Satellite remote sensing of plant functional diversity

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Chapter 6.: General discussion

The central challenges presented in this thesis revolve around how we can use currently operational satellite remote sensing for observational monitoring of terrestrial plant biodiversity at large regional geographic extents without heavy reliance on field measurements for training. Fundamentally, these challenges relate to: i) scale disparities we observe between ecology and remote sensing at conceptual, spatial, spectral, and temporal scales, and ii) the lack of qualitative and quantitative validation of the capabilities of currently operational multispectral satellite remote sensing (Sentinel-2) to estimate spatial patterns of in-situ plant diversity.

Through four research chapters, the capabilities of multispectral satellite remote sensing to map plant functional diversity using Sentinel-2 were examined using different approaches, conditions, scales, and means for validation. The approaches were applied to two different regions with diverse land use and ecosystem types but also with different spatial extents geographically and conceptually from discrete (sampled locations) to continuous (‘wall-to-wall’) modes of inference of plant functional diversity. These analyses build on two different observational approaches linking spectra to plant diversity; i) spectral diversity versus ii) RTM-based functional diversity from optical trait estimates. Means of validation to assess the performance were provided directly through precisely scaled plot-based trait measurements as well as multi-plot functional and taxonomic diversity estimates measured in-situ. In addition, I demonstrated the use of trait databases and literature as well as land use gradients to check the plausibility of spatial plant functional diversity patterns in a qualitative approach. Lastly, I assessed different spatial scales in relation to functional diversity and how scale impacts the diversity patterns observed. All in all, the multitude of possible ways to implement Sentinel-2 observations for studying plant functional and taxonomic diversity is exemplified in the individual chapters, highlighting how the decisions in our workflow influence how we perceive spatial plant diversity patterns from satellite remote sensing. In this chapter, I highlight and review some of the main findings of this thesis:

The spectral variability hypothesis based on Sentinel-2 observations is able to predict taxonomic diversity in our Portugal case study. No evidence was found for a role for environmental or leaf trait heterogeneity as intermediate variables explaining the workings of the spectral variability hypothesis. Instead, the spectral diversity metrics appeared to be dominated by vegetation cover (density, canopy architecture, background signals). To overcome the spectral dominance of vegetation cover, I explored approaches based on (hybrid) RTM inversion to disentangle some of the soil and canopy signals to isolate actual functional plant diversity elements within spectral diversity.

For this, I provided an elaborate validation effort based on in-situ measurements in Northern Portugal to precisely match the scale of Sentinel-2 (clusters of) pixels to assess both individual plant trait estimates as well as the estimated combined community plant functional diversity. This validation was inspired by the discrepancy between scientific acknowledgment on the role of satellite remote sensing for mapping plant biodiversity, yet a lack of validation and performance assessment of viable satellite remote sensing to retrieve plant functional and taxonomic diversity. We advocate the importance of such studies to gain recognition and application among ecologists. Moreover, I examined the responsiveness of plant functional diversity estimates based on spectral trait indicators qualitatively against explicit patterns of land use, historic trait measurements, and across spatial scales in Northern Borneo.

This thesis demonstrates the role Sentinel-2's spectral sensitivity can play in estimating plant functional and taxonomic diversity, retrieving multiple traits simultaneously, and successfully applying the spectral variability hypothesis. Nevertheless, we found that the spatial resolution (20m) challenged validation efforts (laborious at these scales) and interpretation. The latter highlights the spatial mismatch between ecological concepts of scale and that of remote sensing while considerations of scale are critical in the way we perceive patterns of biodiversity. Sentinel-2 pixels were unable to delineate individual canopies but rather present aggregated patterns. Functional diversity estimates based on (clusters of) pixels were hard to translate to discrete alpha and/or beta diversity community concepts. Yet, spatially explicit remote sensing facilitated multi-scale analyses that illustrate how beta diversity drivers become increasingly influential as a predictor of plant diversity at larger spatial community scales.

6.1. Lessons learned

6.1.1. Disentangling spectral diversity

Spectral diversity has increasingly been adopted and studied as a biodiversity metric that captures plant diversity through the reflectance of electromagnetic radiation from plant canopies (Wang and Gamon, 2019). Conceptualization of the mechanisms behind the spectral diversity-plant diversity relationship is either founded by environmental heterogeneity ('surrogacy') driving taxonomic and functional diversity indirectly or through the physical relationship between spectral properties and the (dis)similarity of plant characteristics.

