

ELECTRONIC SUPPLEMENTARY MATERIAL

ESM2- Numerical Examples

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Monitoring habitat conservation status and assessing biodiversity: The Dehesa case

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NUMERICAL EXAMPLES

This document presents six numerical examples that translate the probability-sampling designs and model-assisted estimators developed in the Main Text and Supplementary Material into concrete applications for Dehesa monitoring. Together, the examples cover tree, grassland and shrubland conservation status, carbon removal and carbon farming, grassland biodiversity, and bird biodiversity. Each example summarizes the target population, Earth observation auxiliary information, sampling implementation, estimation procedure, principal results, and its associated reproducible workflow. Throughout these examples, t_1 denotes the initial monitoring occasion and t_T the final monitoring occasion. For the six-year applications, $T = 6$, so t_T corresponds to t_6 .

Repository access and reproducibility

The datasets, R scripts, intermediate quality-assurance products and results required to reproduce the six numerical examples have been assembled in a structured repository. During peer review, a private copy can be provided to the editor and reviewers upon request. Following acceptance, the curated repository will be released publicly in a permanent archive, with a repository URL and persistent identifier.

To reproduce an example from the review copy, open the general README, select the corresponding Numerical Example module, and follow its module-specific README. From the module root, the complete workflow is run in R with `source("Scripts/00_run_all.R", encoding = "UTF-8")`. Each module documents its released inputs, required packages, analytical stages, quality checks and expected results.

Numerical Example 1. Tree Condition

Objective

This numerical example illustrates the permanent stratified pixel panel and model-assisted estimation framework described in Sections 2 and 3.2.2 of the Supplementary Material. Its objective is to estimate the proportion of young trees and paired temporal change using LiDAR-derived height and crown projection as auxiliary information.

Study area and target population

The study uses the 15.52-ha Dehesa plot in Valencia de Alcántara. The centroid-inside sampling frame contains 1,552 pixels: 286 with at least one LiDAR candidate and 1,266 without candidates. Two candidates whose pixel centroids fall outside the plot are excluded from this frame. All 303 LiDAR candidates were checked in the field. The field audit resolved multiple detections of the same tree and identified 265 effective trees in 256 pixels within the frame. These field findings define the reconstructed t_1 finite population; estimation below uses only the responses in the probability sample.

Earth observation and LiDAR support

Airborne LiDAR identified candidate objects and supplied height and crown projection as auxiliary variables. Field verification classified the candidates, distinguished trees from

false detections, and merged 12 candidate records into five individual trees. The 265 effective trees are field-confirmed, whereas their complete young/adult classification is not observed and is simulated for this numerical example. The no-candidate stratum is assumed to contain no effective trees; it was not exhaustively checked in the field.

Sampling implementation

Pixels were independently selected by SRSWOR within the original LiDAR-candidate strata. The permanent panel comprises 30 of the 286 candidate-occupied pixels and 10 of the 1,266 pixels without candidates. The first sample contains 33 candidates representing 29 effective trees after field verification; its other four candidates do not represent additional trees. Under the stated no-candidate assumption, the second sample contains no trees at t1. Young status ($DBH < 15$ cm) was simulated for the 29 effective trees using a height-and-crown logistic model, with six classified as young. The same pixels are followed in the simulated six-year occasion t6.

Model-assisted estimation

Two unpenalized design-weighted binomial logistic models use candidate height and crown projection as auxiliaries. The first estimates the effective-tree total; the second estimates the effective-and-young-tree total. Each model-assisted total combines predictions over the candidate list within the 1,552-pixel frame with the stratified Horvitz–Thompson correction of sampled pixel residuals. Their ratio estimates the proportion of young trees, with Taylor variance incorporating both total variances and their covariance. Paired linearized pixel residuals provide the covariance for the temporal change. The field-confirmed population total is retained as a validation benchmark, not inserted as a known denominator into the estimator.

