Forest Research

Carbon balance of Northern Ireland Forest Service forest on deep peat

Forest Research Report, March 2021

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The Research Agency of the
Forestry Commission

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Summary

- This report includes a scoping review of the updated evidence of greenhouse gas (GHG) fluxes from deep peats and organo-mineral (OM) forest soils.
- The review suggest that CO_2 effluxes are higher from OM soils than deep peat or organic (as expected) for both UK and European/worldwide.
- Although there is a wide variation in estimated CH_4 emissions in the literature, the median estimates are higher from peat than OM soils.
- N_2O emission rates seem to be higher from OM than deep peat for UK but the trend is not clear for studies from Europe and worldwide due to the much larger variation observed.
- The GHG review confirms that fluxes are a very small fraction of the large store of carbon in deep peat, which demonstrates the sensitive balance between the soil and atmosphere where small changes in the soil/peat system can lead to large GHG fluxes.
- This report includes calculations of current carbon storage in forest biomass, deep peat soils, upper litter and fermentation layers and deadwood under Sitka spruce, lodgepole pine and native broadleaves in Forest Service managed forest in Northern Ireland.
- The results suggest that the total area of the NI Forest Service **forest on deep peat is 24,988 ha** of which the largest proportion of 83% is planted with Sitka spruce and 12% with lodgepole pine. The remaining 5 % represents all other species including native broadleaves of which the most common are birch (0.7%), willow (0.5%) and rowan (0.3%).
- The highest carbon stocks (kt C) are located in deep peats under Sitka spruce forest (**11,181 ±914 kt C in 0-100cm peat depth)**, followed by lodgepole pine (**1566 ±128 kt C)** and much lower carbon stocks are in deep peats under Scots pine (**75 ±6 kt C)**, birch (**95 ±8 kt C)**, willow (**61 ±5 kt C)**, rowan (**42 ±3 kt C)** and in general under the native broadleaved species (**254 kt C**) which is related to the area afforested with these tree species in NI.

- The estimated carbon stock in litter and fermentation layers followed the same rank order across tree species as the carbon stock in deep peat soils. Total carbon of both L+H layers under Sitka spruce is **~260 kt C and** under lodgepole pine is **40 kt** while a total store of **~6 kt C** are under native broadleaved species on deep peat.
- Overall, the deadwood carbon store makes a small proportion of all forest carbon on NI Forest Service forest estate, total under Sitka spruce is **~100 kt C,** lodgepole pine is **15 kt C** and native broadleaves is **1.7 kt C.**
- Current total carbon in Sitka biomass growing on deep peat is **2940 kt C** with potential to achieving a total of **3810 kt C** if it reaches the same YC at felling age of 50.
- Current Sitka spruce area distributed by Yield Class (YC) show that nearly as 60% Sitka spruce is in YC 14 and YC16, with 17% in YC12 and 10% in YC18.
- Current total carbon in lodgepole pine biomass growing on deep peat is **423 kt C**, while total carbon stocks in the three mostly distributed native broadleaves are **21kt C** in birch, **12kt C** in willow and **8kt C** in rowan.
- The overall carbon balance of forest on deep peat in NI Forest Service estate is **16348 kt C assuming an average peat depth of 1 metre**. The above and belowground carbon partitioning suggest that 70% of total forest carbon is stored in the deep peat soils for conifers and up to 80% in native broadleaved species.
- Replanting scenarios suggests that replanting deep peats with Sitka spruce using trench mounding as ground preparation, can deliver positive carbon benefits if the second rotation stand grows at YC10 or higher.
- Leaving the site for natural regeneration can deliver a positive carbon balance depending on the species density (trees per ha). Leaving the site for natural regeneration without any ground disturbance is likely to deliver a higher carbon balance compare to when some form of disturbance is applied such as patch scarification.

Contents

I- Carbon stocks in peat soils, humus layers and deadwood

- *1-Forest area on deep peat*
- *2-Soil carbon stocks*
- *3-Carbon stocks of humus layer (litter and fermentation layers)*
- *4-Carbon stocks of deadwood*

II- Carbon in forest biomass of main forest species on deep peat soils

III- Above and below carbon balance of forestry on deep peat soils in NI Forest Service

IV- Review of soil GHG fluxes from afforested land on deep peat and organo-mineral soils.

V- Future questions and recommendations

VI – Acknowledgements

VII – References

Appendix

I. Carbon stocks in peat soils, humus layers and deadwood

This report includes the calculations of carbon storage in peat soils, their upper litter and fermentation layers and deadwood under Sitka spruce, lodgepole pine and native broadleaved species in Forest Service managed forest in Northern Ireland.

1. Forest area on deep peat

Forest Services supplied Forest Research with spatial data for the sub-compartment database of the Forest Service managed forest in Northern Ireland, and an extract of the national soil map for the deep Peat. The Peat layer was used to clip the Forest Service managed forest in Northern Ireland to represent the afforested peat.

The sub-compartment database includes information of the area, elevation, species mix, planting year of every sub-compartment in the Forest Service forests (data set dated October 2020). In mixed stands, the data set attribute table has an area as per component percentage for each species and YC information for the primary and secondary components. The dataset was used to determine the extent of afforested peat. The elevation, species, age and yield class information were used to characterise and tabulate the component structure of the afforested peat.

Using the following fields:

- Total SCArea: actual sub compartment area
- ARF: area reduction factor (value 0.05 indicates tree canopy = 95% SCArea)
- In mixed species stands the primary species was assumed to occupy 70% of the sub-compartment area and the secondary species 30% with any additional species ignored, for example in SS/SP/WIL, SS=70%, SP=30% and WIL=0%.

The calculated combined areas for each species are presented in **Table 1**.

The results suggest that total area of the NI Forest Services forest on deep peat is 24,988 ha of which the largest proportion of 83% is planted with Sitka spruce and 12% with lodgepole pine with the rest 5 % left for all other species including native broadleaved species of which top three most distributed are birch with 0.7%, willow with 0.5% and rowan with 0.3% of total afforested area on deep peat.

Table 1. Extent of different tree species growing on deep peat in the Forest Service forest NI. Combined areas of single species stands with species-specific areas when primary and secondary species in mixed species sub-compartments.

Tree species	Total area (ha)	% of total area
Sitka Spruce	20,744.270	83.018
Lodgepole Pine	2,904.503	11.624
Norway Spruce	247.602	0.991
Birch	175.948	0.704
Japanese Larch	150.309	0.602
Scots Pine	138.553	0.554
Willow	113.603	0.455
Scrub	99.090	0.397
Rowan	77.441	0.310
Alder (Grey)	40.513	0.162
Oak	38.117	0.153
Broadleaf Mixture	33.724	0.135
Ash	32.862	0.132
Alder	32.711	0.131
Hybrid Larch	31.167	0.125
Noble Fir	21.351	0.085
Beech	16.654	0.067
Sycamore	12.890	0.052
Poplar	12.813	0.051
Minor Conifer	10.569	0.042
White Spruce	9.856	0.039
Serbian Spruce	8.158	0.033
Holly	5.416	0.022
European Larch	4.469	0.018
Hazel	3.967	0.016
Grand Fir	3.136	0.013
Mixed Con / Hwd	2.661	0.011
Lawson Cypress	2.354	0.009
Gean	2.277	0.009
Aspen Poplar	2.008	0.008
Whitebeam	1.832	0.007
Western Hemlock	1.420	0.006
Thorn	1.166	0.005
Corsican Pine	1.106	0.004
Western White Pine	1.044	0.004
Douglas Fir	0.413	0.002
Minor Broadleaf	0.400	0.002
Red Oak	0.370	0.001
Monterey Pine	0.337	0.001
Colorado White Fir	0.230	0.001
Horse Chestnut	0.219	0.001
Norway Maple	0.162	0.001
Western Red Cedar	0.020	0.000
ELM	0.004	0.000
Grand total	**24,987.715**	**100**

2. *Soil carbon stocks*

Soil C stocks densities in t C/ha were calculated from the measured soil datasets of the BioSoil survey on 166 plots across GB, of which only 14 were on deep peat (Vanguelova et al., 2013) and used to calculate total carbon stocks using the areas for each tree species shown in Table 1. The BioSoil data for deep peat soil carbon stocks (t C/ha) down to 1m soil depth were also separated for each peat depths (0-5, 5-10, 10-20, 20-40, 40-80, 80-100cm, **Figure 1**) and the variability at different depths used to calculate the variability of peat C stocks for each main tree species The key assumption is that the data derived from this GB survey is representative of soil C stocks on deep peat in the NI Forest Service forests.

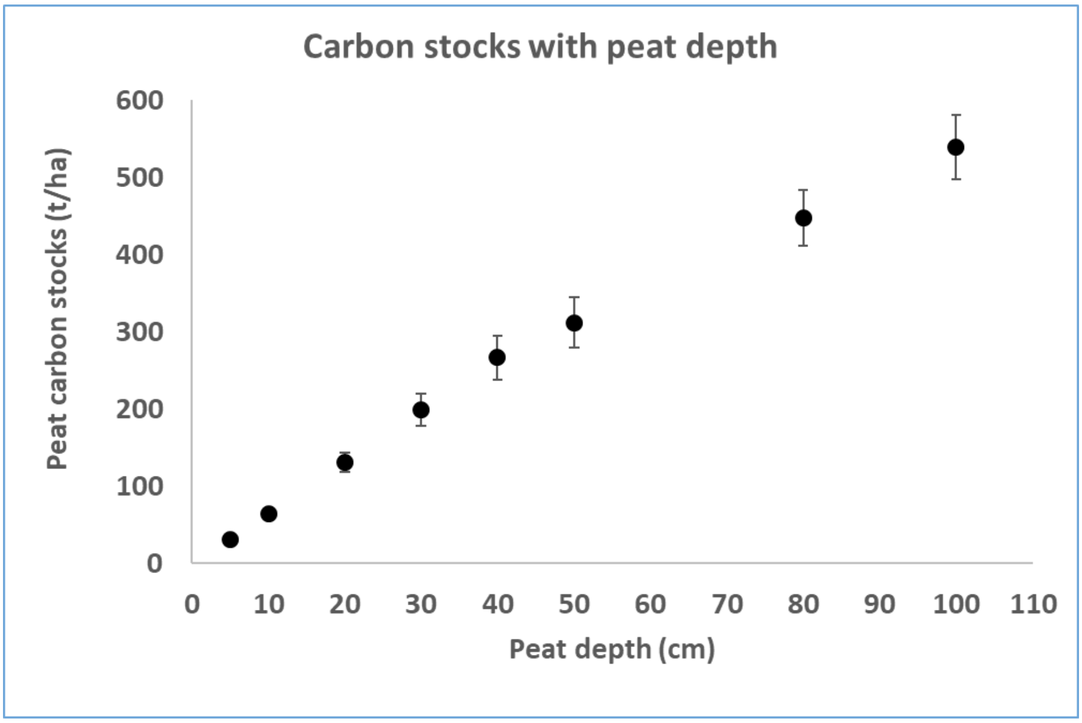


Figure 1. Carbon stocks (t C ha^{-1}) in different deep peat depths measured in the BioSoil survey (Vanguelova et al., 2013). Mean values are represented with black dots and standard errors of the mean are represented with vertical bars.

