The FOrest Biodiversity Index (FOBI): monitoring forest biodiversity potential over space and time

Supplementary material

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1. The FOBI metrics

1.1 Forest biodiversity indicators

Table 1.1: Forest biodiversity indicators identified from the scientific literature. *Information on the association of each indicator with biodiversity according to and its relevance to forest management are provided. The titles of FOBI metrics relevant to each indicator that are taken forward for calculation in the FOBI are provided (relevant FOBI metrics) alongside other potential metrics for which appropriate data or evidence were unavailable to include in the FOBI.*

Indicator	The indicator's association with biodiversity and its relevance to forestry management	Relevant FOBI metric(s)	Relevant metrics for which data or evidence were unavailable
Deadwood volume	Deadwood amount is widely used as an indicator of the biodiversity of forest ecosystems (Forest Europe, 2015; Schuck et al., 2004), as it tends to be positively correlated with woodland living fungal species richness and saproxylic beetle species richness (Gao et al., 2015). Around 20-25% of woodland species in the UK are estimated to depend on dead or dying wood for all or part of their life cycle (Alexander, 2003; Siitonen, 2001). Some species depend on certain sizes of deadwood material, and deadwood size diversity has been related to the diversity of several species groups (e.g. bryophytes (Müller et al., 2015); saproxylic beetles (Bouget et al., 2013; Brin et al., 2009; Johansson et al., 2007; Uhl et al., 2022); lichens (Nascimbene et al., 2013); fungi (Blaser et al., 2013; Uhl et al., 2022). Deadwood can be retained in forests from forest operations such a as thinning and felling, or by supporting and allowing natural process such as tree aging and death through competition for light, or due to storm damage (Forestry Commission, 2017; Uhl et al., 2022). Deadwood can also be intentionally created through girdling standing trees, felling and leaving stems (Humphrey and Bailey, 2012) or damaging parts of trees (veteranisation) (Cavalli and Mason, 2003).	- Deadwood Production Capacity *(modelled surrogate for deadwood volume)*	- Deadwood volume - Deadwood size and type diversity [This information is not collected as part of the Public Forest Estate subcompartment database]

Indicator	The indicator’s association with biodiversity and its relevance to forestry management	Relevant FOBI metric(s)	Relevant metrics for which data or evidence were unavailable
Woodland and tree age or ancientness	Mature woodlands and ancient woodlands in particular (areas that have been continually wooded since 1600 (England) or 1750 (Scotland)) tend to be more structurally and taxonomically diverse than other woodlands, and are particularly important for many rare and specialist woodland species (Coote et al., 2013; Goldberg et al., 2007; Peterken, 2001, 1983). Similarly, older trees, and ancient veteran trees in particular, tend to provide a wider range of tree-related microhabitats (TreMs; such as, tree holes, branch cracks and moss cover), which increase their biodiversity value (Bouget et al., 2013; Gao et al., 2015; Larrieu et al., 2018; Michel and Winter, 2009; Zeller et al., 2022). Ancient woodlands and ancient or veteran trees can be retained via traditional management practices, although ancient woodlands cannot be reinstated once destroyed (Goldberg et al., 2007), and ancient and veteran trees take a long time to establish (although veternisation treatments can be applied (Cavalli and Mason, 2003)).	- Ancient Woodland Cover - Oldest Tree (age)	- Veteran tree density
Ground flora abundance or diversity	This species or composition indicator has been widely studied because it is easily assessed. Vascular plants are primary producers in the food chain and the abundance or diversity of woodland ground flora have been found to be associated with multiple taxa in a range of different forest types (Gao et al., 2015; Zeller et al., 2022; Zerbe and Kreyer, 2007). For example, Gao et al., (2015) found it was consistently of moderate indicator value for bird species richness (although of no value for bryophytes). It is included within a factor of the Index of Biodiversity Potential to represent clearings, edges and other areas with a well-developed herb layer composed of flowering plants (Gonin et al., 2018), and as a UK Biodiversity Indicator (Department for Environment Food and Rural Affairs, 2014). Ground flora can be influenced by forest management, mainly through changing the light environment (e.g., maintaining open areas and canopy gaps) or removing competition (e.g. by ride or verge cutting) (Ferris and Carter, 2000; French et al., 2008). It is considered to directly indicate changes to environmental conditions and habitat management (Department for Environment Food and Rural Affairs, 2014).	N/A	- Ground flora abundance or diversity [This information is not collected as part of the Public Forest Estate subcompartment database]

Indicator	The indicator's association with biodiversity and its relevance to forestry management	Relevant FOBI metric(s)	Relevant metrics for which data or evidence were unavailable
Microhabitat diversity	Monitoring standards on woodland sites protected for nature include assessment of microhabitats (e.g., open space, water bodies, rock features, dead wood, old trees) as these have been associated with species diversity and conservation priority species (Burton and Eggleton, 2016; JNCC, 2004). In a British study, a hierarchical classification of habitat into 'niches' (with components of woodland type, stand stage and microhabitat) was found to predict the occurrences of certain rare species (Broome et al., 2019). A positive association between various woodland taxa and more fine scale, tree-related microhabitats (TreMs), such tree holes, bark cracks and moss cover, have also been found due to the diversity of functions they serve (e.g., shelter, areas for recruitment, sources of food) (Bouget et al., 2013; Gao et al., 2015; Larrieu et al., 2018; Michel and Winter, 2009; Zeller et al., 2022). Woodland managers can look for opportunities to create microhabitats or niches suitable for priority species and particularly for species predicted to be supported in nearby woodlands, thereby increasing the amount of linked, suitable habitat available. Examples of management actions include changing woodland composition or stand stage where suitable microhabitats are present (e.g. water features, rocky outcrops) or creating certain microhabitats (e.g. deadwood, bare ground) (Broome et al., 2018; Forestry Commission, 2017).	- Niche Condition (*modelled*; Scotland) - Niche Diversity (*modelled*; Scotland) - Microhabitat Richness (*modelled*; England)	- Microhabitat or tree-related microhabitat diversity - Soil type or structure diversity [This information is not collected as part of the Public Forest Estate subcompartment database]
Native woodland cover	(Bellamy et al., 2018): The number and complexity of species interactions with particular tree species or woodland communities is expected to be highest among native tree species and woodlands as these relationships have had longer periods of time to evolve (Kennedy and Southwood, 1984) (although see Quine and Humphrey, 2010). Native tree species can also provide habitat for highly specialist species; 11% of the 955 species found to be associated with ash trees (*Fraxinus excelsior*) are highly dependent or restricted to this tree species, including epiphytic lichens, bryophytes and specialist invertebrates such as *Lipsothrix nigristigma* (Mitchell et al., 2014). Woodland managers can increase native woodland cover by retaining, planting and encouraging the establishment and survival (via herbivore control, for example) of native tree species on ecologically suitable sites; controlling the spread of invasive non-native species (Forestry Commission, 2017).	- Native Woodland Cover	- Proportional cover of 'high biodiversity value' woodland types or tree species [At the time of the FOBI conception, the project team felt that there wasn't sufficient generalisable evidence on the relative biodiversity value of tree species and woodland types to implement this]

Indicator	The indicator's association with biodiversity and its relevance to forestry management	Relevant FOBI metric(s)	Relevant metrics for which data or evidence were unavailable
Openness	A proportion (10-25%) of openness within forest canopies is considered appropriate for supporting woodland biodiversity by providing light shade or a heterogeneity of light conditions (Forestry Commission, 2017). Canopy gaps and open habitats in and around a woodland increase structural and environmental heterogeneity by providing the edge and other microhabitat types or microclimates required by some species. The associated increase in light availability provides suitable conditions for shade-intolerant species and is reportedly positively associated with many species across various, including hoverflies, spiders, bats, butterflies, birds, bryophytes, lichens, plants, carabids, and moths (Coote et al., 2013, 2007; Fuentes-Montemayor et al., 2013; Gittings et al., 2006; Kirkpatrick et al., 2018; Košulič et al., 2016; Lewandowski et al., 2021; Zeller et al., 2022). An excess of gaps disadvantages species requiring shady, woodland interior conditions. For example, bryophyte richness was shown to be negatively associated with light levels in one study (Smith et al., 2007), and dense canopy conditions were positively associated with high mycorrhizal and saprotroph diversity in conifer stands (Humphrey, 2005). Light shade or intermediate light levels are positively associated with pinewood ground flora species which are either rare or are the key food plant for rare species (Broome et al., 2014, unpublished; Parlane et al., 2006), or with oak woodland spider species richness (Košulič et al., 2016). Woodland and canopy openness can be increased and maintained via operations such as thinning and felling, creating rides and creating or restoring open habitats such as ponds and peatland, adding and controlled livestock, or by supporting and allowing natural process such as tree aging and death through competition and natural disturbances (Forestry Commission, 2017).	- Open Habitat Cover - Gappyness *(modelled as a surrogate for canopy closure/openness)*	- Canopy closure/openness [This information is not collected as part of the Public Forest Estate subcompartment database]
Inter-woodland & landscape diversity	Environmental heterogeneity within and between woodlands, and in the surrounding landscape, promotes the development of distinct communities via increases in beta and gamma diversity (Jones et al., 2022; Schall et al., 2018). Forest planners can improve landscape scale diversity by considering the make-up of existing landscapes and identifying opportunities for introducing and encouraging a diverse array of woodland types and structures (Forestry Commission, 2017; Grant et al., 2012).	- Landscape Stand Type Diversity - Landscape Stand Structure Diversity - Landscape Woodland Size Diversity	

Indicator	The indicator’s association with biodiversity and its relevance to forestry management	Relevant FOBI metric(s)	Relevant metrics for which data or evidence were unavailable
Topographic diversity	Topographically complex areas are more likely to provide a diversity of microclimates via aspect heterogeneity and differences in sun and wind exposure, which in turn provide suitable conditions for a wider range of species (Opedal et al., 2015; Tinya et al., 2021). Although there is little that can be done at the site level to increase topographic complexity, new woodlands can be sited in areas with higher complexity.	- Topographic Roughness	
Tree composition and structure diversity	Structurally diverse woodlands tend to provide a wider range of conditions and microhabitats, thus improving the diversity of tree and other taxa (Ferris and Humphrey, 1999; Tinya et al., 2021). For example, the vertical complexity of woodland structure has been found to be positively associated with bird species richness (Zellweger et al., 2013), in accordance with the foliage height diversity-species diversity hypothesis (MacArthur and MacArthur, 1961). Tree diversity can also improve woodland resilience by increasing the diversity of natural enemies (Jactel and Brockerhoff, 2007; Jäkel and Roth, 2004) and via a ‘dilution effect’, whereby increased tree species diversity can reduce insect herbivore pest efficiency (Guyot et al., 2016) and the spread of pathogens such as *Phytophthora ramorum* (Haas et al., 2011). Woodland managers can establish and retain a diversity of tree characteristics, species and structures within woodlands via e.g., phased felling and re-stocking; the application of a range of silvicultural approaches (Forestry Commission, 2017; Grant et al., 2012)	- Tree Age Diversity - Tree Size (dbh) Diversity *(modelled)* - Tree Species Diversity - Vertical Complexity *(modelled)* - Stand Type Diversity	- Tree functional diversity - Tree genetic diversity [This information is not collected as part of the Public Forest Estate subcompartment database]
Tree health	Some degree of poor tree health and disturbance, caused by factors such as pests, diseases and disturbances such as storms, can increase biodiversity by improving woodland microhabitat and structural diversity, deadwood volume and openness via increased mortality (Bowd et al., 2021). However, high levels of tree mortality can limit a woodland’s biodiversity value by restricting ecosystem functioning and reducing tree and functional diversity (Boyd et al., 2013). Arguably, indicators of tree health relate to *pressures* on woodland biodiversity, and their impacts are likely to be reflected in other biodiversity indicators (e.g., herbivore damage results in a simplification of woodland structure (Eichhorn et al., 2017) and tree mortality is directly associated with deadwood volume and canopy openness). Actions to improve the resilience of woodlands can be taken at site to landscape scales by assessing the susceptibility to pests and diseases, managing herbivores and improving structural, compositional and functional diversity, for example (Bellamy et al., 2018).	N/A	- Herbivore damage - Tree pest or disease prevalence - Signs of poor tree health - Tree mortality [This information is not collected as part of the Public Forest Estate subcompartment database]

Indicator	The indicator's association with biodiversity and its relevance to forestry management	Relevant FOBI metric(s)	Relevant metrics for which data or evidence were unavailable
Woodland connectivity	Reducing woodland isolation and fragmentation encourages and supports species movements (e.g., in response to a changing climate or disturbance events), and the exchange of individuals, pollen or seeds between populations, which can improve genetic diversity within species and reduce inbreeding and genetic bottlenecking (Jacquemyn et al., 2003). This flow between woodlands can also be impacted by the 'permeability' of the surrounding landscape. Moving through intensively managed and highly modified habitats and land cover types (such as high intensity arable and urban areas) is often associated with high disturbance, energy, and mortality costs. A better connected woodland surrounded by more semi-natural habitats is therefore more likely to have higher rates of genetic exchange, species dispersal and persistence (Hanski, 1999; Johnson et al., 1992). Actions can be taken at a landscape scale to improve connectivity (e.g., planting and restoring woodlands close to existing woodlands) and reduce matrix hostility (e.g., via restoring semi-natural habitats around woodlands) (Bellamy et al, 2018).	- Landscape Woodland Connectivity - Landscape Permeability - Landscape Woodland Aggregation	- Trees outside woodland or hedgerow density [At the time of the FOBI conception, no suitable national dataset existed]
Woodland cover	Higher woodland cover tends to improve woodland connectivity (see 'woodland connectivity' indicator) and, across multiple taxa, species response to woodland isolation have been shown to be negative (Bailey, 2007). There is an established positive species richness and habitat area relationship (MacArthur and Wilson, 1967), particularly strong evidence for more specialist species (Tilman, 1994). Increasing woodland cover provides more habitat and resources for species that depend on this habitat for all or part of their life cycle. Woodland establishment and success can be improved by actions such as planting tree species according to site suitability, encouraging natural regeneration and controlling herbivores.	- Landscape Woodland Cover	

Indicator	The indicator's association with biodiversity and its relevance to forestry management	Relevant FOBI metric(s)	Relevant metrics for which data or evidence were unavailable
Woodland size	Larger woodlands are typically more diverse, suffer less from genetic drift and experience lower levels of extinctions because they can support larger populations and provide higher microclimatic, ecological and environmental heterogeneity (Gardner et al., 2019; Jacquemyn et al., 2003). Humphrey et al., (2015) argue that patch area may be a surrogate measure for patch characteristics with a higher probability of good quality habitat within larger woodlands; they report studies for birds, mammals, plants, carabid beetles and butterflies illustrating the effects on species abundance and richness of good quality habitat presence. Larger, more compact woodlands also tend to be more resilient to ecological disturbances (such as storms) and provide a higher proportion of internal woodland environments that are subject to less disturbance and issues such as pesticide encroachment (Gardner et al., 2019) Woodland planting and restoration can be targeted in areas next to and between existing woodlands to increase the size (and connectivity) of woodland patches.	- Core Area - Woodland Size	

1.2 Calculating the metrics: input and intermediate data

All data preparation and analyses were carried out in R (R Core Team, 2023) unless specified.

1.2.1 The FOBI woodland unit

The FOBI metrics must be calculated and applied to discrete spatial units of Public Forest Estate (PFE) woodland. The finest resolution of spatial units available are subcompartments, as provided in the 'subcompartment database' (SCDB; Table 1.2). Due to homogeneous nature of individual 'subcompartments' (analogous to woodland stands), and the dispersed nature of the subcompartments across a PFE 'block' management zone, neither of these units (subcompartment or management zone 'block') were deemed appropriate for use. A spatial rule was therefore applied to group adjacent subcompartments (separated by ≤100 m) that fall within the same management zone (Figure 1.1). The resultant units are referred to as the 'FOBI woodland units'. Each FOBI woodland unit receives its own metric and FOBI scores.

