

Pacheco-Labrador, J.; Gomasasca, U.; Pabon-Moreno, D.; Li, W.; Migliavacca, M.; Jung, M.; Duveiller, G.; Bustos-Caparrós, J.; Lagranja-Usán, J.; Martín, M. BOSSE. A tool for benchmarking new methods in remote sensing of plant functional diversity, and more

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ABSTRACT

This work presents the first Biodiversity Observing System Simulation Experiment (BOSSE) and how it has been used to solve five methodological fundamental questions in the study of plant functional diversity with remote sensing. BOSSE simulates virtual scenes with plant species and their functional traits, remote sensing imagery, and ecosystem functions, which has allowed assessing the capability of different methodological choices, as well as the impact of spatial resolution. Subsequent works focus on supporting the analysis of experimental data and expand to other areas, such as model transferability through different spatial scales.

Keywords: *Plant functional diversity, remote sensing, virtual simulator, methods*

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BOSSE. A tool for benchmarking new methods in remote sensing of plant functional diversity, and more

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Abstract: *This work presents the first Biodiversity Observing System Simulation Experiment (BOSSE) and how it has been used to solve five methodological fundamental questions in the study of plant functional diversity with remote sensing. BOSSE simulates virtual scenes with plant species and their functional traits, remote sensing imagery, and ecosystem functions, which has allowed assessing the capability of different methodological choices, as well as the impact of spatial resolution. Subsequent works focus on supporting the analysis of experimental data and expand to other areas, such as model transferability through different spatial scales.*

Keywords: *Plant functional diversity, remote sensing, virtual simulator, methods*

BOSSE. Una herramienta para evaluar nuevos métodos de teledetección para estimar la diversidad funcional de la vegetación, y más

Resumen: Este trabajo presenta el primer “Experimento de Simulación del Sistema de Observación” dedicado a la Biodiversidad (BOSSE) y cómo ha sido empleado para resolver cinco cuestiones metodológicas fundamentales en el estudio de la diversidad funcional mediante teledetección. BOSSE simula escenas virtuales con mapas de especies vegetales, sus rasgos funcionales, imágenes de satélite y funciones ecosistémicas, lo que ha permitido evaluar la capacidad de diferentes decisiones metodológicas, así como el efecto de la resolución espacial. Trabajos subsiguientes se focalizan en el soporte al análisis de datos experimentales y se expanden a otras áreas, como la transferibilidad de modelos a través de diferentes escalas espaciales.

Palabras clave: Diversidad funcional de la vegetación, teledetección, simulador virtual, métodos

1. INTRODUCTION

The growing interest in mapping plant functional diversity from spectral imagery contrasts with unresolved gaps between remote sensing and field ecology, as well as the need for new, more demanding field sampling schemes. These limitations prevent robust advances and a clear understanding of the mechanisms behind the relationship between the diversity of remote sensing variables and the diversity of plant functional traits on the ground. As in many developing areas, the available early

studies are hardly comparable. In this case, this is due to the wide range and scarce overlap of methods, sensors, scales, extents, and functional diversity metrics, among others, and they do not cover a sufficiently broad range of situations to ensure the robustness of operational, global products. This makes it difficult to identify which methodological approaches allow remote sensing to achieve accurate estimates of plant functional diversity, nor the advantages and limitations of the different methods and sensors under consideration.

Despite the need for empirical proof, simulations can support the benchmarking of new methods and help to answer simple but fundamental questions. This was the aim of the first Biodiversity Observing System Simulation Experiment (BOSSE) (Pacheco-Labrador *et al.*, 2025). BOSSE generates virtual scenes that encompass spatially explicit, temporally dynamic vegetation traits and species maps, and simulates the corresponding remote sensing variables at the bottom of the atmosphere, and associated ecosystem functions. Despite its relative simplicity, BOSSE has addressed fundamental yet unresolved methodological questions about estimating plant functional diversity from spectral data (Pacheco-Labrador *et al.*, 2026), and could still help guide experimental analyses and answer many more questions. For example, has shed light on questions such as what are the best remote sensing proxies of plant functional diversity or the abundance used to calculate it, which are more resistant to degraded spatial resolution, how to infer diversity in large areas, or whether uncertainties depend on seasonality, among others. We present here the BOSSE model and how it has supported the development of this research domain.

2. MATERIAL AND METHODS

2.1. The BOSSE model

BOSSE integrates multiple models, enabling the simulation of synthetic scenes with vegetation constrained by meteorological time series and the corresponding climatic zone. The scene pixels are assumed to be occupied by one or more identical plants of the same species. These synthetic species are defined

by their plant functional type, the upper and lower bounds of their plant functional trait values, and their sensitivity to meteorology. This enables representing temporal variability. Furthermore, the model simulates interspecific diversity and different spatial patterns of species distributions. Plant traits are approximated by foliar and structural parameters of the SCOPE model (van der Tol *et al.*, 2009) radiative transfer model.

