

Area-based nature protection and stand attributes for assessing economic impacts on forest owners

MARTIN NĚMEC^{ORCID}, ROMAN DUDÍK^{ORCID}, ROMAN SLOUP^{ORCID}

Czech University of Life Sciences Prague, Prague, Czech Republic

*Corresponding author: nemecmartin@fld.czu.cz

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Abstract: Forest conservation planning requires evidence of how administrative protection categories correspond to forest conditions. We linked three project-defined categories to 5 530 plots from the second Czech National Forest Inventory (2011–2015) and adjusted comparisons for stand age, forest vegetation zone, terrain and inventory year. The strong category showed a distinctive combination of attributes: greater broadleaf representation, more frequent standing deadwood and less frequent stump occurrence than both the reference and moderate categories. Adjusted standing-deadwood occurrence reached 31% in the strong category and 19% in the reference category. The directions of these contrasts persisted under alternative classification rules. Protection class explained little additional variation in live or total standing volume. Broadleaf-share differences varied among forest vegetation zones, and tree-diameter differences varied with age and zone. Recorded woody-taxon diversity showed a small difference that depended on the classification rule. Composition, tree dimensions and occurrence indicators therefore distinguished the categories more clearly than growing stock. These cross-sectional associations identify biological inputs for subsequent economic assessment of management restrictions on forest owners; monetary impacts were not quantified. Valuation requires species-specific timber quantities, management alternatives, prices and costs.

Keywords: broadleaf share; deadwood; ecological stratification; management history; woody-taxon diversity

European forest policy connects area-based conservation with wood supply, resilience and socio-economic functions. The EU Biodiversity Strategy and Forest Strategy for 2030 place forest protection within this broader policy setting (European Commission 2020, 2021). The Nature Restoration Regulation identifies standing and lying deadwood, tree species diversity and other structural indicators for monitoring forest ecosystems (European Parliament and Council of the European Union 2024). These recent policy requirements motivate the present assessment of historical inventory data; the

second Czech National Forest Inventory (NIL2) measurements predate their adoption.

Area-based designation can influence harvesting, silviculture, regeneration and timber retention. The management implications depend on the applicable legal provisions, conservation objectives and implementation arrangements. European studies of Natura 2000 describe substantial variation in these relationships among forest systems and jurisdictions (Winter et al. 2014; Winkel et al. 2015). An administrative category consequently represents an exposure classification whose correspond-

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ence with observed stand conditions requires empirical assessment.

Forest-owner impacts depend on the operations affected, feasible management alternatives and payment arrangements. Studies of the Habitats Directive and compensation schemes document these dependencies in Germany, Czechia and Slovakia (Rosenkranz et al. 2014; Dobšínská et al. 2024). Comparative evidence also identifies variation in Natura 2000 payment arrangements and private owners' management practices (Sarvašová et al. 2019; Tiebel et al. 2021). Inventory attributes can identify biological inputs for such assessments, while monetary valuation requires evidence of the specific restrictions experienced by each owner.

Protected forests differ in terrain, productivity, tree composition and land-use history, partly because protected-area placement reflects ecological and administrative selection (Joppa, Pfaff 2009; Branquart et al. 2008). National forest inventories provide consistently collected observations across these conditions and a basis for adjusted comparisons (Vidal et al. 2016; Alberdi et al. 2019). Covariate adjustment describes conditional associations within the observed ecological range; it leaves uncertainty about unmeasured selection and management history.

Forest condition comprises several measurable dimensions. Inventory-based assessments can combine growing stock, tree composition, stand structure and deadwood, subject to the sampling protocol and available variables (Chirici et al. 2012; Borghi et al. 2024). Broadleaf basal-area share describes the allocation of tree basal area, whereas taxon diversity describes its distribution among recorded taxa. Relationships between tree diversity and other forest-associated taxa vary among organism groups and candidate indicators (Gao et al. 2015; Ampoorter et al. 2020). Tree dimensions and tree-related microhabitats provide further habitat information (Asbeck et al. 2021). The present analysis evaluates recorded live woody taxa, tree dimensions, standing-deadwood occurrence and stump occurrence within their respective measurement domains.

The unresolved question concerns how much information a three-category administrative classification provides across these inventory dimensions after ecological standardisation, and how that information changes with the rules used to classify legally heterogeneous areas. Existing inventory

studies have already examined protected forests using multiple indicators (Borghi et al. 2024). Here, separate comparisons of reference, moderate and strong categories, together with alternative mappings, assess whether particular stand attributes consistently distinguish the categories and identify the ecological settings in which their associations vary.

The study forms the biophysical stage of a wider investigation of forest-owner impacts. Its contribution is an empirical assessment of the alignment between administrative categories and measured stand attributes in the Czech NIL2 sample. The resulting profiles identify candidate inputs for later analyses of management alternatives, costs and revenues; monetary impacts are outside the scope of this study. The study also specifies an approach that can be adapted to other national inventories through locally justified category definitions and comparable outcome measures.

Research questions. *RQ₁*: How strongly does presumed-restriction class discriminate live and total standing volume after adjustment for stand age, forest vegetation zone, terrain and measurement year, and how does current-composition standardisation alter the estimates?

RQ₂: How do broadleaf basal-area share, quadratic mean diameter, standing-deadwood occurrence and stump occurrence differ among the reference, moderate and strong presumed-restriction classes?

RQ₃: Which class associations with live volume, broadleaf basal-area share, quadratic mean diameter, standing-deadwood occurrence and stump occurrence vary with main-layer age or forest vegetation zone, and how stable are the principal estimates under alternative category mappings?

Exploratory extension. We assessed whether basal-area-weighted recorded live woody-taxon compositional diversity differed among the same three classes and whether its class association varied with main-layer age or forest vegetation zone.

The research questions address the potential use of inventory data in subsequent economic assessment of six categories of forest-owner income loss: (i) compulsory extension of rotation length; (ii) withdrawal from timber production and designation for spontaneous natural development; (iii) mandatory alteration of species composition during regeneration, reconstruction or conversion; (iv) compulsory reduction in stocking; (v) premature final felling; and (vi) conservation-induced

changes in site conditions affecting productivity. The present study identifies biological inputs for these assessments; monetary valuation requires the corresponding management, legal and economic information.

MATERIAL AND METHODS

Study design and source data. We analysed a cross-sectional extract from the second Czech National Forest Inventory (NIL2), based on measurements collected during 2011–2015. The extract comprised 146 946 records from 7 084 plots: 94 281 live trees, 2 392 standing-dead trees and 50 273 stumps.

The 2011–2015 measurements provide a reference before the 2018–2021 drought-associated bark beetle outbreak examined by Das et al. (2025) in a Czech forest landscape. This timing supports the use of NIL2 for the present historical comparison.

