Missing the Forest for the Trees: Survey Approaches for Monitoring Scottish Woodland Plant Biodiversity

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Executive Summary

Plants form the core of ecosystem health and provide countless benefits to humans, animals, and landscapes. Forests are especially beneficial, yet Scottish woodland biodiversity is poorly understood below the tree canopy. This survey proposes a two-tiered method to evaluate whole-forest biodiversity, from treetops to soil shrubs, evaluating diversity in this category of plants called *Tracheophyta*. By (1) traditionally censusing a few representative plots to inform (2) a satellite-based remote sensing model, this survey's modern approach neatly fits into UK and EU reporting schemes to quantify how many plants are supported by different Scottish wood types and generalise this diversity nationwide. Analysis proposes looking at both time-specific as well as between-time change measures to maximise utility for stakeholders: these dual approaches allow for a neat fit within the Scottish government's portfolio of climate change indicators thanks to explicit comparability with baseline surveys in 2001 and 2014.[1,2] Though these surveys build on existing baselines, they cannot be used to perfectly identify individual species as remote sensing currently peaks at 75% accuracy with existing methods and proposed data.[3] Thus, our survey aims to provide a representative lower bound estimate for cumulative Scottish forest biodiversity to dovetail existing moss, tree, and other monitoring schemes.

Surveying Vegetation

Below the trees, Scottish forest understorey species remain quite understudied.[4] Current knowledge about these vascular plants' (a.k.a., tracheophyte) biodiversity stems from three sources: the Native Woodland Survey of Scotland (NWSS), the National Forestry Inventory (NFI), and the National Plant Monitoring Scheme (NPMS) (Figure 1). While the NWSS is Scotland-specific, the NFI and NPMS both run across the UK with differing aims: the NFI focusses on forest canopy composition for anthropogenic management (e.g., timber harvesting) while volunteers conduct NPMS surveys biased around population centres in the south and east of Scotland.

All three surveys classify landscapes based on "type" rather than taxonomy. The NPMS discriminates 13 landscapes with only two forest types—conifer and broadleaves; the NFI has 8 forests types of varying stand density (e.g., open, felled, coppiced); and the NWS uses 5 National Vegetation Classification (NVC) types across 20 Habitat Action Plan (HAP) types in tandem to account for natural vegetative heterogeneity.[5,6,7] Though plant functional biodiversity work can also derive from traits rather than taxonomy, such approaches remain unfeasible for large-scale monitoring.[8]

To match Scottish and British governmental designations, our survey prefers the Scottish Forestry NVC-HAP classification system with its accessible, consistent methodology.[7,9,10] We proposes a two-tiered process using (1) field surveys of NVC-HAP representative sites to estimate species richness and diversity across (2) interpolated NVC-HAP classifications using space-based remote sensing.

Proposed surveys would utilise stratified annual samples, generating 5 x 5 metre (i.e., 25 m^2 area) plots within 600 woods across 20 Scottish HAP types (30 woods per HAP annually) during peak plant growth between April and August.[1] Plots would split between two sites, one around woods' poles of inaccessibility—its most internal point—with the other within 20 metres of the forest boundary to measure edge effects.[11,12] Each site should be surveyed with at least two plots, recording all vascular plant species' abundance—including trees (Figure 2). Across the 20 year survey, each wood will be sampled four times (i.e., in five-year increments) to understand temporal dynamics.[13] In cases of wholescale deforestation and other logistical challenges (e.g., natural hazards), surveyors would ideally select the nearest similar wood instead without introducing major error.[14] Resulting data would generate a row per species per plot with species-specific counts and plot and site-level covariates.

Generalising Data

Supplementary data would record site climate (e.g., temperature, precipitation) and locations. Given growing changes to growing season and conflicting trends (e.g., temperature above 5.5°C versus frost days) in Scotland, these data can mitigate some (ideally random) spatiotemporal heterogeneity across plots, sites, and years.[15,16] Potential bias is uncertain: larger, mature plants are more likely to be omnipresent, but the few trees (the most identifiable tracheophytes) within a single plot and short understorey growing season may minimise specific bias given that all plants—trees included—start from small seedings. Nevertheless, species-specific covariates about growth time may prove helpful additions after-the-fact, like sprouting probability, average sprouting time, and later growth over time. At minimum, these factors can control for temporal heterogeneity across the survey period. Resampling and bootstrap calculation based on these covariates can help generate uncertainty for occurrence and abundance and carry through biodiversity derivations.[17]