Using these trait maps and meteorological data, BOSSE can simulate corresponding remote sensing imagery of hyperspectral reflectance factors (R), land surface temperature (LST), and sun-induced chlorophyll fluorescence (F), and degrade its spatial resolution relative to the baseline pixel size used to simulate vegetation (considered the 100 % spatial resolution). BOSSE also provides estimates of plant traits from the simulated reflectance (optical traits, OT). Additionally, BOSSE can simulate various ecosystem functions, including gross primary production or evapotranspiration, among others. The simulations are based on SCOPE, and accelerated using statistical surrogates or emulators (Gómez-Dans *et al.*, 2016).

2.2. BOSSE simulations

We used BOSSE to simulate two-year time series of plant trait maps and remote sensing imagery for 180 scenes across four climatic zones (Arid, Tropical, Temperate, and Continental) and three spatial patterns (even, intermediate, and clustered). Fig. 1 presents four examples of these scenes.

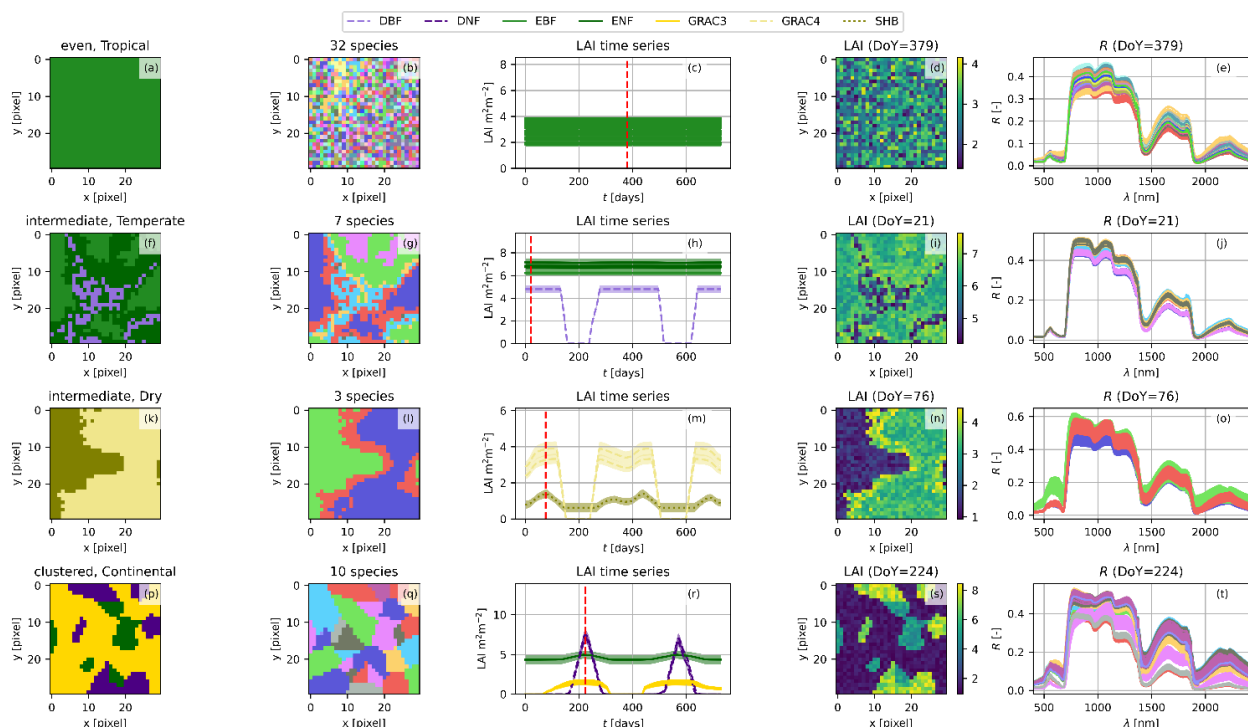


Figure 1. Example of BOSSE synthetic Scenes. These cover four different climatic zones (Tropical (a-e), Temperate (f-j), Dry (k-o), and Continental (p-t)) and three spatial patterns (even (a-e), intermediate (f-j,o-k), and clustered (p-t)). Plant functional types map (1st

column, color code in legend), species maps (2nd column, each represented by a different color), time series of leaf area index (LAI) (3rd column, mean and standard deviation interval of each species, colored by plant functional type), the LAI map at the date of the maximum phenological development (4th column), and hyperspectral reflectance factors of each pixel, colored as the species).

