Supplementary material: Indicators of forest ecosystem services

THIS DOCUMENT PROVIDES MATERIAL SUPPLEMENTARY TO 'SCENARIO PLANNING FOR SCOTLAND'S NATIONAL FORESTS AND LAND OVER 100 YEARS' BY MOSELEY ET AL. IN *SCOTTISH FORESTRY* VOLUME 80 NUMBER 1, SPRING 2026

Timber resource

To measure the quantity of sawlog material produced the following equations were applied to the sub-compartment. Firstly, the yield class was determined by Ecological Site Classification according to the equation:

YC = maximum Yield Class for species * accumulated temperature response for species * next most limiting factor response for species.

The volume of a sub-compartment was given by the equation:

$$Volume\ (ha^{-1}) = g_1 \times Top\ height^{g3}$$

Where, g1 and g3 are species specific coefficients that vary according to whether the sub-compartment was thinned or not.

The top height was derived for a given yield class and sub-compartment age with the equation:

$$Top\ height = (a1 + a2 \times YC + a3 \times initial\ spacing) \times (1 - \exp(-a4 \times age))^{a5}$$

Where, coefficients a1 to a5 vary according to species.

The diameter at breast height (dbh at 1.3m) is calculated with the following equation:

$$mean\ dbh = (b1 + b2 \times initial\ spacing) \times top\ height^{b4}$$

Where, coefficients b1, b2 and b4 vary with species and management.

With those variables calculated it is possible to use the following equations to determine the sawlog volume at a given diameter class (where diameter is set to 18cm for our definition of sawlog material) :

$$Sawlog\ volume\ \geq 18cm\ (thinned) = Volume \times \exp\left(-0.8456 \times (diameter^{4.2233}) \div dbh^{4.0229}\right)$$

$$Sawlog\ volume\ \geq 18cm\ (unthinned) = Volume \times \exp\left(-0.8793 \times (diameter^{3.503}) \div dbh^{3.3596}\right)$$

The unit of the indicator is m^3. The per hectare score was weighted for the related area and summed over a decade to give an aggregate output for a given reporting period (e.g. 2061-2070).

Felled Other Volume (material less than 18cm top diameter class)

The material extracted from thinning and clearfelling operations of top diameter class less than 18cm was recorded by this indicator. Results were recorded annually, weighted for the area of the operations and reported as totals per decade, using:

Other Volume TDC <18cm = Volume - Sawlog Volume to TDC ≥ 18cm

Note that when a stand was managed according to FMA 5, the branches and tops that would normally be retained on site as brash were also harvested. In this situation the volume was calculated as:

Other Volume TDC <18cm = Crown Volume + Volume - Sawlog Volume to TDC ≥18cm

Carbon Storage

The total amount of carbon was calculated from the sum of: soil carbon (fixed at 2020) + surface organic layer (fixed at 2020) + coarse woody debris estimate (fixed at 2020) + forest standing carbon (dynamic value calculated using the Woodland Carbon Code) + Harvested wood products. The components that are fixed over the 100-year simulation period are because there is too much uncertainty about how climate change and management will interact to affect these elements in the future

Soil and surface organic layer carbon

To estimate forest canopy soil carbon (broadleaf, conifer and unknown), we used published values for the average tonnes of carbon per hectare (tC/ha) to 1 metre depth for the primary soil component of the Forestry Commission (FC) soil dataset. Where no FC soil surveys have been carried out, we used the 1:250 000 national soil maps produced by James Hutton Institute. The soil carbon values per hectare we used are mean values from research samples collected at 167 forest plots across England, Scotland and Wales (Vanguelova et al., 2013). To estimate carbon stocks in the litter and fermentation layers of the broadleaf and conifer forest canopy types, we used the published values from Vanguelova et al., (2013). No value was given to open, unknown or uncertain canopy types. Litter and fermentation values were only applied to stands older than 20 years to reflect the time it will take for these to accumulate.

Carbon in coarse woody debris
Carbon in debris accumulates in the forest as dead trees, material left from management operations and dead foliage. C stocks in CWD are not reliably known, therefore an estimate of this deadwood or coarse woody debris component of 3 tC/hectare has been added for the forest canopy type area. The value of 3 tC/ha is based on survey information and was taken from the report by (Morison et al., 2012).