Table 1. Core implementation data for Example 1

Quantity	Value
Plot area	15.52 ha
Centroid-inside EO pixels	1,552
Candidate-occupied pixels in analytical frame	286 (2 outside-frame pixels excluded)
LiDAR candidates checked in the field	303 (301 within the sampling frame)
Field-confirmed effective trees at t1	265 in 256 pixels
Candidate-occupied-stratum sample	$n_1 = 30$ pixels; 33 candidates; 29 effective trees
No-candidate-stratum sample	$n_2 = 10$ pixels; zero trees assumed at t1
Young-tree definition	Effective tree with simulated $DBH < 15$ cm; 6 in sample

Table 2. Estimated proportion of young trees and temporal change

Parameter	t1	t6 (simulated)
Estimated effective-tree total	265.80	270.31
Estimated proportion of young effective trees	0.2218	0.2896
Standard error of proportion	0.0615	0.0591

Change parameter	Estimate	Standard error
$\Delta = P(t6) - P(t1)$	+0.0678	0.0122

Interpretation

The estimated effective-tree total is 265.80 at t1 (SE 14.74; 95% CI 236.91–294.69), close to the field-reconstructed total of 265. The estimated young-tree total is 58.95 (SE 16.14). The estimated proportion of young effective trees is 0.2218 at t1 (SE 0.0615; 95% CI 0.1013–0.3423) and 0.2896 at simulated t6 (SE 0.0591; 95% CI 0.1738–0.4053). Its estimated change is +0.0678, or +6.78 percentage points (SE 0.0122; 95% CI +0.0438 to +0.0918).

The verification of LiDAR candidates and the resulting effective-tree count at t1 are based on field work. Young status and DBH for the sample were simulated, as were mortality, recruitment, growth and the t6 observations. The reported sampling variances are conditional on these simulations and on the assumed absence of trees in pixels without LiDAR candidates; they do not quantify uncertainty in either assumption.

Repository implementation

The field-verified Example 1 module includes the audited candidate-to-tree correspondence, the 1,552-pixel frame, the revised 30 + 10 permanent pixel panel, fixed simulated young-status and t6 inputs, and scripts for the two design-weighted logistic estimators and paired change. From the module root, `source("Scripts/00_run_all.R", encoding = "UTF-8")` validates the inputs and regenerates the estimates. The complete R workflow was run in the staging repository on 28 September 2026; input checks passed, and its t1, t6 and change results, including paired temporal covariance, reproduced the independent calculation. The module README identifies the inputs, simulation assumptions, outputs and checks. This version supersedes the provisional P1–P2 population and 1,554-pixel implementation.

Numerical Example 2. Grassland Condition

Objective

This numerical example implements the permanent stratified pixel–quadrat panel and model-assisted estimators described in Sections 2 and 3.2.1 of the Supplementary Material. It estimates dry matter (DM), crude protein (CP), forage quality (CP/DM), and their changes from t_1 to t_T .

Study area and target population

The definitive analysis frame contains 1,552 pixels: 286 with validated trees and 1,266 without. The permanent sample comprises 5 tree-stratum pixels and 25 no-tree pixels, with four of 400 possible $0.5 \text{ m} \times 0.5 \text{ m}$ quadrats selected in every sampled pixel, giving 120 paired quadrats at t_1 and t_T .

Earth observation support

Wet- and dry-season Sentinel-2 vegetation indices were computed for all pixels and used as auxiliary variables in the model-assisted estimation. These indices provide wall-to-wall information on vegetation condition and seasonal behaviour across the plot.

Sampling implementation

Sampling followed the multistage probability design described in Section 2. Pixels were selected within strata and quadrats were sampled within selected pixels. The final implementation used $n_1 = 5$ pixels in the tree stratum and $n_2 = 25$ pixels in the non-tree stratum, with four quadrats sampled per selected pixel.

Model-assisted estimation

Separate working models for DM and CP use an intercept, wet-season NDVI and tree stratum. Model-assisted totals include between-pixel and within-pixel sampling components. CP/DM uses Taylor linearization, and all $t_T - t_1$ change variances use covariance estimated from the paired-panel residuals.

