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LETTER

The carbon sequestration potential of Scottish native woodland

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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 Woodland Expansion Advisory Group (WEAG) 2012, Sing et al, estimating that 2.96 million hectares 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 Statistics 2020). Recent analysis by Sing and Atkinnenhead (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.
### Table 1. Definition, area, percentage canopy cover and carbon sequestration values for NWM predicted woodlands types.

| Code  | Definition                                                                 | Area (ha) | Canopy cover % | Carbon sequestration (tC) |
|-------|-----------------------------------------------------------------------------|-----------|----------------|--------------------------|
| Sc5  | Peatland with scattered trees/scrub Mosaic + W4 Birch with purple moor grass and open ground | 489,769   | 10             | 5,147,126                |
| W4/Sc5/W17/W18 | W4 Birch (with open ground) + Sc5 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 + W17/W18 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 Mosaic                                                          | 150,223   | 80             | 12,629,894               |
| W7    | W7 Alder-ash with yellow pimpernel                                         | 134,524   | 80             | 11,310,047               |
| W17/W4/W18 | W17/W18 & W4 Birch (with open ground) Mosaic                             | 126,844   | 63             | 8,331,513                |
| Water | Inland Water                                                               | 111,249   | 0              | 0                        |
| W4/   | W4 Birch (with open ground) + W17/W18 Mosaic                              | 106,998   | 48             | 5,341,270                |
| W17/W18 |                                                                 | 106,539   | 17             | 1,903,401                |
| Sc5/W4  | Peatland with scattered trees/scrub Mosaic + W4 Birch with purple moor grass and open ground | 93,587   | 10             | 983,529                  |
| Sc4  | Scattered Birch /Willow                                                    | 91,135    | 30             | 2,873,285                |
| Sc7  | Mixed montane scrub                                                        | 87,819    | 30             | 2,768,747                |
| Sc3  | Birch/Willow                                                               | 83,618    | 23             | 2,021,168                |
| Sc5/W4/W17/W18  | Peatland with scattered trees/scrub + W4 Birch with purple moor grass and open ground + W17/W18 Mosaic | 75,356 | 80 | 6,335,520 |
| W11/W7 | W11 + W7 Mosaic                                                            | 74,393    | 80             | 6,254,573                |
| W10  | W10 Lowland mixed broadleaved with bluebell/wild hyacinth                  | 67,116    | 80             | 5,662,711                |
| W11/W17 | W11/W17 Mosaic                                                            | 60,324    | 30             | 1,901,903                |
| Sc6  | Basin Bog woodland/scrub                                                    | 53,829    | 80             | 4,525,652                |
| W17  | W17 Upland Oak-Birch with bilberry/blueberry                               | 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 Mosaic                                                             | 42,144    | 80             | 3,543,190                |
| W9/W11 | W9/W11 Mosaic                                                              | 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 Mosaic                                                              | 26,202    | 80             | 2,202,894                |
| W18/W4/Sc5/W17/W18 | W18 + W4 + W17/W18 Mosaic 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 Mosaic                                                              | 18,962    | 80             | 1,594,217                |
| W7/W10 | W7/W10 Mosaic                                                              | 18,591    | 80             | 1,563,033                |
| W10/W8 | W10/W8 Mosaic                                                              | 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             | 529,822                  |
| W4/W18 | W4 + W18 Mosaic                                                            | 5,657     | 48             | 282,387                  |
| W17/W4 | W17 + W4 Mosaic                                                            | 5,470     | 63             | 359,260                  |
| W7/W11 | W7/W11 Mosaic                                                              | 5,040     | 80             | 423,722                  |
| W10/W16 | W10/W16 Mosaic                                                             | 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                   |
In the Potential extent of native woodland section, we determine the extent of 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 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 (≥80% canopy cover) and half of the woodland area (1.9 Mha) consists of open woodland and scattered trees (≤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). Aforestation 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 (Scriel et al 2017), reduce flooding through increasing water use and infiltration and slowing overland flow (Nisbet and Thomas 2006, Jackson and Wheater 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 Mt 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.

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Data availability statement

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

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References

Albon S D, McLeod J, Potts J, Brewer M, Irvine J, Towers M, Elston D, Fraser D and Irvine R 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 90 371–45

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 Wookesy 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 (Ibus) 896–903

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
Griscob 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 Wheater 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, Fitchen 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 104090
Morison James, Vanguelova Elena, Broadmadow 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 Woodlands; 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 I and Atkinson 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 Mysterud 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 cleftfelled 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]
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, Links 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 92 324–36
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]