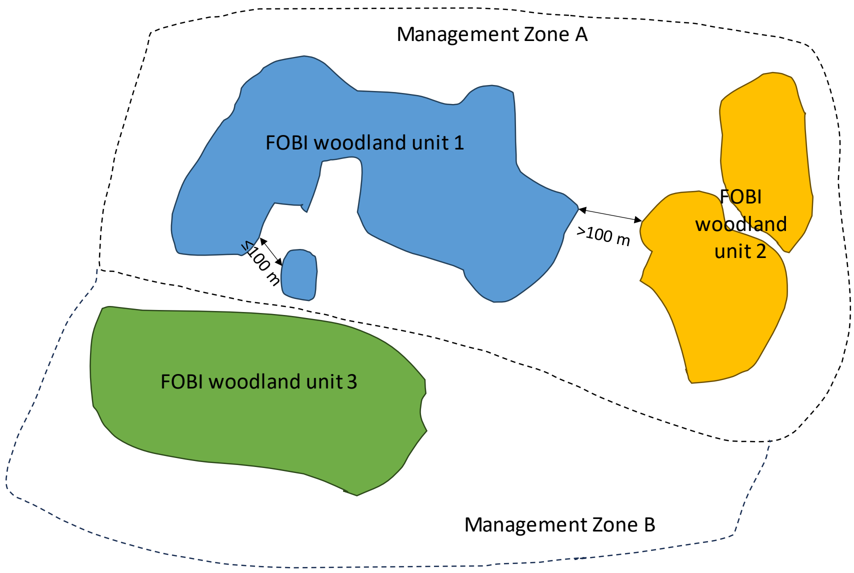


Figure 1.1: An illustration of the spatial method used to aggregate individual Public Forest Estate subcompartments into FOBI woodland units, based on separation distance and management zone.

1.2.2 Data inputs

A range of spatial environmental datasets were used to calculate the FOBI metrics (Table 1.2).

Table 1.2: Raw data inputs used to measure the FOBI metrics

Dataset title (data source)	Description	Update frequency	References
Ancient Woodland Inventory (Natural England / NatureScot)	The Ancient Woodland Inventories identify ancient woodland sites (areas that have been continually wooded since 1600 (England) or 1750 (Scotland)) that are ≥0.5 ha in size. The data are derived through a combination of historical maps, ground survey and aerial imagery. The Scotland AWI was augmented with Forestry and Land Scotland (FLS) survey data (unpublished)	Periodically	Ancient Woodland (England) (arcgis.com) (Goldberg et al., 2007) Map | Scotland's environment web
Ancient Wood Pasture Inventory (NatureScot) (Scotland only)	Results from a preliminary report on ancient woodland pasture sites across Scotland (2013). Coordinates for surveyed sites of potential woodland pasture are used.	Periodically	(Holl and Smith, 2002)
Detailed Aspect Method of Scoring (DAMS) (FR)	A 50 m raster dataset providing modelled windiness scores based on elevation, location and topographic exposure. Information is provided on average wind speed and the frequency of strong winds.	Periodically	Forest Research Decision Support Tools Portal v2.0 (forestdss.org.uk) (Quine and White, 1993)
Ecological Site Classification (ESC) products (Forest Research; FR))	Ecological Site Classification (ESC) provides a method for assessing site suitability and predicting growth for given tree species using information on: i) climate, ii) soil moisture regime (SMR) and iii) soil nutrient regime (SNR). Outputs are provided as a 250 m raster dataset.	Periodically	Forest Research Decision Support Tools Portal v2.0 (forestdss.org.uk) (Pyatt and Ray, 2001)
Forest Management Coupes (FC)	Spatial vector dataset capturing current and future management plans for individual woodland blocks across the Public Forest Estate.	Annually	Forestry Commission (arcgis.com)

Dataset title (data source)	Description	Update frequency	References
Land Cover Map raster data (LCM; Centre for Ecology and Hydrology)	The UKCEH Land Cover Maps (LCMs) provide mapped information on 21 broad land cover classes using satellite imagery. The LCM raster product has been made available (and used here), at increasingly fine resolutions (25m for 2015 product, 20m for 2019/20 and 10m for 2021).	Annually from 2017 (periodically from 1990)	UKCEH Land Cover Maps | UK Centre for Ecology & Hydrology (Marston et al., 2022)
National Forest Inventory (NFI) map (FC)	A spatial vector data product that provides annual information about the size, distribution, composition and condition of UK forests and woodlands (> 0.5 ha with a minimum of 20% canopy cover (or the potential to achieve it) and a minimum width of 20 m (including new planting, clearfell, windblow and restock)). It is produced using a combination of aerial and satellite imagery as well as administrative records of newly planted woodland as indicated by woodland grant schemes. Woodland types are categorised as Interpreted Forest Types (IFT).	Annually	Forestry Commission (arcgis.com)
Open Habitat Survey (Forestry and Land Scotland; FLS) (Scotland only)	Spatial vector dataset capturing data from the FLS Open Habitat Surveys carried out on PFE in Scotland.	Periodically	Available for internal Forestry Commission use
OS Terrain 50 Digital Elevation Model (DEM) (Ordnance Survey)	Elevation model created using OS 50 m terrain data.	Annually (2018 data used throughout due to limited topographic change over time)	OS Terrain 50 | Data Products | OS (ordnancesurvey.co.uk)
Priority Habitats Inventory version 3.0 (PHI) (Natural England, NE) (England only)	Spatial vector dataset capturing the geographic extent and location of Natural Environment and Rural Communities Act (2006) Section 41 habitats of principal importance across England.	Periodically	Priority Habitats Inventory (England) | Natural England Open Data Geoportal (arcgis.com)

Dataset title (data source)	Description	Update frequency	References
Soil Moisture Regime (SMR)	The 250 m resolution Soil Moisture Regime (SMR) raster provides national information on soil moisture and aspects of soil aeration. In the ESC system SMR is broken down into eight classes: i) Very Dry, ii) Moderately Dry, iii) Slightly Dry, iv) Fresh, v) Moist, vi) Very Moist, vii) Wet, and viii) Very Wet.	Periodically	Forest Research Decision Support Tools Portal v2.0 (forestdss.org.uk) (Pyatt and Ray, 2001)
Soil Nutrient Regime (SNR)	The 250 m resolution Soil Nutrient Regime (SNR) raster represents the availability of soil nutrients for plant growth nationally. In the ESC system SNR is broken down into six classes: i) Very poor, ii) Poor, iii) Medium, iv) Very rich, and v) carbonate.	Periodically	Forest Research Decision Support Tools Portal v2.0 (forestdss.org.uk) (Pyatt and Ray, 2001)
Subcompartment database (SCDB) (Forestry Commission; FC)	A spatial vector dataset that serves as the authoritative data source for woodland inventories on the public forest estate (PFE) land. It is derived from ground-based surveys and woodland management plans, and is used as one of the main instruments for informing decision-making on the PFE. It is continually maintained and updated. Data are collected and mapped for individual PFE subcompartments (recognisable parcels of contiguous woodland that are treated as a single management unit; analogous to forest stands).	Annually	Forestry Commission (arcgis.com)
Topographic Roughness Index (TRI)	A 50 m raster dataset derived from the ***digital elevation model (DEM)*** which captures local altitudinal variation by measuring the mean of the absolute differences between the value of a cell (elevation in m) and the value of its 8 surrounding cells using the 'terrain' function of the R 'raster' package.	Annually (2018 data used throughout due to limited topographic change over time)	(Hijmans, 2017)

Dataset title (data source)	Description	Update frequency	References
Topographic Wetness Index (TWI)	A 50 m raster dataset derived from the ***digital elevation model (DEM)*** which captures a measure of soil wetness.	Annually (2018 data used throughout due to limited topographic change over time)	(Sørensen et al., 2006)
Woodland component tables (FC)	This database accompanies the SCDB spatial dataset and provides a detailed inventory of every 'component' held within each subcompartment. Components are distinct woodland features below 0.5 ha in size; their location within the subcompartment is not mapped. Information on their species composition, planting years and proportional area of the subcompartment is provided.	Annually	Available for internal Forestry Commission use

1.2.3 Intermediate and modelled data preparation

Several intermediate datasets were produced from the raw data inputs (Table 1.2) for metric calculation. The raw and intermediate datasets used and generated are highlighted below with ***bold, italicised text***. In cases where the ***Subcompartment Database (SCDB)*** and ***woodland component tables*** were lacking information required for local scale (within woodland) metric calculation, modelling was used to provide estimates (e.g., tree top height).

i. Subcompartment database point grid

To better integrate the ***SCDB*** with the various raster processing and fine grain environmental variation across a subcompartment of FOBI woodland unit (e.g., for tree allometric calculations), the subcompartment database polygons (with associated component table data) were converted into a 50 m resolution grid of points, referred to as the ***SCDB point grid data***. Any small subcompartments that were missed in the production of the initial point dataset were accounted for by adding the centroid from their spatial polygon to the existing points.

ii. Modelled component yield class and site suitability

A key intermediate dataset for multiple FOBI metrics is a measure of the estimated productivity of subcompartment components as indicated by 'yield class'. Due to the potential unreliability and patchy availability of this information in the ***SCDB***, species-specific yield class rasters were created using algorithms derived from the Ecological Site Classification (ESC) system (Pyatt and Ray, 2001). Species-specific ***soil moisture regime (SMR)*** and ***soil nutrient regime (SNR) datasets*** were first modified to reflect the likely ground treatments (including soil drainage and fertilizer application) applied to fast-growing conifer types (these include Sitka Spruce, Douglas and other productive firs, and Norway spruce). These data are fed as inputs into ESC algorithms along with other ESC climatic variables (accumulated temperature (AT), continentality (CT), DAMS, and Moisture Deficit (MD)), and a series of species-specific parameters, to generate final tree species ***site suitability*** and ***yield class*** rasters (Pyatt and Ray, 2001).

The final stage in this section of the analysis is to draw upon the ESC ***site suitability*** and ***yield class*** rasters generated in the previous step to assign values to all individual components via a raster extraction process using the ***SCDB point grid data***. The ESC algorithms are restricted to a limited list of more common tree species. Components relating to species outside of this list were therefore matched with the most appropriate surrogate ESC species. Where a SCDB component had a generic species entry (e.g., 'OK' representing oak species) for which there were multiple possible ESC surrogates (e.g., oak species could be assigned either sessile or pedunculate oak), the ESC surrogate was assigned by selecting the candidate species with the highest ESC suitability score. In Scotland, either silver birch or downy birch was selected as a surrogate for an unlisted broadleaved species, depending on the birch species with the highest ESC ***site suitability*** score. The rationale for using birch species is twofold. Firstly, on a given site below the tree line in GB, one of silver and downy birch will always be suitable for the site, and will grow at a rate typical of common broadleaved tree species. This assumption is safe in Scotland because of the absence of shallow calcareous soils. In England such a strategy would need to account for those soils, e.g., by using sycamore. In addition, in England, there is a greater frequency of forests on lowland sites with more fertile soils, that means species such as oak and beech are more likely to dominate. A second reason for using birch species as representative of mixed broadleaved stands is that growth models only exist for oak, beech and an aggregated model often referred to as SAB (sycamore, ash and birch). The SAB models lacking the data to credibly model individual species, pool the growth data for all those species resulting in a model that broadly represents their growth characteristics. When considering other broadleaved species, it is most common to map those to SAB models and adjust the maximum achievable yield class accordingly. As a result of these complications, a comprehensive look-up table of ESC candidate species was used to assign broadleaf surrogates in England.

Additional rules were applied to ensure yield class values fell within expected ranges for select tree species types. These included ensuring that shrub species including holly and hawthorn had a yield class value capped at a maximum of two. A minimum yield class threshold was assigned to select conifer species because typically very low yield classes tend to be highly localised (e.g., very wet areas), and amelioration activities are generally applied if a stand's growth is lower than expected. Also, the nature of soil mapping is such that only the primary soil type is considered, but the secondary and tertiary soil types might be highly suited for a given species. Given this we positioned the yield class minima for Sitka spruce at 12, to represent the likely average yield across the site when soil factors were limiting.

iii. Modelled subcompartment thinning status

The ***thinning status*** was assigned to individual subcompartments by inspecting the degree of exposure each subcompartment was subject to. Exposure was captured via the ***Detailed Aspect Method of Scoring (DAMS)*** raster (Table 1.2); values were assigned to individual points in the ***SCDB point grid data*** using a raster extract process. Across both countries (with the exception of the North-East region of England) a simple rule is applied whereby thinning is assumed when the DAMS score is less than or equal to 16. For the North-East region of England, this threshold is reduced to 14 for subcompartments that lie on peat, peaty gleys or surface water gleys soil types. All SCDB points with DAMS scores above these thresholds are assumed to be unthinned because of the high risk of windblow. Where there were multiple thinning status types recorded for a single subcompartment, the most frequently recorded type is assigned. The final thinning status for a given subcompartment was then allocated to each of its individual components.

iv. Modelled tree diameter above breast height (dbh), tree top height and mean basal area

To develop ***tree diameter above breast height (dbh)*** and ***tree top height*** values for each SCDB component, the ESC-derived ***yield class*** values were used alongside information from the ***SCDB and woodland component tables*** on tree component age (derived from planting year), assumed tree spacing (2 m was assumed throughout) and assumed ***thinning status*** as inputs into Forest Yield algorithms (Mathews et al., 2016). The Forest Yield algorithm uses these data along with species-specific parameters to run tree allometric equations to calculate i) mean dbh, ii) minimum dbh, iii) maximum dbh, iv) the dbh range, and v) ***tree top height*** for each component (Mathews et al., 2016). ***Basal area*** was then calculated for each component (mean cross-sectional area at breast height of all trees within a component per hectare) using ***dbh*** and assumed stem density via Forest Yield. ***Mean basal area*** was then calculated as the mean cross-sectional area at breast height of all tree components per hectare for each subcompartment.

The Forest Yield model only accounts for a limited range of more common tree species. To account for this, ESC surrogates were again identified for each SCDB component using the same rules as outlined in Section 1.2.3.ii. In circumstances where a self-thinning model or no thin model was lacking for a species, as is common for broadleaved species, a methodology was developed to utilise models representing thinned stands to cover unthinned management. Naturally this has some limitations and does not fully capture the stand dynamics but simply using thinned models would not capture the reality of stand basal area and stocking density in simulations. To emulate an unthinned stand with a thinned model, species were characterised as either of low, intermediate or high shade tolerance using the scientific literature (e.g., Hill et al., 2004) and constructed self-thinning models. Unthinned stands were then simulated by allowing the trees to grow as per thinned models of dbh, but with adjusted stocking density according to the initial numbers of trees. At the end of each iteration of yearly growth, if the number of trees at a given dbh was greater than the limit set by the self-thinning model, the number of trees was reduced accordingly to represent mortality. While this method overestimates the dbh of unthinned stands (because in practice trees will add less diameter increment in dense unthinned stands, and hence this approach will underestimate the number of trees present), the method enables the estimation of standing deadwood (for the Deadwood Production Capacity metric) and a more accurate description of the stand state in terms of basal area.

v. Assigned land management alternative types

For various metrics, calculations were adapted according to the ***land management alternative (LMA) types*** (e.g., Duncker et al., 2012) assigned to SCDB components. Nine LMA types were used as an indicator of land use intensity, from LMA1 (natural reserve) to LMA7 (short rotation forestry) and LMA9 (Open land; Table 1.3). An LMA type was assigned to each component based on: i) the ***SCDB component tables*** land use type (e.g., open, unplanted, planted high forest); ii) the management type derived from the ***Forest Management Coupes*** dataset; iii) tree species (***woodland component tables***); iv) tree planting year (***woodland component tables***), and v) rotation length (***SCDB***) (Table 1.3).