Remote sensing imputation will leverage field variables and specific light wavelengths (i.e., bands) to impute indices for unsampled areas using normalised difference vegetation vigour indices (NDVVI) and narrowband vegetation indices (NBVIs). The latter derives specific drivers of species turnover by comparing reflectance wavelengths to derive bands most sensitive to specific causal variables (e.g., moisture or temperature) that drive observed trends among surveyed sites.[18] Further accounting for canopy openness will uniquely improve diversity estimates.[19] Notably, realistic model design allows identifying specific band reflectance from understory vegetation, giving good understorey biodiversity estimates.[20]

Thus, this survey straddles affordability and feasibility to survey with (1) representative sampling locations, (2) representative species sampling, (3) sufficient locations, (4) sufficient detectability, and (5) appropriate temporal resolution.[21] With (1) 600 sites and 4 plots, (2) a complete within-plot census, (3) 150 sites per habitat type, and (5) quinquennially repeated surveying, the survey uses remote sensing to (3) generalise to physically unsurveyed areas and (4) quantify detectability. Nonetheless, we invariably underestimate richness and diversity and instead generate a lower bound estimate for total Scottish tracheophyte biodiversity in forested woodlands. Uncertainty about climate-dependent species-specific dynamics also limit weather variables' controls for heterogeneous abundance trends and necessitate more local-scale research.[22]

Analysing Biodiversity

Limited sample coverage implies that observed species like also exist outside surveyed plots: given vegetative heterogeneity, measures of richness thus maximise intuitive interpretability for stakeholders. Unsurprisingly, existing research on site plant richness most often uses raw species counts and the Chao2 index.[23] Our particular sampling strategy suggests that more specialised alternatives like Chao's adjusted estimator, which combines Horovitz-Thompson with the Shannon index, would provide better unbiased estimates.[24]

But unlike diversity, spatiotemporal species richness sacrifices most abundance data.[25] When measuring α and β-diversity, common species are relatively less important given likely underestimation of abundance: Shannon diversity would suit us better than Simpson's diversity while remaining comparable to most literature, unlike Hill numbers with negative alpha values.[11,26,27]

In contrast, γ-biodiversity measurements mainly leverage dissimilarity measures: turnover metrics—Morisita-Horn and Jaccard indices—especially suit this analysis's spatiotemporal pairwise comparisons. With Morisita-Horn more sensitive to prevalent species' relative abundance, Jaccard better suits our objectives.[28] However, γ-diversity metrics decrease usable data for inference (e.g., 4 surveyed periods generate 3 turnover metrics) and less commonly appear in vegetation biodiversity monitoring. Nonetheless, both Jaccard's index and Shannon's diversity appear in previous British forest understorey biodiversity estimation, but richness and turnover must be cumulatively evaluated to overcome individual metric limitations. [29,30]

Moreover, remote sensing imputation allows exploring many alternative measures of dissimilarity and diversity—too numerous to enumerate here.[26,30] Notably, such methods include built-in error estimates that match or exceed utility of traditional bootstrap errors: examples include regression analysis, Bayesian state-space models, and machine learning predictions.[31]

With such computational strategies, our survey—by measuring across and accounting for representative gradients—aims to meaningfully estimate minimum forest tracheophyte biodiversity and support monitoring and analysis of ecological trends.