We used the Python package pyGNDiv (Pacheco-Labrador *et al.*, 2023) to calculate functional diversity from the plant trait maps and the remote sensing variables. pyGNDiv allows normalizing diversity metrics to the trait dataset's dimensionality, thereby enabling a direct comparison (same scale). Specifically, we computed the Rao's quadratic entropy index (Q_{Rao}) (Botta-Dukát, 2005) and partitioned diversity at different scales (alpha, beta, gamma) using the variance approach (Laliberté *et al.*, 2020). We used these simulations to determine 1) how to compute plant functional diversity over large extents, 2) which spectral variables or combinations captured plant functional diversity best, 3) how to validate plant functional diversity estimates, 4) how phenology affected the estimation error, and 5) which spectral variables were more robust to degrading spatial resolution.

3. RESULTS

The comparison of functional diversity metrics computed from plant trait maps and remote sensing imagery at the same spatial resolution (i.e., assuming pure pixels) proved that averaging multiple small samples (e.g., 9 pixels) should be used to compute functional diversity metrics rather than large samples occupying the entire study area. Using larger scenes (90-by-90 pixels), we found that the second alternative leads to saturation and convergence of diversity values (Fig. 2), hiding the differences between scenes of different diversity levels.

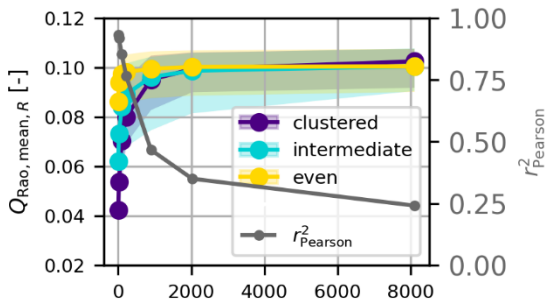


Figure 2. Example of diversity metric saturation with window size across different spatial patterns and its correlation with plant functional diversity derived from plant traits.

We also found that the best-performing remote sensing variables are those accounting for the presence of bare soil. In our study, the optical traits (plant trait estimates based on reflectance) and sun-induced chlorophyll fluorescence (for which we set a threshold) achieved the best estimates, followed by hyperspectral reflectance and spectral indices. Land surface temperature was the worst estimator. However, comparing medians rather than means improved the performance of variables most affected by background effects (Fig. 3).

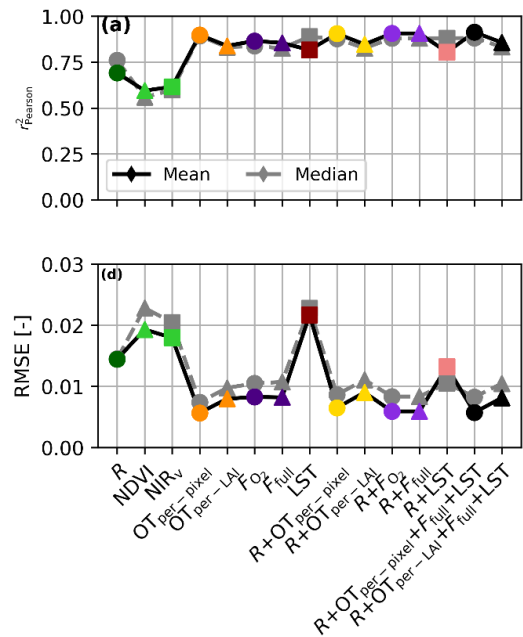


Figure 3. Correlation and error statistics for the estimation of plant functional diversity using different remote sensing proxies, and their combination

In agreement with this finding, we observed that estimation errors remain relatively constant across phenology, except during periods when soil contribution becomes relevant (i.e., leaf area index below 1), where they increase (Fig. 4).

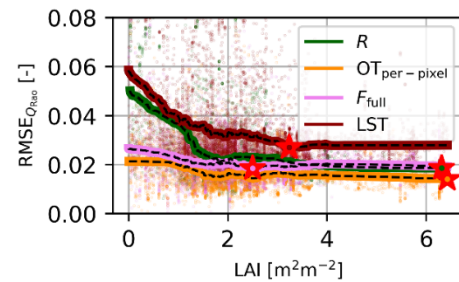


Figure 4. Plant functional diversity estimation root mean squared error as a function of the leaf area index for different remote sensing proxies. Lines are smoothed trends, and the red stars indicate the location of the minimum error

Analyses also revealed that using leaf area index instead of plant coverage as a surrogate of abundance improved the accuracy but reduced the correlation in the estimation of Rao's Q metric, and mostly worsened the partitioning of diversity (not shown).

When we degraded the spatial resolution of the remote sensing variables, we found that the best estimators previously identified to infer Rao's Q were also the most

robust to mixed pixels effects (Fig. 5). However, we also found a significant decrease in performance across all

variables when the pixel size was three times the plant size or larger.