Table 1.3 – Land management alternative types used and rules for assignment.

LMA type	Rule set used
LMA 1 – Nature reserve	Management type = 'minimum intervention (nature reserve)'.
LMA2 – Edge woodland	Management type = 'minimum intervention'.

LMA type	Rule set used
LMA3 – Low impact silvicultural system	Management type = i) 'clearfell with seed trees', ii) 'group selection', iii) 'group shelterwood', iv) 'irregular shelterwood', v) 'single tree selection', vi) 'strip shelterwood', or 'shelterwood'.
LMA4 – Long term retention	Management type = 'long term retention'. Also includes components that don't satisfy any other LMA criteria where management type is not classified as 'Other/Open land'.
LMA5 – Even aged forestry (predominately spruce)	Land use = 'planted high forest (PHF)' and tree species is either Sitka Spruce or Norway Spruce. Also includes components where management type = 'clearfell' and tree species is either Sitka or Norway spruce.
LMA6 – Even aged forestry (predominately other species)	Land use = 'planted high forest (PHF)' and tree species is not either Sitka Spruce or Norway spruce. Also includes stands where land use = 'clearfell' and tree species is not either Sitka or Norway Spruce.
LMA7 – Short rotation forestry	Planting year is later than 2010 and rotation is between 1-30 years.
LMA8 – Peatland restoration	Not used in the current study due to data gaps.
LMA9 – Open land	Land use = open land cover types (e.g., 'agricultural land', 'open'). Also includes stands that don't satisfy any other LMA criteria with a management type of 'Other/Open land'.

vi. Landscape 'woodland habitat' map

To create a national ***woodland habitat map***, the ***National Forest Inventory (NFI) map*** was filtered to retain certain Interpreted Forest Types (IFT) (Table 1.4). Felled and windblown areas are included as these can be considered a 'woodland habitat type' and are expected to be re-planted. This subset of the ***NFI IFT*** dataset is then converted to raster format (25m resolution) and passed into a workflow which groups areas of spatially contiguous areas of woodland separated by 25 m or less into the same 'woodland habitat unit' using the R 'raster' package's 'clump' function (Hijmans, 2017). This ***woodland habitat map*** with unit identifier is used to inform several of the landscape-scale metrics, including Landscape Woodland Connectivity.

Table 1.4: NFI Interpreted Forest Types (IFT) types used to define woodland habitat (Forestry Commission, 2010)

NFI IFT type	Description (Forestry Commission, 2010)
Assumed woodland	Areas where woodland grant schemes indicate planned planting but where there is also no current sign of woodland according to aerial imagery
Broadleaved	Woodland comprised almost exclusively of broadleaved species.
Conifer	Woodland comprised almost exclusively of conifer species.
Coppice	Areas under this management regime are estimated via the very even, smooth appearance on aerial photographs.
Coppice with standards	Areas of coppice that also include larger broadleaved trees (often oak).
Felled	Areas of woodland where the trees have been harvested or felled.
Ground prep	Ground prepared for new planting. Areas recently converted from some other land use to woodland.

NFI IFT type	Description (Forestry Commission, 2010)
Low density	The low 'density' polygons are areas that were mapped by NIWT but not mapped by NFI but investigation of the archive images shows a higher density than at present.
Mixed mainly broadleaved	Mixed stands with a predominance of broadleaved species.
Mixed mainly conifer	Mixed stands with a predominance of conifer species.
Shrub	Includes areas that may possibly be woodland where growth is close to the ground and shows a rough character but no clear differentiation between broadleaved/conifer. May also include ground colonised by woody species.
Windblow	Stands affected by windblow.
Young trees	Areas where planting is clearly visible, but trees cannot yet be allocated between conifer or broadleaved because of their immaturity.

vii. FOBI woodland structure types

FOBI woodland structure types were allocated to each treed woodland component (Table 1.5). For structure types that correspond with younger stands ('seedlings', 'saplings', and 'regeneration and scrub' types), classification was based on either calculated ***tree top height***, ***dbh,*** or both. The remaining classes were based on species-specific dbh ranges specified in an external lookup table, or according to the ruleset specified in Table 1.5.

To arrive at a final structural type per component the most dominant type was selected according to the proportional area cover of each type. This step was repeated to get the dominant structure type for each subcompartment.

Table 1.5: Rules used to classify FOBI woodland structure types

FOBI woodland structure type	Classification rule
Permanently open	***SCDB component tables*** open land cover types (e.g., 'agricultural land', 'open') and locations where subcompartments overlapped with either open habitat ***NFI IFT*** types or ***Land Cover Map (LCM)*** types.
Temporary open	Subcompartments that overlap with areas of ***NFI IFT*** felled types.
Seedlings	Calculated top height < 1 m.
Regeneration or Scrub	Top height 1-5 m and dbh > 0.07 m^2.
Saplings	Top height 1-5 m and dbh < 0.07m^2.
Pole	Calculated dbh within species-specific range.
Mature	Calculated dbh within species-specific range.
Veteran	Calculated dbh within species-specific range, or tree age 80-105 years, not intercepting with recorded Ancient Semi-Natural Woodlands (ASNW) or Plantations on Ancient Woodland Sites (PAWS) woodland according to the ***Ancient Woodland Inventory***.
Veteran plus	Calculated dbh within species-specific range, or tree age > 80 years, intercepting ASNW or PAWs woodland according to the ***Ancient Woodland Inventory.***
LEPO (Long-established of planted origin)	Calculated dbh within species-specific range and tree age > 105 years, that do not intercept with recorded ASNW or PAWs woodland according to the ***Ancient Woodland Inventory***.

viii. FOBI woodland stand types

Fifteen distinct ***FOBI woodland stand types*** were developed as an adaptation of Forest Development Types (Haufe et al., 2021) and assigned to each subcompartment (Table 1.6). The tree species present and their relative proportion in a subcompartment is derived from an analysis of the subcompartment 'component data' which provides Information on species composition and proportional area of the subcompartment occupied (Table 1.2) .The woodland classification process involves matching the lists of tree species forming the components of a given subcompartment to each of the FOBI woodland types in turn, using a pre-defined series of rules and criteria allocated to each of the 15 woodland types. These rules are based on a series of 'primary' tree species for each woodland type, alongside 'secondary' species and the upland/lowland status of the subcompartment based on elevation. Primary tree species are the dominant species in the woodland type. Usually these species contributes ≥ 50 % of the stand basal area but in FOBI this is interpreted as representing ≥ 50 % of the total subcompartment area as captured by the component data. . Secondary species (composed of one or multiple tree species per woodland type) are those which contribute ≤ 50 % of the subcompartment area. Steps are used in the model to account for multiple potential woodland type matches for single subcompartments. The typical primary species associated with each of the 15 woodland types is provided in Table 1.6, alongside a classification into native or non-native types based on Ditchburn et al., (2020) used to calculate Native Woodland Cover.

Table 1.6: FOBI woodland stand types used to classify SCDB woodland subcompartments.

FOBI woodland stand type code	Typical species composition (primary species)	Assumed 'nativeness' (Ditchburn et al., 2020)
A1-A2	Sitka spruce, Norway spruce, Douglas fir	Non-native
B1-B2	Corsican pine, lodgepole pine, Japanese larch	Non-native
C1-C2	,Beech, small-leaved lime	Non-native (Scotland) Native (England)
	Sycamore	Non-native
D1-D2	Scot's pine	Native
I	Ash, common alder, grey willow	Native
E1-E2	Oak, hornbeam, ash	Native
F	Oak	Native
G1-G2	Silver birch, downy birch	Native
H	Ash	Native
J	Juniper	Native
K	Blackthorn, hawthorn	Native

ix. Microhabitat presence and Niches for Species 'niches'

A variety of environmental spatial datasets were used to derive the likely presence or absence of twelve microhabitats within a subcompartment. These microhabitats consist of bareground, deadwood, glades, wet ground/water, complex understorey with glades, woodland edge/scrub, dry bark, wet bark, dry rock, wet rock (Table 1.8). The methods used to define and map the presence of microhabitats are adapted from the Niches for Species (N4S) model, which uses a hierarchical classification of woodlands (with components of woodland type, woodland structure and microhabitat) into 'niches' to predict the occurrences of certain rare species (Broome et al., 2019, 2018). Adaptations were made to the original N4S methodology for classifying the ***SCDB*** subcompartment according to N4S woodland types, N4S woodland structure types (the same as ***FOBI woodland structure types***), and microhabitat presence:

- N4S Niche component 1 – ***N4S woodland stand type*** (Scotland only): in the original N4S model, these were derived from the Native Woodland Survey of Scotland (NWSS) ground survey data (Nelson, 2010). Six of these types could be mapped to ***FOBI woodland stand types*** (the first six rows in Table 1.7). The scope of the ***N4S woodland stand types*** was extended to include new scrub, productive and non-native high forest woodland types (Table 1.7). Alongside the stand type classifications, other spatial environmental data were overlaid to identify which subcompartments reflective of ecological continuity and historical management for the N4S model. All subcompartments with at least one component with a 'mature' ***FOBI woodland structure type*** and a **basal area** value < 20 m^2/ha, or any subcompartment that intercepted a 100 m buffer from locations surveyed for ancient woodland pasture (Holl and Smith, 2002), were classified as 'wood-pasture and parkland'. All subcompartments that intersected the ***Ancient Woodland Inventory*** were classified as Ancient Semi Natural Woodlands.
- N4S Niche component 2 – N4S structure types (Scotland only): in the original N4S model, these were derived from the Native Woodland Survey of Scotland (NWSS) ground survey data (Nelson, 2010). The methods used to adapt this N4S classification to the SCDB to provide ***FOBI woodland structure types*** (which are used in place of N4S structure types) are detailed in Section 1.2.3 vii & Table 1.5.
- N4S Niche component 3 - ***N4S microhabitats*** (Scotland and England): SCDB information and modelled intermediate data were used for identifying the likely presence of microhabitats such as deadwood and 'complex understorey with glades'. Spatial data for each microhabitat were developed using ArcGIS (v. 10.6.1; ESRI, 2022) and overlap between mapped microhabitats and the SCDB were identified using R. Two new microhabitats were added to the original N4S list: grassland and grassland mosaics (Table 1.8).

Information on microhabitat presence was used for England (to estimate the Microhabitat Richness metric), whereas FLS opted to integrate the full N4S assessment to produce two N4S-derived metrics instead.

Table 1.7: Niche component 1 - FOBI woodland stand type code used for mapping the Niches for Species (N4S) 'woodland stand type' classifications to the PFE in Scotland.

N4S woodland stand type	FOBI woodland stand type code	Original N4S type or newly added for FOBI
1. Upland mixed ashwood	H2	Original
1 Upland birchwood	G1 & G2	Original
2 Upland oakwood	F2	Original
3 Lowland mixed deciduous	E1 & E2	Original
4 Native pine	D1& D2	Original
5 Wet woodland	I2	Original
6 Shade-casting conifers	A1 & A2	Newly added
7 Non shade-casting conifers	B1 & B2	Newly added
8 Non-native broadleaves	C1 & C2	Newly added
9 Blackthorn & hawthorn scrub	K	Newly added
10 Juniper	J	Newly added

Table 1.8: Niche component 3 - Microhabitat definitions and datasets used

Microhabitat	Method	Datasets used
Deadwood	**Deadwood Production Capacity** metric outputs (Section 1.2.4.iii) were converted to presence/ absence of deadwood. Presence was assumed in sites where the value was equal to or higher than the third quartile of this metric's national range.	Deadwood Production Capacity metric outputs (Section 1.2.4.iii)
Water / wet ground	Original N4S method	(Broome et al., 2019)
Woodland edge / scrub	Scrub was captured by analysing the ***Soil Nutrient Regime (SNR)*** data to identify subcompartments on poor nutrient soils. Scrub was also identified using ***NFI IFT*** 'scrub' class. Hard edges were derived using original N4S method.	***SNR, NFI, SCDB***
Tree / bark (dry)	Original N4S method	(Broome et al., 2019)
Tree / bark (humid)	Original N4S method	(Broome et al., 2019)
Complex understorey with glades	Subcompartments with a regeneration and scrub ***FOBI woodland structure types*** and a basal area < 20 m^2/ha (glades), or one that has six or more ***FOBI woodland structure types*** associated with it.	***SCDB, woodland component tables***
Glade	Subcompartments with a basal area < 20 m^2/ha (glades).	***SCDB, woodland component tables***
Rock (dry)	Original N4S method, adapted for England to make use of alternative datasets	(Broome et al., 2019) Distinct datasets used for England: • **Ordnance Survey Master Map** – filtered to keep land from types corresponding with exposed rock • **Landform_50K (GB) - British Geological Society –** filtered to retain only features that correspond with rock types.

Microhabitat	Method	Datasets used
Rock (humid)	Original N4S method, adapted for England to make use of alternative datasets	(Broome et al., 2019) Distinct datasets used for England: • **Ordnance Survey Master Map** – filtered to keep land from types corresponding with exposed rock • **Landform_50K (GB) - British Geological Society -** filtered to retain only features that correspond with rock types. • **Water Framework Directive (WFD) Surface Water Cycle 2**
Bare ground	Original N4S method	(Broome et al., 2019)
Grassland	Semi-natural grassland classes	***LCM*** ***Open Habitat Survey*** Distinct datasets used for England: • ***Priority Habitats Inventory version 3.0*** - grassland primary habitat types
Grassland with mosaics	Semi-natural grassland classes and heathland habitats	***LCM*** ***Open Habitat Survey*** Distinct datasets used for England: • ***Priority Habitats Inventory version 3.0*** - grassland and heathland habitat types

x. Open Semi-Natural Habitats map

Open semi-natural habitat within and surrounding the PFE was defined by extracting the ***Land Cover Map (LCM)*** semi-natural open habitat classes (excluding woodland, arable, improved grassland, inland rock, and urban/suburban LCM classes) and a rasterized version (10 m) of the ***Open Habitat Survey*** (Scotland) or the **Priority Habitats Inventory** (PHI; non-woodland types) (England). The ***National Forest Inventory (NFI) map*** was used to mask out areas on woodland sites that corresponded with artificial surfaces, including roads and installations such as windfarms, using the IFT attribute information.

xi. Glossary of terms

Here we provide a table providing a glossary of technical terms specific to the UK woodland planning framework and habitat descriptions used.

Table 1.9: Glossary of terms

Technical term	Definition
Ancient woodland (ASNW)	Areas of woodland that have persisted since 1600 in England, Wales, and Northern Ireland, and since 1750 in Scotland. These years are based on first known maps of woodland (Goldberg et al., 2007).

Technical term	Definition
Improved (grassland)	Grassland that is managed to improve agricultural production via fertilizer, regular reseeding, or other methods. This habitat usually has a limited range of commonly occurring or sown grasses and wildflowers.
Native woodland	Native woodland is comprised of native tree species (those that became established in the British Isles after the most recent glacial period and were not introduced by humans). The FOBI model uses the FOBI woodland stand type classes to determine woodland native status (Table 1.6), which is based on Ditchburn et al., (2020).
Niche	Niche refers to the match of a species to a specific set of environmental conditions. In the context of the current study the term 'niche' refers to the unique combinations of i) woodland type, ii) woodland structural type, and iii) microhabitat type (see Section 1.2.3 ix and Broome et al., (2019).
Semi-natural (habitats)	Habitats that have been 'created by traditional human activities and require maintenance through management, such as grazing, coppicing, cutting or burning' (Ridding, 2021). The intensive history of human occupation in the UK means even very natural ecological assemblages are generally referred to as 'semi-natural' .

