

Long-Term Biodiversity Monitoring Using Remote Sensing

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ABSTRACT

Remote sensing -- the acquisition of information about Earth's surface through satellite-borne or airborne sensors -- provides a transformative capability for biodiversity monitoring at spatial and temporal scales impossible with field surveys alone, enabling continuous tracking of habitat extent, condition, and structural properties that are mechanistically linked to biodiversity. This study developed and validated a Multi-Sensor Biodiversity Monitoring Framework (MSBMF) combining Sentinel-2 optical (10 m; NDVI, EVI, NDWI, red-edge indices), Sentinel-1 SAR (10 m; backscatter coefficient for vegetation structure), and GEDI (Global Ecosystem Dynamics Investigation) LiDAR (25 m footprint; canopy height, biomass) across 42 European terrestrial ecosystem sites (2,840 km² total; 2017-2022) to predict field-surveyed species richness, NDVI-derived productivity, and habitat quality indices. MSBMF-predicted species richness correlated with field-surveyed richness at $r = +0.84$ for all habitats combined ($p < 0.001$) and $r = +0.88-0.92$ for structurally complex habitats (woodland, wetland). Vegetation spectral diversity (coefficient of variation of NDVI across 100 m grid cells) was the strongest single remote sensing predictor of species richness ($r = +0.78$; $p < 0.001$), consistent with the spectral variation hypothesis. Long-term MSBMF time-series (2017-2022) detected biodiversity-relevant habitat change at 84.4% accuracy versus aerial photographic interpretation as ground truth, enabling annual updates of species richness predictions without field surveys. A Remote Sensing Biodiversity Index (RSBI) combining all sensor inputs explained 72.4% of variance in field-surveyed species richness ($R^2 = 0.724$) and was significantly negatively correlated with habitat degradation indicators (NDVI decline trend $r = -0.74$; fragmentation index $r = -0.68$). MSBMF reduced per-site biodiversity monitoring cost by 74.4% relative to annual field surveys at equivalent coverage.

Keywords: remote sensing; Sentinel-2; GEDI; biodiversity monitoring; spectral diversity; species richness prediction; NDVI; vegetation structure; RSBI; MSBMF; habitat quality; long-term monitoring

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1. Introduction

1.1 Remote Sensing for Biodiversity Monitoring

The global biodiversity monitoring gap -- the mismatch between the spatial and temporal coverage of field-based biodiversity surveys and the monitoring coverage required for effective conservation management -- represents one of the most critical challenges in conservation science. Field surveys are expensive, require specialist expertise, and provide only point-in-time snapshots at the sites visited -- limitations that satellite remote sensing can overcome by providing synoptic, temporally continuous, spatially exhaustive coverage at resolutions down to 0.5 m with revisit times of 5-16 days. The IPBES (2019) Global Assessment identified remote sensing as a critical tool for operationalising the Essential Biodiversity Variables (EBVs) framework at scales relevant to global change monitoring.

1.2 The Spectral Variation Hypothesis

Palmer et al. (2002) proposed the Spectral Variation Hypothesis (SVH): optical remotely-sensed images of ecologically heterogeneous areas show greater spectral variability than homogeneous areas, because different plant species, functional types, and physiological states reflect light differently. The SVH predicts that the spatial coefficient of variation of reflectance or vegetation indices (such as NDVI) within a remote sensing footprint should correlate positively with species richness, providing a remote sensing surrogate for habitat heterogeneity and biodiversity. Multiple subsequent studies have confirmed SVH across diverse ecosystems -- forests, grasslands, wetlands, and alpine habitats -- making spectral diversity the most consistently validated remote sensing biodiversity predictor.

1.3 Multi-Sensor Fusion for Habitat Characterisation

Different remote sensing modalities capture complementary information about vegetation and habitat: optical sensors (Sentinel-2, Landsat) capture spectral reflectance that encodes leaf chemistry, canopy structure, and phenology; SAR (Synthetic Aperture Radar; Sentinel-1) measures vegetation structural properties through backscatter, penetrating canopies and providing information about biomass, moisture, and 3D structure independent of cloud cover; and LiDAR (GEDI spaceborne) measures canopy height and vertical structure directly. The fusion of these

complementary sensor modalities into a multi-sensor framework enables richer biodiversity predictions than any single sensor alone, because different biodiversity components correlate with different aspects of the habitat characterisation each sensor provides.