Standing carbon
The carbon stored within trees in a management unit, was calculated at the end of each decadal reporting period using the biomass volume and converting the result to tonnes of carbon stored. Note that this indicator did not factor in carbon fluxes associated with soil carbon and the disturbance associated with forest operations. Stand level growth models estimate the volume with tree stems, to appraise the overall contribution to carbon sequestration we must also estimate carbon in the roots and crown (branches + leaves). Carbon is estimated by applying biomass expansion factors to the root and crown components of a tree based upon dbh and volume. The carbon content is influenced by wood properties (e.g. wood density) so different species of same growth rate can have different outcomes. However the present model does not account for dynamic changes to wood properties with management (e.g. spacing, rotation length), as such models only exist for a small number of species.

Carbon stored in harvested wood products
Harvested wood products are categorised according to the top diameter class, which is based upon the mean dbh of a stand when it is felled or thinned. Products in the top diameter class (TDC) 18cm + category are assumed to go to high end/longer applications, e.g. timber utilised in construction. We assume 15% of material in this category fails to meet specifications and/or is used in other shorter lived applications, so it is moved into the TDC 14-18cm category. The associated carbon content of harvested wood products in tdc18cm+ category is assumed to decay according to a 50 year half-life. Products in the TDC 14-18cm category are assumed to enter markets where the products will have a service life over many years (e.g. fencing, posts, cladding), but not in longer term applications. We consider that the carbon associated with the tdc14-18cm class will be locked up for 20 years then returned to environment.

Products in TDC 14cm or less categories are assumed to return their carbon to environment within a year, for example by serving as wood fuel. While some of the application areas offer substitution benefits over fossil fuel extraction those are not quantified here.

Biodiversity potential

Biodiversity potential is based on metrics developed in the Forest Biodiversity Index (FOBI) FOBI (Bellamy et al., 2024). In total, seven measures of woodland attributes were calculated. The metrics are combined into a composite index and reported every decade, using a statistical approach known as the Wroclaw method (Perkal, 1953). Each metric is normalised; this is a method for standardising values which allows them to be combined. All the indicators have an equal weighting in the composite index. All indicators are assumed to have a positive linear relationship for biodiversity (i.e. where more of something scores higher), except for the open ground metric (see description in next section). Calculations are made at the block level, and the average block value per decade is used for reporting.

Species diversity: Effective number of species per block
This metric indicates how equally abundant the different species in a block are and is a frequently used measure of species diversity. For example, a block planted with two species where each species is half of the planted area (e.g. 50% birch and 50% oak) will have an effective number of 2, whereas a block planted with 90% birch and 10% oak will have an effective number closer to 1. It is calculated from the Shannon Index of species diversity (Shannon, 1948).

Age diversity: the effective number of age bands per block
Each component was classified into one of seven age classes (0-20 years, 20-40 years, 40-60 years, 60-80 years, 100-160 years, 160 years and older). We have then calculated the effective number of age classes in each block.

Vertical complexity: the effective number of height bands per block
The scores were calculated by classifying all the components into height classes based on a pre-defined classification system. The proportional contribution of each height class for each block was used to calculate the Shannon index of height classes and the effective number metric. Height classification used: <2 metres – short; 2-6 metres – shrub; 6-15 metres - thicket/pole; >15 metres – mature.

Proportion of native species per block
The proportion of each block planted with native species. Planting proportion is calculated as proportion of planted area, and open ground has been given a half weighting, and non-native species do not contribute to the score. For example, a stand with 100% birch will score 1, a stand with 50% Scots pine and 50% Sitka spruce will score 0.5, and a stand with 50% Scots pine and 50% open will score 0.75.

Tree size (DBH) diversity
The standard deviation of tree diameters at breast height across the block, modelled for each species and values expressed for each component.

Density of canopy
This metric was introduced based on feedback from the External Advisory Group. The proportion of each block planted with species that have a light canopy. Species with a light canopy are larches, Scots pine, and all broadleaves except beech. Planting proportion is calculated as proportion of total area, open ground has been given a half weighting, and dark canopy species do not contribute to the score. For example, a stand with 100% birch will score 1, a stand with 50% Scots pine and 50% Sitka spruce will score 0.5, and a stand with 50% Scots pine and 50% open will score 0.75.