1.2.4 Calculating the metrics: final metric calculations

i. Ancient Woodland Cover

Ancient woodland sites are extracted from the ***Ancient Woodland Inventory*** maps (Table 1.2; excluding Plantation on Ancient Woodlands in England (not mapped in Scotland)). Any overlap with non-native subcompartment types is removed (England and Scotland; Table 1.6). This is converted to a 50 m raster, which is used to calculate the percentage cover of mapped ancient semi-natural woodland across each FOBI woodland unit (%).

Limitations: The Ancient Woodland Inventories are currently under review in both countries to integrate smaller ancient woodland fragments (≥ 0.25 ha, current minimum mappable unit is 2 ha) and to integrate other associated types such as wood pasture and parkland.

ii. Woodland Size and Core Area

Some FOBI woodland units are adjacent to private woodlands and sit within larger areas of contiguous woodland habitat. As the size of the ***woodland habitat*** unit that a FOBI woodland unit sits within is expected to be more ecologically meaningful as a biodiversity indicator, the FOBI approach measures the area of this surrounding woodland habitat unit (Woodland Size; ha), minus an internal 50 m buffer from the woodland habitat unit's edge (Core Area; ha). More complex shaped woodlands receive lower Core Area scores than more compact woodlands of a similar size.

iii. Deadwood Production Capacity

Deadwood volume data is not collected on the ground and reported as part SCDB survey. Instead, the FOBI approach estimates the deadwood volume (m^2/ha) expected to be left on site by deadwood type, according to the deadwood source and likely management system (Figure 1.2). All tree allometric feature estimates (***dbh***, ***tree top height*** and volume) were generated using Forest Yield model algorithms (Mathews et al., 2016) described in 1.3.iv. The following deadwood components were estimated:

- Full retention of deadwood volume arising from stem, stump, roots & crown is assumed for those trees predicted to die via windblow (Figure 1.2, C) or competition between trees in unthinned stands (Figure 1.2, A).
- Both the estimated source of deadwood and the degree of retention of deadwood from felling (of the previous rotation, assuming the same tree composition as current rotation; Figure 1.2, A & B)) and thinning operations (from current rotation; Figure 1.2, B) are subject to the management system assigned to any given SCDB component. In stands designated as nature reserves (***land management alternative (LMA) 1***) deadwood is sourced from the entire tree (stem, stump, roots & crown) and 100% retention is assumed. In contrast, 10% of the stem is assumed to be retained and 100% of the stump, root, and crown in stands corresponding to:
    - Continuous cover forestry (***LMA3***)
    - Long term retention (**LMA4)**
    - Long-established of planted origin 'LEPO' ***FOBI woodland structure type***
    - Overlap with the ***Ancient Woodland Inventory***

  For all other thinned or felled sites, 100% retention is assumed for deadwood sourced from stump, root, and crown material.

- For clearfell sites (Figure 1.2, D), where information on the previously felled trees is unavailable, a national mean of deadwood volume (of stump, roots and crown material) per hectare arising from felling sources is assigned.

To remove a small number of large outliers, this metric was capped at the value of 1000 m^2/ha.

Limitations: This approach provides a modelled estimate of the capacity of a woodland subcompartment or FOBI woodland unit to produce deadwood rather than a recording of deadwood found on site. Deadwood decay is not estimated, but only deadwood resulting from the current rotation is accounted for (or from the previous rotation for felled areas).

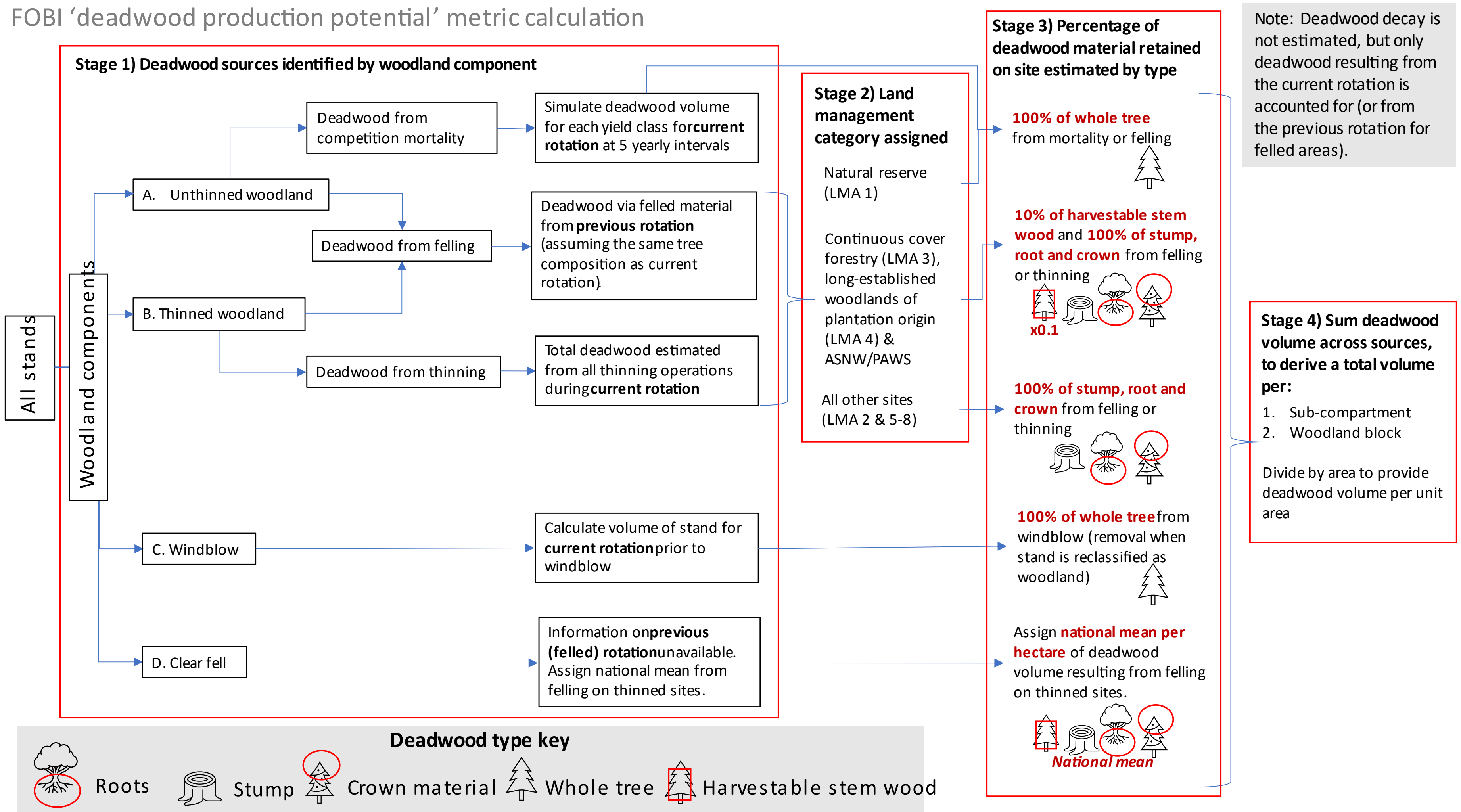


Figure 1.2: Schematic for the methodology used to generate 'deadwood production potential' metric

iv. Gappyness

In the absence of survey data on canopy closure, estimated ***mean basal area*** values (which represent the estimated mean cross-sectional area at breast height of all tree components per hectare) were used as a proxy. Higher mean basal area values were assumed to predict lower levels of canopy openness, or 'gappyness'. This metric has been shown to display an n-shaped association with some taxa (Table 1.1), where 10-15 m^2/ha basal area (assumed to reflect a canopy cover of around 70% (Hale et al., 2009 and personal communication; Kennedy and Southwood, 1984)) is used to represent the highest biodiversity value (e.g., Košulič et al., 2016). Therefore, raw ***mean basal area*** estimates are transformed to a 0-1 scale, whereby this optimal range of 10-15 m^2/ha mean basal area was attributed a value of one, decreasing linearly either side to zero value at 30 m^2/ha and 0 m^2/ha mean basal area (Figure 1.3).

Limitation: This is a modelled estimate of canopy openness based on predicted mean basal area values. It is therefore subject to some uncertainty. Optimal values are assumed based on limited evidence in the scientific literature. In reality, this will vary between taxonomic groups and forest contexts.

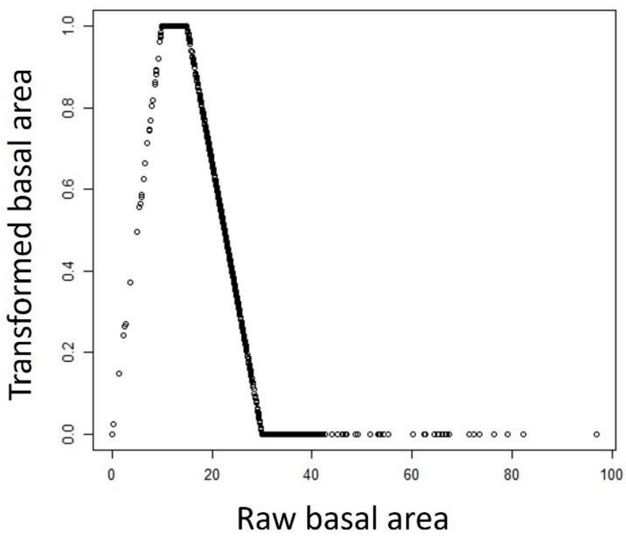


Figure 1.3: Plotted relationship between raw mean basal area ***and transformed gappyness values***

v. Landscape Land Cover Diversity

This metric is generated by calculating the effective number of ***Land Cover Map*** land cover types (of a total of 21 types) that occur within a 1 km buffer around each FOBI woodland unit.

vi. Landscape Permeability

The percentage cover land cover types classified as 'permeable' to woodland species (non-urban, semi-natural habitats with the exception of improved grassland and arable), as defined by the ***open semi-natural habitat map*** and ***woodland habitat map,*** within a 1 km buffer a FOBI woodland unit.

vii. Landscape Stand Structure Diversity

The effective number of ***FOBI woodland structure types*** intersecting a 1 km buffer around a FOBI woodland unit.

Limitation: This metric only accounts for woodland on the public forest estate, as data on structure types is not available (and could not be generated using the same methods) for private stands.

viii. Landscape Stand Type Diversity

The effective number of ***FOBI woodland stand types*** falling within a 1 km buffer around each FOBI woodland unit.

Limitation: This metric only accounts for woodland on the public forest estate, as data on structure types is not available (and could not be generated using the same methods) for private stands.

ix. Landscape Woodland Aggregation

The degree to which woodlands mapped as part of the ***woodland habitat map*** (25 m resolution) are spatially aggregated (clumped) within a 1 km buffer of the woodland block. The aggregation index was calculated using the 'landscapemetrics' R package (Hesselbarth et al., 2019).

x. Landscape Woodland Connectivity

An index of connectivity between a FOBI woodland unit and surrounding woodlands. This approach accounts for both the area and spatial configuration of surrounding woodlands (using the ***woodland habitat map***) using a negative exponential dispersal function and incidence function model (IFM; (Watts and Handley, 2010)):

$$S_i = \sum_{j \neq i} A_j e^{-aD_{ij}}$$

Where A_j is the area of a surrounding ***woodland habitat map*** unit, j (spatially contiguous area of woodland; area used as a surrogate for population size or carrying capacity), and e is the natural exponent. α describes the rate at which woodland dependent species are expected to move between woodland units, based on the percentage of dispersers reaching a specific distance. In this case a negative exponential dispersal function was set to represent 5% of dispersers reaching 400 m and 99.9% of dispersers reaching 922 m (Eycott et al., 2011). D_{ij} is the Euclidean distance between the FOBI woodland unit, i, and the surrounding ***woodland habitat map*** unit, j (a search distance cut off is applied at 922 m - woodlands beyond this distance from FOBI woodland unit i are not accounted for). Therefore, the contribution from ***woodland habitat map*** unit j to the FOBI woodland unit i will decline along a negative exponential dispersal function. S_i is the sum of the contribution from all surrounding woodland habitat units to the target FOBI woodland unit.

The method utilises the 'st_distance' function within the 'sf' package (Pebesma, 2018; Pebesma and Bivand, 2023)to calculate the distances between each FOBI woodland unit and surrounding woodland habitat units.

Limitations: Because this metric accounts for the entire area of any ***woodland habitat map*** unit within the 922 m search distance, small modifications to a landscape that result in the inclusion or exclusion of large units within this search distance can result in large year-to-year differences in the indicator results (this is particularly true for regions with large areas of spatially contiguous woodlands, such as in parts of Scotland). End users also reported finding the resulting raw output scale hard to interpret. Future modifications could involve only including the portion of a woodland that falls within the search distance, which would enable for the normalisation of scores by the area of the search window.

xi. Landscape Woodland Cover

The percentage cover of all woodland habitat, as defined by the ***woodland habitat map,*** within a 1 km buffer around each FOBI woodland unit.

xii. Landscape Woodland Size Diversity

The standard deviation in Woodland Size of all ***woodland habitat map*** units, intersecting a 1 km buffer around each FOBI woodland unit.

xiii. Microhabitat Richness (England only)

The number of ***Niches for Species microhabitats*** of a potential total of twelve (Table 1.8) predicted to be present within a FOBI woodland unit.

xiv. Native Woodland Cover

The percentage area of a FOBI woodland unit's tree canopy (excluding open and felled areas) that is comprised of subcompartments that are classified as native ***FOBI woodland stand types*** (Table 1.6).

xv. Oldest Tree

The age of the oldest planted tree recorded via the SCDB in the FOBI woodland unit.

Limitations: retained veteran and ancient trees that have not been planted are typically not recorded as part of the ***SCDB*** and so are not captured by this metric. Planting year information provided by the ***SCDB*** and ***woodland component tables*** are sometime missing or erroneous (a series of sense-checking rules were put in place to try to detect and correct for these instances where possible), in which case this metric could not be calculated.

xvi. Open Habitat Cover

The percentage area of open semi-natural habitats (according to the ***open semi-natural habitat map***) and felled woodland (according to the ***National Forest Inventory (NFI) map***) within a FOBI woodland unit and between any spatially disparate parts (separated by ≤100 m) of a FOBI woodland unit. A minimum convex polygon around each FOBI woodland unit was generated using the 'mcp' function of the 'adehabitatHR' R package (Calenge, 2006) and used for delineating this calculation.

The relationship between woodland biodiversity and open habitat is typically non-linear (n-shaped) (Table 1.1). This metric is therefore transformed to a 0-1 scale whereby 10-25% open space is attributed an optimum value of one (Hale et al., 2009 and personal communication; Kennedy and Southwood, 1984)), decreasing linearly either side of this range to zero value at 100% and 0% open space (Figure 1.4).

Limitations: The FLS ***Open Habitat Survey data*** for Scotland is ongoing and incomprehensive. It is updated on an infrequent basis (roughly every two years).