For comparisons among the three presumed-restriction classes, eligibility required at least one recorded live tree, positive first-stage live volume and live basal area, a main-layer age of 20–130 years, assignment to forest vegetation zones (LVS, 'lesní vegetační stupeň' in Czech) 1–7, and complete covariate data. Sequential exclusions removed 297 plots without recorded live trees (220 reference, 47 moderate and 30 strong), 657 plots with main-layer age outside the specified range (including 208 reference, 83 moderate and 62 strong plots above 130 years), and 600 plots with missing LVS ($n = 507$) or assignment to LVS 8–9 ($n = 93$), leaving a final analytical sample of 5 530 plots.

The age and LVS limits were adopted as pragmatic analytical boundaries intended to limit model extrapolation across sparsely represented

combinations of stand age and ecological conditions. Live-tree records were required to derive main-layer age and live-tree structural attributes using the adopted processing procedure. Positive live basal area was necessary to calculate basal-area-based species proportions, while positive first-stage live volume maintained compatibility with the logarithmic volume specification used in sensitivity analysis. Requiring complete covariate data allowed the adjusted models to be fitted without imputation.

These criteria define the scope of the analysis but do not, by themselves, establish adequate covariate overlap among the presumed-restriction classes. The reported associations therefore pertain to the eligible sample within the specified age and vegetation-zone ranges. Analyses of standing-dead-tree and stump occurrence are additionally conditional on the presence of recorded live trees. Complete survey weights and spatial-cluster identifiers were unavailable. Inference is model-based for the analytical sample. HC3 (heteroskedasticity-consistent type 3) covariance estimates address heteroskedasticity under an assumption of independent plot errors; uncertainty associated with the full NIL2 sampling design and spatial dependence remains unquantified.

Administrative exposure classification. The classification is presented in Table 1. Exposure was inherited from supplied plot-level overlays of Czech specially protected areas ('zvláště chráněná území', ZCHÚ), whose legal categories originate in Act No. 114/1992 Coll. (Czech National Council 1992). The project-defined classification is reported here as 0 (reference outside the evaluated ZCHÚ classes), 1 (moderate presumed restriction) and 2 (strong presumed restriction). The source classification codes 1 and 2 were relabelled for presentation;

Table 1. Primary classification of presumed forestry restriction

Code	Analytical label	Source categories	Role
0	no evaluated ZCHÚ designation	no ZCHÚ category listed in Groups 1 or 2	reference exposure
1	moderate presumed forestry restriction	NPP; PP; NP C–D; CHKO II–IV; unzoned CHKO	project-defined moderate class
2	strong presumed forestry restriction	NPR; PR; NP A; NP B; CHKO I	project-defined strong class

ZCHÚ – specially protected area; NPR – national nature reserve; PR – nature reserve; NPP – national nature monument; PP – nature monument; NP – national park; CHKO – protected landscape area; OP – protective zone; EVL – site of community importance; PO – special protection area

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plot membership was unchanged. These nominal codes do not form a linear dose scale. The grouping reflects the project assumption of greater constraints on timber-oriented management in national nature reserve (NPR), nature reserve (PR), national park (NP) A–B and protected landscape area (CHKO) I, with the remaining evaluated designations forming the moderate comparison. Presumed constraints concern harvesting, regeneration and timber retention; actual plot-level restrictions and their implementation were not observed.

Each plot was assigned once. A strong-class designation took precedence over a moderate-class designation in an overlap; a moderate designation applied when no strong designation was present; all remaining plots formed the reference. Formally, it is expressed by Equation (1):

$$R_i = \begin{cases} S, & S_i = 1; \\ M, & S_i = 0 \wedge M_i = 1; \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

where:

- R_i – plot i 's analytical class, with $S = 2$ and $M = 1$;
- S_i – indicator of a strong-class designation (1 = present, 0 = absent);
- M_i – indicator of a moderate-class designation (1 = present, 0 = absent).

The hierarchy produced 4 074 reference, 1 164 moderate and 292 strong plots. Other flags did not alter the primary class; 525 reference plots carried a protective zone (OP), site of community importance (EVL), special protection area (PO), Ramsar or biosphere-reserve flag. Alternative mappings separately reassigned (i) reference plots with OP to moderate; (ii) reference plots with EVL or PO to moderate; and (iii) NP B from strong to moderate. Overlapping NPR or PR retained strong precedence in the third mapping. NP A–C were the national-park zone codes present in the supplied overlay; the lookup assigns NP D to the moderate class if encountered. Layer version, overlay algorithm, boundary rule and historical zoning were unavailable.

Plot-level outcomes. The main stock measure used the supplied generalised local-density contribution, `gldsity_csot_bk_m3_ha`. Its reconstruction follows the NIL2 one-phase estimator (Adolt 2017). For record j on plot i , see Equation (2):

$$q_{ij} = \frac{\hat{v}_{ij}}{z_{ij}} + I_{ij} \frac{v_{ij} - \hat{v}_{ij}}{z_{ij}^H} \quad (2)$$

where:

- q_{ij} – record j 's contribution to volume per ha on plot i ($\text{m}^3 \cdot \text{ha}^{-1}$);
- $\hat{v}$ – modelled stem volume (m^3);
- v – volume for a height-measured stem (m^3);
- z – the record-specific inclusion-zone area (ha);
- z^H – the secondary height-sampling-zone area (ha);
- I_{ij} – indicator equal to 1 when the secondary-sample inputs, including measured height, are complete, and 0 otherwise.

Plot-level live, standing-dead and total standing volume were obtained by aggregating record-level contributions as follows [Equation (3)]:

$$V_i^L = \sum_{j \in L_i} q_{ij}; \quad V_i^D = \sum_{j \in D_i} q_{ij}; \quad V_i^T = V_i^L + V_i^D \quad (3)$$

where:

- V_i^L, V_i^D and V_i^T – live, standing-dead and total standing volume on plot i ;
- L_i and D_i – index the corresponding non-stump records.

Seven analytical plots had negative live totals from the estimator's second-stage correction; identity-link analysis retained them. The positive first-stage proxy $\Sigma(\hat{v}_{ij}/z_{ij})$ supplied a log-scale sensitivity outcome.

Main-layer age was the basal-area-weighted median stem age among live trees in the International Union of Forest Research Organizations (IUFRO) upper layer, with all live trees used when an upper-layer age was unavailable. For selected live-stem set U_i and basal-area contribution $w_{ij} = g_{ij}/z_{ij}$, see Equation (4):

$$A_i = \inf \left\{ a : \sum_{j \in U_i: a_{ij} \leq a} w_{ij} \geq \frac{1}{2} \sum_{j \in U_i} w_{ij} \right\} \quad (4)$$

where:

- g_{ij} – basal area of stem j on plot i ;
- A_i – plot i 's main-layer age;
- a – candidate median age;
- U_i – live-stem set;
- a_{ij} – stem age;
- w_{ij} – basal-area contribution.