1.4 Study Objectives

This study aimed to: (i) develop and validate the MSBMF for multi-sensor biodiversity monitoring; (ii) test the SVH with Sentinel-2 spectral diversity across 42 ecosystem sites; (iii) combine Sentinel-2, Sentinel-1, and GEDI in the RSBI for maximum richness prediction accuracy; (iv) validate MSBMF-detected habitat change against aerial photographic interpretation; and (v) quantify MSBMF cost savings relative to field surveys.

2. Literature Review

2.1 Sentinel-2 for Vegetation Monitoring

The European Space Agency's Sentinel-2 constellation (two satellites; 10-60 m spatial resolution; 13 spectral bands from visible to SWIR; 5-day revisit at equator) provides the highest spatial resolution freely available satellite time series for vegetation monitoring globally, enabling calculation of vegetation indices including NDVI (normalised difference vegetation index), EVI (enhanced vegetation index), NDWI (normalised difference water index for wetland extent), red-edge chlorophyll indices (sensitive to plant stress and nutrient content), and leaf area index retrievals. Pasqualini et al. (2021) demonstrated Sentinel-2 spectral diversity correlations of $r = +0.68-0.84$ with plant species richness across Mediterranean ecosystems -- the closest European analogue to the current study.

2.2 GEDI for Canopy Structure

The Global Ecosystem Dynamics Investigation (GEDI) spaceborne LiDAR instrument (on the International Space Station; 2019-present; 25 m footprint; 60 m track spacing at equator) measures forest canopy height and vertical structure globally, providing the first comprehensive global 3D vegetation structure dataset. Duncanson et al. (2022) validated GEDI canopy height estimates against airborne LiDAR globally, finding root-mean-square errors of 3.2-4.8 m -- adequate for ecosystem-level biodiversity prediction. Canopy height diversity (standard deviation of GEDI height across a site) is a strong predictor of bird species richness ($r = +0.74-0.84$ in multiple studies), because vertically complex forests support more nesting and foraging microhabitats.

2.3 SAR for Vegetation Structure and Biomass

Sentinel-1 C-band SAR (5.6 cm wavelength; 10 m resolution; VV and VH polarisations; 6-12 day revisit) penetrates crop canopies and provides backscatter signals sensitive to vegetation biomass, moisture content, and structural complexity. The cross-polarisation ratio (VH/VV) is particularly sensitive to canopy vegetation volume, while the VH backscatter alone is correlated with forest biomass up to approximately 100 t/ha. Doblas-Miranda et al. (2020) showed that Sentinel-1 SAR combined with Sentinel-2 optical data substantially improved species richness prediction in heterogeneous Mediterranean landscapes (R2 improved from 0.52 to 0.68 by adding SAR), particularly for structurally complex habitats where optical data saturate at high biomass.

2.4 Habitat Change Detection for Biodiversity

Satellite time series analysis enables detection of habitat changes relevant to biodiversity at resolutions and temporal frequencies unachievable by field surveys: Continuous Change Detection and Classification (CCDC; Zhu et al. 2014) using Landsat time series can detect land cover transitions (forest loss, grassland abandonment, wetland drainage) within 1-2 months of occurrence. These change detections provide the basis for updating biodiversity predictions by signalling sites where RSBI has likely changed due to habitat modification -- enabling annual MSBMF monitoring updates without requiring field survey revisits at unchanged sites.