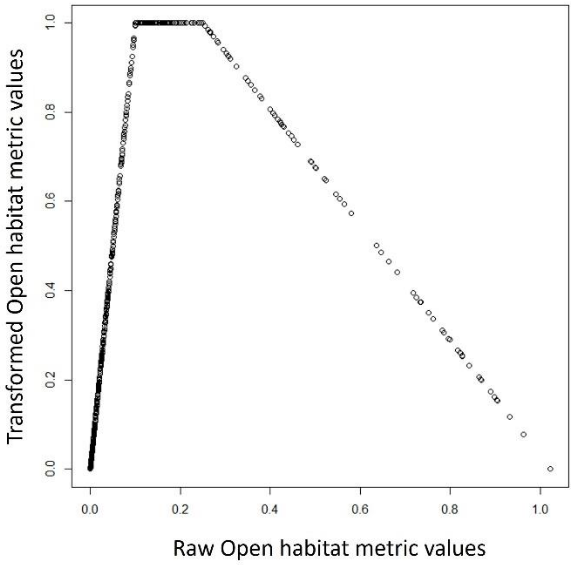


Figure 1.4: plotted relationship between raw and transformed Open Habitat Cover metric values.

xvii. Stand Type Diversity

The effective number ***FOBI woodland stand types*** that each FOBI woodland unit's subcompartments are classified into by area.

xviii. Topographic Roughness

The median ***Topographic Roughness Index*** (an index of altitudinal variation; Table 1.2) raster value across a FOBI woodland unit.

xix. Tree Age Diversity

The effective number of tree age bands (0-20, 20-40, 40-60, 60-80, 100-160, >160 years) present by area (according to the ***SCDB*** and ***woodland component tables***) within each FOBI woodland unit.

Limitations: retained veteran and ancient trees that have not been planted are typically not recorded as part of the ***SCDB*** and so are not captured by this metric. Planting year information provided by the ***SCDB*** and ***woodland component tables*** are sometime missing or erroneous (a series of sense-checking rules were put in place to try to detect and correct for these instances where possible), in which case this component was excluded from the calculation.

xx. Tree Size Diversity

The standard deviation of modelled ***tree diameters at breast height (dbh)*** values across the FOBI woodland unit.

xxi. Tree Species Diversity

The effective number of tree species present by area across the FOBI woodland unit according to the ***SCDB*** and ***woodland component tables***. Species data used for these calculations was derived from the Woodland component tables (see Table 1.2).

xxii. Vertical Complexity

The effective number of modelled ***tree top height*** bands (<2; 2-6; 6-15; >15 m) present by area for each FOBI woodland unit.

xxiii. Scotland-only niche metrics

For full details of the Niches for Species model, please refer to Broome et al., (2019).

- *Niche Availability (Scotland only)*

  The proportional area of each FOBI woodland unit that provides a potential niche (suitable ***N4S woodland stand type***, ***FOBI woodland structure typ***e and ***N4S microhabitats*** combinations, defined using expert opinion) for one or more woodland protected species (of over 130 species across a range of taxonomic groups) falling within their estimated geographic range (Broome et al., 2019).

- *Niche Diversity (Scotland only)*

  The effective number of niches (suitable ***N4S woodland stand type***, ***FOBI woodland structure typ***e and ***N4S microhabitats*** combinations) provided for one or more woodland protected species (of over 130 species across a range of taxonomic groups, defined using expert opinion) falling within their estimated geographic range (Broome et al., 2019) across a FOBI woodland unit.

Limitations: These outputs are derived from expert-based suitability models; the protected species' ranges are estimated using available species records or modelled data (Broome et al., 2019).

2. Interactive outputs

The FOBI Spatial Data Explorer (Figure 2.1) and FOBI Tracker (Figure 2.2) tools were made available to the FE and FLS users via weblinks. The public forest agencies were keen to limit use to internal users before publicising links to enable wider use, however, a demonstration version of the Spatial Data Explorer is being made available on the project website: *<removed for review anonymisation purposes>*

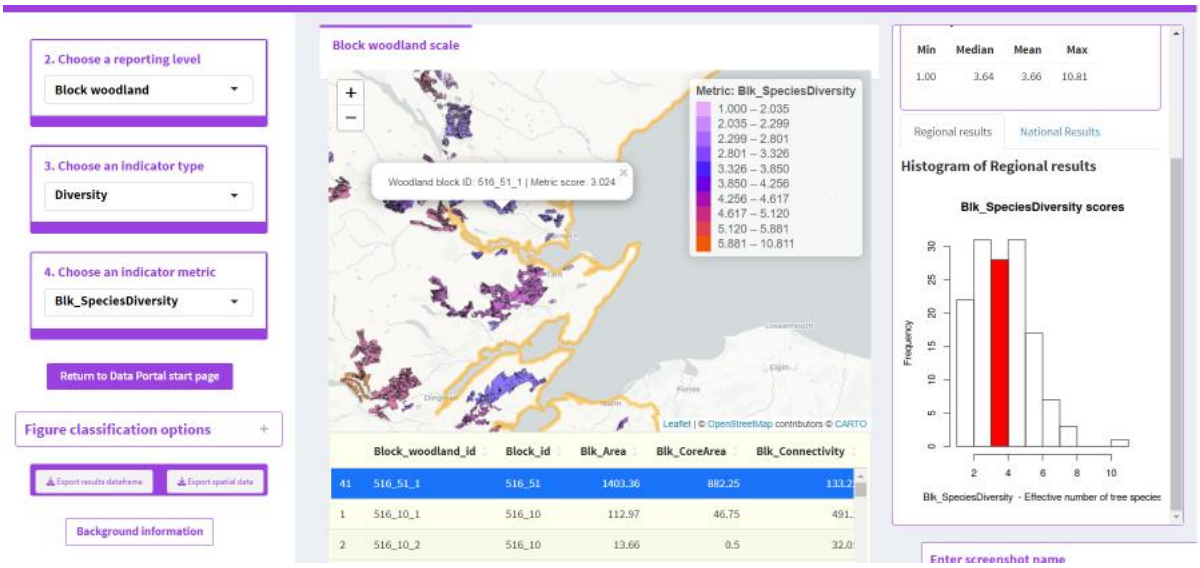


Figure 2.1: A screenshot of a the FOBI Spatial Data Explorer (v1.1), the bespoke online interactive tool co-designed for exploring an individual year's FOBI results across space.

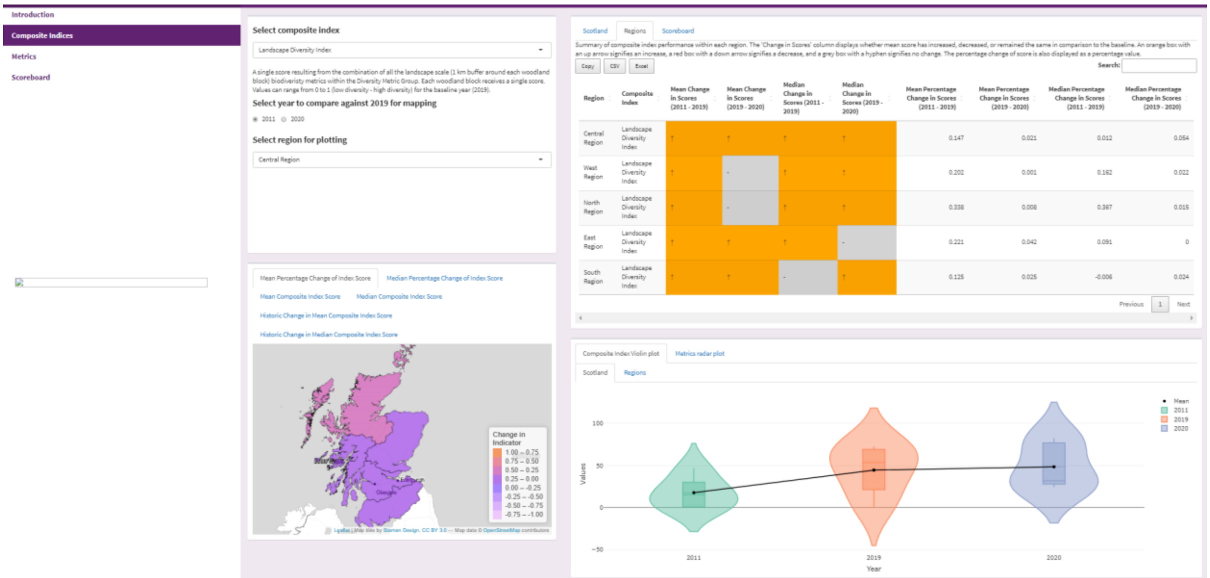


Figure 2.2: A screenshot of a the FOBI Tracker Tool (v1.1), the bespoke online interactive tool co-designed for exploring an FOBI trends over time.

3. FOBI metric and composite index statistics for England

3.1 FOBI woodland unit area and its relationship with diversity-type metrics

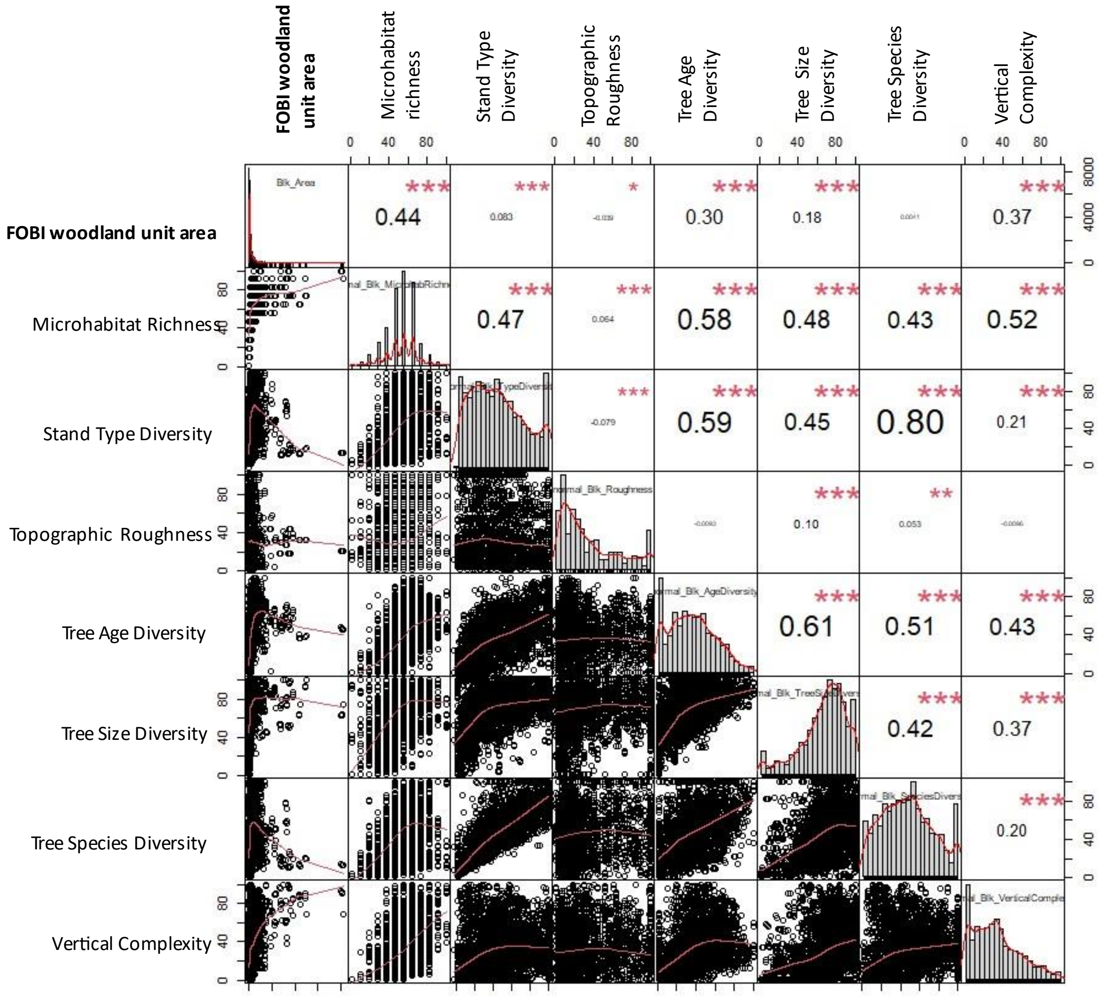


Figure 3.1: Relationship between the Local Diversity metrics and FOBI woodland unit area for England

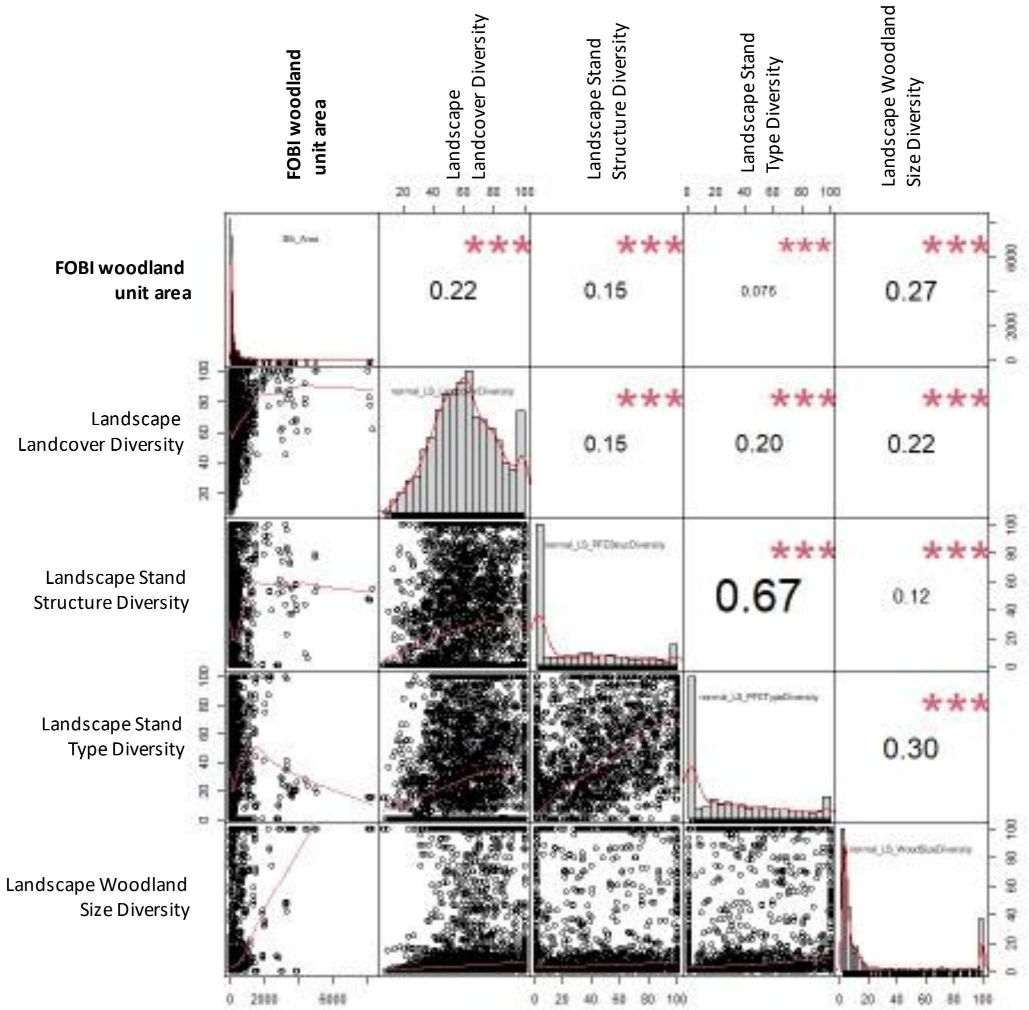


Figure 3.2: Relationship between the Landscape Diversity metrics and FOBI woodland unit area for England