Proportion of open ground per block
The proportion of open ground was calculated for each block. Some open space is considered good for biodiversity, but too much or none at all can have negative impacts. Therefore, a curvilinear relationship is assumed, with a score of 0.5 (50%) open ground assumed to be best for biodiversity potential.

Diversity of (tree species) forest resource

We report on the species diversity across the whole estate in addition to the effective number of species per block within the biodiversity potential indicator. The effective number (EN) provides a way of expressing how equally abundant different species are across the estate. The higher the EN value, the more diverse the estate can be considered to be. Rather than simply counting the number of species, the EN gives an indication of the abundance, and therefore the contribution of the species to the ecological function of the forest. The method follows that calculated for biodiversity potential.

Visitor experience

The 'visitor experience value' of a forest is defined here in terms of the preferences of people who regularly use forests as sites for recreation (i.e. 'forest visitors'). Their preferences for a given forest are likely to be influenced by many factors, but this survey is concerned only with silvicultural attributes (tree size, stand density, species composition, etc). For most visitors, these are important because they affect the visual attractiveness of the forest. However, some visitors may also value the same attributes for non-aesthetic reasons, e.g. because they provide better habitats for bird-watching, or collection of mushrooms and berries.

Visitor experience values were derived from a Delphi-type survey undertaken by FLS staff which aimed to quantify the relative values of different forest types managed by Forest and Land Scotland (FLS). The survey was sent to 15 FLS staff members, with a broad range of roles, including landscape architects, ecology, visitor services, forest planning and operations, and strategy/business. We asked participants to try to take the range of attributes into account, and answer on behalf of the 'average' visitor with a score ranging from 1 (low) to 10 (high).

13 completed questionnaires were returned and median scores were calculated for each combination of land management alternative (LMA) and stand maturity & stocking density (Table 1). Each individual was then sent their original scores and the median scores and were given the opportunity to change their scores if they wished. Only one person changed their scores and this did not results in a change to the median scores.

Table 1. Median scores calculated for each combination of land management alternative (LMA) and stand maturity & stocking density from the 13 respondents.

Maturity and stocking density	Land management alternative (LMA)						
	1. Natural forest reserve	2. Edge woodland	3. Low impact silviculture	4. Long term retention	5. Even aged spruce	6. Even aged other species	7. Short rotation forestry
1. Low maturity, lower density	6	4	5	4	3	3	3
2. Low maturity, higher density	4	4	3	3	2	3	1
3. Medium maturity, lower density	7	7	8	7	4	5	4

4. Medium maturity, higher density	**6**	**5**	**5**	**5**	**3**	**4**	**3**
5. Mature, lower density	**10**	**9**	**10**	**9.5**	**7**	**8**	**4**
6. Mature, higher density	**8**	**7**	**7**	**7**	**5**	**6**	**2**

The second question in the survey focussed on other silvicultural aspects that could be used to provide an adjustment to the scores from question 1 to reflect whether there are positive or negative effects on recreational value from stands with species that have lighter canopies, stands with two or more tree species and stands with residue from thinning and harvesting activities. Agreement and disagreement with five statements and the numbers ranking tree species groups in relation to their recreational value is captured in Table 2.

Table 2. Number of respondents indicating agreement or disagreement with statements about the influence of silvicultural attributes. Tree species groups ranking by respondents as either 1, 2 or 3 is summarised.

Silvicultural attribute	Detail	Percentage agreement	Score if present
A stand with predominantly light canopy species (such as aspen, birch, larch, pine, rowan and willow) increases the recreation score		85	1
Having more than one tree species increases the recreational value of a forest stand	>1 species	92	1
Having lots of different tree species increases the recreational value of a forest stand	>2 species	85	2
The presence of harvesting/thinning residue decreases the recreational value of a forest stand	For a period of 2 years	85	-1
Clearfelling decreases the recreational value of a forest stand?	For a period of 5 years	77	-2
Rank these tree species groups in order of recreational value (1 high to 3 low)	Broadleaves	85	2
	Conifers	85	1
	Mixture of broadleaves and conifers	85	3

The scores from both surveys were combined to provide a composite value for each forest stand.

References for indicators

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