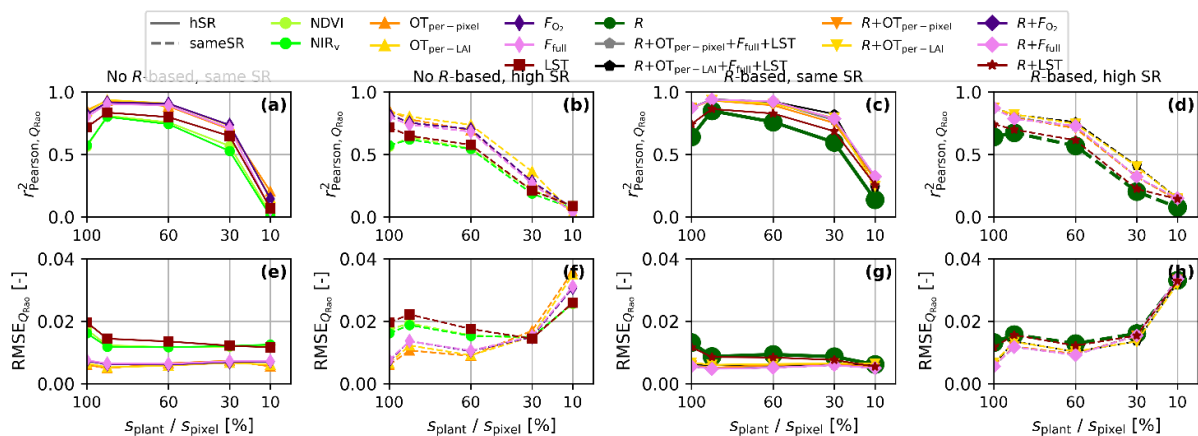


Figure 5. Correlation and error of estimation of plant functional diversity for different remote sensing proxies, compared with metrics computed from field plant traits at high spatial resolution or the same spatial resolution of the sensor

4. DISCUSSION AND CONCLUSIONS

Despite modeling limitations (e.g., 1D radiative transfer modeling), BOSSE has allowed us to answer fundamental questions regarding the methods to infer plant functional diversity from space. We found our results plausible with previous empirical studies. The advantage of BOSSE was having all the information at the desired level of uncertainty available, which enabled understanding how different methodological choices or observational conditions modified the capability of remote sensing to capture plant functional diversity. We expect BOSSE to continue supporting methodological developments, not limited to the field of plant functional diversity. Current analyses focus on assessing spatial mismatches in model scale transfer and on understanding empirical results from proximal hyperspectral imagery to infer plant functional diversity (Lagranja *et al.*, this conference), among others.

5. AGRADECIMIENTOS

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6. REFERENCIAS

Botta-Dukát, Z. (2005). Rao’s quadratic entropy as a measure of functional diversity based on multiple

traits. *Journal of Vegetation Science*, 16(5), 533–540. <https://doi.org/10.1111/j.1654-1103.2005.tb02393.x>

Gómez-Dans, J. L., Lewis, P. E., & Disney, M. (2016). Efficient Emulation of Radiative Transfer Codes Using Gaussian Processes and Application to Land Surface Parameter Inferences. *Remote Sensing*, 8(2), 119. <https://doi.org/10.3390/rs8020119>

Laiberté, E., Schweiger, A. K., & Legendre, P. (2020). Partitioning plant spectral diversity into alpha and beta components. *Ecology Letters*, 23(2), 370–380. <https://doi.org/10.1111/ele.13429>

Pacheco-Labrador, J., de Bello, F., Migliavacca, M., Ma, X., Carvalhais, N., & Wirth, C. (2023). A generalizable normalization for assessing plant functional diversity metrics across scales from remote sensing. *Methods in Ecology and Evolution*, 14(8), 2123–2136. <https://doi.org/10.1111/2041-210X.14163>

Pacheco-Labrador, J., Gomasasca, U., Li, W., Migliavacca, M., Jung, M., & Duveiller, G. (2025). BOSSE v1.0: The Biodiversity Observing System Simulation Experiment. *Geosci. Model Dev.*, 18(21), 8401–8422. <https://doi.org/10.5194/gmd-18-8401-2025>

Pacheco-Labrador, J., Gomasasca, U., Pabon-Moreno, D. E., Li, W., Migliavacca, M., Jung, M., & Duveiller, G. (2026). Benchmarking remote sensing methods to capture plant functional diversity from space. *Ecological Informatics*, 94, 103636. <https://doi.org/10.1016/j.ecoinf.2026.103636>

van der Tol, C., Verhoef, W., Timmermans, J., Verhoef, A., & Su, Z. (2009). An integrated model of soil-canopy spectral radiances, photosynthesis, fluorescence, temperature and energy balance. *Biogeosciences*, 6(12), 3109–3129. <https://doi.org/10.5194/bg-6-3109-2009>