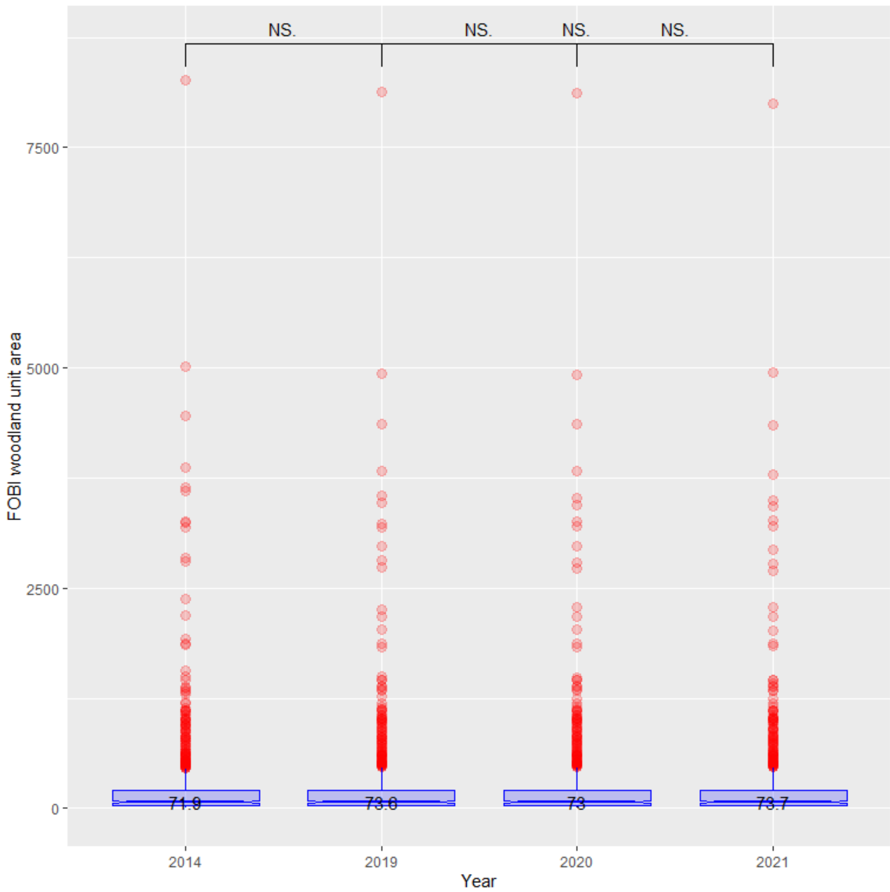


Figure 3.3: Boxplot of FOBI woodland unit area between years for England, highlighting that there has been no significant change over time according to a Bonferroni corrected t-test.

3.2 Metric benchmark values derived from the 2019 data

Table 3.1: England's 2019 'benchmark' maximum and minimum values used to remove outliers and normalise each metric before aggregation. *Metrics coloured in grey were not taken forward for aggregation.*

Metric	2019 Maximum	Final Benchmark	Benchmark Type	2019 Minimum	Final Minimum
Ancient Woodland Cover	1.0	0.3	Baseline 90th percentile	0.0	0.0
Core Area	48047.3	12745.3	Baseline 90th percentile	0.0	0.0
Deadwood Production Capacity	1000.0	502.9	Baseline 95th percentile	0.0	0.0
Gappyness	1.0	1.0	Baseline maximum	0.0	0.0
Landscape Land Cover Diversity	7.4	5.6	Baseline 95th percentile	1.3	1.0
Landscape Permeability	1.0	1.0	Baseline maximum	0.0	0.0

Metric	2019 Maximum	Final Benchmark	Benchmark Type	2019 Minimum	Final Minimum
Landscape Stand Structure Diversity	5.4	3.7	Baseline 95th percentile	1.0	1.0
Landscape Stand Type Diversity	11.3	6.4	Baseline 95th percentile	1.0	1.0
Landscape Woodland Aggregation	99.3	99.3	Baseline maximum	47.4	65.0
Landscape Woodland Connectivity	53352.3	16440.2	Baseline 90th percentile	0.0	0.0
Landscape Woodland Cover	0.9	0.5	Baseline 95th percentile	0.0	0.0
Landscape Woodland Size Diversity	37722.3	6764.8	Baseline 90th percentile	0.0	0.0
Microhabitat Richness	12.0	12.0	Baseline maximum	1.0	1.0
Native Woodland Cover	1.0	1.0	Baseline maximum	0.0	0.0
Oldest Tree	369.0	219.0	Baseline 95th percentile	5.0	1.0
Open Habitat Cover	1.0	1.0	Baseline max	0.0	0.0
Stand Type Diversity	11.3	7.1	Baseline 95th percentile	1.0	1.0
Topographic Roughness	65.0	35.0	Baseline 95th percentile	0.0	0.0
Tree Age Diversity	6.7	6.7	Baseline maximum	1.0	1.0
Tree Size Diversity	29.0	20.4	Baseline 95th percentile	0.0	0.0
Tree Species Diversity	16.1	10.1	Baseline 95th percentile	1.0	1.0
Vertical Complexity	3.9	3.9	Baseline maximum	1.0	1.0
Woodland Size	53372.7	16809.7	Baseline 90th percentile	2.0	2.0

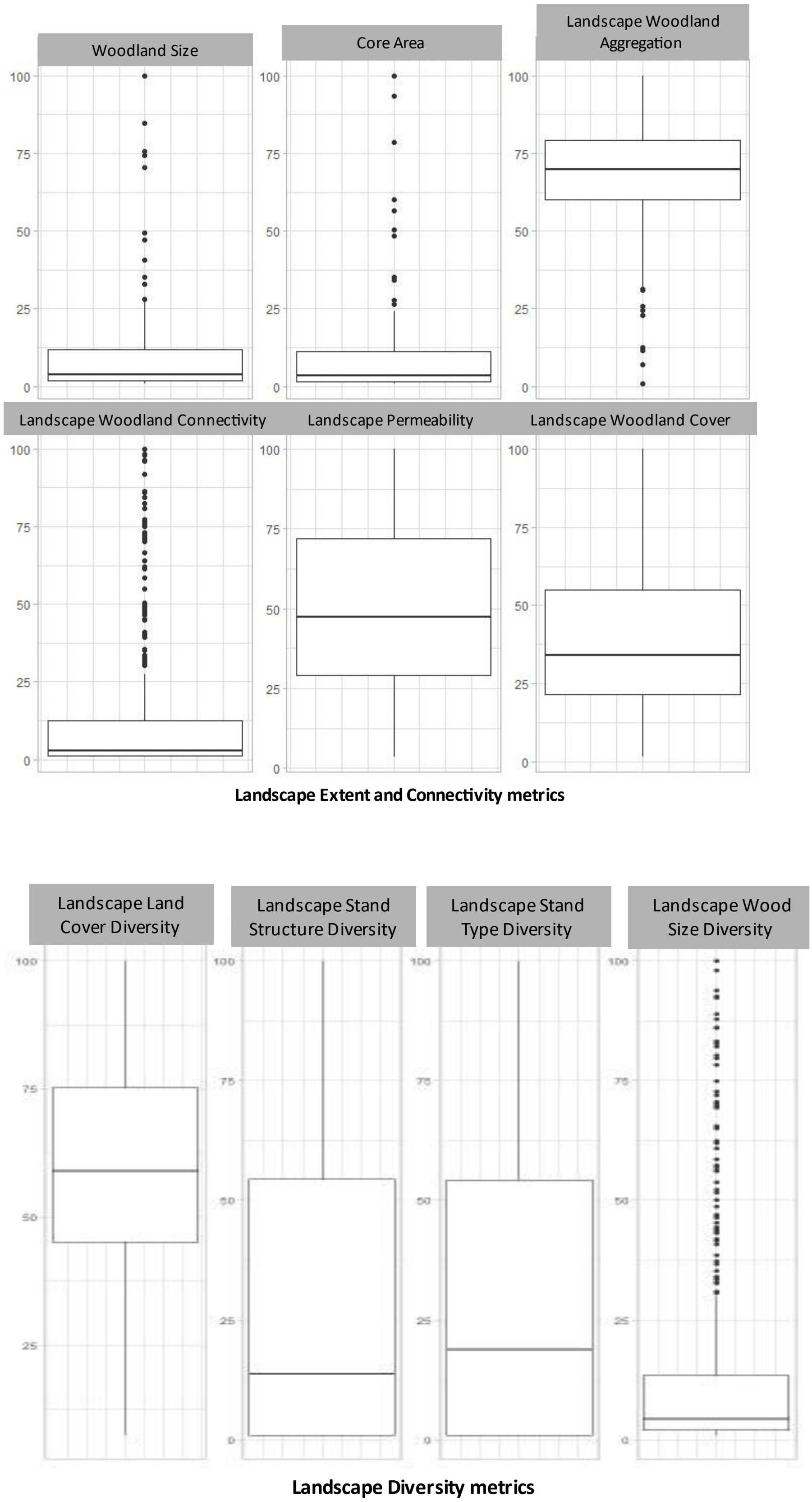
3.3 Statistical checks on normalised metrics

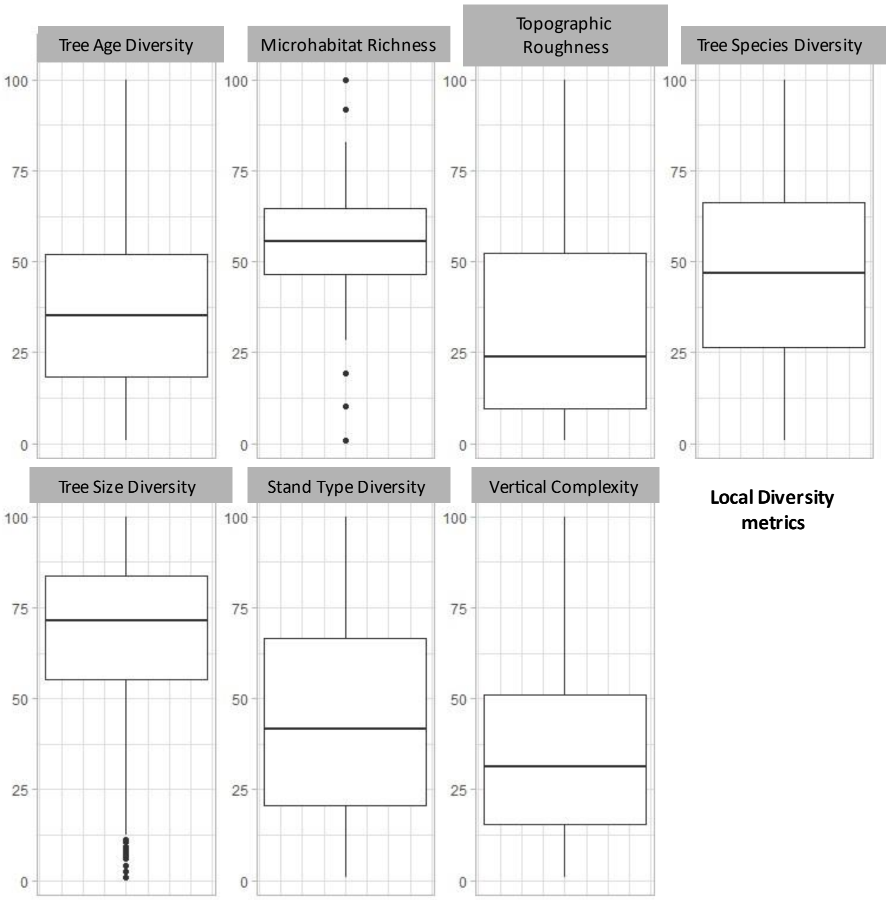
Table 3.2: Statistical checks on the for the normalised 2019 (baseline year) metrics

Metric	Min	Max	Mean	Median	Std	Skew	Kurt	Proportion unique values
Ancient Woodland Cover	1.00	100.00	20.90	1.00	33.00	1.58	0.98	0.37
Core Area	1.00	100.00	19.40	3.37	33.20	1.81	1.55	0.62
Deadwood Production Capacity	1.00	100.00	40.60	36.80	26.80	0.64	-0.34	0.92
Gappyness	1.00	100.00	48.30	48.90	32.10	-0.01	-1.13	0.76

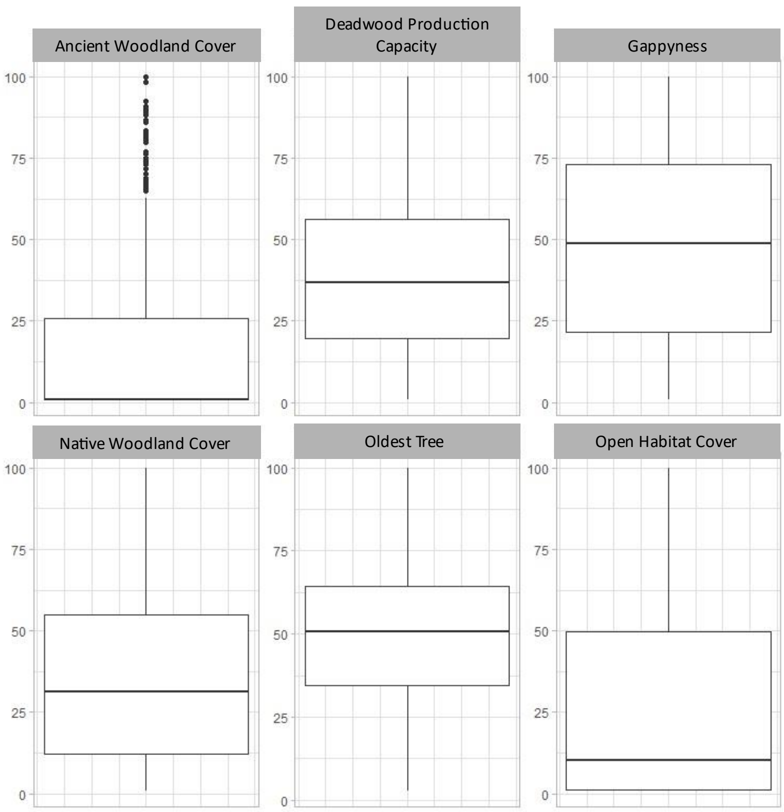
Metric	Min	Max	Mean	Median	Std	Skew	Kurt	Proportion unique values
Landscape Land Cover Diversity	7.47	100.00	60.20	58.90	21.00	0.09	-0.56	0.94
Landscape Permeability	3.71	100.00	51.20	47.30	27.20	0.36	-0.96	0.92
Landscape Stand Structure Diversity	1.00	100.00	29.40	13.80	33.30	0.81	-0.73	0.57
Landscape Stand Type Diversity	1.00	100.00	30.10	18.90	32.60	0.82	-0.64	0.55
Landscape Woodland Aggregation	1.00	100.00	68.80	69.80	14.80	-0.85	1.99	1.00
Landscape Woodland Connectivity	1.00	100.00	19.50	2.95	33.10	1.77	1.45	0.90
Landscape Woodland Cover	1.76	100.00	40.50	34.20	25.70	0.82	-0.10	0.95
Landscape Woodland Size Diversity	1.00	100.00	19.50	4.27	31.90	1.83	1.75	0.86
Microhabitat Richness	1.00	100.00	54.00	55.50	15.30	-0.25	0.64	0.01
Native Woodland Cover	1.00	100.00	37.10	31.40	29.50	0.71	-0.52	0.87
Oldest Tree	2.83	100.00	52.40	50.50	23.50	0.33	-0.51	0.16
Open Habitat Cover	1.00	100.00	29.00	10.20	35.20	1.03	-0.47	0.67
Stand Type Diversity	1.00	100.00	44.90	41.70	29.00	0.35	-0.92	0.92
Topographic Roughness	1.00	100.00	34.20	23.90	29.40	0.94	-0.32	0.06
Tree Age Diversity	1.00	100.00	36.10	35.10	23.10	0.31	-0.60	0.91
Tree Size Diversity	1.00	100.00	67.20	71.30	23.20	-0.92	0.53	0.93
Tree Species Diversity	1.00	100.00	47.60	46.70	26.70	0.23	-0.77	0.93
Vertical Complexity	1.00	100.00	34.50	31.30	24.30	0.58	-0.38	0.91
Woodland Size	1.00	100.00	19.60	3.62	33.00	1.80	1.52	0.63