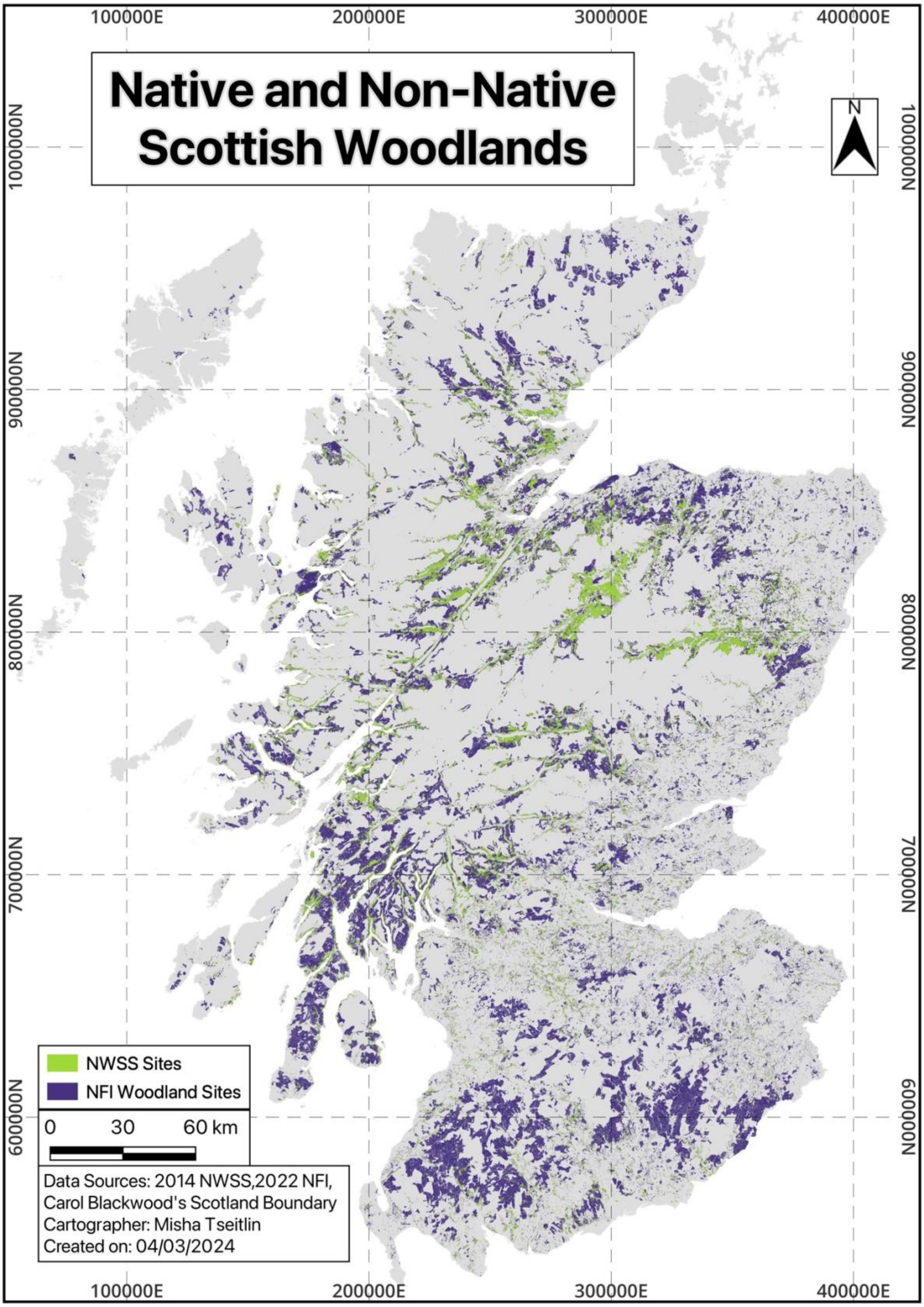

Figure 1: Surveyable woods per the 2014 National Woodland Survey of Scotland (NWSS) and 2022 National Forest Inventory (NFI).[32,2,33] Habitat Action Plan (HAP) classifications are not public and omitted. Shetland woods are too small and sparce to visualise. Map coordinate reference system (CRS) is the British National Grid.[34]