Table 1. Core implementation data for Example 2

Quantity	Value
Plot area	15.52 ha
Analysis frame	1,552 pixels
Tree-stratum sample	$n_1 = 5$ pixels
No-tree-stratum sample	$n_2 = 25$ pixels
Quadrats per sampled pixel	4 of 400
Permanent quadrat panel	120 quadrats
Auxiliary information	Wet-season NDVI + tree stratum

Table 2. Estimated grassland productivity and nutritional quality

Indicator	t_1	t_T
Mean dry matter (kg ha ⁻¹)	1,967.057 (SE 17.480)	2,071.994 (SE 21.768)
Mean crude protein (kg ha ⁻¹)	192.881 (SE 3.101)	207.541 (SE 2.468)
Crude protein content (%)	9.806 (SE 0.152)	10.016 (SE 0.132)

Table 3. Estimated temporal changes

Change indicator	Estimate	SE	95% CI
Δ Dry matter (kg ha ⁻¹)	+104.938	22.851	(60.150, 149.726)
Δ CP/DM (percentage points)	+0.211	0.215	(-0.211, 0.633)

Interpretation

Estimated DM increases from 1,967.057 kg ha⁻¹ at t_1 to 2,071.994 kg ha⁻¹ at t_T , a change of +104.938 kg ha⁻¹ (SE 22.851). CP increases from 192.881 to 207.541 kg ha⁻¹, a change of +14.660 kg ha⁻¹ (SE 4.013).

CP/DM changes from 9.806% to 10.016%. Its estimated increase of +0.211 percentage points is small relative to its SE of 0.215. The quadrat responses are synthetic, so these results illustrate the multistage design and paired-covariance workflow rather than observed grassland condition.

This example illustrates how multistage probability sampling and Sentinel-2 auxiliary information can be combined to monitor both productivity and nutritional quality within a statistically rigorous framework.

Repository implementation

The corresponding module follows the repository-access arrangements described above. Its workflow includes sample selection, field-data processing, Sentinel-2 auxiliary-variable generation, model fitting, estimation of dry matter and crude protein, and change assessment under the pure-panel framework.

Numerical Example 3. Shrubland Condition

Objective

This numerical example implements the probability-sampling and model-assisted procedures described in Sections 2 and 3.2.1 of the Supplementary Material for estimating shrub cover, shrub area and paired change in the definitive no-tree domain.

Study area and target population

The target domain contains the 1,266 no-tree pixels of the definitive EO frame, equivalent to 12.66 ha. The permanent sample contains 25 pixels and four of 400 possible quadrats per pixel, giving 100 paired $0.5 \text{ m} \times 0.5 \text{ m}$ quadrats at t_1 and t_T .

Earth observation and LiDAR support

The t_1 ground-reference response is shrub-cover proportion interpreted from PNOA imagery. LiDAR provides the wall-to-wall shrub auxiliary for the no-tree domain. The t_T auxiliary and paired quadrat responses are simulated while preserving the t_1 panel.

Sampling implementation

Sampling followed the multistage probability design described in Section 2. The final implementation used 25 sampled pixels in the non-tree stratum and four quadrats per selected pixel, yielding 100 observed quadrats.

Model-assisted estimation

Separate linear working models at t_1 and t_T use an intercept and the pixel-level LiDAR shrub auxiliary. Status is the population mean prediction plus inverse-probability residual correction. Variance combines between-pixel and within-pixel components, and change uses the paired residual covariance.

Table 1. Core implementation data for Example 3

Quantity	Value
No-tree domain	$N_2 = 1,266$ pixels
Domain area	12.66 ha
Potential quadrats per pixel	$M = 400$
Sampled pixels	25
Quadrats per sampled pixel	4
Observed paired quadrats	100

Table 2. Estimated shrub cover

Indicator	t_1	t_T
Shrub-cover proportion	0.15060 (SE 0.04276)	0.13558 (SE 0.03350)
Shrub area (ha)	1.9066 (SE 0.5413)	1.7165 (SE 0.4241)

Table 3. Estimated temporal change

Change indicator	Estimate	SE
Δ Shrub-cover proportion	−0.01502	0.01325
Δ Shrub area (ha)	−0.1901	0.1678

Interpretation

Estimated shrub cover is 0.15060 at t_1 (SE 0.04276) and 0.13558 at t_T (SE 0.03350). The paired change is −0.01502, or −1.502 percentage points (SE 0.01325; 95% CI −0.04099 to 0.01096). Corresponding shrub area changes from 1.9066 to 1.7165 ha.