Species labels served two calculations. For broad-leaf share and Model B, the 75 source labels were

mapped to spruce, pine, other conifers, beech, oak and other broadleaves. Seventy-three source labels occurred among all live records and 70 occurred among live records in the analytical sample. For broadleaf basal-area share, see Equation (5):

$$100 \times \frac{(w_{ij} \times \text{broadleaf}_{ij})}{\sum w_{ij}} \quad (5)$$

Recorded live woody-taxon compositional diversity was evaluated as an exploratory outcome. Normalised source labels were retained at their recorded taxonomic resolution; several labels represented genera, combined taxa or broader groups and were not resolved further. Taxon basal-area proportions, Shannon entropy and the corresponding effective number of taxa were calculated using Equation (6):

$$G_{is} = \sum_{j \in L_i: s_{ij}=s} w_{ij}, \quad p_{is} = \frac{G_{is}}{\sum_s G_{is}}, \quad (6)$$

$$H_i = - \sum_{s: p_{is} > 0} p_{is} \ln p_{is}, \quad {}^1D_i = \exp(H_i)$$

where:

- G_{is} – expanded live basal area on plot i for taxon s ;
- s_{ij} – recorded taxon label of live stem j on plot i ;
- p_{is} – proportion of total live basal area attributable to taxon s ;
- H_i – Shannon entropy (a plot containing one recorded taxon had $H_i = 0$);
- ${}^1D_i$ – the corresponding effective number of recorded taxa (Hill 1973; Jost 2006).

Shannon H was the inferential diversity measure. The effective taxon number $\exp(H_i)$ and inverse Simpson diversity [see Equation (7)] were derived companion metrics.

$${}^2D_i = \frac{1}{\sum_s p_{is}^2} \quad (7)$$

Recorded taxon richness was descriptive because the nested NIL2 inclusion zones make observation of a taxon dependent on its abundance and stem-size distribution. The measure represents the composition of live woody taxa covered by the NIL2 stem protocol. Other organism groups, regeneration, functional diversity and genetic diversity require additional observations.

Quadratic mean diameter (QMD) used inclusion-zone expansion $e_{ij} = 1/z_{ij}$, see Equation (8):

$$D_{q,i} = \sqrt{\frac{\sum_{j \in L_i} e_{ij} d_{ij}^2}{\sum_{j \in L_i} e_{ij}}} \quad (8)$$

where:

- $D_{q,i}$ – quadratic mean diameter on plot i ;
- e_{ij} – inclusion-zone expansion;
- d_{ij} – diameter at breast height;
- L_i – indexes live non-stump records.

Standing-deadwood and stump occurrence indicated at least one corresponding record at the inventory visit.

Covariates and statistical analysis. Model A adjusted for age, categorical LVS, slope, aspect and year. LVS records Czech altitudinal forest-site conditions. Age used a restricted cubic spline with knots at 25, 57, 87 and 120 years (the sample 5th, 35th, 65th and 95th percentiles; Harrell 2015). Aspect entered as sine, cosine and a flat-or-undefined indicator; LVS 1 and 2011 were references. Model B added basal-area shares of spruce, pine, other conifers, beech and oak, with other broadleaves omitted. Model A was the primary reporting specification. Shannon H was analysed with Model A because current species shares are constituents of the diversity outcome. Differences between Models A and B describe the sensitivity of conditional associations to composition adjustment. Equation (9) represents Model A. Model B added $\theta^T C_i$, where C_i contains the five basal-area composition shares.

$$Y_i = \beta_0 + \beta_S 1(R_i = S) + \beta_M 1(R_i = M) + f(A_i) + \gamma^T \text{LVS}_i + \delta^T Z_i + \tau^T T_i + \varepsilon_i \quad (9)$$

where:

- Y_i – outcome;
- $1(\cdot)$ – indicator;
- β_0 – intercept;
- β_S and β_M – class coefficients;
- γ , δ and τ – coefficient vectors;
- LVS_i – vector of forest vegetation zone indicators for plot i ;
- Z_i – vector of terrain terms for plot i ;
- T_i – vector of inventory-year indicators for plot i ;
- f – age spline;
- ε_i – residual.

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Ordinary least squares with heteroskedasticity-consistent type 3 (HC3) covariance estimated arithmetic differences (MacKinnon, White 1985). Linear models were primary because they give directly interpretable adjusted differences, reported in percentage points for percentage and occurrence outcomes. Standardised means assigned every plot to each class, retained observed covariates and averaged predictions (Muller, MacLehose 2014). Linear contrasts supplied differences, with two-sided *t*-tests and 95% confidence intervals (CIs) using $n - \text{rank}(X)$ residual degrees of freedom. Incremental class R^2 equalled full-model R^2 minus R^2 from the same model without class indicators. The HC3 covariance matrix used for inference is given in Equation (10):

$$\widehat{\text{Var}}_{\text{HC3}}(\hat{\beta}) = (X^T X)^{-1} \left[\sum_i \frac{\hat{e}_i^2 x_i x_i^T}{(1 - h_{ii})^2} \right] (X^T X)^{-1} \quad (10)$$

where:

Left-hand side – HC3 covariance matrix of the ordinary least-squares coefficient estimator;

X – the design matrix;

x_i – column vector of predictors for plot i ;

$\hat{e}_i$ – its residual;

h_{ii} – its leverage.

The three exposure categories remained separate in every analysis. Joint class coefficients were evaluated with a two-degree-of-freedom Wald test. Holm correction covered the two co-primary Model-A volume tests (Holm 1979). The secondary composition family comprised broadleaf basal-area share and exploratory Shannon diversity; the structure family comprised *QMD*; and the intervention-related family comprised standing-deadwood and stump occurrence. Benjamini–Hochberg (BH) adjustment was applied to outcome-level tests within each family (Benjamini, Hochberg 1995). Three pairwise differences were estimated for every outcome: moderate minus reference, strong minus reference and strong minus moderate. Each contrast label states the subtraction order; a positive estimate denotes a higher adjusted mean in the first-named class. Holm's procedure adjusted the three pairwise *P*-values within each outcome. All tests were two-sided; multiplicity-adjusted $P < 0.05$ defined statistical support.

Fractional-logit and binomial-logit quasi-maximum-likelihood models with sandwich covariance

and empirical standardisation assessed whether these contrasts depended on the response link (Papke, Wooldridge 1996).

Model-A class $\times$ age and class $\times$ LVS interactions were tested separately for live volume, broadleaf basal-area share, Shannon *H*, *QMD*, standing-deadwood occurrence and stump occurrence, using six class-by-spline and 12 class-by-zone terms. Benjamini–Hochberg correction covered the six global tests within each modifier. Pointwise profiles followed supported global tests. The Shannon analysis and its interaction profiles retained exploratory status.

All Model-A outcomes and interaction tests were repeated under the three alternative mappings. Volume sensitivities used ages 30–110 years, excluded the upper 1% of the live-volume distribution and analysed the log-transformed positive first-stage proxy. No values were imputed. Analyses were reproduced using Python (Version 3.13.5, 2025), NumPy (Version 2.3.5, 2025) and SciPy (Version 1.17.0, 2026).

