle *et al* 2009). Therefore, each woodland type predicted by the NWM will have a different carbon storage potential. Currently

our estimates do not fully capture this complexity. We apply one carbon storage value (Perks *et al* 2010) scaled by the assumed canopy cover of different woodland types, to broadly account for differences in carbon storage for the different woodland compositions predicted by the NWM. Our calculations also assume linear carbon uptake, whereas in reality accumulation rates are likely to vary significantly at different stages of maturity. To improve on this approach, we would require carbon sequestration and storage values specific to each of the main NVC classes used by the NWM, covering a range of variables such as soil type, age and species composition. This information is not currently available for Scottish native woodlands, therefore further work will be needed to gather data for this purpose. Our analysis can be used to prioritise woodland types for detailed carbon measurements, namely W11 (upland oak/birch) and W18 (Scots pine).

Our estimates do not account for changes in soil carbon as woodlands establish, which could be substantial (Matthews *et al* 2020). Afforestation on deep peat, especially when drainage occurs before tree planting, results in large carbon emissions from loss of soil organic matter (Morison *et al* 2010). It is known that tree planting on organo-mineral soils can also lead to loss of soil carbon on decadal scales (Friggens *et al* 2020), particularly if tree planting includes substantial ground preparation. The change in soil carbon under naturally regenerating woodlands, particularly composed of open woodland and scattered trees, is not well understood. As natural regeneration does not involve the same level of soil disturbance as planting, it has the potential to become a net carbon sink much sooner than planted trees, which may have to offset soil carbon losses for several decades after planting. This could be critical in the next few decades of climate change mitigation.

We have assumed the maximum hypothetical expansion of native woodland in the Scottish uplands. The NWM does not model the extent of woodland potential in lowland and urban parts of the country. Future work needs to assess how additional constraints impact the available area for woodland cover. Constraints may include presence of agricultural land; land designations such as national parks or national scenic areas; areas protected for conservation or historic value; areas of deep peat soils; and other areas of potential land-use conflict (Sing *et al* 2013, Thomas *et al* 2015). Accounting for some of these restrictions reduces the land suitable for woodland creation across the whole of Scotland to 2.96 Mha (Sing & Aitkenhead 2020). Creation of open woodland and scattered trees may be possible in areas deemed unsuitable for woodland creation. More work is needed to understand the constraints and barriers to woodland creation (Burton *et al* 2019) and how these vary for different woodland types, treescapes and woodland creation mechanisms. Research by Pollock *et al* (2015) has shown that birch woodlands in Scotland can regenerate with livestock grazing present, if there is sufficient good quality forage present. Silvopasture and farm woodlands also have the potential to store greater carbon than grassland pasture, whilst still supporting livestock (Beckert *et al* 2016). Some conservation areas, such as heathland, are currently protected from being converted to woodland, however small increases in shrub cover, scattered trees and woodland patches may not negatively impact and could potentially increase the biodiversity of these habitats (Fuller and Calladine 2014).

The potential for natural regeneration to achieve woodland expansion on timescales suitable to contribute to near-term climate targets needs to be better understood. Although woodland can regenerate with deer present, provided their impact is low (Scott *et al* 2000, Tanentzap *et al* 2013), high browsing pressure from sheep and deer are a major constraint on tree regeneration in the Scottish uplands, with deer numbers increasing over the last few decades (Albon *et al* 2017). In many parts of the Scottish uplands, a lack of seed sources and competition from grasses may mean natural regeneration would be very slow even when grazing is reduced (Bunce *et al* 2014). In places where seed source is lacking, direct seeding may be a viable method of establishing native woodland at some sites (Willoughby *et al* 2019). Modelling of Scottish upland birch woodlands by Tanentzap *et al* (2013) shows how regeneration rates can be predicted using the variables of deer browsing pressure, adult tree sizes and locations, and ground favourability. Their analysis has the potential to predict above-ground carbon storage in response to changes in these variables. For example, they suggest that in a landscape with 8000 adult trees and 80% substrate favourability, browsing an average of 10% of trees could lead to the storage of at least 60 tC after 30 years. This represents substantially faster uptake of carbon than we assume, suggesting our estimates may be conservative. Greater understanding of the amount of carbon stored and rate of sequestration in different native woodland types, combined with such analysis, could prove a powerful tool for future land management decision making, particularly in relation to the government's net-zero targets.