The change confidence interval includes zero, so the simulated decline is not statistically distinguishable from zero at the 5% level. The weak relationship between LiDAR auxiliary and quadrat response provides little precision gain; residual correction preserves design consistency.

This example illustrates how high-resolution aerial imagery, LiDAR-derived structural information and probability sampling can be combined to monitor shrubland condition in heterogeneous Mediterranean landscapes. The integration of Earth observation and LiDAR information with field observations provides a practical framework for repeated assessments of shrub cover and structural stability.

Repository implementation

The corresponding module follows the repository-access arrangements described above. Its workflow includes PNOA image processing, LiDAR canopy-height modelling, quadrat-level cover estimation, model-assisted estimation and temporal-change assessment under the pure-panel framework.

Numerical Example 4. Carbon Removal

Objective

This numerical example integrates the probability-sampling outputs from Numerical Examples 1–3 to illustrate the estimation of carbon removal and its relevance to carbon-farming applications. Tree carbon and the synthetic shrub-carbon proxy are treated as persistent living-biomass carbon stocks. In contrast, the carbon temporarily contained in grassland dry matter is reported as an annual biomass-carbon indicator and is neither added to the persistent woody stock nor accumulated as carbon removal.

Monitoring period

The example considers a six-year monitoring period ($T = 6$). Tree and shrub carbon stocks are estimated at each annual monitoring occasion, and their changes are combined to assess farm-level carbon removal in persistent living biomass. Grassland biomass carbon is likewise estimated annually but is reported separately as a non-persistent indicator of the carbon contained in standing herbaceous biomass; it is not accumulated across monitoring occasions.

Study area and target population

The study area is the 15.52-ha Dehesa plot in Valencia de Alcántara described in the preceding examples. The tree component comprises 301 LiDAR candidates at t_1 and 305 at t_6 ; only sampled-pixel classifications enter the estimator. The paired field samples contain 33 candidates at t_1 , of which 29 were confirmed as effective trees in the field, and 35 candidates at simulated t_6 , of which 31 are effective trees. Tree carbon stock is expressed per hectare of the full study area. The shrub component refers to the 1,266 no-tree pixels, corresponding to a 12.66-ha domain. The grassland component uses the definitive 1,552-pixel EO frame, stratified according to candidate presence. Before integration with tree carbon, shrub carbon estimated for the no-tree domain is converted to its full-farm equivalent.

Carbon stocks and carbon flows

For sampled effective trees, tree aboveground biomass (AGB) is estimated from simulated DBH assigned to field-confirmed trees at t_1 and effective trees in the simulated t_6 panel linked to LiDAR-derived height and crown area. Because the selected allometric equation predicts aboveground biomass only, belowground biomass is estimated using the adopted root-to-shoot ratio of 0.40 for single-stemmed *Quercus ilex* trees (Canadell & Rodà, 1991). Accordingly, total living tree biomass is calculated as $B_{\text{tree}} = 1.40 \text{ } AGB$. Biomass is converted to carbon using the IPCC default carbon fraction of 0.47 (IPCC, 2006), so that $C_{\text{tree}} = 0.47 B_{\text{tree}}$. Carbon stocks and stock changes may subsequently be expressed as CO₂ equivalent using $\text{CO}_2\text{e} = C_{\text{tree}}(44/12)$. For every LiDAR candidate, the conditional carbon prediction is multiplied by its estimated effective-tree probability from the design-weighted logit model. The model-assisted total then adds the Horvitz–Thompson correction of sampled-pixel carbon residuals, with observed carbon set to zero for non-tree candidates.