Figure 1 shows that up to 40 cm depth peat C stocks increase almost linearly with increasing peat depth, while peat carbon stocks decrease proportionally with peat depth deeper than 40 cm. The reason for this non-linear increase in peat carbon stocks with depth is due to peat water content and bulk density. Peat carbon stocks are calculated using peat carbon concentration, peat density and peat depth. The shallow peaty layer contains less water and is of slightly higher density compared to lower depths which are almost always water saturated and less dense (Vanguelova et al., 2013, Vanguelova et al., 2016, **Figure 2).**

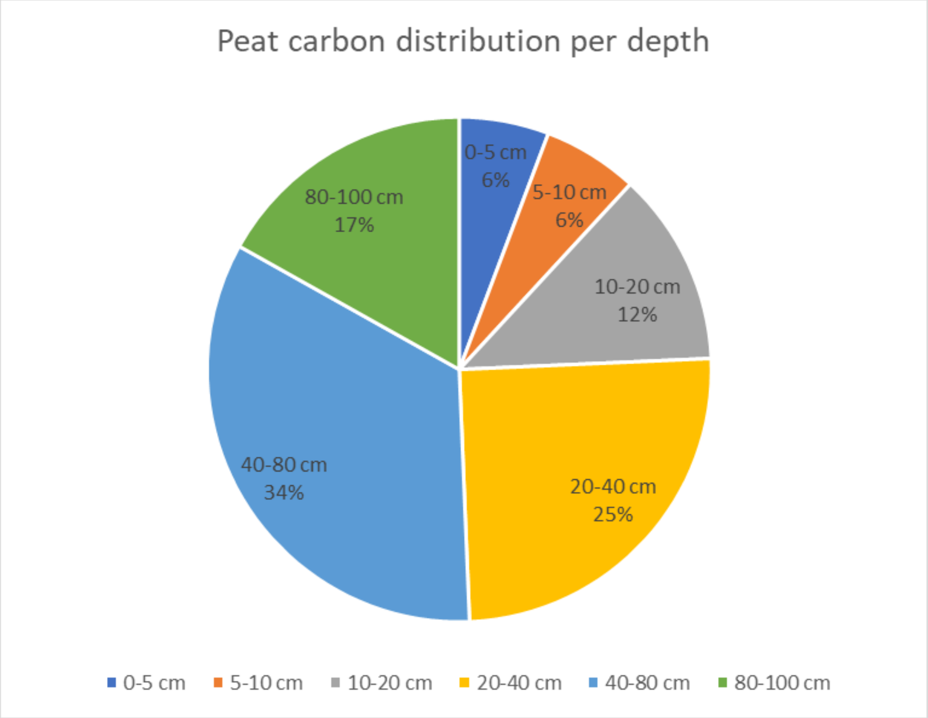


Figure 2. Peat carbon stock distribution per peat depth.

Total carbon stocks in peat soils and their variability under Sitka spruce, lodgepole pine, Scots pine, birch, willow and rowan and total native broadleaves are shown in **Figures 3 and 4**. Native broadleaf species-specific peat carbon stocks are shown in **Table 2.** Total carbon stocks in litter (L) and fermentation layer (F) and in both layers (L+F) under Sitka spruce and lodgepole pine are shown in Figure 5 and under native broadleaves in Figure 11. Native broadleaf species-specific L, F and L+F carbon stocks are shown in **Table 3**. Total carbon stocks in lying, standing deadwood and stumps under Sitka spruce and lodgepole pine are shown in Figure 12 and under native broadleaved in Figure 13. Native broadleaf species-specific deadwood stocks are shown in Table 4.

The results show that the highest carbon stocks are located in deep peats under Sitka spruce forest (**11,181 ±914 kt C in 0-100cm peat depth, Figure 3a)**, followed by lodgepole pine forest (**1566 ±128 kt C, Figure 3b)** and much smaller carbon stocks are located in deep peats under Scots pine (**75 ±6 kt C, Figure 2a)**, birch (**95 ±8 kt C, Figure 2b)**, willow (**61 ±5 kt C, Figure 2c)**, rowan (**42 ±3 kt C Figure 2d)** and in general in total under the native broadleaved species (**254 kt C Figure 2e**) which is related to the area afforested with these tree species in NI. From the native broadleaved species, peats under birch have highest carbon storage followed by willow>rowan>oak>ash. The reported figures of deep peat carbon stocks are based on the assumption that peat depth in the NI Forest Service estate is on average 1m. The soil mapping is based on all soils with peat layer depth of >50 cm depth, so there will be forest on peats shallower than 1m depth and some areas on deep peat of >1m depth. This is an important uncertainty which can only be quantified by ground truthing of measuring peat depth. The data in Figure 1 provide peat carbon stocks per depth so if local or regional knowledge is available on peat depth, then peat carbon stocks can be calculated for the specific depth and uncertainties in these estimates reduced.

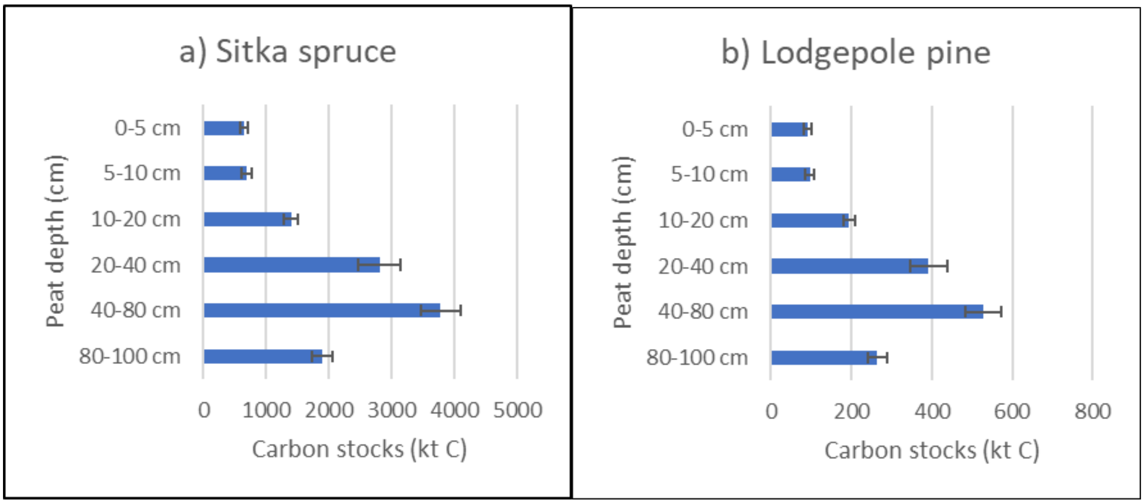
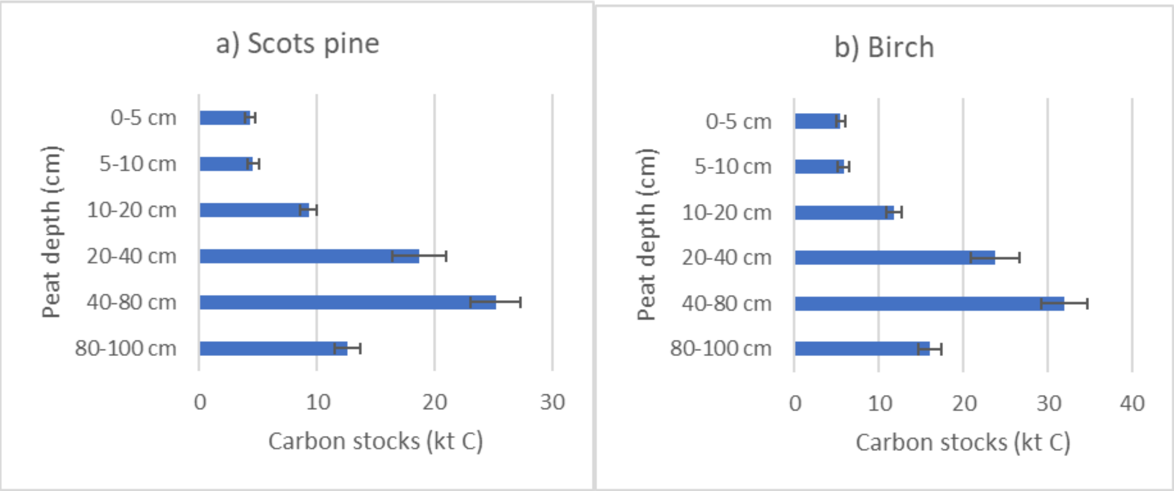


Figure 3. Total carbon stocks (kt C) at different depths in deep peat soil under a) Sitka spruce, b) lodgepole pine. Note the difference in x-axis scales. Variability of total carbon stocks are calculated based on variability of peat carbon stocks for each depth. The total carbon stocks for the full **0-100 cm peat depth are 11,181 (±914) kt C,** and **1566 (±128) kt C, respectively**. *1 kilotonnes (kt C) of C= 1000 tonnes (t C) of C.*



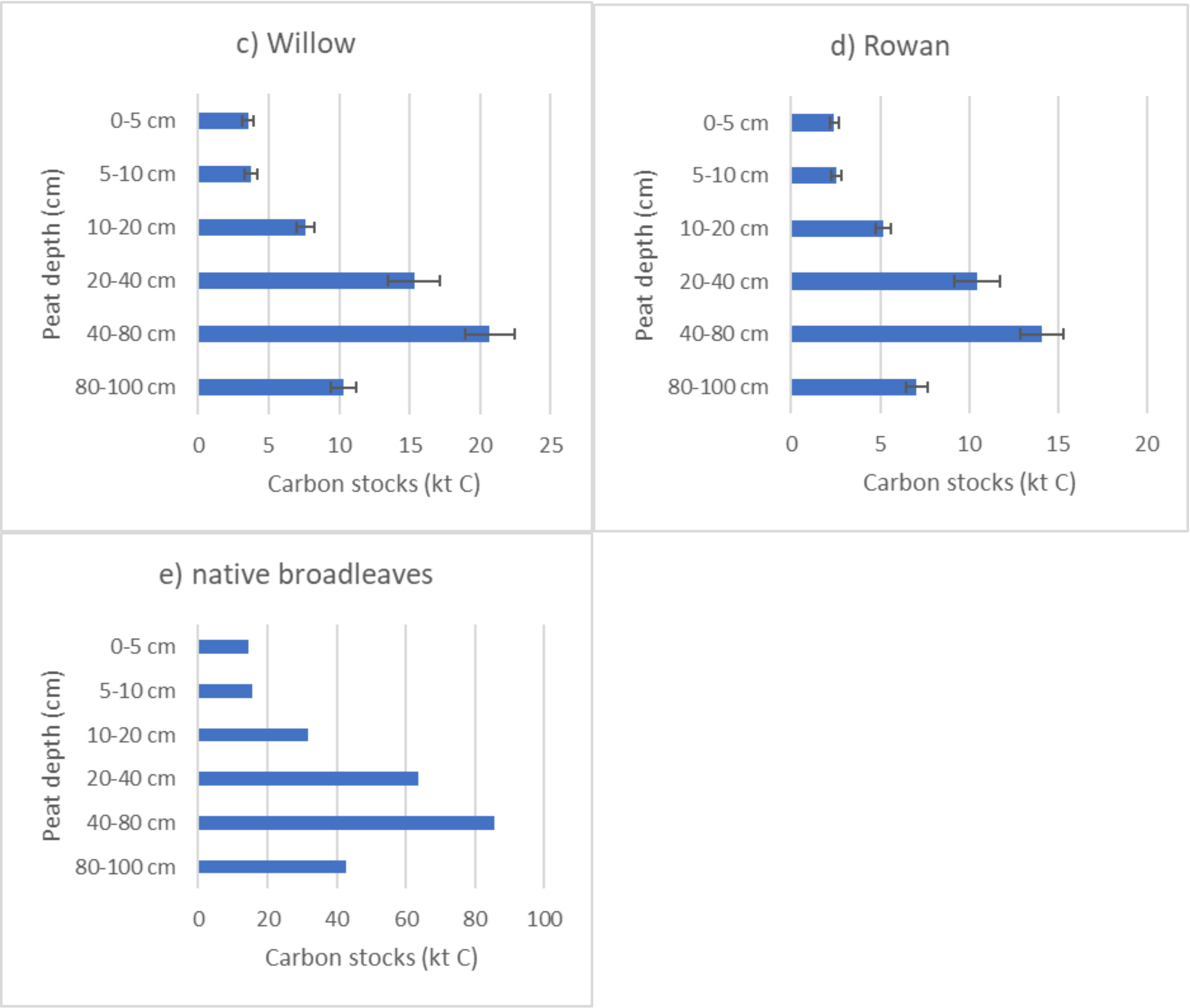


Figure 4. Total carbon stocks (kt C) at different depths in deep peat soil under a) Scots pine, b) birch, c) willow, d) rowan and e) all native broadleaved species. Variability of total carbon stocks are calculated based on variability of peat carbon stocks for each depth. The total carbon stocks for the full **0-100 cm peat depth are 75 (±6) kt C, 95 (±8) kt C**. **61 (±5) kt C, 42 (±3) kt C** and **254 kt C**, respectively.