Expansion of native woodlands would have many benefits in addition to carbon sequestration and climate mitigation. Native woodlands support and increase biodiversity (Scridel *et al* 2017), reduce flooding through increasing water use and infiltration and slowing overland flow (Nisbet and Thomas 2006, Jackson and Wheeler 2008, Dadson *et al* 2017), improve water quality and provide physical and mental health benefits through providing opportunities for recreation (Ward Thompson *et al* 2005). Future work needs to characterise the full array of benefits provided by expansion of native woodlands.

Conclusions

Improving our understanding of carbon storage in naturally regenerated native woodlands is crucial to achieving the UK government's targets for woodland expansion and net-zero carbon emissions. By combining spatial data on the potential for native woodland across the Scottish uplands with carbon sequestration estimates based on Scottish native woodlands sites, our analysis shows that there is the potential for 3.9 Mha of new native woodland sequestering 6.96 Mt CO₂ yr⁻¹. Expanding woodlands to just 10% of this potential would double existing native woodland in Scotland and could provide a multitude of benefits, including carbon removal equivalent to approximately 4% of the UKCCC's target for all UK woodlands. By considering natural regeneration, alongside tree planting, there is the potential for more ambitious woodland creation targets, although factors such as grazing, seed availability and ground disturbance, as well as constraints around land use and policy, will need to be taken into account. Further work is now needed on how variables such as species assemblage, age, soil type or the method of woodland creation affect sequestration, as this will improve our understanding of the current and potential future carbon storage of these ecosystems.

Acknowledgments

We acknowledge funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement no. 771492) and the North Face Explore Fund through the European Outdoor Conservation Association. DVS acknowledges a Philip Leverhulme Award. CES is funded by a Natural Environment Research Council (NERC) Independent Research Fellowship (NE/S015396/1). We acknowledge the developers of the Potential for Native Woodland Model and for discussions with David Balharry that inspired this work. The findings in this paper do not represent a policy position of NatureScot.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Tasmin I Fletcher  <https://orcid.org/0000-0002-7348-1007>

Catherine E Scott  <https://orcid.org/0000-0002-0187-969X>

Dominick V Spracklen  <https://orcid.org/0000-0002-7551-4597>

References

- Albon S D, McLeod J, Potts J, Brewer M, Irvine J, Towers M, Elston D, Fraser D and Irvine R J 2017 Estimating national trends and regional differences in red deer density on open-hill ground in Scotland: identifying the causes of change and consequences for upland habitats *Scottish Natural Heritage Commissioned Report*
- Beckert M R, Smith P, Lilly A and Chapman S J 2016 Soil and tree biomass carbon sequestration potential of silvopastoral and woodland-pasture systems in North East Scotland *Agroforestry Systems* **90** 371–83
- Bunce R G H, Wood C M, Smart S M, Oakley R, Browning G, Daniels M J, Ashmole P and Cresswell J 2014 The landscape ecological impacts of afforestation in the British uplands and some initiatives to restore native woodland cover *J. Landscape Ecol.* **7** 5–24
- Burton V, Metzger M J, Brown C and Moseley D 2019 Green Gold to Wild Woodlands; understanding stakeholder visions for woodland expansion in Scotland *Landscape Ecology* **34** 1693–713
- Butt N, Campbell G, Malhi Y, Morecroft M, Fenn K and Thomas M 2009 *Initial Results from Establishment of a Long-term Broadleaf Monitoring Plot at Wytham Woods* (Oxford, United Kingdom: University of Oxford)
- Dadson S J *et al* 2017 A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the UK *Proc. R. Soc. A* **473** 20160706
- Forestry Commission 1994 *The management of semi-natural woodlands: 6. Upland Birchwoods* Forestry Commission 1–28 Forestry Commission Practice Guide, Edinburgh
- Forestry Commission 2017 *The UK Forestry Standard* (Edinburgh: Forestry Commission) 978-0-85538-999-4
- Forestry Statistics 2020 *Forestry Statistics 2020* Forest Research
- Friggens N L, Hester A J, Mitchell R J, Parker T C, Subke J and Wookey P A 2020 Tree planting in organic soils does not result in net carbon sequestration on decadal timescales *Global Change Biol.* **26** 5178–88
- Fuller R and Calladine J 2014 Landscape transition through natural processes: implications for biodiversity of tree regeneration on moorland *Ecology and conservation of birds in upland and alpine habitats: Proceedings of the BOU Annual Conference (University of Leicester, 1-3 April 2014)* ed Davide Scridel (Ibis) 896–900
- Gilbert D and Cosmo L D 2003 Towards restoration of treeline woodland and montane scrub *Botanical Journal of Scotland* **55** 177–87
- Grassi G, House J, Dentener F, Federici S, den Elzen M and Penman J 2017 The key role of forests in meeting climate targets requires science for credible mitigation *Nat. Clim. Change* **7** 220–6