RESULTS

Analytical support. Reference, moderate and strong classes represented 73.7%, 21.0% and 5.3% of the sample. Strong-class support ranged from 13 plots in LVS 1 to 89 in LVS 6 (Figure 1), requiring particular caution when interpreting statistical significance and generalising stratified estimates. Selected unadjusted characteristics of the analytical sample are presented in Table 2.

RQ1: Standing stock. After adjustment for the ecological and inventory covariates in Model A, estimated live standing volume lay within a narrow range across the three protection classes: 340.25 m³·ha⁻¹ in the reference class, 343.15 m³·ha⁻¹ under moderate protection and 343.44 m³·ha⁻¹ under strong protection (Figure 2). The omnibus class test did not identify a difference in live volume among classes [$\chi^2(2) = 0.25$, $P = 0.883$; Holm-adjusted $P = 1.000$], and protection class increased the in-sample R^2 by only 0.000032, equivalent to 0.0032% of the observed variance in live volume. All three pairwise live-volume contrasts had 95% confidence intervals spanning zero and were unsupported after Holm adjustment.

Total standing volume showed the same pattern. The Model-A omnibus test gave no statistical evidence of a class difference [$\chi^2(2) = 0.80$, $P = 0.669$;

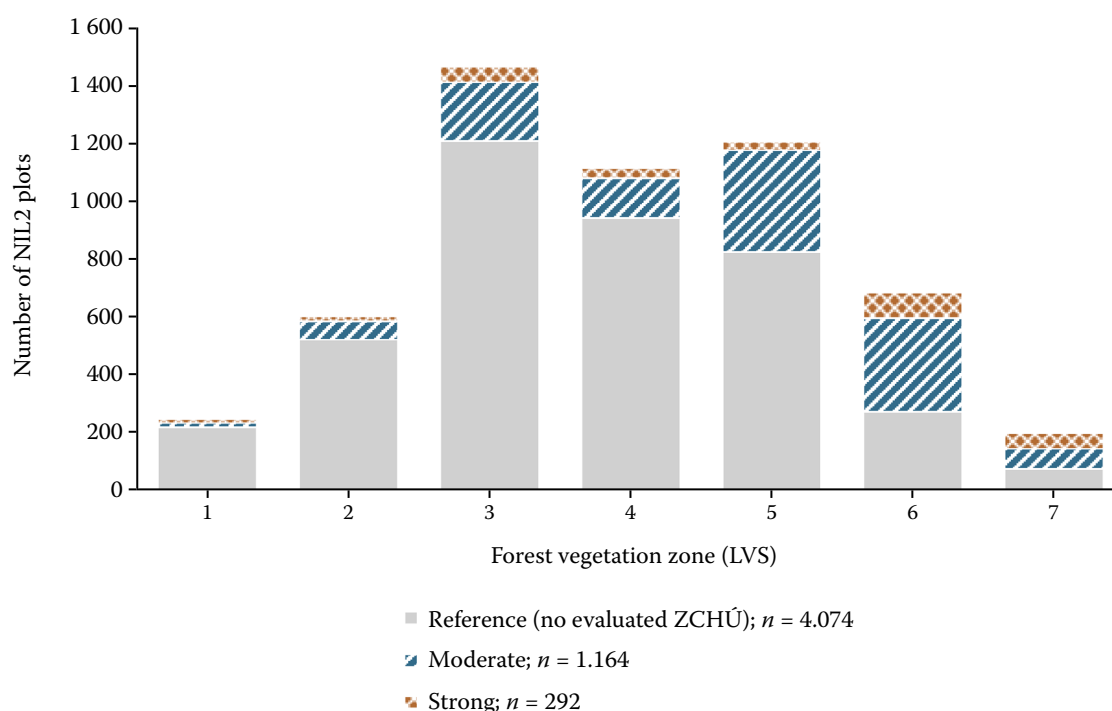


Figure 1. Distribution of the 5 530 analytical plots from the second Czech National Forest Inventory (NIL2) across forest vegetation zones (LVS) and project-defined presumed-restriction classes

Bar segments show plot counts; the reference class comprises plots with no evaluated specially protected area (ZCHÚ) designation

Holm-adjusted $P = 1.000$], and the incremental R^2 was 0.000100, equivalent to 0.0100% of the observed variance in total standing volume. The largest estimated contrast was $+9.76 \text{ m}^3 \cdot \text{ha}^{-1}$ for strong protection relative to the reference class, but its 95% confidence interval ranged from $-12.04 \text{ m}^3 \cdot \text{ha}^{-1}$ to $31.57 \text{ m}^3 \cdot \text{ha}^{-1}$; the remaining pairwise intervals likewise included zero (Figure 2).

Model B led to the same inference for both live volume (global $P = 0.724$) and total standing volume (global $P = 0.363$): all six pairwise confidence intervals included zero.

RQ₁ and RQ₃: Sensitivity of standing-stock results. Under Model A, the omnibus protection-class tests remained statistically unsupported

across the three alternative mappings ($P = 0.730$ – 0.900 for live volume and 0.510 – 0.782 for total volume). Analyses restricted to ages 30–110 years and analyses excluding the upper 1% of live-volume observations yielded global P -values of at least 0.489. Analyses of log-transformed positive first-stage volume proxies yielded $P = 0.353$ and 0.188 .

RQ₂: Stand configuration and intervention-related attributes. Broadleaf basal-area share varied across classes [$\chi^2(2) = 19.76$, $BH P = 1.02 \times 10^{-4}$]. Moderate–reference, strong–reference and strong–moderate contrasts were $+1.80$ (95% CI -0.57 to 4.17 ; Holm $P = 0.137$), $+9.64$ (5.37 to 13.91 ; Holm $P = 2.98 \times 10^{-5}$) and $+7.84$ (3.47 to 12.20 ; Holm $P = 8.64 \times 10^{-4}$) percentage points (Figure 3).

Table 2. Selected unadjusted characteristics of the analytical sample

Class	<i>n</i>	Age (years)	Live volume ($\text{m}^3 \cdot \text{ha}^{-1}$)	Broadleaf BA (%)	Standing dead (%)	Stumps (%)
Reference	4 074	72.1 ± 30.2	335.7 ± 207.4	30.1	17.3	90.0
Moderate	1 164	71.6 ± 29.8	359.8 ± 216.9	25.3	21.3	91.2
Strong	292	73.3 ± 30.0	340.5 ± 211.9	33.2	37.0	82.5

n – number of plots; BA – basal area; SD – standard deviation; values are mean ± SD for age and live volume and means for percentages