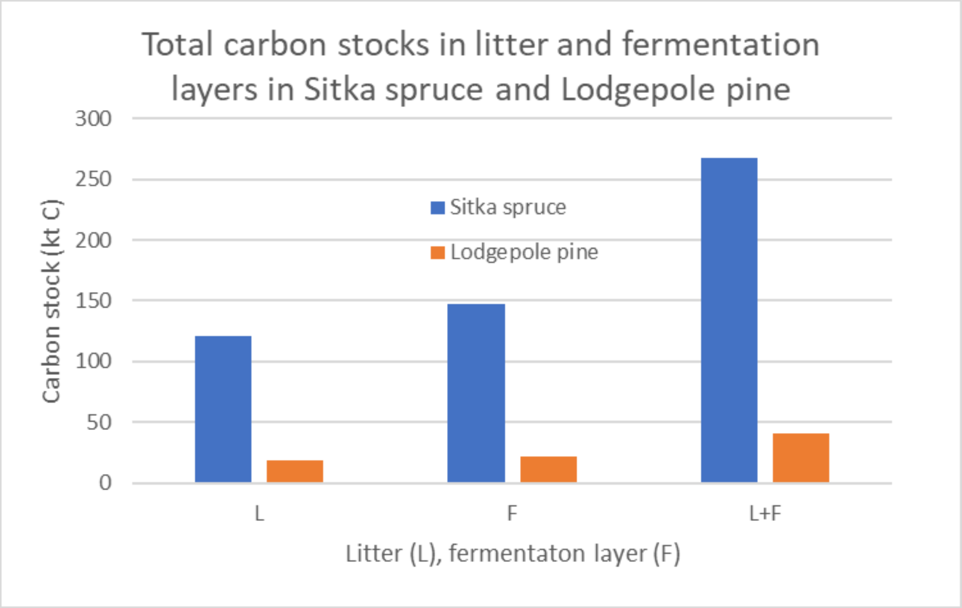
Table 2. Carbon stocks in deep peats under different native broadleaved species in NI Forest Service forest. The stocks are presented per peat depth and total for the top 1m of peat. *1 kilotonnes (kt C) of C= 1000 tonnes (t C) of C.*

Native broadleaves	0-5 cm kt C	5-10 cm kt C	10-20 cm kt C	20-40 cm kt C	40-80 cm kt C	80-100 cm kt C	Total 0-100cm kt C
Birch (BI)	**5.45**	**5.81**	**11.79**	**23.75**	**32.02**	**16.01**	**94.84**
Willow (WIL)	**3.52**	**3.75**	**7.61**	**15.34**	**20.68**	**10.34**	**61.23**
Rowan (RO)	**2.40**	**2.56**	**5.19**	**10.45**	**14.09**	**7.05**	**41.74**
Oak (OAK)	**1.18**	**1.26**	**2.55**	**5.15**	**6.94**	**3.47**	**20.55**
Ash (ASH)	**1.02**	**1.08**	**2.20**	**4.44**	**5.98**	**2.99**	**17.71**
Poplar (POP)	**0.40**	**0.42**	**0.86**	**1.73**	**2.33**	**1.17**	**6.91**
Holly (HO)	**0.17**	**0.18**	**0.36**	**0.73**	**0.99**	**0.49**	**2.92**
Elm (EL)	**0.14**	**0.15**	**0.30**	**0.60**	**0.81**	**0.41**	**2.41**
Hazel (HA)	**0.12**	**0.13**	**0.27**	**0.54**	**0.72**	**0.36**	**2.14**
Gean (GN)	**0.07**	**0.08**	**0.15**	**0.31**	**0.41**	**0.21**	**1.23**
Aspen Poplar (ASP)	**0.06**	**0.07**	**0.13**	**0.27**	**0.37**	**0.18**	**1.08**
Whitebean (WHB)	**0.06**	**0.06**	**0.12**	**0.25**	**0.33**	**0.17**	**0.99**
Total	**14.59**	**15.53**	**31.54**	**63.55**	**85.68**	**42.84**	**253.74**

3. *Carbon stocks of humus layer (litter and fermentation layers)*

Carbon stocks in litter and fermentation layers (L and F layers) (t C/ha) were estimated based on the extensive survey dataset of BioSoil (Vanguelova et al., 2013) and areas for each tree species from **Table 1**. Using carbon stocks in litter and fermentation layers (t C/ha) under conifers and broadleaved forest and area (ha) to calculate and scale up total carbon in litter and fermentation layers under both broadleaves and conifer forests. Total carbon stocks in litter (L) and fermentation layer (F) and in both layers (L+F) under Sitka spruce and lodgepole pine and under native broadleaves are shown in **Figure 5**. Native broadleaf species-specific L, F and L+F carbon stocks are shown in **Table 3**.

The carbon storage in litter and fermentation layers follows the same rank order between tree species as the carbon storage in deep peat soils. Total carbon of combined L+H layers under Sitka spruce is ~260ktC and under lodgepole pine is 40 kT C (**Figure 5**) and under native broadleaved species ~6 kT C (**Table 3**). The carbon store in L and F layers are similar. The L layer is often considered as a component of the above-ground biomass, while the F layer is accounted as belowground carbon. Although the total carbon stocks of F layer (150kt C) under Sitka spruce are a small proportion of the carbon stored in the deep peats underneath (11182 kt C), it is an important element to be quantified and taken into account. Evidence from recent chronosequence studies and repeat soil surveys (Vanguelova et al., 2019, Rasaiskaite et al., 2020), indicate the rate of accumulation of the humus layer under Sitka spruce and wider conifer plantations is on average 0.6 t C/ha/y. Thus, these inputs of carbon generated by tree litter and roots need to be taken into account when calculating changes of soil carbon due to afforestation. It should also be noted that the carbon stored in litter and humus litter is sensitive to ground disturbance due to planting, thinning and clearfelling, although some research evidence has shown that burying the humus layer due to ground preparation for restocking potentially store more stable carbon with soil depth (Swain et al., 2010).



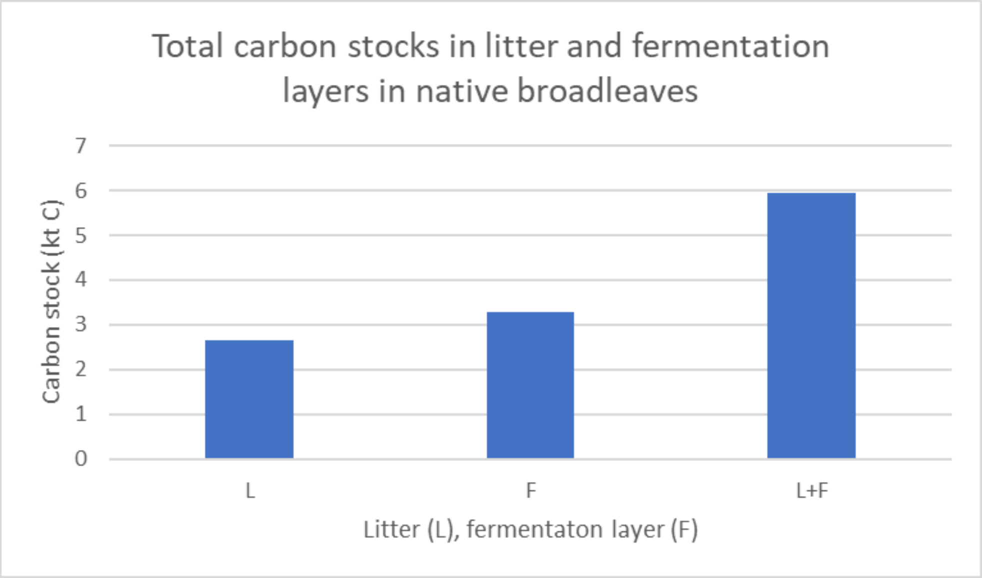


Figure 5. Total carbon stocks (kt C) in litter (L) and fermentation layer (F) and total of both layers (L+F) under a) Sitka spruce and lodgepole pine and b) native broadleaves on deep peat areas of NI Forest Service forest.

Table 3. Carbon stocks in litter (L) and fermentation layer (F) and in both layers (L+F) under different native broadleaved species on deep peat in NI Forest Service forest. *1 kilotonnes (kt C) of C= 1000 tonnes (t C) of C.*

Native broadleaves	L kt C	F kt C	L+F kt C
Birch (BI)	0.954	1.177	2.132
Willow (WIL)	0.722	0.891	1.614
Rowan (RO)	0.355	0.438	0.793
Oak (OAK)	0.243	0.300	0.544
Ash (ASH)	0.195	0.241	0.436
Poplar (POP)	0.098	0.121	0.218
Holly (HO)	0.036	0.044	0.080
Elm (EL)	0.021	0.026	0.047
Hazel (HA)	0.011	0.014	0.025
Whitebean (WHB)	0.009	0.011	0.020
Gean (GN)	0.006	0.007	0.013
Aspen Poplar (ASP)	0.005	0.006	0.010
Total	**2.655**	**3.276**	**5.931**