- Griscom B W *et al* 2017 Natural climate solutions *Proc. Natl Acad. Sci.* **114** 11645–50
- Hale K 2015 Long-term carbon storage in a semi-natural British woodland *Ph.D Thesis* University of Liverpool
- Hale K, Spencer M, Peterken G F, Mountford E P and Bradshaw R H W 2019 Rapid carbon accumulation within and unmanaged, mixed, temperate woodland *Scand. J. For. Res.* **34** 208–17
- Jackson B and Wheeler H 2008 The impact of upland land management on flooding: insights from a multiscale experimental and modelling programme *J. Flood Risk Manage.* **1** 71–80
- Matthews K B, Wardell-Johnson D, Miller D, Fitton N, Jones E, Bathgate S, Randle T, Matthews R, Smith P and Perks M 2020 Not seeing the carbon for the trees ? Why area-based targets for establishing new woodlands can limit or underplay their climate change mitigation benefits *Land Use Policy.* **97** 104690
- Morison James, Vanguelova Elena, Broadmeadow Samantha, Perks Mike, Yamulki Sirwan and Randle Tim 2010 *Understanding the GHG Implications of Forestry on Peat Soils in Scotland* Forestry Research 1-55
- Morison J, Matthews R, Miller G, Perks M, Randle T, Vanguelova E, White M and Yamulki S 2012 Understanding the carbon and greenhouse gas balance of forests in Britain, Forestry Commission Research Report, Edinburgh
- Nisbet T and Thomas H 2006 The role of woodland in flood control: a landscape perspective *14th annual IALE(UK) 2006 conference on Water and the Landscape* ed B Davies and S Thompson (Oxford, UK: IALE) 118–25
- O'Neill C, Lim F K S, Edwards D P and Osborne C P 2020 Forest regeneration on European sheep pasture is an economically viable climate change mitigation strategy *Environ. Res. Lett.* **15** 104090
- Ostle N J, Levy P E, Evans C D and Smith P 2009 UK land use and soil carbon sequestration *Land Use Policy* **26** 274–283
- Patenaude G L, Briggs B D J, Milne R, Rowland C S, Dawson T P and Pryor S N 2003 The carbon pool in a British semi-natural woodland *Forestry: An International Journal of Forest Research* **76** 109–19
- Perks M P, Nagy L, Meir P, Auld M, Wood M, Atkinson N, Staples-Scott L, Harvey G, McGhee W and Tipper R 2010 *Carbon sequestration benefits of new native woodland expansion in Scotland* Scottish Forest Alliance
- Peterken G F 1996 *Natural Woodland; Ecology and Conservation in Northern Temperate Regions* (Cambridge: Cambridge University Press) pg 20
- Pollock M L, Milner J M, Waterhouse A, Holland J P and Legg C J 2015 Impacts of livestock in regenerating upland birch woodlands in Scotland *Biological Conservation* **123** 443–52
- Scott M and 2000 *Montane Scrub (Natural Heritage Management Series)* (Perth: Scottish Natural Heritage) 1 85397 103 0
- Scott D, Welch D, Thurlow M and Elston D A 2000 Regeneration of *Pinus sylvestris* in a natural pinewood in NE Scotland following reduction in grazing by *Cervus elaphus* *Forest Ecology and Management* **130** 199–211