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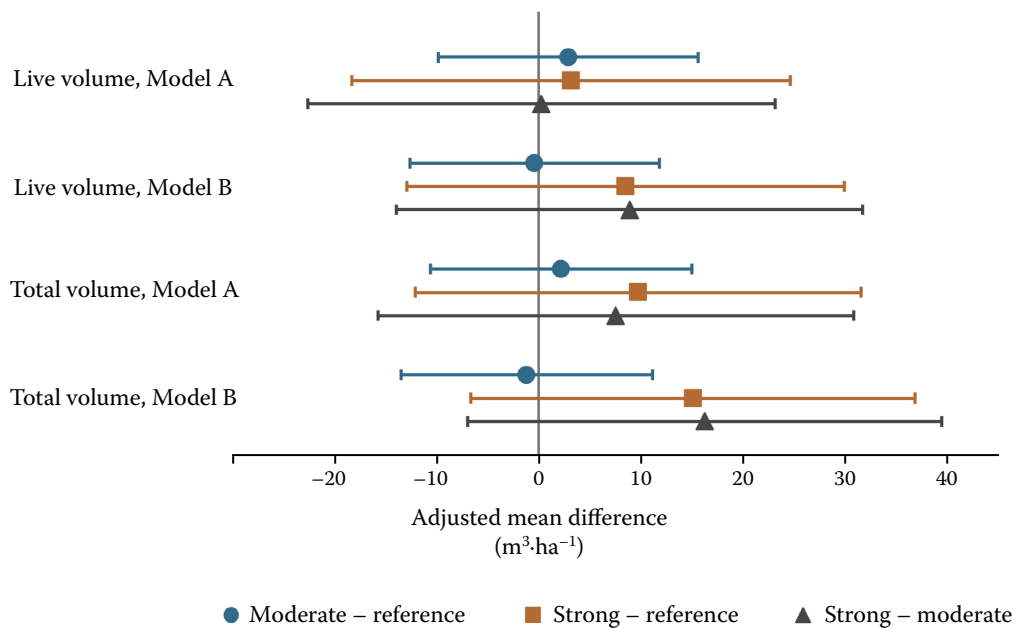


Figure 2. Covariate-adjusted pairwise differences in live and total standing volume under Models A and B (NIL2, 2011–2015; $n = 5\,530$)

Labels give the subtraction order: moderate – reference, strong – reference or strong – moderate; positive estimates indicate a higher value in the first-named class; the reference class (code 0) comprises plots with no evaluated specially protected-area (ZCHÚ) designation; Model A includes main-layer age, forest vegetation zone, terrain and inventory year; Model B additionally includes current basal-area composition; points show adjusted mean differences and bars show pointwise 95% confidence intervals based on HC3 heteroskedasticity-consistent covariance estimates; the vertical line marks zero difference; the intervals are unadjusted for multiple comparisons; Holm adjustment was applied to the three pairwise tests within each outcome

Fractional-logit standardisation gave 10.47 points for the strong–reference contrast.

QMD differed by class [$\chi^2(2) = 14.94$, $P = 0.000569$]. Moderate–reference and strong–reference contrasts were 7.91 mm (95% CI 2.76 to 13.07; Holm $P = 0.0053$) and –8.79 mm (–18.12 to 0.53; Holm $P = 0.0645$). The strong–moderate contrast was –16.70 mm (–26.52 to –6.89; Holm $P = 0.0026$).

Reassigning NP B changed the *QMD* omnibus test to $P = 0.104$. The resulting moderate–reference estimate was +5.44 mm (unadjusted 95% CI 0.39 to 10.50) and is treated descriptively because the global test was unsupported. Strong–reference contrasts remained positive for broadleaf share and standing-deadwood occurrence and negative for stump occurrence under all three alternative mappings.

Adjusted standing-deadwood occurrence was 18.71%, 17.92% and 31.27% in the reference, moderate and strong classes. The moderate–reference, strong–reference and strong–moderate differences

were –0.79 percentage points (95% CI –3.59 to 2.02; Holm $P = 0.583$), +12.56 points (6.83 to 18.29; Holm $P = 3.66 \times 10^{-5}$) and +13.35 points (7.37 to 19.32; Holm $P = 3.66 \times 10^{-5}$), respectively.

Adjusted stump occurrence was 90.02%, 91.07% and 83.08% in the reference, moderate and strong classes. The moderate–reference, strong–reference and strong–moderate differences were +1.05 percentage points (95% CI –0.98 to 3.08; Holm $P = 0.309$), –6.94 points (–11.47 to –2.40; Holm $P = 0.005$) and –7.99 points (–12.70 to –3.27; Holm $P = 0.003$), respectively. Logit sensitivities estimated strong–reference differences of 11.07 points for standing deadwood and –6.59 points for stumps.

RQ₃; Ecological and age-related heterogeneity. Broadleaf-share associations varied among LVS [$\chi^2(12) = 52.92$, BH $P = 2.55 \times 10^{-6}$]; *QMD* associations varied with age [$\chi^2(6) = 17.61$, BH $P = 0.044$] and LVS [$\chi^2(12) = 27.24$, BH $P = 0.021$] (Figure 4). Moderate–reference *QMD* contrasts were +16.71 mm in LVS 5 and +14.22 mm in LVS 6; the