Shrub carbon is estimated using an explicitly calibrated synthetic relationship between shrub cover and biomass because an empirical site-specific biomass model is unavailable. For this numerical illustration, the resulting shrub-carbon estimate is treated as a persistent living-biomass stock. Grassland biomass carbon is calculated annually as $C_{\text{grass},t} = 0.47DM_t$, where DM_t is the estimated standing dry matter at occasion t . Because this aboveground herbaceous biomass is subject to grazing, senescence, and decomposition, it is reported separately as an annual biomass-carbon indicator and is neither interpreted as nor accumulated toward permanent carbon removal.

Component integration

Component-specific model-assisted estimates, occasion-specific variances and within-component paired temporal covariances are retained. Tree carbon is expressed per hectare of the full 15.52-ha study area. Shrub carbon, initially estimated per hectare of the 12.66-ha no-tree domain, is multiplied by 12.66/15.52 to obtain its full-farm contribution before being combined with tree carbon. The resulting estimates represent the farm-level persistent living-biomass carbon stock and its change, with the associated uncertainty propagated from the component estimates. Grassland biomass carbon follows the predefined six-year D–W–D–D–W–D sequence and is reported separately at each monitoring occasion; it is neither added to the persistent woody stock nor accumulated across years.

Table 1. Core implementation data for Example 4

Component	Carbon accounting role	Main information source
Trees	Persistent stock	LiDAR candidates + field-verified effective-tree status at t_1 and simulated DBH and t_6 panel
Shrubs	Synthetic persistent-stock proxy	Cover panel + calibrated proxy
Grassland	Annual biomass-carbon indicator	Model-assisted dry matter $\times 0.47$
Integration	Persistent living-biomass stock change	Area-weighted tree and shrub stocks with propagated uncertainty

Table 2. Carbon stocks, flows and removals

Component	Main result
Tree stock	10.7097 $\rightarrow$ 12.5461 Mg C ha ⁻¹
Shrub proxy (domain)	3.1493 $\rightarrow$ 3.2230 Mg C ha ⁻¹
Integrated woody stock	13.2786 $\rightarrow$ 15.1752 Mg C ha ⁻¹

Component	Main result
Integrated woody change	+1.8966 Mg C ha ⁻¹ (SE 0.2833)
Grassland biomass-carbon indicator	0.9245–1.0848 Mg C ha ⁻¹ across annual monitoring occasions

Interpretation

Effective-tree living-biomass carbon stock increases from 10.7097 to 12.5461 Mg C ha⁻¹ over the six-year monitoring period, representing a change of +1.8364 Mg C ha⁻¹ (SE 0.2766). The area-weighted synthetic shrub proxy contributes an additional +0.0601 Mg C ha⁻¹ to the full-farm persistent woody-stock change. Consequently, integrated woody carbon stock increases from 13.2786 to 15.1752 Mg C ha⁻¹.

The corresponding integrated woody-stock change is +1.8966 Mg C ha⁻¹ (SE 0.2833; 95% CI 1.3412–2.4519), equivalent to +6.9541 Mg CO_{2e} ha⁻¹ (SE 1.0389). Annual grassland biomass-carbon indicators range from 0.9245 to 1.0848 Mg C ha⁻¹ across the six monitoring occasions. These values represent the carbon temporarily contained in standing herbaceous biomass; they are not included in the persistent woody-carbon stock or its change and are not accumulated as carbon removal.

Because the shrub component is a calibrated synthetic proxy and parts of the field data are simulated, the integrated woody result is partly synthetic and cannot support carbon crediting or certification. Operational carbon-farming applications would additionally require site-specific empirical biomass calibration, non-simulated monitoring data and compliance with the applicable requirements concerning baseline setting, additionality, permanence, reversal risk, leakage, uncertainty, avoidance of double counting, and monitoring, reporting and verification.

Repository implementation

The field-verified Example 4 module contains validated local inputs from Numerical Examples 1–3 and scripts that estimate effective-tree probabilities, model DBH for sampled effective trees, calculate above- and belowground tree carbon, propagate component uncertainty, and integrate tree carbon with the area-weighted shrub proxy. Annual grassland biomass-carbon indicators remain separate. From the module root, `source("Scripts/00_run_all.R", encoding = "UTF-8")` runs input validation, component estimation and integration. The complete R workflow was run in the staging repository on 28 September 2026: all 22 local input and cross-file checks passed, and the recalculated integrated woody change was +1.8966 Mg C ha⁻¹ (SE 0.2833), as reported above. Its README records the analytical stages, expected outputs, checks and synthetic-data limitations.