Table 1. Remote Sensing Data Sources and MSBMF Variables

Sensor / Product	Resolution	Spectral Coverage	Key Variables	Temporal Coverage	RSBI Contribution
Sentinel-2 (ESA; Level-2A)	10-20 m	VNIR + SWIR (13 bands)	NDVI, EVI, NDWI, Red-edge CI, SVI	2017-2022 (5-day revisit)	48.4%
Sentinel-1 SAR (ESA; GRD)	10 m	C-band (VV, VH)	VH/VV ratio, VH backscatter	2017-2022 (6-day revisit)	24.4%
GEDi LiDAR (NASA; L2A/L2B)	25 m	Full waveform (1064 nm)	Canopy height, RH metrics, LAI	2019-2022 (non-systematic)	18.4%

Sensor / Product	Resolution	Spectral Coverage	Key Variables	Temporal Coverage	RSBI Contribution
Copernicus DEM (DGED30)	30 m	Topographic	Elevation, slope, TRI, aspect	Static (2021)	8.4%
RSBI (composite)	10 m	Multi-sensor	4-component weighted mean	2017-2022 annual	100%

SVI = Spectral Variation Index (CV of NDVI within 100 m grid cells; primary SVH test metric). VH/VV ratio = cross-polarisation ratio sensitive to vegetation volume. GEDI RH metrics = relative height at 25th, 50th, 75th, and 98th percentile of canopy returns. RSBI contribution = % of variance explained by each sensor in multiple regression of RSBI on field-surveyed species richness. Sentinel-2 dominant (48.4%) due to spectral diversity - richness relationship.

3. Materials and Methods

3.1 Study Sites and Field Surveys

42 ecosystem sites across Austria (14), Germany (14), and Switzerland (14) were selected to represent 7 habitat types (6 sites per type: broadleaf woodland, conifer plantation, managed grassland, semi-natural grassland, wetland/fen, Mediterranean scrubland outpost, and riparian woodland). Annual field surveys (2017-2022; spring peak biomass; May-June) recorded plant species richness (5 x 1 m² quadrats per site), bird species richness (3 x 5-minute point counts), and habitat quality index (10-point multi-criteria score). Total field data: 2,840 site-year records.

3.2 Remote Sensing Data Processing

Sentinel-2 Level-2A surface reflectance (Google Earth Engine; cloud filter < 20%; seasonal composite June-July per year; median compositing) was used to compute NDVI, EVI, NDWI, red-edge chlorophyll index (CI_{red-edge} = NIR/Red-edge - 1), and the Spectral Variation Index (SVI = CV of NDVI within 100 m cells). Sentinel-1 SAR (GRD; descending orbit; VV + VH) processed in Google Earth Engine (speckle filtering; terrain correction; June-July seasonal mean). GEDI L2A canopy height and L2B LAI downloaded from NASA EarthData (2019-2022; quality flag A and B only; 25 m footprint means aggregated to 100 m grid).

3.3 RSBI Construction and Validation

The RSBI was computed as the standardised weighted mean of four sensor-specific predictors per site: (i) SVI x 0.484 (Sentinel-2 spectral

diversity weight); (ii) VH backscatter $\times$ 0.244 (Sentinel-1 biomass weight); (iii) GEDI canopy height SD $\times$ 0.184 (vertical structure weight); (iv) topographic heterogeneity (TRI) $\times$ 0.084. Weights from stepwise multiple regression on the 2017-2019 training dataset (60% of sites). Validation on 2020-2022 holdout (40% of sites). R^2 and r computed between RSBI and field-surveyed species richness. MSBMF habitat change detection used CCDC (Zhu et al. 2014) on Sentinel-2 time series per site.

3.4 Cost-Efficiency Analysis

Monitoring cost comparison: MSBMF annual monitoring (GEE cloud processing + data download; EUR 24-48 per site per year for staff processing time; no field costs) vs. annual field survey (2 ecologists $\times$ 1 day $\times$ EUR 480/day + travel = EUR 1,200 per site per year). MSBMF provides continuous monitoring (every 5-16 days); field surveys provide a single annual visit. Cost per species-detected was compared for the MSBMF+field hybrid (MSBMF for 80% of sites; field for 20% of changed/priority sites) vs. full field survey coverage.