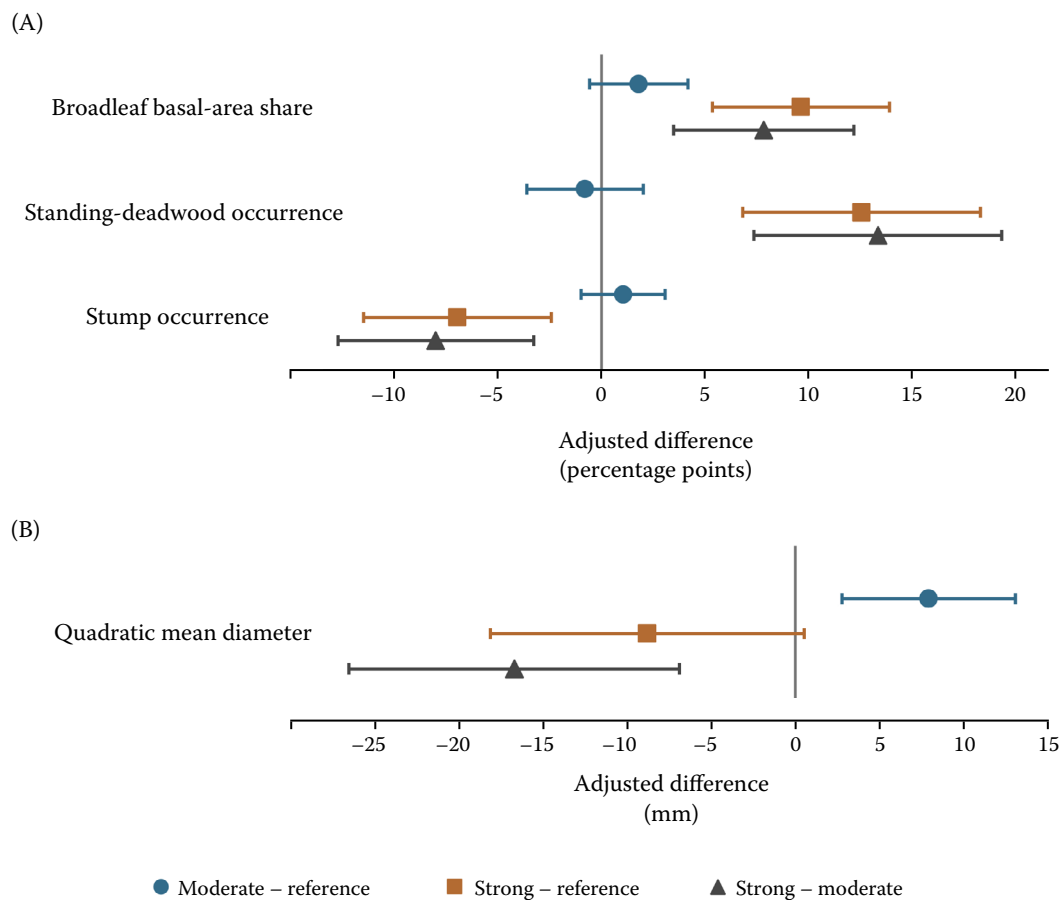


Figure 3. Model-A pairwise contrasts in stand configuration and occurrence indicators: (A) broadleaf basal-area share, standing-deadwood occurrence and stump occurrence in percentage points, (B) quadratic mean diameter (*QMD*) in millimetres

Points – adjusted differences; bars – pointwise HC3 95% confidence intervals; vertical line at zero – no adjusted difference; every label states the subtraction order: moderate – reference, strong – reference or strong – moderate; pairwise *P* values in the text use Holm adjustment

strong–reference contrast was –31.70 mm in LVS 7. The strong–moderate *QMD* contrast in LVS 6 was –31.29 mm (95% CI –49.09 to –13.50). Other displayed *QMD*-by-LVS pointwise intervals included zero. These individual intervals were unadjusted. The multiplicity-adjusted global interactions for live volume, standing deadwood and stumps were unsupported.

Recorded live woody-taxon compositional diversity: exploratory analysis. Under the primary mapping, the three-class test for Shannon *H* gave $\chi^2(2) = 8.65$, BH *P* = 0.013, and an incremental *R*² of 0.001299. Standardised *H* was 0.485 in the reference class, 0.447 in the moderate class and 0.503 in the strong class (Figure 5). The moderate–reference difference was –0.0376 (95% CI –0.0659 to –0.0093; Holm *P* = 0.027), correspond-

ing to a geometric-mean effective-taxon-number ratio of 0.963 (0.936 to 0.991). The strong–reference difference was +0.0180 (–0.0309 to 0.0670; Holm *P* = 0.470). The strong–moderate difference was +0.0556 (0.0051 to 0.1062; Holm *P* = 0.062).

The class association varied among forest vegetation zones [$\chi^2(12) = 24.95$, BH *P* = 0.030]; the class × age test gave *P* = 0.685. Classification sensitivities bounded the result. Omnibus *P*-values were 0.0288 after reassignment of protective-zone flags, 0.216 after reassignment of EVL or PO plots and 0.0341 after transfer of national-park zone B to the moderate class. Among the three alternative mappings, the LVS interaction retained BH support only after the NP B transfer (BH *P* = 0.0213). The primary profile was small, ecologically contingent and sensitive to the legal-to-analytical coding rule.

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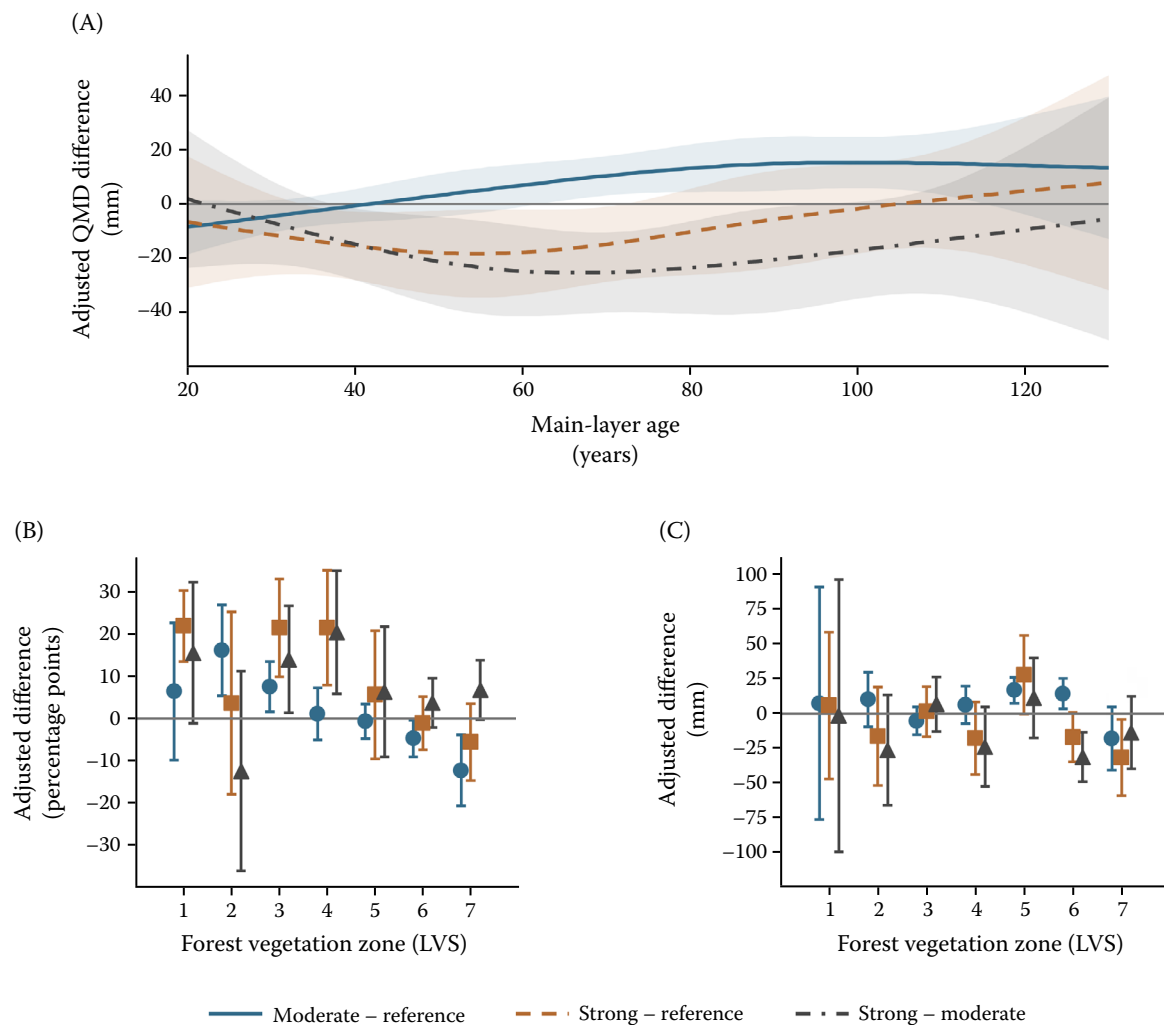


Figure 4. Conditional Model-A class contrasts by main-layer age and forest vegetation zone (LVS): (A) quadratic mean diameter (QMD) by age, (B) broadleaf basal-area share by LVS, and (C) QMD by LVS

Lines and points – adjusted differences; shading and error bars – pointwise 95% confidence intervals; horizontal line at zero – no adjusted difference; the three series show moderate – reference, strong – reference and strong – moderate; global Benjamini–Hochberg-adjusted interaction tests supported the displayed profiles; pointwise intervals are exploratory and unadjusted for multiple comparisons

Applicability to forest-owner profit-loss assessment. For extended rotation periods, withdrawal from timber production and premature harvesting (categories *i*, *ii* and *v*), stand age, standing volume and tree dimensions provide starting conditions for growth and harvest scenarios. The adjusted volume contrasts describe current stocks; valuation requires the timing and quantity of future removals under each management alternative.