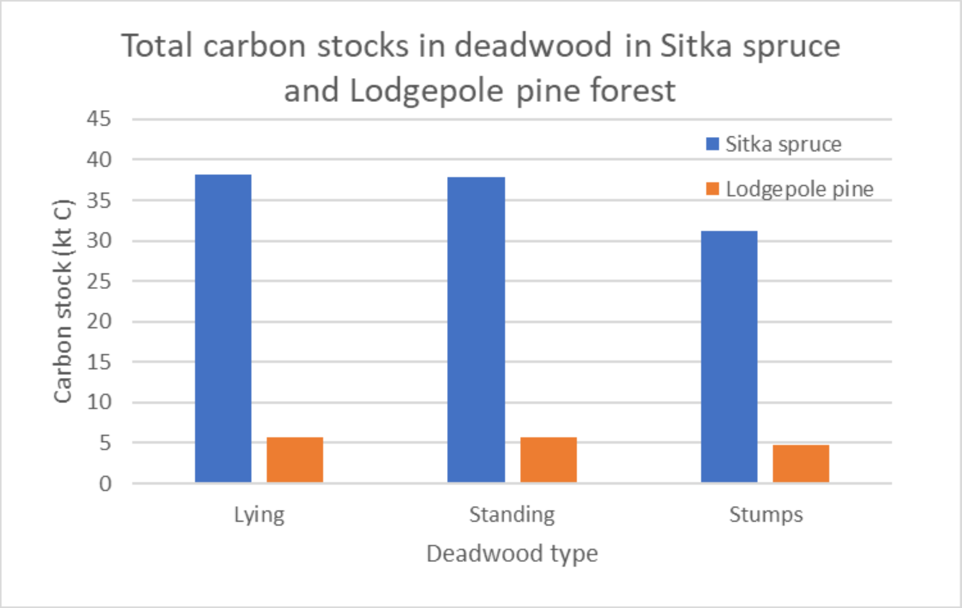
4. *Carbon stocks of deadwood*

Carbon stocks in deadwood (t C/ha) for conifers and broadleaves were estimated using a new database compiled from extensive surveys (NFI (Struther et al., *in preparation*) and BioSoil (Vanguelova, Moffat, Morison *in preparation*)). Using carbon stocks in deadwood (t C/ha) under conifers and broadleaf forests across all soil type and species areas (ha) presented in **Table 1,** the total carbon storage in deadwood was estimated for the forest on deep peat in NI Forest Services. Total carbon stocks in lying, standing deadwood and stumps under Sitka spruce, lodgepole pine and under native broadleaved in **Figure 6**. Native broadleaf species-specific deadwood stocks are shown in **Table 4.**

The carbon storage in deadwood follows the same rank of order between tree species as the carbon storage in deep peat soils. The estimated deadwood carbon stock is similar between lying, standing and stumps for Sitka spruce and lodgepole pine (Figure 6a), while lying deadwood makes a larger proportion of carbon stock under native broadleaved species. This difference arises from the deadwood volume data from the NFI and BioSoil surveys, which should reflect the more intensive management of conifer compared to broadleaved species. The conifer plantations on deep peat in NI are less managed than conifer plantations on other soil types, thus the true proportion of deadwood in different categories (lying, standing and stumps) for the conifers may follow more the deadwood proportion of distribution of broadleaf species.

However, deadwood in cool and wet climate and in wet deep peat is likely to decompose slowly and due to the high water table conditions and thus some of the deadwood carbon could become part of the peat carbon.

Overall, the deadwood carbon stock makes a small proportion of all forest carbon. For example, the total under Sitka spruce is ~100 kt C compared to 260 kt C in L and F layers, 11,182 kt C in deep peat to 1 m depth and ~2900 kt C in aboveground Sitka spruce biomass.



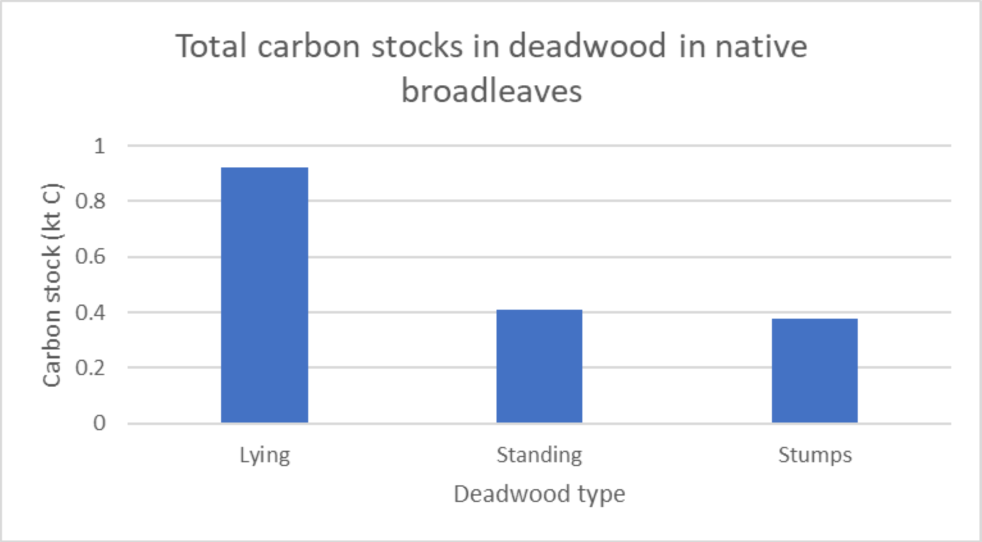


Figure 6. Total carbon stocks (kt C) in deadwood types in Forest Service forest in NI on deep peat under a) Sitka spruce and b) native broadleaves.

Table 4. Carbon stocks in lying, standing deadwood and stumps under different native broadleaved species in NI Forest Service forest on deep peat.

Native broadleaves	Lying deadwood kt C	Standing deadwood kt C	Stumps kt C
Birch (BI)	0.332	0.147	0.135
Willow (WIL)	0.251	0.112	0.102
Rowan (RO)	0.124	0.055	0.050
Oak (OAK)	0.085	0.038	0.034
Ash (ASH)	0.068	0.030	0.028
Poplar (POP)	0.034	0.015	0.014
Holly (HO)	0.012	0.006	0.005
Elm (EL)	0.007	0.003	0.003
Hazel (HA)	0.004	0.002	0.002
Whitebean (WHB)	0.003	0.001	0.001
Gean (GN)	0.002	0.001	0.001
Aspen Poplar (ASP)	0.002	0.001	0.001
Total	**0.924**	**0.410**	**0.376**

II. Carbon in forest biomass of main forest species on deep peat soils

The estimation of biomasses was carried out using a sequence of programs used in generating the Woodland Carbon Code tables (Randle and Jenkins, 2011). Recent developments towards revising the tables have been undertaken and later models were used in the presentation of results here. Firstly, mensurational values were created (similar to yield tables), accounting for 'standard spacing' and management; these values were then used as inputs to a biomass calculation program (Matthews and Duckworth 2005; Randle *et al.*, 2014), which calculates biomass values for the components of roots, stump, roundwood, sawlogs, tips/tops, branches and foliage. Such relationships are only available for a limited number of species so 'mapping' of species to others with similar characteristics is necessary (for example, the broadleaves of birch, willow and rowan were modelled as sycamore). Finally, a further program was used which removes data discontinuities and derives values for early growth, ensuring the sum of the components is consistent with the total of the whole. For Sitka spruce and lodgepole pine modelled biomass from a 'no thinned' management regime was used (conifer plantation on deep peat are not thinned in NI) and for the native broadleaves using 1500 tree per ha for current broadleaves on deep peat. To represent the natural regeneration broadleaves, tree density on average of 300 trees/ha was used, e.g. scaled to 20% canopy cover. Carbon in biomass was calculated on the basis of 50% C in biomass and scaled up using species mapped area on deep peat from **Table 1**.

The Sitka spruce occupies the largest area on deep peat soils in the NI Forest Services estate (e.g. 83% of total forest on deep peat, **Table 1**). The current Sitka spruce area distributed by Yield Class (YC, **Figure 7)** shows that nearly as 60% Sitka spruce is in YC 14 and YC16, with 17% in YC12 and 10% in YC18. The total amount of carbon in biomass follows the same pattern (**Figure 8**). Carbon in biomass partitioned between different above-ground components (**Figure 9**) shows that as expected the largest component of 60% of carbon in stored in Sitka spruce stems (including round wood, saw wood, stem tips), followed by coarse roots (23%), branches (11%), foliage (5%) and stumps (1%). This partitioning is important to account for when calculations are made about carbon storage and lifespan of carbon in end products. In NI, brash made of branches and foliage is usually left on the site after clear-felling, so although slowly, part of this carbon will be incorporated into the soil with time. In addition, Sitka spruce needles make a fast decomposing input to soils and can contribute up to 70% of nutrient input to soil compare to other biomass parts (Vanguelova and Nisbet, SLA report for FLS, 2021), so it is an important carbon input to soils. Current total carbon in Sitka biomass growing on deep peat is **2940 kt C** (**Figure 8)** compared to total of **3810 kt C** if it remains the same YC at felling age of 40 (**Figure 10**).

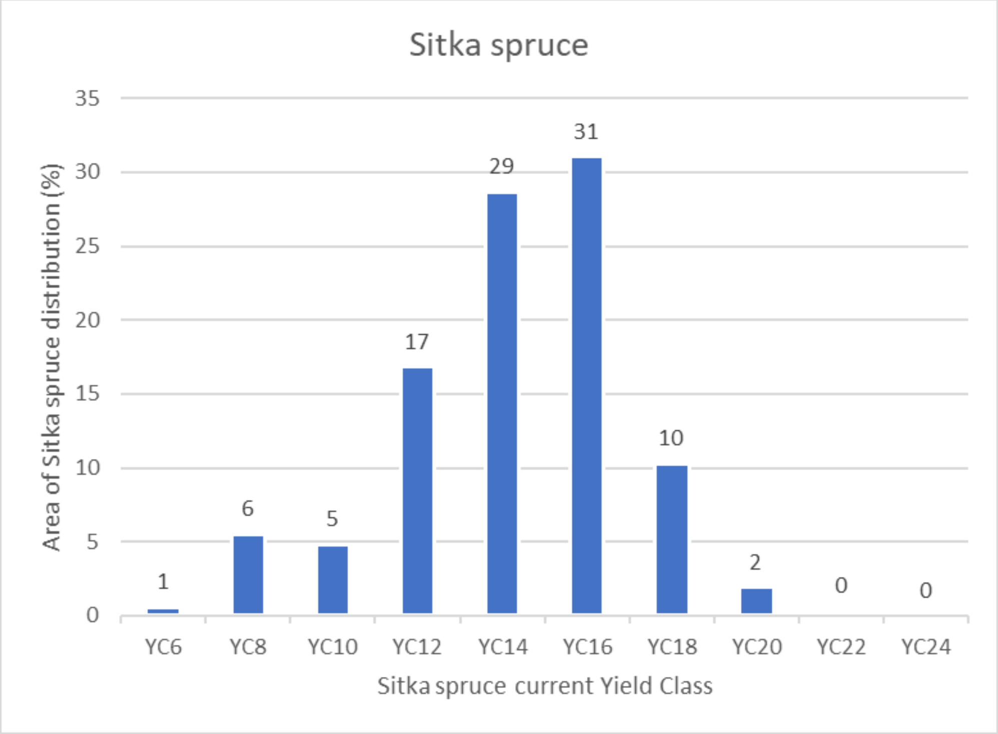


Figure 7. Current area of Sitka spruce on deep peat distribution across different Yield Classes (YC). Bars are total area and numbers indicated percentage in each YC from total area.