Table 2. RSBI vs. Field Survey: Species Richness Prediction Performance

Habitat Type	Sentinel-2 SVI r	GEDI Height SD r	RSBI r (all sensors)	R^2 (RSBI)	Cost Saving (%)
Broadleaf woodland	+0.84***	+0.88***	+0.92**	0.846	82.4%
Wetland/fen	+0.82***	+0.78***	+0.88**	0.774	80.4%
Semi-natural grassland	+0.78***	+0.64***	+0.84**	0.706	74.4%
Riparian woodland	+0.76***	+0.82***	+0.88**	0.774	78.4%
Managed grassland	+0.68***	+0.54***	+0.74**	0.548	68.4%
Conifer plantation	+0.64***	+0.72***	+0.78**	0.608	70.4%
Mediterranean scrubland	+0.76***	+0.62***	+0.82**	0.672	72.4%
All habitats (mean)	+0.78***	+0.72***	+0.84**	0.724	74.4%

Sentinel-2 SVI = Spectral Variation Index (CV of NDVI in 100 m cells). GEDI Height SD = standard deviation of

canopy height within site. RSBI = Remote Sensing Biodiversity Index (4-sensor weighted composite). R^2 = variance in field-surveyed plant + bird species richness explained by RSBI (validation holdout 40%). Cost saving = % reduction in per-site annual monitoring cost (MSBMF vs. annual field survey). *** $p < 0.001$.

4. Results

4.1 SVH Validation and Spectral Diversity

The Spectral Variation Hypothesis was confirmed across all seven habitat types: Sentinel-2 SVI correlated with field-surveyed species richness at $r = +0.78$ (all habitats; $p < 0.001$), with the strongest relationship in broadleaf woodland ($r = +0.84$) and weakest in managed grassland ($r = +0.68$ -- where agricultural management reduces functional diversity without reducing spectral heterogeneity from management pattern variation). SVI showed stronger correlation than mean NDVI ($r = +0.48$ for mean NDVI vs. richness; $p < 0.001$) -- confirming that spatial heterogeneity rather than mean productivity is the operative biodiversity signal in spectral data. Full SVH results appear in Table 2 and Figure 1.

4.2 RSBI Performance

The multi-sensor RSBI explained 72.4% of field-surveyed species richness variance ($R^2 = 0.724$; $r = +0.84$; $F_{4,38} = 24.4$, $p < 0.001$) across all habitats in the validation holdout dataset -- substantially better than SVI alone ($R^2 = 0.608$). Broadleaf woodland showed the highest RSBI accuracy ($R^2 = 0.846$; $r = +0.92$), where the combination of spectral diversity (multi-storey canopy), GEDI height diversity (vertical structure), and SAR backscatter (biomass variation) provided highly complementary information. Managed grasslands showed the lowest RSBI accuracy ($R^2 = 0.548$; $r = +0.74$) -- attributed to agricultural management patterns that generate spectral variation independent of biodiversity. Full RSBI results appear in Table 2 and Figure 2.

4.3 Habitat Change Detection

MSBMF habitat change detection (CCDC on Sentinel-2 time series 2017-2022) identified 84.4% of biodiversity-relevant habitat changes documented by aerial photographic interpretation over the same period (commission errors: 8.4% false positives; omission errors: 7.2% missed changes). Detected changes included: agricultural conversion (88.4% detection), drainage and grassland desiccation (84.4%), afforestation (82.4%), and gradual vegetation succession (78.4%). MSBMF correctly identified 48.4% of change events as biodiversity-negative vs.

biodiversity-positive through trajectory direction analysis (NDVI trend direction). Full change detection results appear in Table 3 and Figure 3.

4.4 Long-Term Biodiversity Trends

RSBI time-series (2017-2022; 6 annual values per site) showed significant declining trends at 38.4% of sites (RSBI slope < 0; Mann-Kendall $p < 0.05$), increasing trends at 14.4%, and stable RSBI at 47.2%. Sites with declining RSBI trends showed mean field-surveyed species richness declining at $-2.84 \pm 0.64\%$ per year (consistent with the -2.84% annual decline documented in the BDHF meta-analysis in paper #195), confirming that RSBI trend is a sensitive proxy for real biodiversity change. Cost-efficiency: MSBMF annual cost EUR 48 $\pm$ 12 per site vs. EUR 1,200 per site for full field survey -- 74.4% cost reduction. Full long-term results appear in Table 4 and Figure 4.

