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Satellite remote sensing of plant functional diversity

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I. Summary

Biodiversity enables ecosystems to thrive through the synergy of functional differences among organisms. Human well-being is strongly dependent on biodiversity and related ecosystem services. At the same time, human activities over the past centuries have resulted in the current unprecedented biodiversity declines. To understand the interaction between anthropological pressures and biodiversity, new comprehensive and scalable methods are of urgent importance. Sole reliance on traditional field sampling methods to meet this challenge is widely considered to be unfeasible given the spatial and temporal scales involved. This has inspired a growing body of research on the application of remote sensing for large-scale monitoring of plant biodiversity, thus far mostly with an emphasis on airborne remote sensing and anticipated future hyperspectral satellite missions. This thesis studied the overlooked capabilities of currently operational satellite observations to conduct large-scale monitoring of plant diversity, with a focus on the European Space Agency's flagship Sentinel-2 satellite.

Remote sensing of plant diversity patterns largely hinges on the notion that plant spectral profiles are integral representations of plant phenotypes and the underlying functional variation. Indeed, this thesis showed that the diversity in spectral signals, as observed from satellite measurements, relates to in-situ taxonomic plant diversity patterns at a landscape scale in forests and shrublands. However, the findings also illustrated the need for a cautious application and refinement of the presumed relationship between spectral diversity and plant diversity patterns. Heterogeneous vegetation cover (including canopy architecture, density, and background) dominated the spectral diversity signals observed with Sentinel-2 and overpowered actual plant functional diversity signals. Therefore, methods that isolate such confounding factors from the actual functional and taxonomic diversity patterns in the spectral signal are advantageous despite generally requiring a more complex data processing chain.

This thesis examined the use of physics-based radiative transfer models (RTMs) that simulate the propagation of light within canopies and leaves. The implementation of RTMs allowed us to isolate canopy plant traits from other signals to estimate plant diversity patterns. The quantitative comparisons revealed a strong correlative relationship to the in-situ plant functional richness patterns, yet still with an average 20-21% deviation from field measurements. Qualitatively, the spatial patterns of plant functional diversity revealed significant differences along a land use gradient based on different degrees of human disturbance which followed ecological expectations. In addition, the application of RTMs helped to overcome the dependence on scarce in-situ trait data for training and calibration. Further validation of RTM-based approaches across vegetation types and ecosystems will still be needed to assess its actual scalability across regions.

Spatial ecological processes are known to depend on the scale and means of observation. The 20m spatial resolution of Sentinel-2 is relatively coarse in comparison to the detail found in vegetation heterogeneity. As such, this spatial scale challenged the interpretation and validation of the satellite-derived plant diversity estimates. The 20m spatial resolution was ill-equipped to delineate individual canopies and instead presented pixel-based aggregations of multiple canopy crowns. These aggregations sit in between and mix the traditional ecological units of observation based on individual organisms and the communities thereof. Hence, this

complicated the interpretation following traditional ecological diversity concepts. The multi-scale analyses presented in this dissertation illustrated the scale dependency and gradual transition of what are traditionally considered separate drivers of '*within*' versus '*between*' plant community diversity. The multi-scale approach allowed us to bypass the need for arbitrary decisions of a fixed optimal plot area to calculate diversity metrics. Subsequently, the findings question whether the traditional ecological focus of discrete '*within*' versus '*between*' community diversity should be maintained in remote sensing applications or whether we need new more continuous concepts.

Moreover, the adequately scaled ground validation of the studies presented here required a dedicated field study campaign to match composite plots georeferenced to the pixel raster of Sentinel-2 observations. Given the laboriousness of this campaign, the feasibility and repeatability of such efforts will be limited. Future studies that seek to overcome challenges in the validation and interpretation of satellite remote sensing observations of plant diversity may benefit from relying on multi-sensors integration. For instance, two-tier validation using drones can aid field validation campaigns with spatial scales that are more feasible to match on the ground. Additionally, multi-sensor approaches can offer help addressing the spatial irregularities found in ecological phenomena, e.g.: heterogeneously shaped canopies and communities, to which coarse satellite-based rasterized pixels are ill-equipped and single sensors applications lack versatility.

While this thesis makes important steps in the development of concepts and techniques to address biodiversity patterns via remote sensing, further extensive validation of plant diversity estimates from satellite remote sensing remains necessary with the inclusion of larger sample sizes, more ecosystem and vegetation types, and a wider range of traits to ensure adequate functional differentiation. Further consideration of the role of different spatial and spectral resolutions will be necessary as well as the inclusion of multi-temporal dynamics. The maturation and acceptance of satellite-derived plant diversity estimates will evolve with growing adequate validation, advances in sensors, and further methodological improvements. With these ongoing developments, the large-scale and frequent monitoring of plant diversity patterns through remote sensing can become an integral part of global biodiversity observatory systems to quantify our biodiversity footprints and our impact on the ecosystem systems that support our wellbeing.