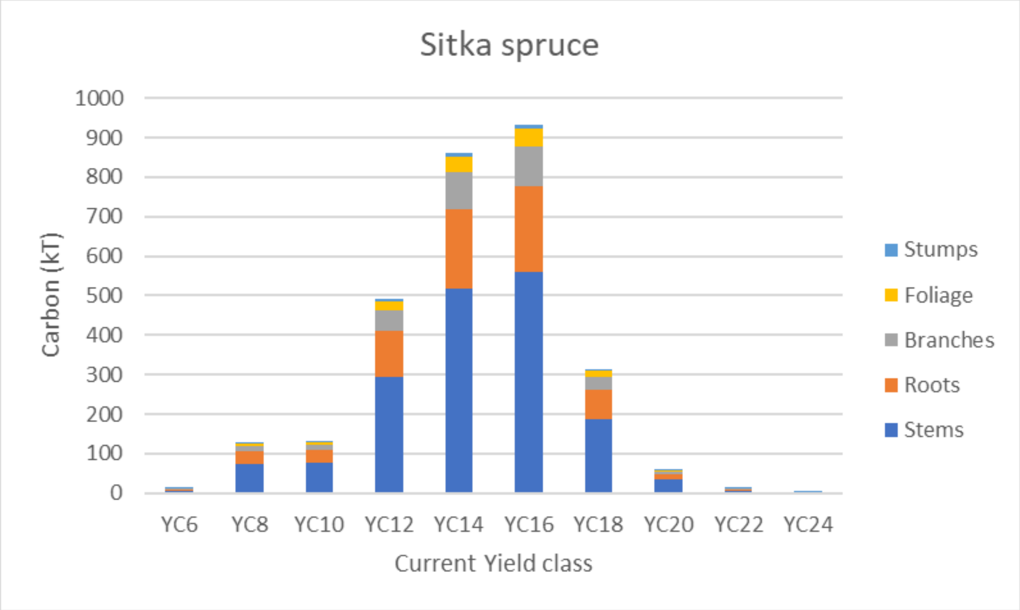


Figure 8. Total carbon stocks (**2940kt C**) in Sitka spruce biomass on deep peat in NI Forest Service. Carbon in biomass was also partitioned between stems (include round wood, sawlog and stems tips), coarse roots, stumps, branches and foliage and shown in different colours.

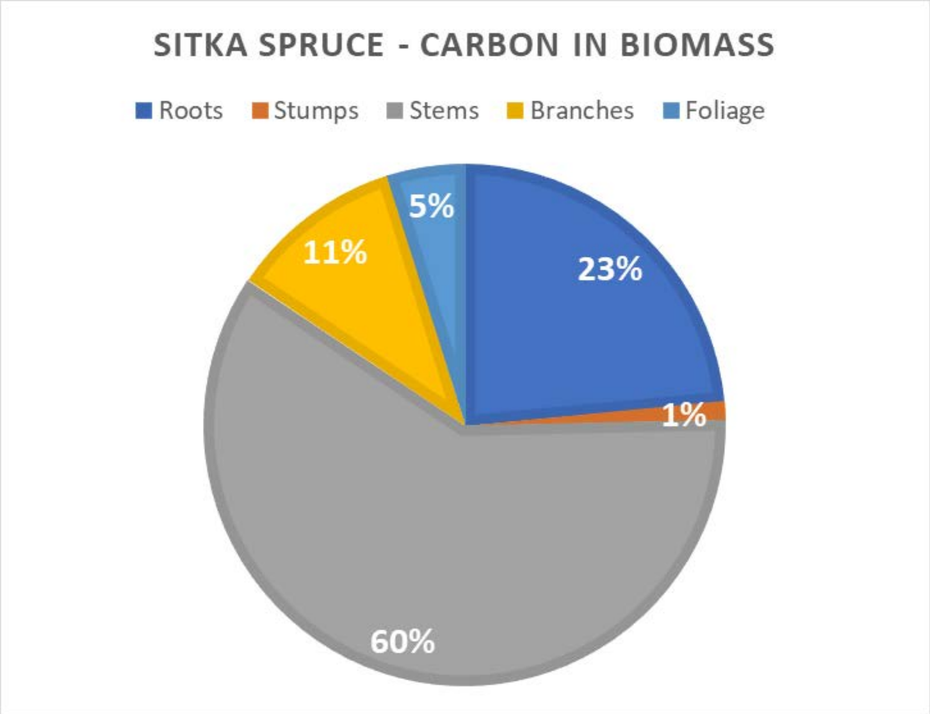


Figure 9. Percentage of carbon in Sitka spruce biomass partitioned between stems (include round wood, sawlog and stems tips), coarse roots, stumps, branches and foliage and shown in different colours.

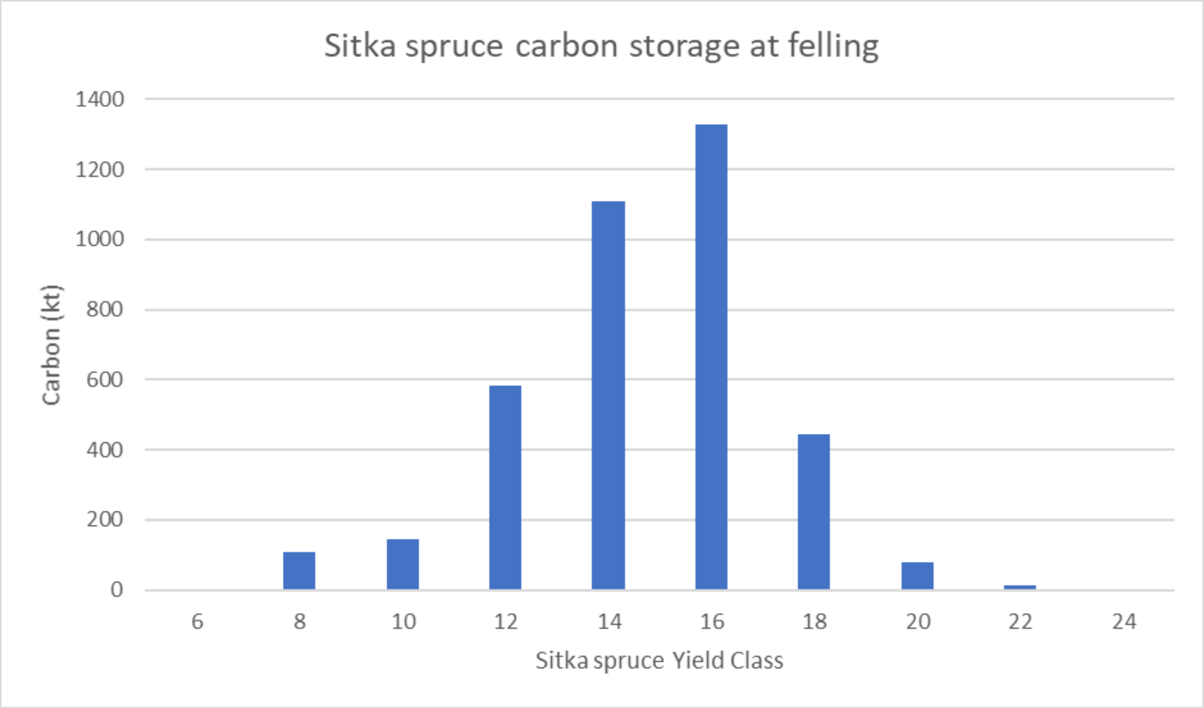


Figure 10. Partitioned total carbon stocks (**3810 kt C)** in Sitka spruce biomass on deep peat in NI Forest Service forests at clear fell age of 40 years per Yield Class.

Lodgepole pine occupies the second largest area on deep peat soils in the NI Forest Services estate (e.g. 12% of total forest on deep peat, Table 1). The current lodgepole pine area distributed by Yield Class (YC) reported in **Figure 11** shows that nearly 95% is below YC12, with 40% in YC 8 and 18 and 22% in YC 6 and YC10, respectively. The total carbon stock in biomass follows the same pattern (**Figure 12**). Carbon in biomass partition between different aboveground components shown in **Figure 13** that as expected the largest component of 63% of carbon in stored in lodgepole pine stems (including round wood, sawlog, stem tips), followed by coarse roots (18%), branches (12%), foliage (5%) and stumps (2%). Current total carbon in lodgepole pine growing on deep peat is **423 kt C** (**Figure 12**).

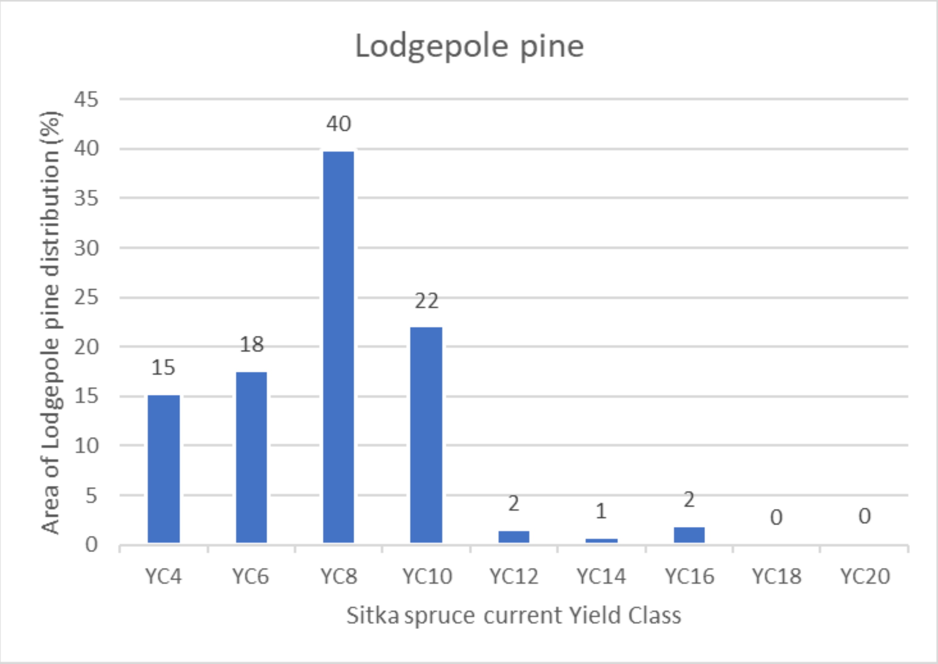


Figure 11. Current area of lodgepole pine on deep peat distribution across different Yield Classes (YC). Bars are total area and numbers indicated percentage in each YC from total area.

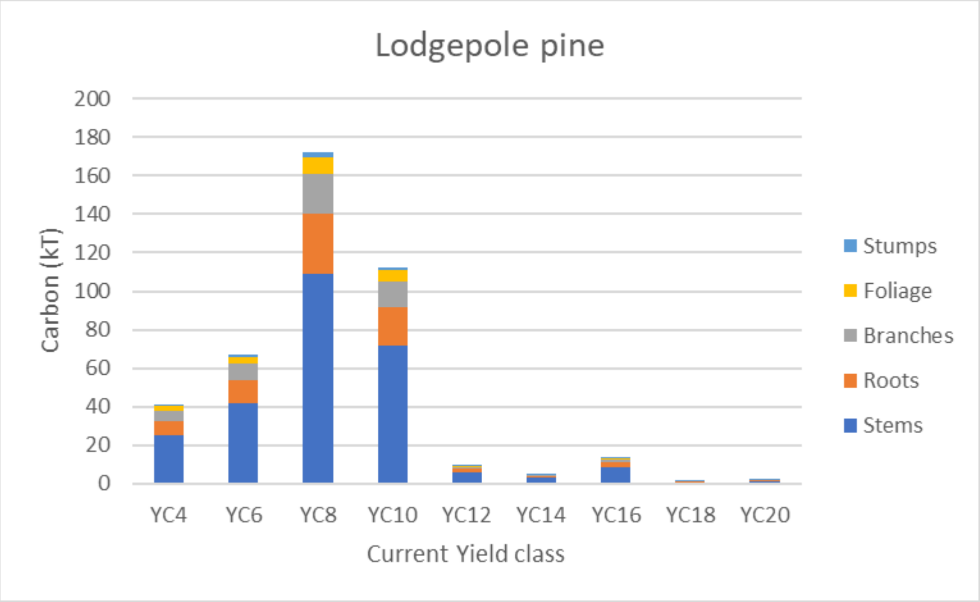


Figure 12. Total carbon stocks (**423kt C**) in lodgepole pine biomass on deep peat in NI Forest Services. Carbon in biomass was also partitioned between stems (include round wood, sawlog and stems tips), coarse roots, stumps, branches and foliage and shown in different colours.