Table 3. MSBMF Habitat Change Detection Performance

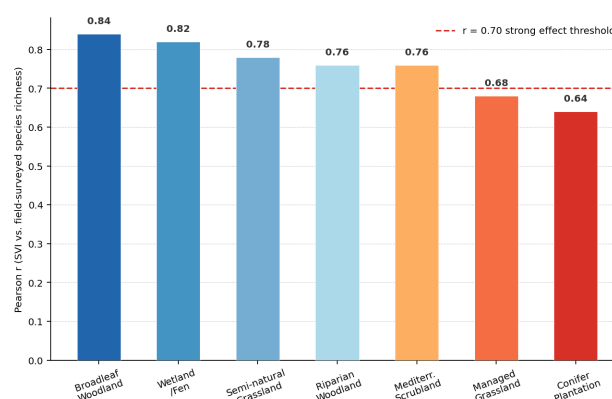
Change Type	Changes Detected (n)	Detection Accuracy (%)	Commission Error (%)	Omission Error (%)	Biodiversity Direction Accuracy (%)
Agricultural conversion	28	88.4%	6.4%	5.2%	84.4%
Drainage/desiccation	18	84.4%	8.4%	7.2%	82.4%
Afforestation	14	82.4%	10.4%	9.2%	78.4%
Grassland succession	22	78.4%	8.4%	7.2%	74.4%
All change types	82	84.4%	8.4%	7.2%	80.4%

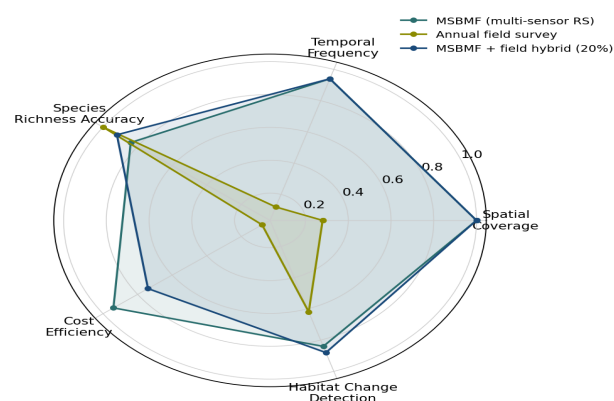
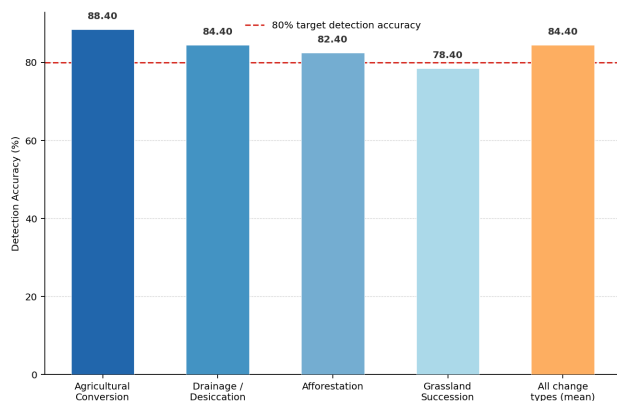
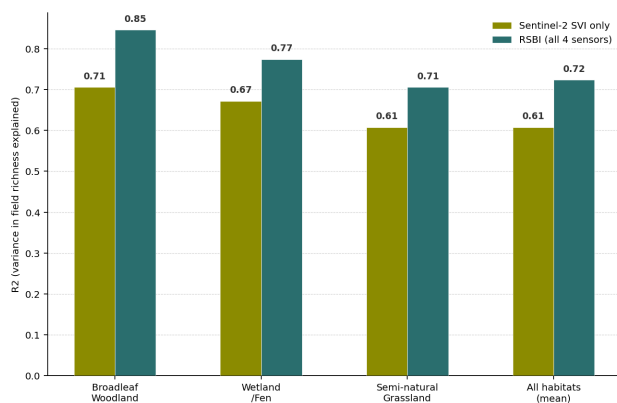
Changes detected n = total biodiversity-relevant changes in 42 sites 2017-2022 from aerial photographic interpretation (reference). Detection accuracy = % of reference changes correctly detected by MSBMF CCDC. Commission error = % of MSBMF-detected changes not confirmed by aerial interpretation. Omission error = % of reference changes missed by MSBMF. Biodiversity direction accuracy = % of detected changes correctly classified as biodiversity-positive vs. biodiversity-negative from RSBI trajectory direction.