For mandatory species replacement (category *iii*), species-specific basal area and volume describe the initial composition. For reduced stocking (category

iv), basal area and stem density can be derived from the stem records and their inclusion zones. Both categories require a specified target stand and the associated silvicultural operations.

For changes in site conditions (category *vi*), LVS provides ecological stratification. Quantification requires site-productivity measurements or yield models describing the change. Across all six categories, the inventory inputs need to be linked to documented restrictions, a feasible management alternative without the evaluated restriction, timber prices, operating costs and the timing of cash flows.

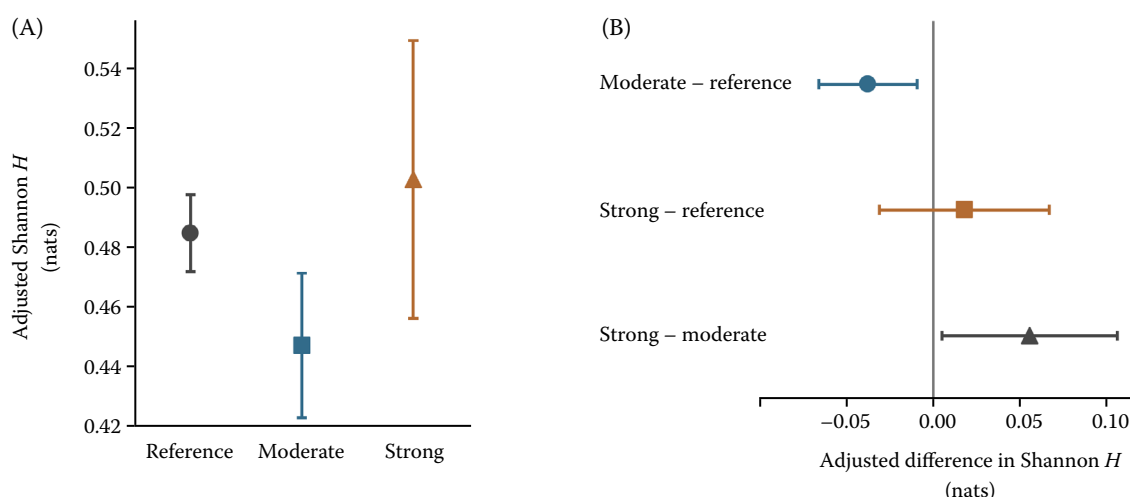


Figure 5. Exploratory basal-area-weighted Shannon diversity of recorded live woody taxa across three project-defined presumed-restriction classes: (A) empirically standardised class means under Model A, (B) moderate – reference, strong – reference and strong – moderate, with every label giving the subtraction order

Vertical line at zero – no adjusted difference; points – estimates; bars – HC3 95% confidence intervals; confidence intervals for pairwise contrasts are unadjusted; Holm-adjusted P -values for all three comparisons are reported in the text; the measure is confined to the live-stem assemblage represented by NIL2

DISCUSSION

Protection-category profiles. The most consistent differences concerned broadleaf representation, standing-deadwood occurrence and stump occurrence. The strong category differed from both the reference and moderate categories in these three attributes, and the directions persisted under alternative mappings. Their joint assessment identifies a reproducible category profile within this sample. The small, imprecise moderate–reference contrasts leave differences between these two categories unresolved under the primary mapping. Interpretation therefore requires the separate pairwise comparisons retained in this analysis.

Protection category explained little additional variation in current live or total standing volume after ecological standardisation. Standing stock integrates growth, mortality and removals over time, while composition and occurrence indicators describe specific features of that stock and its history. In the Central Apennines, Lombardi et al. (2008) reported differences in deadwood volume between managed and unmanaged stands alongside comparable living-tree volumes. This provides a useful qualitative parallel, although their management comparison and volume measures differ from the administrative exposure and occurrence outcomes analysed here. The uncertainty of the NIL2 volume

contrasts leaves the extent of any underlying stock difference unresolved; an equivalence claim would require a defined margin and a dedicated test.

Interpretation in relation to European evidence. The pairwise comparisons locate the clearest differences in standing-deadwood and stump occurrence in the strong category (Figure 3). Thus, retaining three separate categories shows that the occurrence pattern was concentrated in the strong category, with little evidence of separation between moderate and reference plots for these outcomes.

The combination of more frequent standing deadwood and less frequent stumps is consistent with differences in past tree retention and cutting, although these processes were not measured directly. Stump occurrence alone cannot quantify harvesting intensity without information on the timing and extent of past cutting. Keren and Diaci (2018) reported a similar direction of difference in paired old-growth and selection-managed forests in south-eastern Europe: old-growth stands contained greater snag volume and lower stump volume. Their findings provide a directional comparison; the NIL2 indicators record whether at least one standing-dead tree or stump was present, so the magnitudes cannot be compared with volume differences. Moreover, the analysis of Polish protected forests by Bujoczek et al. (2018) identified variation in deadwood volume associated

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with forest type and inputs of recently dead trees. Mortality history therefore remains a plausible contributor to the NIL2 standing-deadwood contrast after the measured ecological covariates have been considered.

The biodiversity interpretation follows from the measurement boundary. The adjusted occurrence estimates describe how frequently the inventory recorded standing deadwood. They provide no estimate of its quantity, substrate diversity or associated organisms. The moderate relationship between deadwood volume and saproxylic species richness reported by Lassauce et al. (2011) cannot be transferred directly to these binary outcomes. The observed difference in occurrence identifies where additional measurements of deadwood dimensions, decay stages, and associated taxa would be informative.

The compositional analyses also distinguish two biological dimensions (Figures 3 and 5). Broadleaf basal-area share was higher in the strong category than in both the reference and moderate categories, by 9.64 and 7.84 percentage points, respectively. However, the strong–reference Shannon contrast was only +0.0180, with a confidence interval spanning zero (−0.0309 to 0.0670). Greater broadleaf representation therefore coexisted with an unresolved difference in basal-area-weighted diversity of recorded live woody taxa. This combination is possible because broadleaf share measures the allocation of basal area to one group, whereas Shannon H measures its distribution among all recorded taxa. A stand dominated by one broadleaved taxon can have high broadleaf share and low Shannon diversity. The different responses of richness, conservation-relevant species and functional diversity reported by Lelli et al. (2019) further support keeping the interpretation specific to the measured component of composition.