Figure 3.4: Boxplots of the normalised 2019 (baseline year) metrics





Local Diversity metrics



Local Condition metrics

3.4 Correlation analysis results

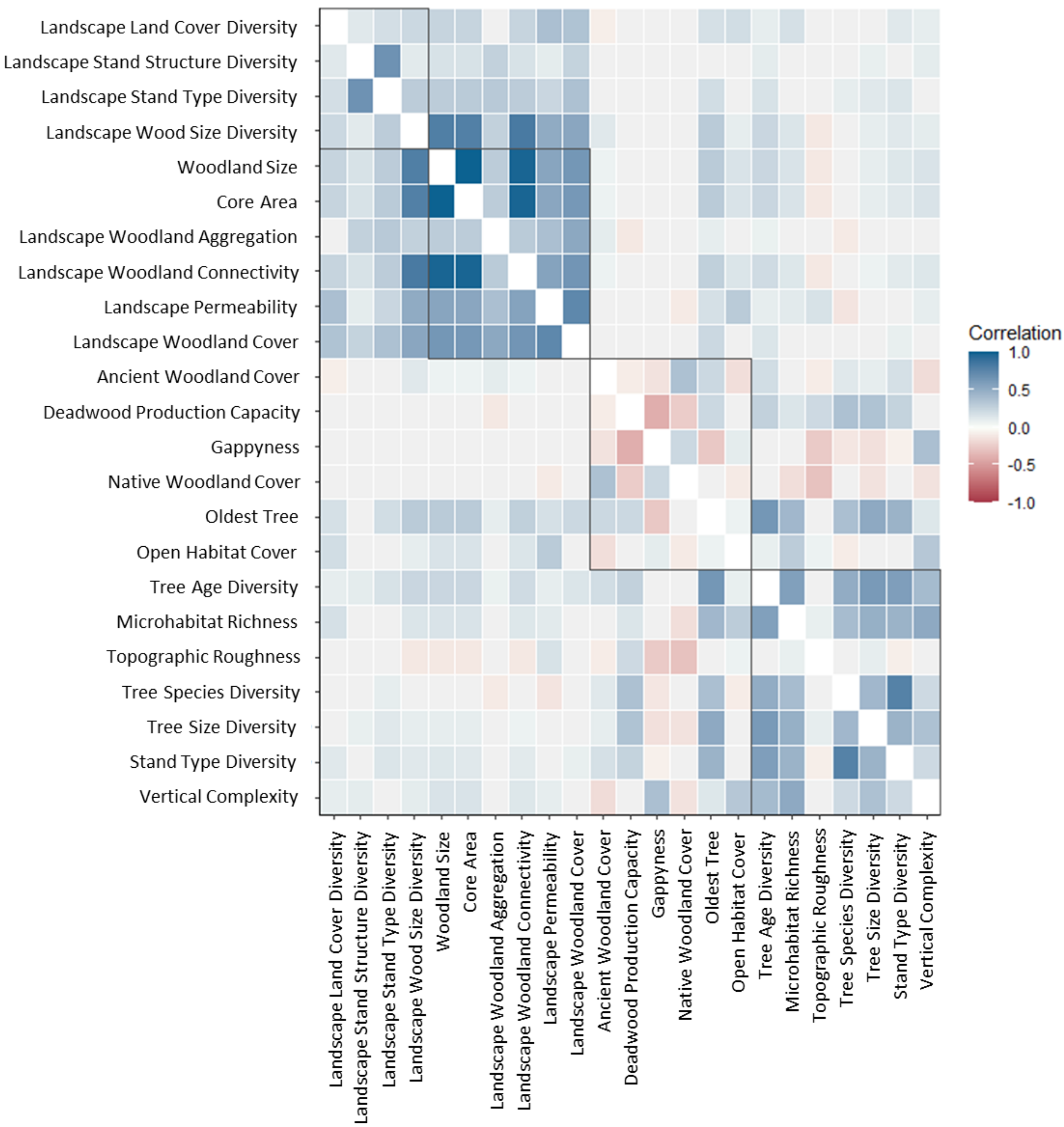


Figure 3.5: Correlation matrix showing the degree to which all FOBI metrics are correlated according to the Pearson's rank correlation coefficient.

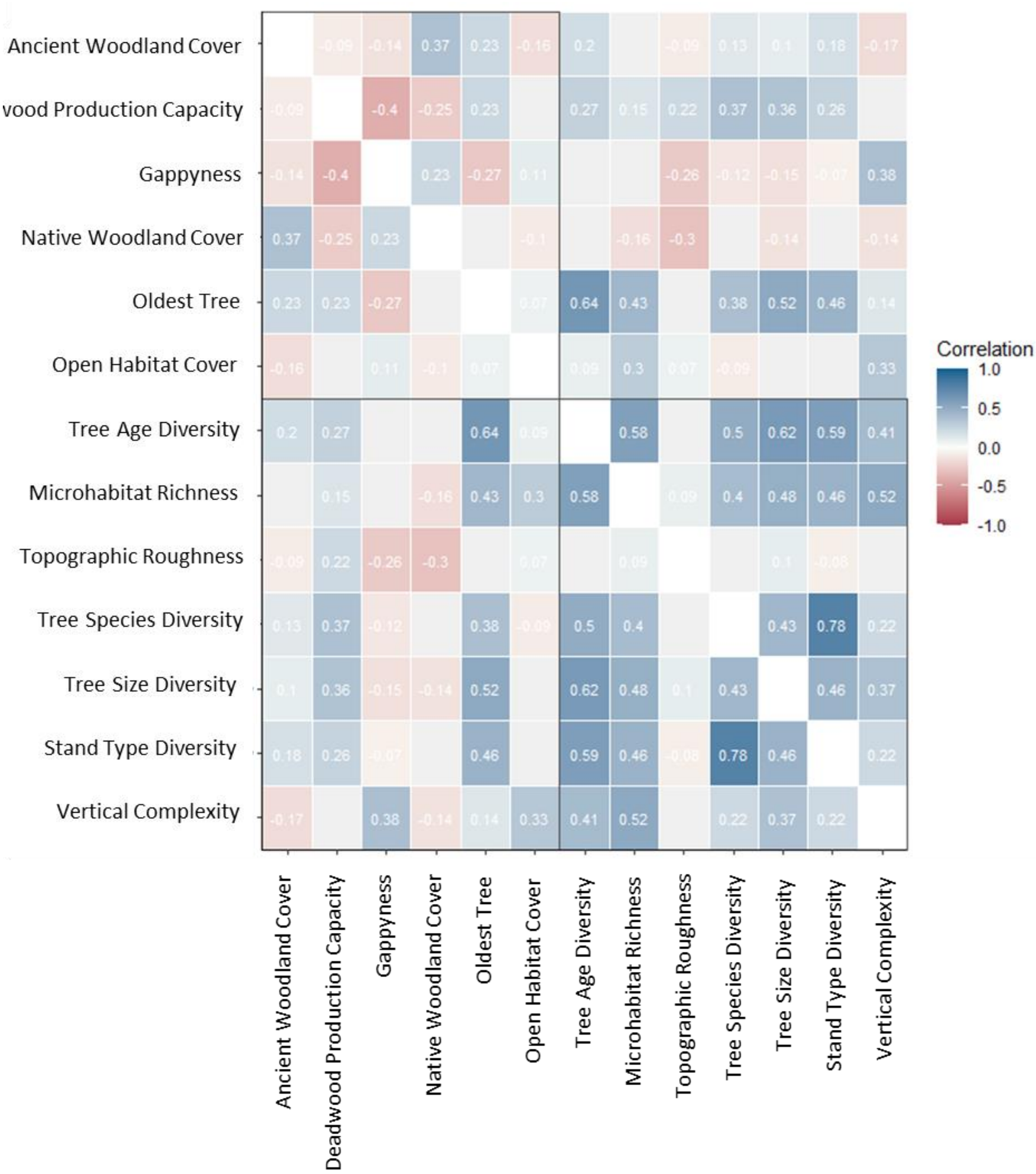


Figure 3.6: Correlation matrix showing the degree to which FOBI metrics within the Local scale grouping are correlated according to the Pearson's rank correlation coefficient.

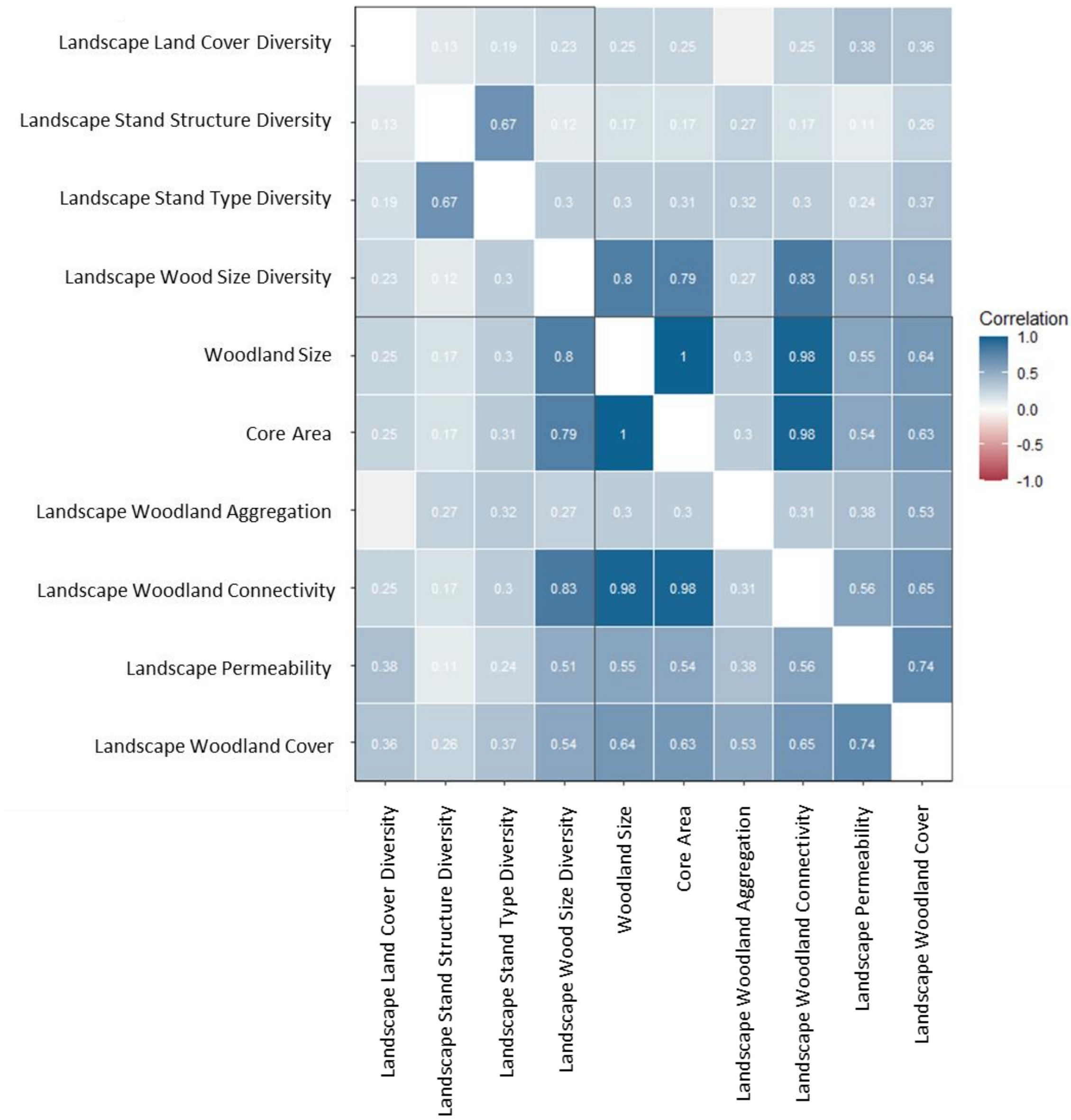


Figure 3.7: Correlation matrix showing the degree to which FOBI metrics within the Landscape scale grouping are correlated according to the Pearson's rank correlation coefficient.

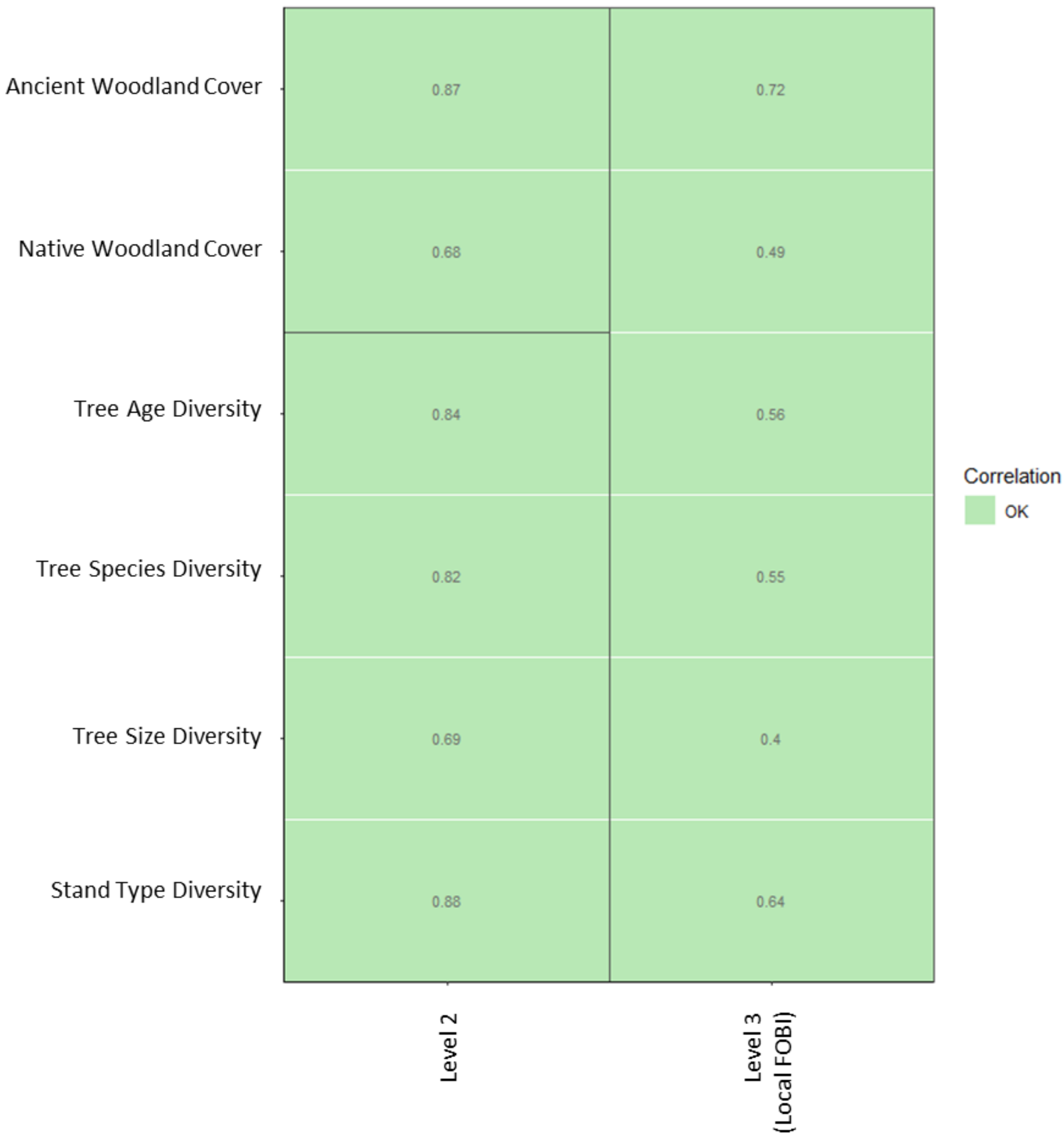


Figure 3.8: Correlation matrix showing the degree to which FOBI metrics included for aggregation within the Local FOBI are correlated with the Level 2 and 3 composite indices, according to the Pearson's rank correlation coefficient.