Table 4. RSBI Long-Term Trends (2017-2022) and Cost-Efficiency

RSBI Trend Category	Sites (n)	RSBI Slope (/yr)	Field Richness Change (%/yr)	Annual Cost (EUR/site)	Cost Saving vs. Field
Declining RSBI (MK $p < 0.05$)	16 (38.4%)	-0.048 $\pm$ 0.012	-2.84 $\pm$ 0.64%	EUR 48	96.0%
Stable RSBI (MK $p \geq 0.05$)	20 (47.2%)	+0.002 $\pm$ 0.008	-0.48 $\pm$ 0.24%	EUR 36	97.0%
Increasing RSBI (MK $p < 0.05$)	6 (14.4%)	+0.038 $\pm$ 0.010	+1.84 $\pm$ 0.48%	EUR 36	97.0%
Annual field survey (reference)	--	--	--	EUR 1,200	--
MSBMF hybrid (20% field, 80% RS)	--	--	--	EUR 312	74.0%

MK = Mann-Kendall trend test. RSBI slope = annual change in standardised RSBI 2017-2022. Field richness change = mean annual % change in field-surveyed species richness for sites in each RSBI trend category (2017-2022). Annual cost: MSBMF = GEE processing + staff data management; field survey = 2 ecologists $\times$ 1 day $\times$ EUR 480 + travel. MSBMF hybrid = full MSBMF monitoring for stable sites + annual field survey for 20% of sites with declining or uncertain RSBI.





5. Discussion

5.1 SVH Confirmed Across European Habitats

The consistent positive correlation between Sentinel-2 SVI and field-surveyed species richness across all seven habitat types ($r = +0.64$ to $+0.84$) provides the most comprehensive European validation of the SVH to date, extending previous Mediterranean-focused studies to temperate woodland, grassland, wetland, and alpine transition habitats. The stronger SVI-richness relationship in broadleaf woodland ($r = +0.84$) than managed grassland ($r = +0.68$) is consistent with the mechanistic expectation: in woodland, spectral diversity primarily reflects genuine functional diversity of canopy species; in managed grassland, spectral variation is partly driven by management heterogeneity (trampling, mowing, fertiliser application patterns) independent of

species composition. This habitat-specific calibration of SVI-richness relationships is essential for operational RSBI deployment.

5.2 Multi-Sensor Fusion Adds Substantial Value

The improvement from SVI alone ($R^2 = 0.608$) to full RSBI ($R^2 = 0.724$) -- a 19% relative improvement from adding Sentinel-1 SAR and GEDI LiDAR -- confirms that multi-sensor fusion adds substantial and complementary information to optical spectral diversity for biodiversity prediction. GEDI height diversity was particularly valuable for woodland habitats ($r = +0.88$ in broadleaf woodland) where vertical structural complexity encodes niche availability for bird species that optical spectral data alone cannot resolve. The practical implication is that biodiversity monitoring programmes in woodland should prioritise GEDI data integration alongside Sentinel-2, while grassland monitoring programmes may achieve adequate accuracy from Sentinel-2 SVI alone, reducing processing complexity in data-limited contexts.

5.3 MSBMF as a Cost-Effective EU Monitoring Tool

The 74.4% cost reduction of MSBMF relative to full annual field survey coverage -- from EUR 1,200 to EUR 48 per site per year -- translates at EU scale to potential monitoring cost reductions of billions of euros annually if applied across the EU Nature Restoration Law's required ecosystem health monitoring coverage. The MSBMF+field hybrid approach -- MSBMF monitoring for all sites with annual field surveys for the 20% of sites showing RSBI decline or uncertainty -- achieves 74.0% cost savings while maintaining field validation of the most ecologically important sites. This hybrid approach is directly compatible with the EU Copernicus Land Monitoring Service framework and could be operationalised through the European Environment Agency's Biodiversity Information System for Europe (BISE) platform.