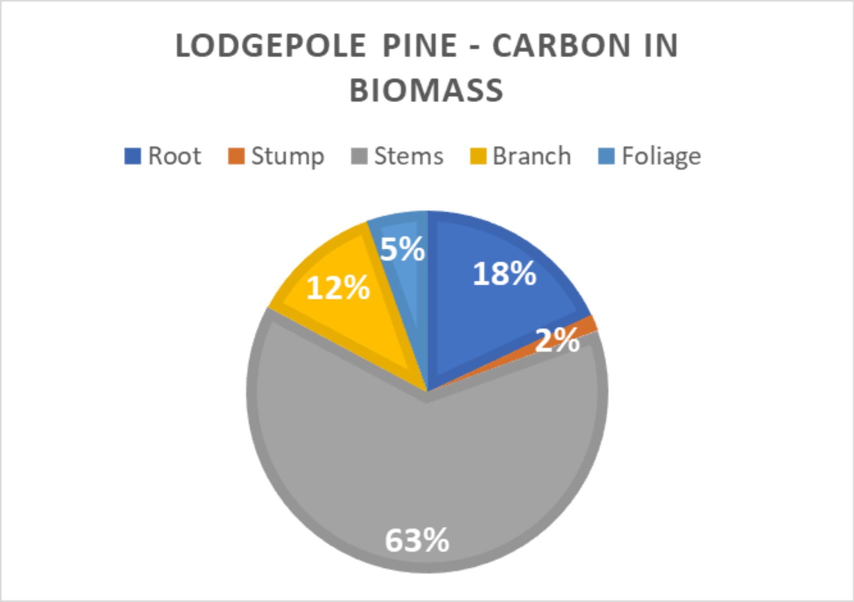


Figure 13. Percentage of carbon in lodgepole pine biomass partitioned between stems (include round wood, sawlog and stems tips), coarse roots, stumps, branches and foliage and shown in different colours.

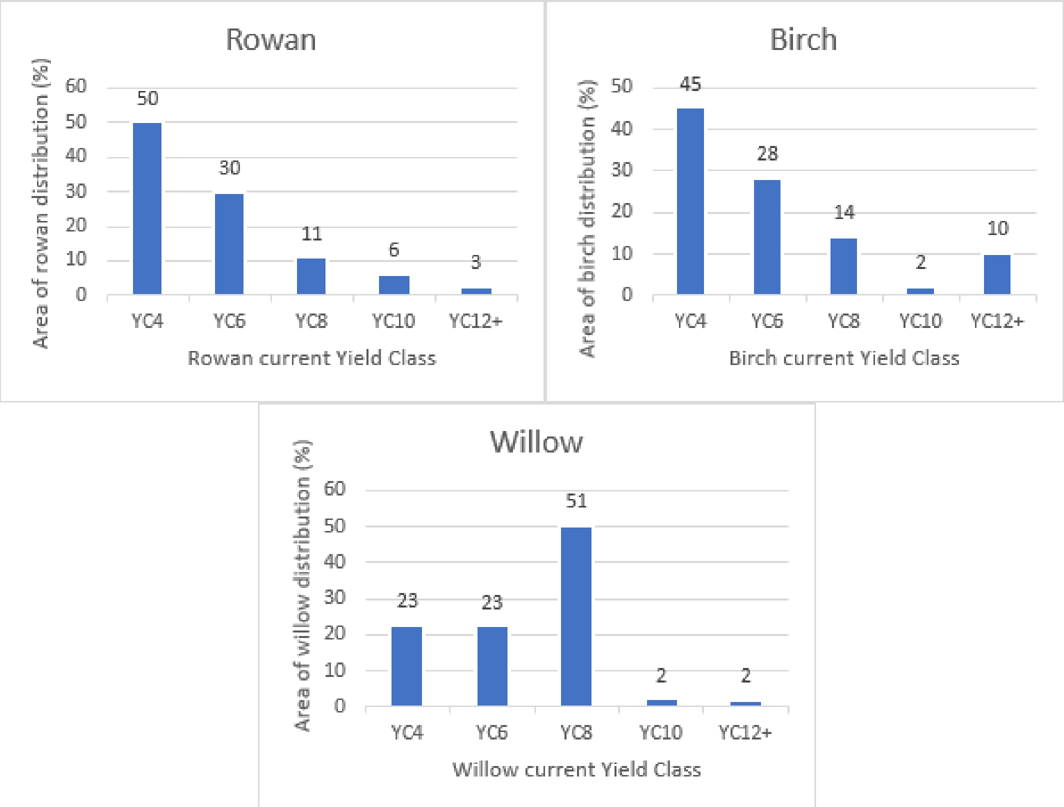


Figure 14. Current area of birch, willow and rowan on deep peat distribution across different Yield Classes (YC). Bars are total area and numbers indicated percentage in each YC from total area.

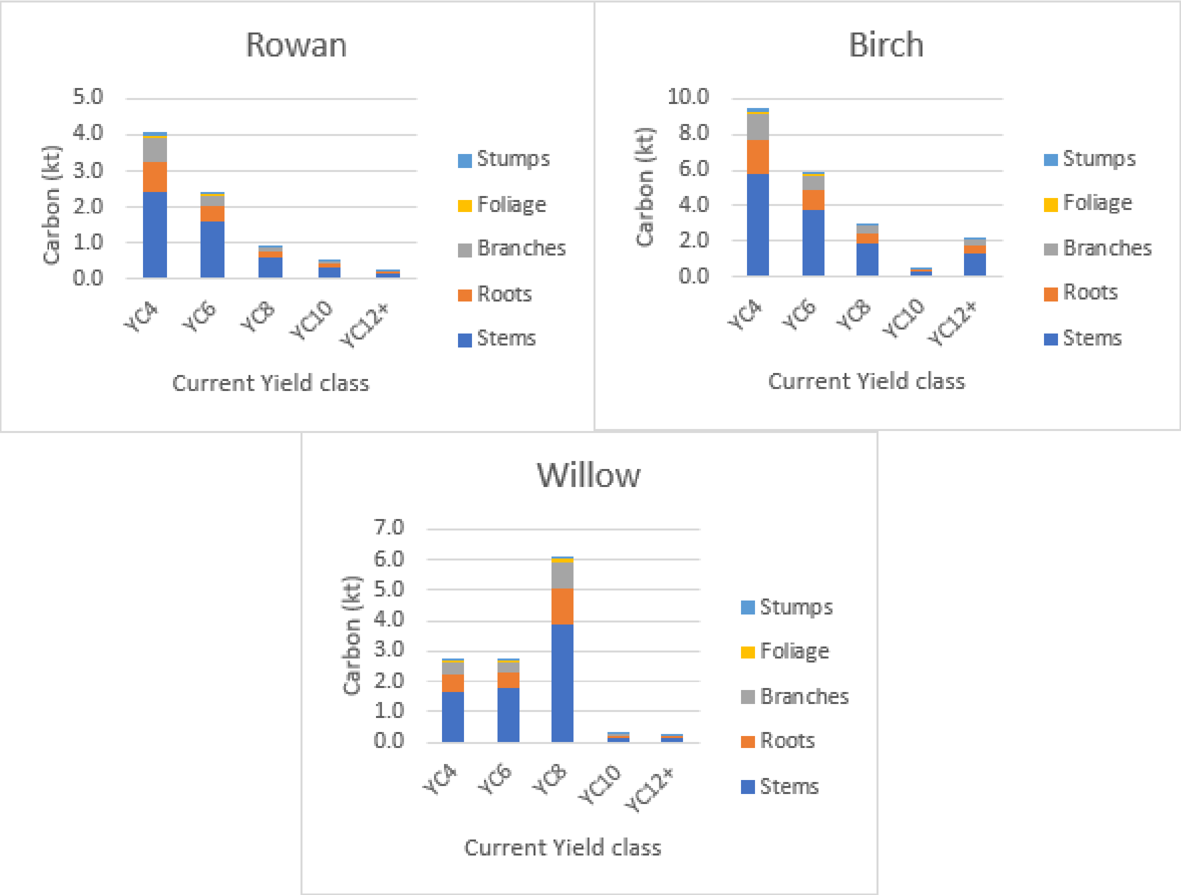


Figure 15. Total carbon stocks (**21kt C**) in birch, (**12kt C**) in willow and (**8kt C**) in rowan biomass on deep peat in NI Forest Service forest. Carbon in biomass was also partitioned between stems (include round wood, sawlog and stems tips), coarse roots, stumps, branches and foliage and shown in different colours.

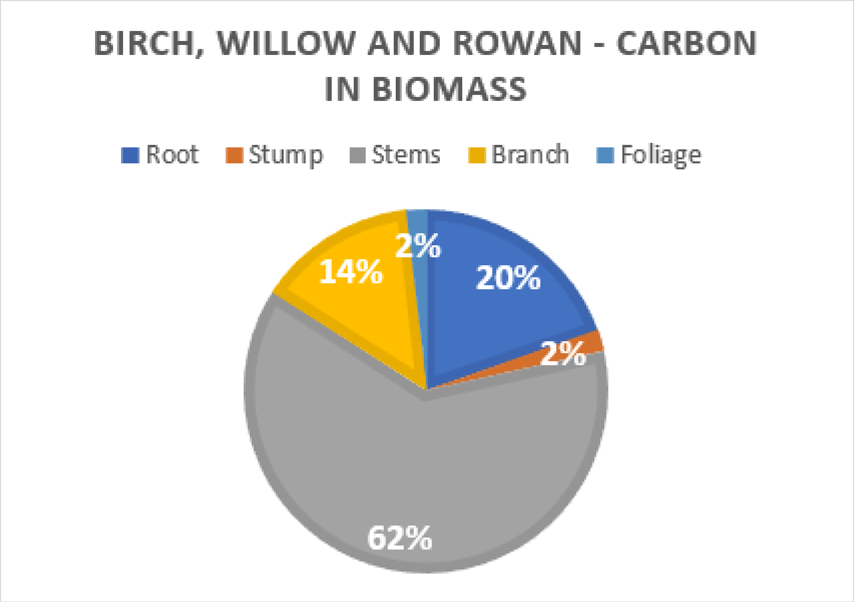


Figure 16. Percentage of carbon in birch, willow and rowan biomass partitioned between stems (include round wood, sawlog and stems tips), coarse roots, stumps, branches and foliage and shown in different colours.

III. Above and below carbon balance of forestry on deep peat soils in NI Forest Service

The above-ground and below-ground carbon balance for each of the main species (Sitka Spruce, lodgepole Pine and top 3 native broadleaved species – birch, willow and rowan) on deep peat across the Forest Service estate in NI was compiled and presented in **Table 5**. Overall carbon of peat and top 5 species tree biomass on deep peat is **16,348 kt C** (16.3 Mt C). Carbon stored in deep peat soils down to 1m depth under conifer species make on average 70% of the total forest carbon balance. This proportion is well established for highly organic soils across GB (Morison, et al., 2010, 2012; Vanguelova et al., 2013) and Europe (De Vo et al., 2015). Carbon storage in peat soils down to 1m depth under native broadleaved species even reached 80% (**Table 5**). This highlights the importance of the belowground carbon stock which is large and vulnerable to disturbance (Vanguelova et al., 2016, 2019).