Numerical Example 5. Flora Biodiversity

Objective

This numerical example implements the biodiversity framework in Section 3.2.3 of the Supplementary Material. It estimates grassland functional-group composition, Shannon diversity, Hill numbers and change from a permanent pixel–quadrat panel.

Study area and target population

The definitive frame contains 1,552 pixels. The permanent sample comprises 5 tree-stratum pixels and 25 no-tree pixels, with four quadrats per pixel. At each of the 120 quadrats, 50 point-intercept contacts are classified as grasses, legumes or others at t_1 and t_T .

Earth observation support

Sentinel-2 vegetation indices were used as auxiliary variables within the multinomial model-assisted estimation framework. These variables provide information on vegetation conditions and contribute to improving the estimation of functional-group proportions throughout the monitored Dehesa.

Sampling implementation

Sampling followed the multistage probability design described in Section 2 of the Supplementary Material. Vegetation observations collected in sampled quadrats were used to estimate the composition of the grassland community and the associated biodiversity indicators.

Model-assisted biodiversity estimation

Separate design-weighted multinomial-logit working models at t_1 and t_T use wet-season NDVI, with others as the reference category. Farm composition is the mean of the 1,552 estimated pixel probabilities. Shannon and Hill indicators are derived from these probabilities, and only point estimates are reported for the one-farm illustration.

Table 1. Core implementation data for Example 5

Quantity	Value
Community assessed	Grassland functional groups
Permanent panel	30 pixels; 120 quadrats
Observation protocol	50 point contacts per quadrat and occasion
Functional groups	Grasses, legumes, others
Model framework	Design-weighted multinomial logit
Uncertainty	Point estimates at one-farm level

Table 2. Estimated changes in functional-group composition

Functional group	Estimated change ($t_T - t_1$)
Grasses	+0.12565

Functional group	Estimated change ($t_T - t_1$)
Legumes	+0.05990
Others	-0.18555

Results are frame-aggregated estimates from the fitted models, not values evaluated at a single NDVI level.

Table 3. Estimated Shannon diversity change

Diversity index	t_1	t_T	Change
Alpha Shannon	1.08880	1.00649	-0.08231
Gamma Shannon	1.09148	1.01269	-0.07879
Beta Shannon	0.00268	0.00620	+0.00352

Interpretation

Estimated grasses increase from 0.36975 to 0.49540 and legumes from 0.27878 to 0.33868, while others decrease from 0.35147 to 0.16592. The changes sum to zero, as required for compositional data.

Shannon alpha decreases from 1.08880 to 1.00649 and gamma from 1.09148 to 1.01269, while additive beta increases from 0.00268 to 0.00620. Hill $q = 1$ and $q = 2$ also decline. The contacts are simulated and first-stage variance cannot be estimated from one farm.

This example illustrates how biodiversity indicators can be estimated within the same probability-sampling and model-assisted framework used for habitat-condition assessment. It also demonstrates how compositional information can be translated into ecologically interpretable diversity measures suitable for repeated monitoring and conservation-status evaluation.

Repository implementation

The corresponding module follows the repository-access arrangements described above. Its workflow includes vegetation-data processing, multinomial model fitting, estimation of functional-group proportions, computation of biodiversity indicators and temporal-change assessment.

Numerical Example 6. Bird Biodiversity

Objective

This numerical example implements the biodiversity framework described in Section 3.2.3 of the Supplementary Material for highly mobile fauna. It estimates bird-group composition and the associated Shannon and Hill diversity indices, together with their changes between monitoring occasions, using independent occasion-specific line-intersect sampling (LIS) samples, habitat covariates and design-weighted multinomial-logit working models.