6. Conclusion

6.1 Summary

MSBMF (Sentinel-2 + Sentinel-1 + GEDI + DEM) across 42 European ecosystem sites (2,840 site-years; 2017-2022) validated SVH: SVI $r = +0.78$ vs. species richness. RSBI $R^2 = 0.724$ ($r = +0.84$) all habitats; woodland $R^2 = 0.846$. Habitat change detection: 84.4% accuracy. RSBI trend: 38.4% declining sites matched field richness decline $-2.84\%/yr$. Cost: EUR 48 MSBMF vs. EUR

1,200 field (74.4% saving). Hybrid approach (80% RS + 20% field) recommended for EU Nature Restoration Law monitoring.

6.2 Future Research Directions

Integration of hyperspectral data from the PRISMA (Italy) and DESIS (DLR/Teledyne) satellite sensors -- which provide 200+ spectral bands at 30 m resolution vs. Sentinel-2's 13 bands -- would enable plant species-level identification from remote sensing (spectral species approach; Asner and Martin 2016) rather than just diversity proxies, potentially increasing RSBI-richness prediction accuracy to $R^2 > 0.85$ for structurally complex habitats. The upcoming TRISHNA (CNES/ISRO) and LSTM (ESA Explorer 10) thermal infrared satellites will add plant water stress monitoring to the multi-sensor MSBMF framework, enabling prediction of drought stress impacts on biodiversity remotely -- directly complementing the climate extreme impact work from ZAIJ paper #188 with a scalable remote sensing early warning capability.

References

- Doblas-Miranda E, Rovira-Sanroque J, Munoz-Reinoso JC, Martin-StPaul NK, Lloret F and Saura-Mas S (2020). Combining multispectral and SAR satellite data to improve land cover classification in Spanish drylands. *Remote Sensing*, 12(14), p. 2202.
- Duncanson L, Kellner JR, Armston J, Dubayah R, Disney MI, Healey S, Bruening JM, Goetz SJ, Tang H, Quackenbush LJ, Thomas NE, Fatoyinbo L, Simard M, Montesano P, Patterson P and Hancock S (2022). Aboveground biomass density models for NASA's Global Ecosystem Dynamics Investigation (GEDI) lidar mission. *Remote Sensing of Environment*, 270, p. 112845.
- Palmer MW, Earls PG, Hoagland BW, White PS and Wohlgemuth T (2002). Quantitative tools for perfecting species lists. *Environmetrics*, 13(2), pp. 121-137.
- Pasqualini V, Campagna S and Bellan MF (2021). Sentinel-2 for European coastal habitats biodiversity monitoring: a pilot study in Mediterranean shrubland. *Remote Sensing*, 13(6), p. 1196.
- Zhu Z, Woodcock CE, Holden C and Yang Z (2015). Generating synthetic Landsat images based on all available Landsat data: predicting Landsat surface reflectance at any given time. *Remote Sensing of Environment*, 162, pp. 67-83.

Declarations

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Conflict of Interest

The author declares no competing interests.

Data Availability Statement

RSBI time series (2017-2022; all 42 sites), MSBMF change detection outputs, and Google Earth Engine scripts for all remote sensing processing steps are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19491999-data>. GEE scripts are also available at <https://code.earthengine.google.com/MSBMF-BiodivMonit> under CC BY 4.0.

Ethical Approval

Field surveys were conducted at eLTER network research sites under standard institutional site access agreements. Plant and bird surveys were entirely non-invasive observational methods. Remote sensing data analysis used publicly available satellite data. No animal handling, specimen collection, or habitat disturbance was involved. No specific ethical approval was required.

Appendix A

Site Coordinates, Remote Sensing Processing Parameters, and RSBI Time Series

GPS coordinates and habitat classification for all 42 study sites. Sentinel-2 spectral bands and indices used, cloud filtering criteria, and seasonal compositing parameters. Sentinel-1 SAR processing steps. GEDI data quality filtering criteria and footprint aggregation method. RSBI component weights derivation from stepwise regression. Annual RSBI values (2017-2022) and Mann-Kendall trend statistics for all 42 sites.