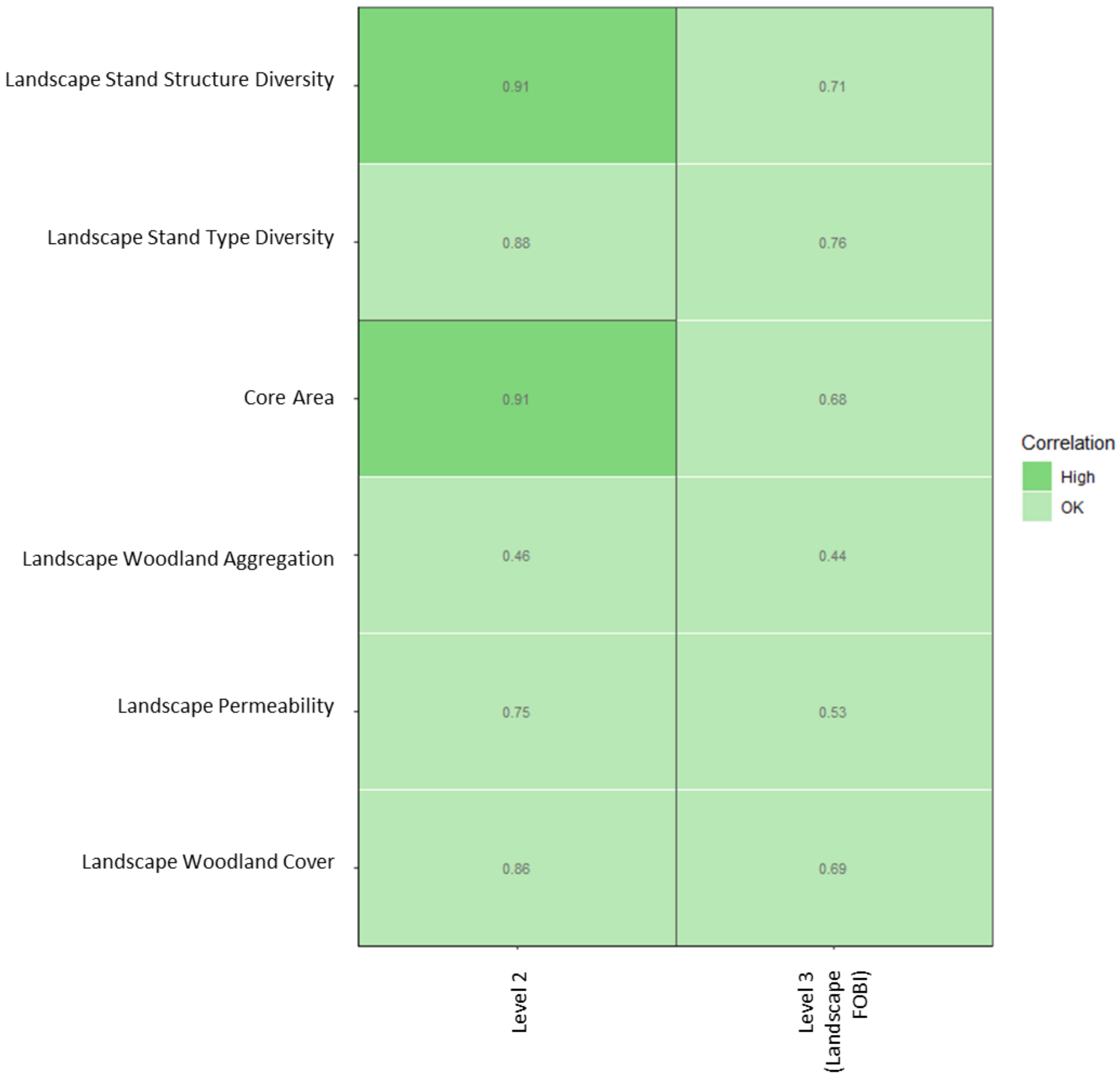


Figure 3.9: Correlation matrix showing the degree to which FOBI metrics included for aggregation within the Landscape FOBI are correlated with the Level 2 and 3 composite indices, according to the Pearson's rank correlation coefficient.

3.5 Weighting

Table 3.3: Statistical results for the different weighting procedures tested

Local Biodiversity Index					
Weighting system		**Equal Metric Weights**	**Equal Metric Weights**	**Equal Level 2 Subindex Weights**	**Equal Level 2 Subindex Weights**
Weights set		**Manually**	**Optimised weights**	**Manually**	**Optimised weights**
Cronbach's Alpha	Local Diversity Index with metrics	0.84	0.84	0.84	0.84
	Local Condition Index with metrics	0.54	0.54	0.54	0.54
	Local Biodiversity Index with Level 2 sub-indices	0.33	0.33	0.32	0.32
	Sum	1.71	1.71	1.70	1.70
Silent metrics at any level?		No	No	No	No
Local Diversity correlation with Local Biodiversity Index		0.83	0.82	0.68	0.68
Local Condition correlation with Local Biodiversity Index		0.64	0.66	0.79	0.79
Condition:Diversity correlation with Local Biodiversity Index ratio		1.30	1.24	0.86	0.86
Level 3: Local Condition and Local Diversity correlation		0.19	0.2	0.19	0.19
Landscape Biodiversity Index					
Weighting system		**Equal Metric Weights**	**Equal Metric Weights**	**Equal Level 2 Subindex Weights**	**Equal Level 2 Subindex Weights**
Weights set		**Manually**	**Optimised weights**	**Manually**	**Optimised weights**
Cronbach's Alpha	Landscape Diversity Index with metrics	0.80	0.80	0.80	0.80
	Landscape extent and connectivity Index with metrics	0.80	0.80	0.80	0.80
	Landscape Biodiversity Index with Level 2 sub-indices	0.39	0.39	0.39	0.39
	Sum	1.99	1.99	1.99	1.99
Silent metrics at any level?		No	No	No	No
Landscape Diversity correlation with Landscape Biodiversity Index		0.75	0.75	0.59	0.61
Landscape Extent and Connectivity correlation with Landscape Biodiversity Index		0.78	0.78	0.90	0.88
Diversity: Condition correlation with Local Biodiversity Index ratio		0.96	0.96	0.66	0.69
Level 3: Local Condition and Local Diversity correlation		0.25	0.25	0.25	0.25

3.6 FOBI trends over time

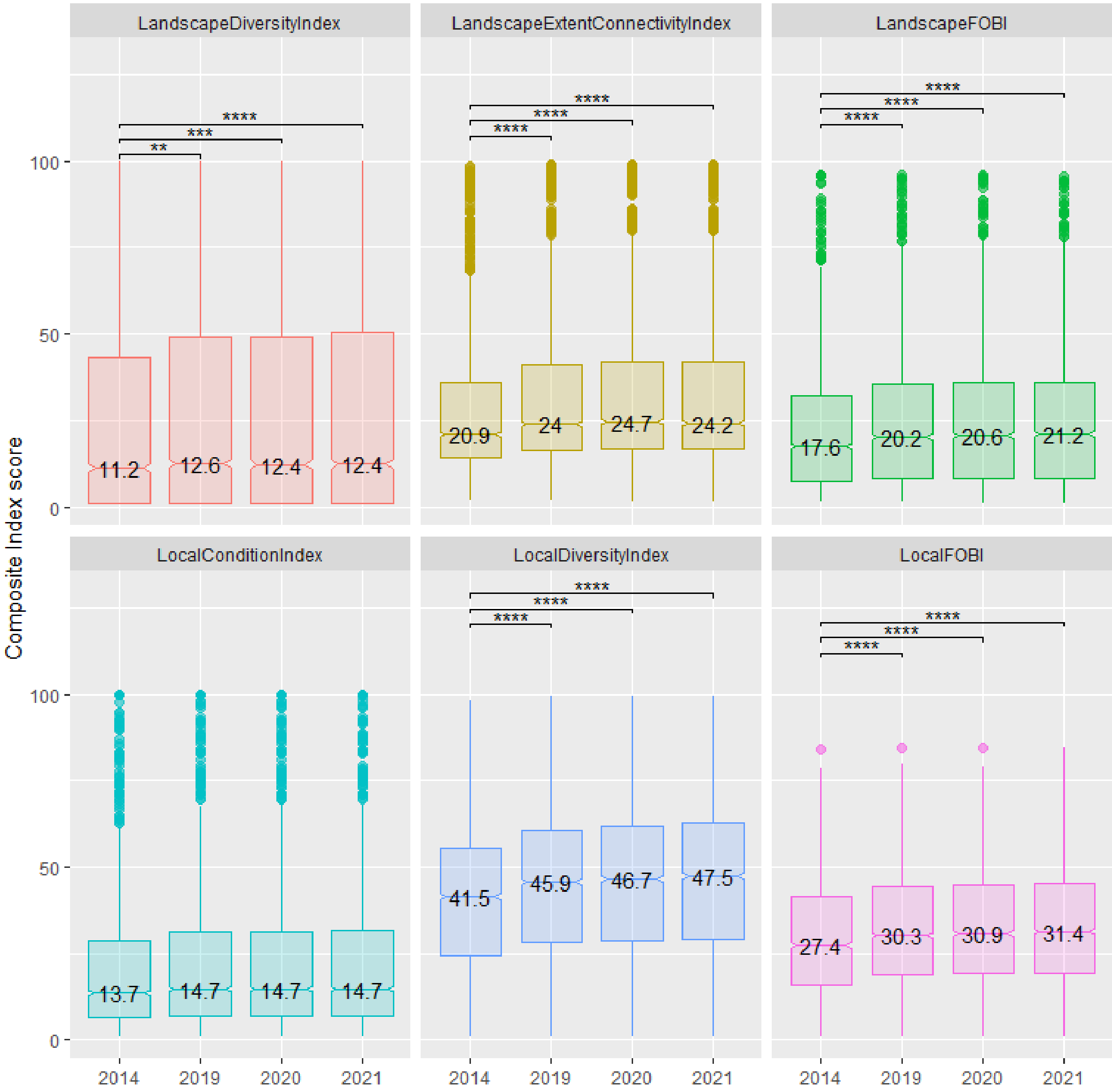


Figure 4.0: Boxplot of the FOBI composite index scores by year for England. Median scores for the year are labelled. *Statistically significant changes between years are indicated according to a Bonferroni corrected t-test (** p<0.01, *** p<0.001, **** p<0.0001).*

a)

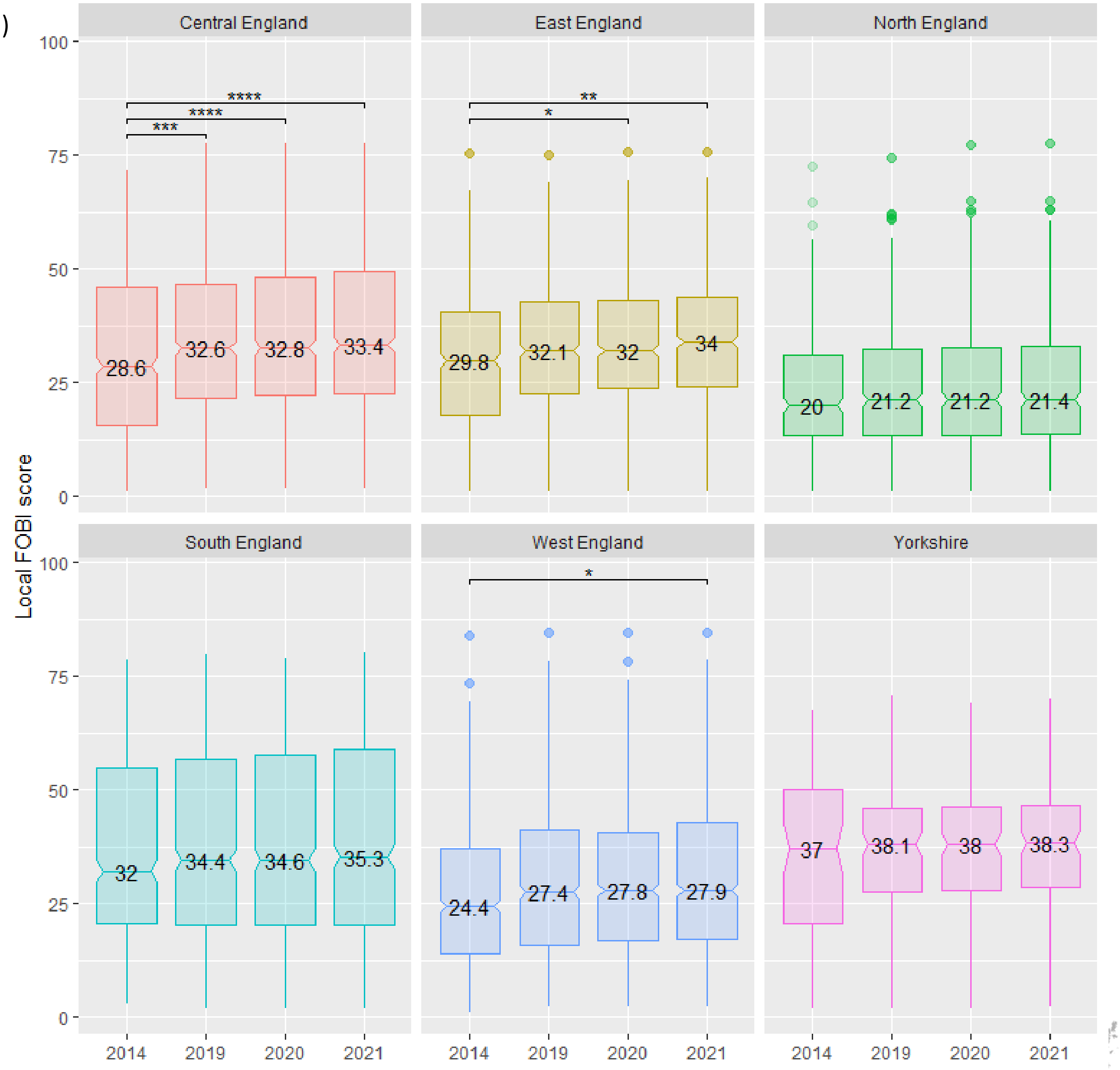


*Figure 4.1: a) **Boxplot of the Local FOBI results by year for England, broken down by the Public Forest Estate Region.** Median Local FOBI scores for the year are labelled. Statistically significant changes between years are indicated according to a Bonferroni corrected t-test (* p<0.05; ** p<0.01, *** p<0.001, **** p<0.0001). **b) Map of Great Britain with the Public Forest Estate Regions in England***

b)

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