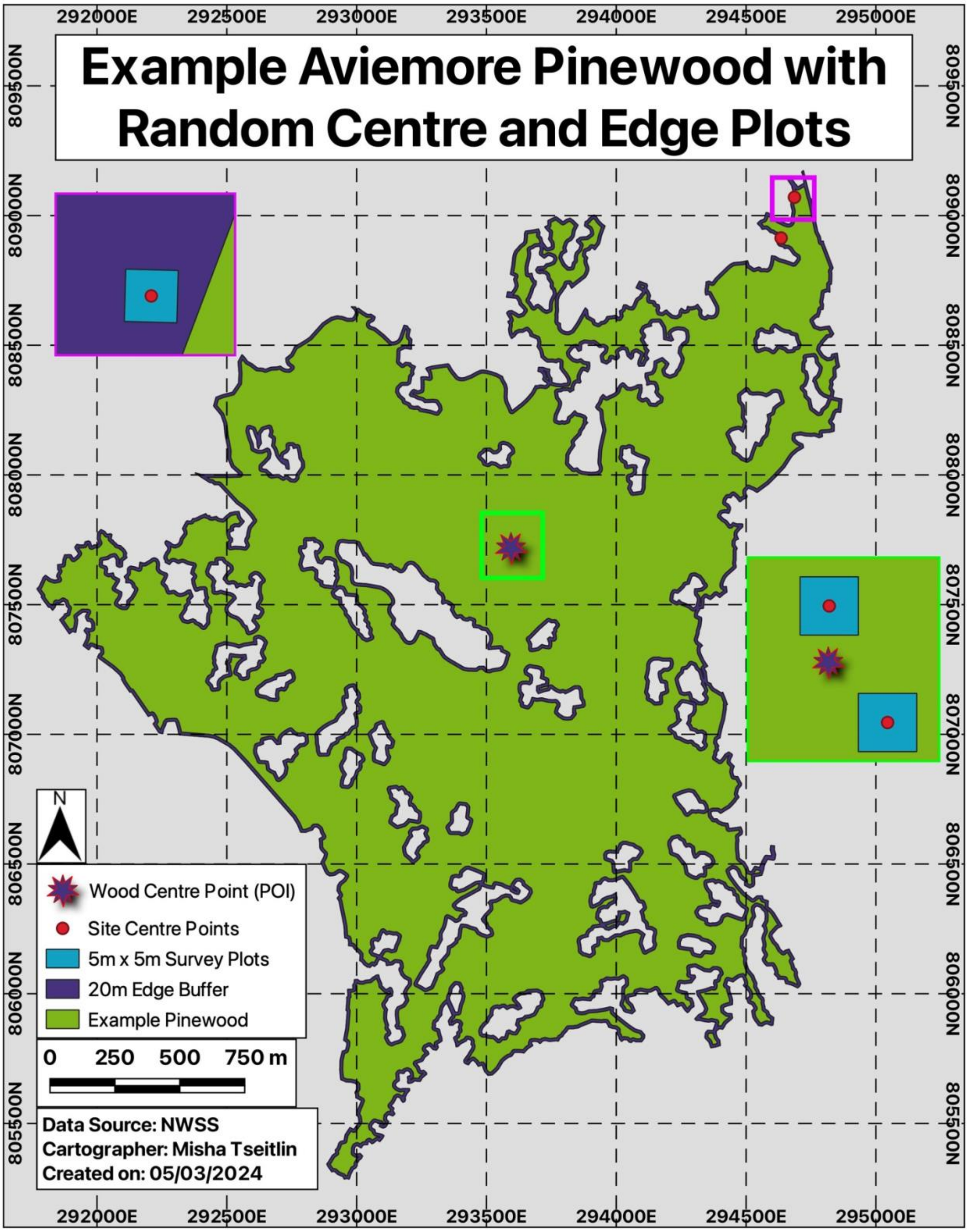

Figure 2: Example of survey design for one NWSS wood in Aviemore, Scotland—west of Loch Morlich with Native Pine Woodlands as its National Vegetation Classification (NVC).[2] The wood's centre point is calculated using the pole of inaccessibility (POI), and four survey plots—two around the centre and two within 20m of the wood edge—are randomly selected. Plots are 5m by 5m squares where all understorey vegetation would be censused. Map coordinate reference system (CRS) is the British National Grid.

References

1. Wood, C. M., Smart, S. M. & Bunce, R. G. H. Woodland Survey of Great Britain 1971–2001. *Earth Syst. Sci. Data* **7**, 203–214 (2015).
2. Scottish Forestry. Native Woodland Survey of Scotland. Scottish Forestry Open Data (2021).
3. Tuominen, S. *et al.* Assessment of Classifiers and Remote Sensing Features of Hyperspectral Imagery and Stereo-Photogrammetric Point Clouds for Recognition of Tree Species in a Forest Area of High Species Diversity. *Remote Sens.* **10**, 714 (2018).
4. Nordén, B. *et al.* Effects of ecological continuity on species richness and composition in forests and woodlands: A review. *Écoscience* **21**, 34–45 (2014).
5. *Survey Guidance Notes: National Plant Monitoring Scheme.* (Plantlife, Salisbury, 2019).
6. NFI Survey Manual for third cycle field samples. *Forest Research* https://www.forestresearch.gov.uk/tools-and-resources/national-forest-inventory/nfi-survey-manual-for-third-cycle-field-samples/.
7. Averis, B. & Rodwell, J. *Native Woodland Survey of Scotland: Manual for Recording National Vegetation Classification Communities and Habitat Action Plan Types in the Native Woodlands Survey of Scotland*. https://forestry.gov.scot/images/corporate/pdf/NWSS-AverisAndRodwellManual.pdf (2006).
8. Ricotta, C. & Pavoine, S. A new look at functional beta diversity. 2024.02.25.580632 Preprint at https://doi.org/10.1101/2024.02.25.580632 (2024).