Study area and target population

The 15.52-ha study area is represented by the definitive auxiliary EO frame of 1,552 pixels. The target parameter is the occasion-specific composition of the bird community across the study area. The simulated LIS design uses two transects at each monitoring occasion and distinguishes four bird groups. The independent occasion-specific samples contain 81 detected birds at t_1 and 55 at t_T . The simulated finite bird sets used to generate detections are not treated as known population inventories; estimation is based exclusively on the LIS detections and pixel-level auxiliary information.

Earth observation and habitat support

Earth observation and habitat-related variables, including vegetation indices, shrub cover and tree-presence information, were used as auxiliary variables in the multinomial model-assisted estimation framework. These variables support the estimation of species probabilities throughout the monitored Dehesa and provide ecological information linking bird occurrence to habitat conditions.

Sampling implementation

Each simulated LIS detection is linked to an EO pixel and includes NDVI, shrub cover, tree presence, inclusion probability and inverse-probability design weight. Counts at t_1 are 21, 30, 3 and 27 for *Parus major*, *Lullula arborea*, *Miliaria calandra* and Other; at t_T they are 9, 23, 3 and 20. At each occasion, a uniform random phase locates a pair of horizontal transects separated by half the EO-frame bounding-rectangle height. The phases are drawn independently between occasions, without conditioning either selection on the other. Detection strips do not overlap within an occasion; overlap between occasions is permitted. The original working LIS inclusion-probability formula and estimation procedure are retained.

Model-assisted biodiversity estimation

Separate weighted multinomial-logit models at t_1 and t_T use standardised NDVI, shrub cover and tree presence, with Other as reference. Frame predictions yield composition and diversity. Hessian covariance and a numerical delta method estimate uncertainty; change variance assumes independent occasion-specific samples.

Table 1. Core implementation data for Example 6

Quantity	Value
Sampling method	Two-transect LIS; independent occasion-specific phases
Detected birds at t_1	81
Detected birds at t_T	55
Bird groups	Parus, Lullula, Miliaria, Other
Auxiliary variables	NDVI, shrub cover, tree presence
Model framework	Weighted multinomial logit
Change uncertainty	Independent occasions + delta method

Table 2. Estimated bird-community composition and change

Species/group	t_1	t_T	Change
<i>Parus major</i>	0.20928	0.12264	−0.08665
<i>Lullula arborea</i>	0.46480	0.50527	+0.04047
<i>Miliaria calandra</i>	0.02626	0.03436	+0.00809
Other	0.29965	0.33774	+0.03808

Table 3. Estimated Shannon diversity change

Diversity index	t_1	t_T	Change
Shannon α	0.94244	1.03768	+0.09524
Shannon γ	1.14014	1.08470	−0.05543

Interpretation

Parus major declines from 0.20928 to 0.12264, a change of −0.08665 whose 95% confidence interval excludes zero. Changes for *Lullula arborea*, *Miliaria calandra* and Other have confidence intervals that include zero.

Shannon alpha changes from 0.94244 to 1.03768 and gamma from 1.14014 to 1.08470; both change intervals include zero. Hill $q = 2$ gamma changes from 2.85450 to 2.59346 and its change interval also includes zero. The change intervals exclude zero for declines in additive Shannon beta and multiplicative Hill beta at $q = 1$ and $q = 2$. All bird data are simulated and illustrate the estimators rather than observed community change.

This example demonstrates how line-intercept sampling, habitat covariates and multinomial model-assisted estimation can be combined to monitor highly mobile fauna within the same statistical framework used for vegetation biodiversity assessment. It also illustrates the integration of field observations and Earth observation information for repeated biodiversity monitoring at the farm level.

Repository implementation

The corresponding module follows the repository-access arrangements described above. Its workflow includes bird-observation processing, habitat-covariate generation, multinomial model fitting, estimation of bird-group composition, computation of biodiversity indicators and temporal-change assessment. The workflow generates both LIS samples from independent occasion-specific transect phases, records their coordinates and seeds, and verifies detection geometry and EO-pixel correspondence. The working weights retain the original treatment of irregular boundaries and edge effects; uncertainty remains the fitted-model Hessian/delta approximation for a calibrated simulation.