Table 5. Carbon stock in deep peat soils down to 100 cm depth, biomass of main tree species growing on deep peat in NI Forest Services and grand total of both above and belowground carbon storage. Percentage distribution of carbon in soils and biomass out of total forest carbon budget is also presented.

Species	Total soils 0-100 cm kT C	Total biomass kT C	Overall total kT C	Total soils 0-100 cm % of total	Total biomass % of total
Sitka Spruce	11,181	2940	**14,121**	74	26
Lodgepole Pine	1566	423	**1989**	73	27
Birch	95	21	**116**	78	22
Willow	61	12	**73**	80	20
Rowan	42	8	**50**	81	19
Grand total	**12,944**	**3404**	**16,348**		

Decisions on future restocking of these areas is likely to depend on the amount of carbon sequestration that will be produced. In Scotland, after consideration of the carbon balance of Sitka spruce on peat soils and taking account of the carbon losses caused by disturbance of peat due to the required site preparation prior to planting (draining and deep ploughing), the current FC Scotland Practice Guidelines state that a second rotation of Sitka spruce will produce positive carbon balance only where YC>8 (Forestry Commission Scotland, 2015). This assessment is however assuming worst case scenario of very high peat disturbance during preparation for planting (e.g. 30% loss of total peat C) due to drainage and deep ploughing. Such drastic ground preparation is unrealistic for second rotation Sitka spruce planting, particularly taking into account the current guidelines for minimal disturbance on highly organic soils as stated in the UK Forestry Standard (Forestry Commission, 2017). In the NI Forest Service Estate, the main preparation for planting is through trench mounding which disturbs predominately the top 50 cm of the peat and it is likely to cause no more that 10% loss of peat carbon (Vanguelova, 2009 report to FLS on soil disturbance scenarios). Applying this rate of disturbance, the total balance (Sitka spruce roundwood carbon only minus peat carbon loss due to disturbance at 10% down to 50 cm peat depth) is shown in **Figure 17.** The results suggest that carbon balance is negative for Sitka spruce of YC6 and positive from YC8 onwards, with a very minimal carbon gain at YC8 (0.5 t/ha). Currently in NI Forest Services, Sitka spruce of YC6 occupies only 1% of the combined area of Sitka plantations on deep peat (**Figure 7**). The Forest Service has produced a report based on results from recent forest inventory data (consisting of repeated measurements of sample plots) which indicates a decline in the growth of Sitka spruce with increasing age across NI on peat with depth >50 cm (NI Forest Service internal report, 2021). Thus, the current predicted yield of Sitka stands may decrease by the time of felling, particularly during a second rotation. We therefore recommend a cautionary approach to account for the risk that Sitka spruce may not reach expected YC in the second rotation, and suggest a predicted YC<10 as the threshold to identify areas where peatland restoration should be the priority as it is likely that Sitka spruce plantations of YC<10 will not deliver positive carbon balance. Replanting deep peats by trench mounding and second rotation stand of YC10 and higher could deliver a net carbon accumulation between 2 and 6 t C/ha (accounting for roundwood only) and higher if all biomass components accounted for. Currently the area of Sitka spruce of YC6 - YC10 represents 10% of the total carbon in Sitka plantations across the NI Forest Service. So, there will be approximately 90% of the peatland under Sitka spruce (YC12 and above) which will deliver positive carbon balance if replanted. However, if a much lighter ground preparation techniques is applied such as patch scarification at only 5% estimated carbon loss from just the top 20 cm of peat, the carbon balance of Sitka spruce will be positive across all YC with delivery of 25 to 45 t C/ha in roundwood at the end of the second rotation (**Figure 18**). The difference in carbon balance between these two example ground preparation practices is very large and shows that ground disturbance needs to be minimised and taken into account when decisions are made for replanting or restoring on deep peat. It is important to note that these carbon balance scenarios are based only on the extractable timber of Sitka spruce such as carbon in roundwood not the rest of the biomass carbon which could increase the balance with 40-50% if carbon in coarse roots, branches, stumps and foliage is included.

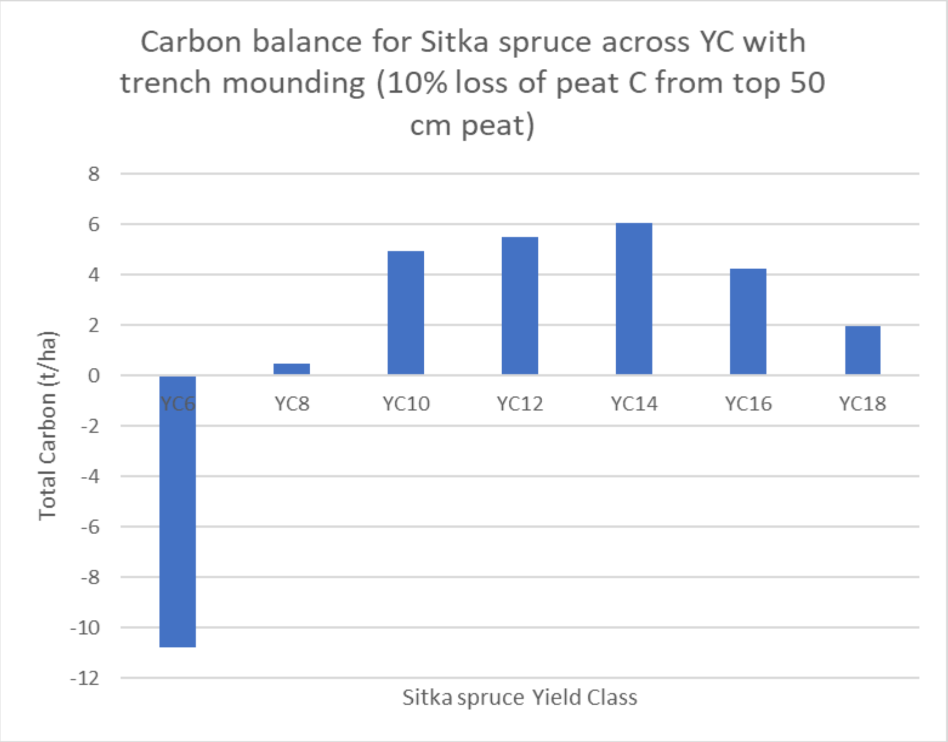


Figure 17. Carbon balance (carbon accumulation per hectare) of Sitka spruce (roundwood only) across different Yield Classes at felling age (50 years for YC6-14 and 40 years for YC16-YC18) taking into account the likely loss of carbon from the peat due to ground preparation disturbances by trench mounding, at 10% carbon loss from total peat C stocks (0-50cm) depth.

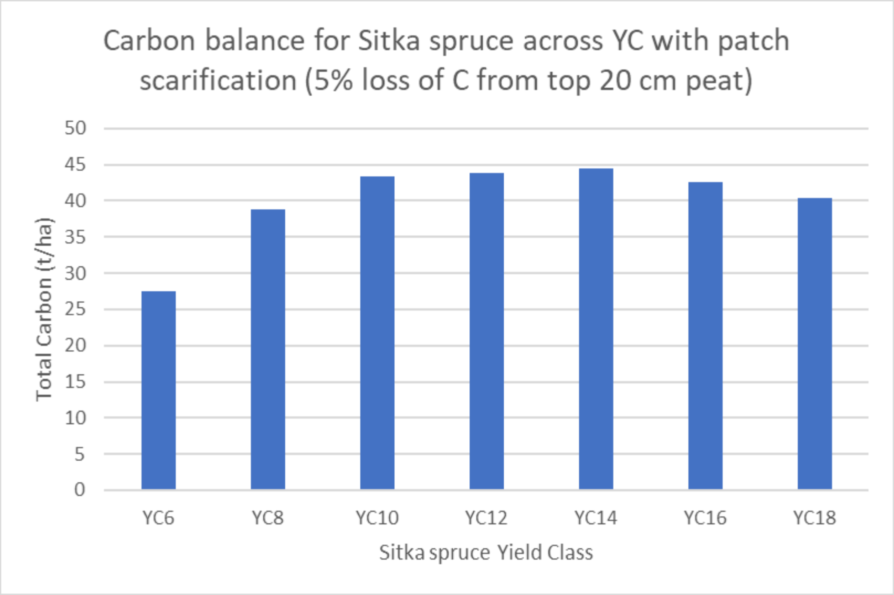


Figure 18. Carbon balance (carbon accumulation per hectare) of Sitka spruce (roundwood only) across different Yield Classes at felling age (50 years for YC6-14 and 40 years for YC16-YC18) taking into account the likely loss of carbon from the peat due to ground preparation disturbances by patch scarification, at 5% carbon loss from total peat C stocks (0-20cm) depth.

An alternative option for the fate of the afforested peat is to fell the current conifer plantation as planned and then leave the site for natural regeneration by broadleaves with minimal ground preparation or disturbance. This scenario was modelled using the carbon balance for the three most abundant native broadleaved species (birch, willow and rowan) on deep peat; assuming a density of 300 stems per ha, a rotation length of 50 years similar to the Sitka spruce and including roundwood only across the different potential YC's**.**

If light patch scarification, using an excavator, is applied on the surface of the deep peat before the land is left for natural regeneration, a 5% loss of peat carbon is likely from the top 20 cm of the peat soils. In this scenario, carbon balance could be between 2 and 9 t C/ha after 50 years of natural regeneration (**Figure 19**); this increases to between 9 and 16 t C/ha after 50 years, if the regeneration is successful with no ground disturbance (**Figure 20**). The carbon accumulation potential of broadleaved regeneration depends on the YC the native species can achieve. Natural broadleaved regeneration can deliver 20% canopy cover with between 200-400 stems per ha. Currently, the broadleaves on deep peat are not predicted to reach high YC, e.g. 80% of birch and rowan are YC6 - 8 and 50% of willow is YC10 (**Figure 14**). The carbon benefit they deliver is estimated to be 2 - 6 t C/ha if the ground is scarified, and 9 - 13 t C/ha if no disturbance is required. Overall, the carbon benefits arising from native broadleaved regeneration is positive even when ground preparation is required; as the carbon losses due to scarification are outweighed by the carbon storage in the biomass of native broadleaved species.