9. Forestry Commission Scotland. Native Woodland Survey of Scotland: Glossary of Terms.
10. Rodwell, J. S. *National Vegetation Classification: Users' Handbook*. (Joint Nature Conservation Committee, Peterborough, 2006).
11. Chraibi, E. *et al.* A Remote Sensing Approach to Understanding Patterns of Secondary Succession in Tropical Forest. *Remote Sens.* **13**, 2148 (2021).
12. Riutta, T., Slade, E. M., Morecroft, M. D., Bebber, D. P. & Malhi, Y. Living on the edge: quantifying the structure of a fragmented forest landscape in England. *Landsc. Ecol.* **29**, 949–961 (2014).
13. Wauchope, H. S., Amano, T., Sutherland, W. J. & Johnston, A. When can we trust population trends? A method for quantifying the effects of sampling interval and duration. *Methods Ecol. Evol.* **10**, 2067–2078 (2019).
14. Ross, L. C., Woodin, S. J., Hester, A., Thompson, D. B. A. & Birks, H. J. B. How important is plot relocation accuracy when interpreting re-visitation studies of vegetation change? *Plant Ecol. Divers.* **3**, 1–8 (2010).
15. Kendon, M. *et al.* State of the UK Climate 2021. *Int. J. Climatol.* **42**, 1–80 (2022).
16. Liu, Q. *et al.* Extension of the growing season increases vegetation exposure to frost. *Nat. Commun.* **9**, 426 (2018).
17. McRae, L., Deinet, S. & Freeman, R. The Diversity-Weighted Living Planet Index: Controlling for Taxonomic Bias in a Global Biodiversity Indicator. *PLOS ONE* **12**, e0169156 (2017).
18. Onyia, N. N., Balzter, H. & Berrio, J.-C. Normalized Difference Vegetation Vigour Index: A New Remote Sensing Approach to Biodiversity Monitoring in Oil Polluted Regions. *Remote Sens.* **10**, 897 (2018).

19. Moeslund, J. E. *et al.* Light detection and ranging explains diversity of plants, fungi, lichens, and bryophytes across multiple habitats and large geographic extent. *Ecol. Appl.* **29**, e01907 (2019).
20. Rautiainen, M. & Heiskanen, J. Seasonal Contribution of Understory Vegetation to the Reflectance of a Boreal Landscape at Different Spatial Scales. *IEEE Geosci. Remote Sens. Lett.* **10**, 923–927 (2013).
21. Buckland, S. T. & Johnston, A. Monitoring the biodiversity of regions: Key principles and possible pitfalls. *Biol. Conserv.* **214**, 23–34 (2017).
22. Wilson, R. Warmer and wetter: how climate change is impacting the Caledonian pine forest. *Reforesting Scotl.* (2023).
23. Guy, P., Sibly, R., Smart, S. M., Tibbett, M. & Pickles, B. J. Mycorrhizal type of woody plants influences understory species richness in British broadleaved woodlands. *New Phytol.* **235**, 2046–2053 (2022).
24. Chao, A. & Shen, T.-J. Nonparametric estimation of Shannon's index of diversity when there are unseen species in sample. *Environ. Ecol. Stat.* **10**, 429–443 (2003).
25. Wilsey, B. J., Chalcraft, D. R., Bowles, C. M. & Willig, M. R. Relationships Among Indices Suggest That Richness Is an Incomplete Surrogate for Grassland Biodiversity. *Ecology* **86**, 1178–1184 (2005).
26. Kacic, P. & Kuenzer, C. Forest Biodiversity Monitoring Based on Remotely Sensed Spectral Diversity—A Review. *Remote Sens.* **14**, 5363 (2022).
27. Shannon, C. E. A mathematical theory of communication. *Bell Syst. Tech. J.* **27**, 379–423 (1948).
28. Ricker, M. *et al.* Mexico's Forest Diversity: Common Tree Species and Proposed Forest-Vegetation Provinces. *Forests* **13**, 1598 (2022).

29. Ferris, R., Peace, A. J., Humphrey, J. W. & Broome, A. C. Relationships between vegetation, site type and stand structure in coniferous plantations in Britain. *For. Ecol. Manag.* **136**, 35–51 (2000).

30. Baeten, L. *et al.* Distinguishing between turnover and nestedness in the quantification of biotic homogenization. *Biodivers. Conserv.* **21**, 1399–1409 (2012).

31. Besson, M. *et al.* Towards the fully automated monitoring of ecological communities. *Ecol. Lett.* **25**, 2753–2775 (2022).

32. Blackwood, C. Scotland Country Boundary. EDINA https://doi.org/10.7488/ds/1759 (2017).

33. Forestry Commission. National Forest Inventory Scotland 2022. Forestry Commission Open Data (2024).

34. Pimenta, W. Viridis Palette Generator. *waldyrious.net* https://waldyrious.net/viridis-palette-generator/.