- Scridel D, Groom J D and Douglas D J T 2017 Native woodland creation is associated with increase in a Black grouse *Lyrurus tetrix* population *Bird Study* **64** 70–83
- Sing L and Aitkenhead M 2020 Analysis of Land Suitability for Woodland Expansion in Scotland: update 2020 *ClimateXChange, Edinburgh* (<https://doi.org/10.7488/era/494>)
- Sing L, Towers W and Ellis J 2013 Woodland expansion in Scotland: an assessment of the opportunities and constraints using GIS *Scottish Forestry* **67** 18–25
- Speed J D M, Austrheim G, Hester A J and Myserud A 2010 Experimental evidence for herbivore limitation of the treeline *Ecology* **91** 3414–20
- Spracklen B D, Lane J V, Spracklen D V, Williams N and Kunin W E 2013 Regeneration of native broadleaved species on clearfelled conifer plantations in upland Britain *For. Ecol. Manage.* **310** 204–2012
- The Scottish Government 2019 *Scotland's Forestry Strategy 2019-2029* (Edinburgh: The Scottish Government) 978-1-78781-558-2
- Tanentzap A J, Zou J and Coomes D A 2013 Getting the biggest birch for the bang: restoring and expanding upland birchwoods in the Scottish Highlands by managing red deer *Ecology and Evolution* **3** 1890–901
- Thomas H J D, Paterson J S, Metzger M J and Sing L 2015 Towards a research agenda for woodland expansion in Scotland *For. Ecol. Manage.* **349** 149–61
- Towers W, Hall J, Hester A, Malcolm A and Stone D 2004 *The Potential for Native Woodland in Scotland: the Native Woodland Model* (Perth: Scottish Natural Heritage)
- UK Committee on Climate Change (UKCCC) 2020 Reducing emissions in Scotland progress Report to Parliament (<https://www.theccc.org.uk/publication/reducing-emissions-in-scotland-2020-progress-report-to-parliament/>) [Accessed: October 2020]
- UK Committee on Climate Change (UKCCC) 2019 Net Zero Technical Report (<https://www.theccc.org.uk/publication/net-zero-technical-report/>). [Accessed: October 2020]
- Valatin G 2012 Additionality and climate change mitigation by the UK forest sector *Forestry* **85** 446–62
- Ward Thompson C, Aspinall P, Bell S and Findlay C 2005 It gets you away from everyday life: local woodlands and community use—what makes a difference? *Landscape Res* **30** 109–46
- Willoughby I H, Jinks R L and Forster J 2019 Direct seeding of birch, rowan and alder can be a viable technique for the restoration of upland native woodland in the UK *Forestry: An International Journal of Forest Research* **92** 324–38
- Wilson J D, Anderson R, Bailey S, Chetcuti J, Cowie N R, Hancock M H, Quine C P, Russell N, Stephen L and Thompson D B A 2014 Modelling edge effects of mature forest plantations on peatland waders informs landscape-scale conservation *J. Appl. Ecol.* **51** 204–13
- Woodland Expansion Advisory Group 2012 *Report of the Woodland Expansion Advisory Group to the Cabinet Secretary for Rural Affairs and Environment, Richard Lochhead MSP.* (<https://scotland.forestry.gov.uk/images/corporate/pdf/WEAGFinalReport.pdf>) [Accessed: October 2020]