The exploratory Shannon result was principally a small moderate–reference difference: −0.0376 (Holm-adjusted $P = 0.027$). The strong–moderate contrast remained unsupported after Holm adjustment ($P = 0.062$), despite its unadjusted confidence interval excluding zero. Protection class added only 0.001299 to model R^2 , equivalent to approximately 0.13% of the observed variation in H . These results provide limited evidence of compositional differentiation and do not establish a progressive increase in recorded woody-taxon diversity across the three categories.

Ecological heterogeneity and classification sensitivity. The interaction analyses show where the sample-wide contrasts require ecological qualification (Figure 4). Broadleaf-share associations varied among forest vegetation zones (BH-adjusted $P = 2.55 \times 10^{-6}$), while quadratic mean diameter (QMD) associations varied with both age ($P = 0.044$) and vegetation zone ($P = 0.021$). For example, the strong–moderate QMD contrast was −31.29 mm in LVS 6, compared with −16.70 mm in the sample-wide model. The LVS-specific estimate illustrates the variation identified by the global interaction test; its pointwise confidence interval was unadjusted for multiple comparisons. These results support reporting broadleaf composition by vegetation zone and tree dimensions by age and zone when interpreting category differences.

Hämäläinen et al. (2024) found in Swedish inventory analyses that management-related differences in living-tree and deadwood structures depended on productivity and stand age. The NIL2 interactions extend this ecological qualification to the Czech administrative categories, using LVS to represent forest-site conditions. Their detailed profiles remain uncertain because only 292 analytical plots belonged to the strong category, with 13–89 plots in individual zones. Furthermore, the age profiles compare different stands observed during one inventory period. They combine developmental differences with cohort and site histories and cannot describe the trajectory of an individual stand.

The alternative mappings identify a separate dependence on category construction. Reassigning national-park zone B from strong to moderate changed the QMD omnibus P -value from 0.000569 to 0.104 and reduced the moderate–reference estimate from +7.91 mm to +5.44 mm. The exploratory Shannon association also depended on the reference definition: reassigning reference plots carrying EVL or PO flags to the moderate category yielded an omnibus P -value of 0.216. Consequently, the QMD and Shannon findings require the classification rule to remain explicit in their interpretation.

Broadleaf share, standing-deadwood occurrence and stump occurrence had more consistent strong–reference directions across all three alternative mappings. Their directions also persisted under alternative response links. These checks support the three-attribute profile under the specific classification and model alternatives examined.

Transferability, application and limits. The practical contribution is the identification of which measured attributes distinguish the categories after ecological adjustment. Borghi et al. (2024) used 18 Italian inventory indicators to assess biodiversity, naturalness and old-growth status, demonstrating the scope for combining inventory measurements. In the present analysis, the separate outcome models show why indicator selection matters: protection class accounted for an additional 0.0032% of observed variation in live standing volume and 0.0100% in total standing volume, while the broadleaf and occurrence contrasts identified a clearer strong-category profile (Figures 2 and 3). This supports retaining composition and occurrence measures alongside standing stock when monitoring these categories.

The volume findings also constrain subsequent owner-impact assessment. All pairwise volume confidence intervals included zero under both the primary ecological adjustment and the additional current-composition adjustment. Nevertheless, the strong-reference total-volume interval extended from -12.04 to $+31.57 \text{ m}^3\cdot\text{ha}^{-1}$, leaving the magnitude of any underlying difference unresolved. These results provide little support for assigning a uniform difference in current standing volume to the protection categories. They do not establish equivalent stocks or quantify differences in future harvests.

The other outcomes specify additional biological information needed for economic analysis. The broadleaf-share contrast calls for species-specific volumes and timber assortments. Linking these quantities to assortment prices would provide the revenue component of a management comparison. The *QMD* interactions call for stem-size distributions differentiated by age and vegetation zone, followed by identification of the trees included in feasible harvesting operations. This distinction matters because harvesting-cost models use characteristics of actual removals, including mean harvested stem size and removal volume (Ahtikoski et al. 2024). Higher standing-deadwood occurrence identifies a need to quantify dead and retained timber, while lower stump occurrence identifies a need to reconstruct the timing and extent of previous cutting. Translating these attributes into owner impacts for the six profit-loss categories requires dated provisions, documented management alternatives and corresponding calcu-

lations of timber revenues, harvesting and regeneration costs, and cash-flow timing.

Transfer to another inventory therefore requires locally documented category definitions, compatible outcome measurements and sufficient ecological overlap for the intended comparisons. The Czech estimates apply to the 5 530 eligible plots with recorded live trees, ages of 20–130 years and LVS 1–7. Excluding older stands and plots without live trees may alter category representation, with an undetermined effect on the adjusted contrasts. The reference category also included 525 plots carrying conservation flags outside the evaluated ZCHÚ hierarchy, so it represents the stated administrative comparison. Missing overlay dates prevent confirmation that category assignments describe protection at the time of measurement. Missing management histories limit attribution of the stand differences, while unavailable survey weights and spatial-cluster identifiers leave design-based and spatial uncertainty unquantified. Repeated observations linked to historical designations and management records would address these specific inferential gaps.

CONCLUSION

Within the analysed NIL2 sample, the strong category was characterised by greater broadleaf basal-area share, more frequent standing deadwood and less frequent stumps. Adjusted strong-reference differences were +9.64, +12.56 and -6.94 percentage points, respectively. All three attributes also distinguished strong from moderate plots, while the corresponding moderate-reference comparisons remained statistically unresolved. The strong-reference directions persisted across the alternative category mappings and response-link specifications examined.

Protection class contributed little additional explanation of the current standing volume. Broadleaf and *QMD* interactions showed that some category differences depended on ecological setting, and the *QMD* and exploratory Shannon findings were sensitive to category construction. The resulting monitoring implication is specific: retain broadleaf composition and deadwood and stump occurrence as complementary descriptors, interpret *QMD* within age and vegetation-zone strata, and report sensitivity to the classification rule. For subsequent owner-impact assessment, stand age, volume and

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tree dimensions provide starting conditions for extended-rotation, withdrawal-from-production and premature-harvest scenarios (categories *i*, *ii* and *v*). Species composition supports assessment of mandatory species replacement (*iii*), while basal area and stem density support reduced-stocking scenarios (*iv*). LVS supports ecological stratification for site-condition changes (*vi*), whose productivity consequences require additional data. Monetary impacts were not quantified here; subsequent valuation across these categories requires documented management alternatives, dated legal provisions, prices, costs and cash-flow timing.

Data and code availability: The study used records from the second Czech National Forest Inventory (NIL2), supplied by the National Forest Institute (NLI), Czech Republic. The analysis code and aggregate model outputs are available from the corresponding author on reasonable request. Requests concerning access to and reuse of the source inventory records should be directed to NLI.

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