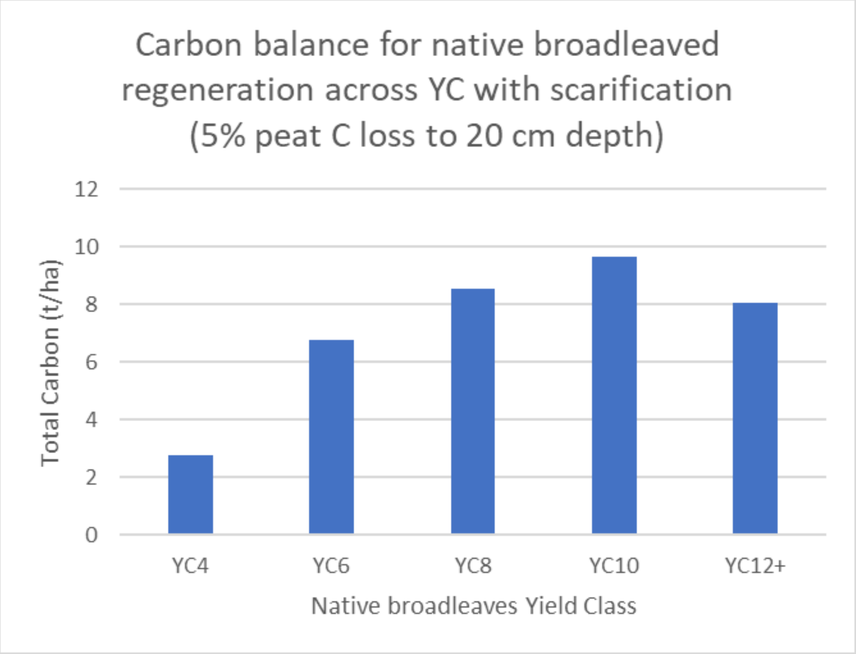


Figure 19. Carbon balance (carbon per hectare) of native broadleaved regeneration across different potential Yield Classes accounting for ground preparation disturbances by patch scarification, at 5% carbon loss from total peat C stocks (0-20cm) depth.

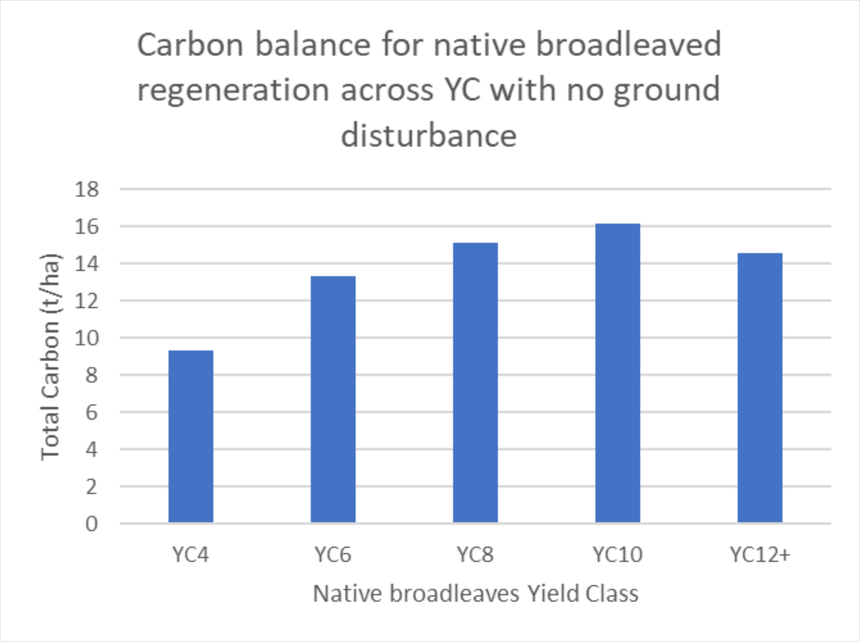


Figure 20. Carbon balance (carbon per hectare) of native broadleaved regeneration across different potential Yield Classes with no ground disturbance.

IV. Review of soil GHG fluxes from afforested land on deep peat and organo-mineral soils

We have conducted a literature review for soil GHG fluxes from forests standing on deep peat and organo-mineral soils. Because of the scarcity of GHG flux data from NI (and Ireland), we have reviewed published soil fluxes from all UK and worldwide forests, mainly from temperate regions. The review is summarised as follows (see Tables and Figures in the Appendix 1.):

- Greenhouse gas (GHG) fluxes from afforested land or their management are very variable with the majority of recent work carried out in the Scandinavian boreal region with high soil organic (O) content such as peatland or organo-mineral soil (OM).
- There are several studies from UK but mainly from England and Scotland. In total there are 6 studies on organo-mineral soils (some reported studies from different sites), but only 2-3 studies on deep peat.
- Simultaneous measurements of all GHG fluxes are scarce in general especially for Europe and worldwide. This is important in order to calculate the global warming potential (GWP) and the contribution of each gas so that appropriate measures can be taken to implement/adapt mitigation measures to reduce emissions.
- There is still a lack of flux measurements over the whole calendar year and even fewer over multiple years that takes account of seasonal and interannual variations. For example, fluxes are measured over only one or a few seasons, over several years but only during summer, or only a few months after an event to test effect of particular variables such as felling. This is an important limitation for accurate estimation of the fluxes and robust comparison between different soil types and forest management approaches.
- Most of the measurements have been made by period static chamber measurement techniques that do not take account of the diurnal variations in emission. This is important particularly for soil CO_2 effluxes as emissions are generally sensitive to variations in soil temperature.
- Not all literature indicates details of their site characteristics e.g. soil type, soil organic depth, organic and mineral C&N (C:N ratio) and/or water table depth, etc.
- As indicated by Morison et al. (2012), there are many ways in which the soil GHG flux results could be categorised. For example, by soil type, tree species, tree age, management, climatic regions, or land use, or by different methodologies, monitoring and the integration period for up-scaling. All these will obviously affect the overall magnitudes and conclusions on GHG fluxes. For this literature review, the data on afforested soil GHG fluxes (Table A1.) were categorised by soil type as “OM” or “deep peat” for UK and as “OM” or “organic” for the wider European and world soils (mainly temperate) because we cannot be sure if it could be classed as deep peat. The classification in this review was deemed to be the best option based on the available data and for consistency with previous reviews.
- Because of the large variations in the literature values in general and within each category, flux results were summarised based on mean and median values for each soil type category as shown in Figures A1, A2 and A3 for CO_2, CH_4 and N_2O respectively. Note, fluxes were not included in the mean or median results when values were reported for one season only. In conclusion:
    - CO_2 effluxes (Figure A1) is highest from OM soils than deep peat or organic (as expected) for both UK and wider European or worldwide.

- CH_4 emission (Figure A2) seems to be higher from deep peat than OM at least based on median results.
- N_2O emission seem to be higher from OM than deep peat for UK but the trend is not clear for wider European and worldwide due to the much larger variations.

V. Future questions and recommendations

- Undertake peat depth measurements across the NI Forest Services estate, particularly covering sites under the main tree species to improve the belowground carbon stocks. The survey should be stratified by elevation classes (<150; >150-300; >300m) to develop a relationship of peat depth and elevation. In addition, slope influences peat depth and depending on the available resources, a range of slopes should be included in the survey, or if funds are limited the variability of slope restricted. The data would help derive a peat depth - elevations relationship to inform the climatic conditions needed for peat formation.
- Recalculate peat carbon stocks per elevation (<150; >150-300; >300) for Sitka spruce, lodgepole pine and native broadleaves using the revised peat depth - elevation relationships.
- Include the carbon balance for open peatland habitat for comparison with afforested and natural woodland/regenerated peatlands.
- Carry out measurement of naturally regenerated broadleaved woodland on deep peat in NI to justify the density of tree species, their growth and tree species distribution.
- Assess the Litter and Fermentation layer carbon stocks for deep peats in NI for different YC of Sitka spruce to provide some evidence for the declining yields reported from the NI Forest Inventory data.

VI. Acknowledgments

This study was funded by the Department of Agriculture, Environment and Rural Affairs (DAERA), Northern Ireland under an SLA with Forest Research. We would like to acknowledge DAERA colleagues for the spatial datasets provision of deep peat soil and forest cover, tree species, Yield Class and age and all relevant attributes. We also acknowledge DEARA colleagues for their valuable input and guidance through the development of this project. We also would like to acknowledge the FR modelling group colleagues Robert Matthews and Paul Henshall for their input to the biomass modelling.

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Appendix -1

Table A1. Greenhouse gas fluxes reported for UK forest soils on organo-mineral and deep peat sites and for other European and worldwide sites. Negative values indicate uptake by the soil, positive values indicate emissions. Red fonts denote those references that were not included in the overall summary mean/median figures because they were measured only over summer season.
Table in attachment as pdf document.

Figures A1, A2 and A3 show the mean and median fluxes of CO_2, CH_4 and N_2O, respectively for in each soil type category reported in the literature.
Left of the dotted line is for UK, right of the line is for other European and worldwide reports.

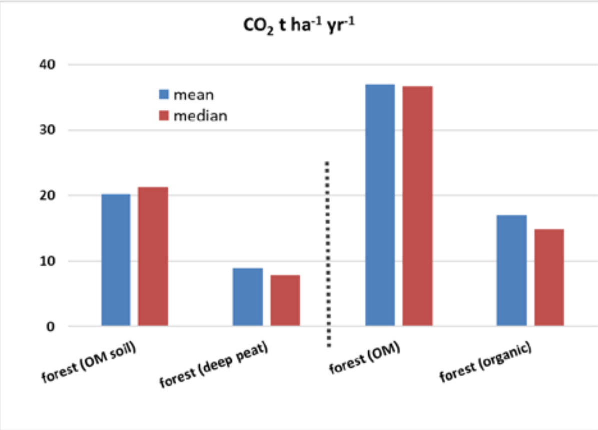

Figure A1.

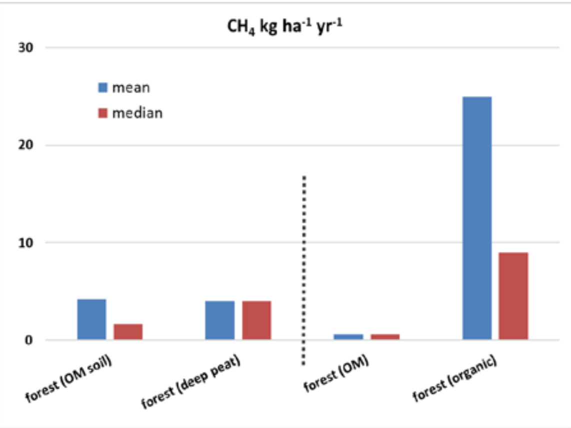

Figure A2.

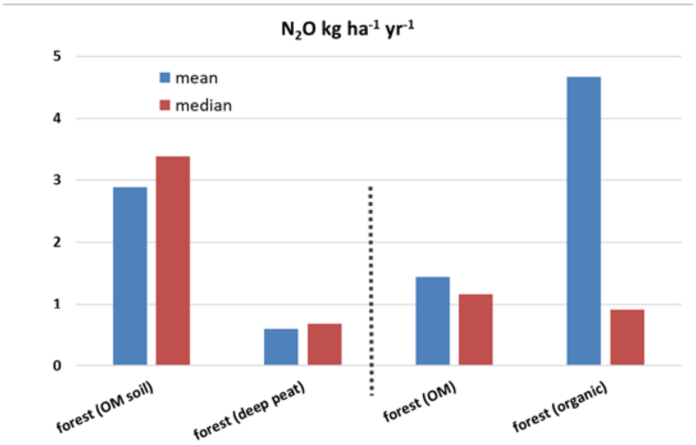
N_2O kg ha^{-1} yr^{-1}
mean
median
0
1
2
3
4
5
forest (OM soil)
forest (deep peat)
forest (OM)
forest (organic)

Figure A3.

Forest Research

Alice Holt Lodge
Farnham
Surrey GU10 4LH, UK

Tel: 0300 067 5600

Fax: 01420 23653

Email:research.info@forestry.gsi.gov.uk

www.forestry.gov.uk/forestresearch

Northern Research Station
Roslin
Midlothian EH25 9SY, UK

Tel: 0300 067 5900

Fax: 0 131 445 5124

Forest Research in Wales
Edward Llwyd Building
Penglais Campus
Aberystwyth
Ceredigion
SY23 3DA

Tel: 01970 621559

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