At the leaf level, spectral dissimilarity has been shown to reflect functional and phylogenetic dissimilarities between individuals (Schweiger et al., 2018). Yet, this does not directly translate to the scale of satellite remote sensing where signals are complex and leaves are aggregated to (multiple) canopies that can include a soil signal and additional environmental and angular influences. Despite the unfavorable spatial resolutions of satellite remote sensing, studies have shown a promising positive relationship between spectral diversity and in-situ plant diversity, e.g. Torresani et al. (2019), Madonsela et al., (2017), and Rocchini et al. (2004; 2007). However, empirical validation and characterization of what is measured within spectral diversity and what mechanisms relate it to plant diversity remain limited and untransparent in the current body of research.

Chapter two looked into the use of spectral diversity derived from Sentinel-2 applied over a heterogeneous landscape encompassing shrub- and forested land. RTM simulations based on the collected trait dataset indicated that spectral diversity indeed has a strong correlation with leaf trait diversity at the leaf level (Fig. 2.2). When scaling up from the leaf to the canopy scale, this relationship becomes considerably weaker (Fig. 2.2). Logically, within the canopy reflectance signal, structural, canopy, and soil characteristics become influential on the overall spectral signal and can obscure spectral signals present at the leaf level, especially at lower vegetation cover densities (Asner, 1998). Optimization of canopy RTM simulations revealed a trade-off in describing either the in-situ trait diversity or the actual Sentinel-2 spectral diversity highlighting the importance of canopy and soil characteristics (Fig. 2.2).

The combination of a coordinated field data campaign georeferenced to Sentinel-2 information allowed for direct comparisons between community spectral, taxonomic, and trait diversity, as well as confounding factors to further assess the workings of spectral diversity when applied at large scales using satellite remote sensing. The empirical observations of the study area showed that spectral diversity indeed relates to taxonomic diversity (Fig. 2.3, Spearman's $\rho = 0.61$) in line with the 'spectral variability hypothesis'. I further examined the mechanisms behind this positive relationship, both through environmental factors as well as functional traits. Despite the relationship between spectral diversity and taxonomic diversity (Fig. 2.3), spectral diversity observed from Sentinel-2 revealed no clear correlation with in-situ measurements of leaf trait diversity. In addition, neither landscape morphology nor vegetation cover served as environmental 'surrogates' linking spectral diversity and taxonomic diversity. In other words, although the 'spectral variability hypothesis' appeared to hold for taxonomic diversity using Sentinel-2 observations in our case study, the exact drivers of the relationship remained concealed despite consideration of functional properties, landscape morphology, and vegetation cover. Future studies can elaborate on this relationship by integrating and exploring the spectral species concept (Féret and Asner, 2014), unmeasured canopy traits, structural diversity (Schneider et al., 2020), fire regimes, plant phenology, grazing, dead biomass, and soil types for further consideration (Pausas and Vallejo, 1999; Rossi et al., 2021; Schneider et al., 2017; Vivian and Cary, 2012; Zarnetske et al., 2019).

By breaking down the spectral diversity signal in different contributing components, chapter two highlighted the importance of vegetation cover as a driver of spectral diversity patterns. Vegetation cover, measured through the Plant Area Index (PAI), influences the extent to which soil, litter, and understory appear in the spectral reflectance signal of a Sentinel-2 pixel. Additionally, vegetation cover is tied to the present canopy architecture dictated by morphological traits. Canopy traits tend to have a profound impact on the spectral signal of vegetation across a broad range of the electromagnetic spectrum (Asner, 1998; Gu et al., 2016). Within our heterogenous study site, the variation in vegetation cover dominates the spectral diversity signal observed from Sentinel-2 (53-84% of the explained variance by fixed effects, Fig. 2.4). This shows that, while spectral diversity is relatively straightforward to deploy, caution is required to characterize what exactly is measured within spectral diversity. Vegetation cover, structural diversity and soil characteristics do not necessarily covary with functional or taxonomic plant diversity. Across different ecosystems, variation in vegetation density might align more strongly with leaf trait diversity (Sheil and Bongers, 2020; Walter et al., 2020), while in other ecosystems vegetation cover density could mask or be ordinal or even negatively related (e.g. fertilized monocultures) to plant diversity (Rossi et al., 2021; Villoslada et al., 2020).

Thus, our findings indicated that direct application of spectral diversity metrics circumvents the challenges and difficulties in isolating direct plant diversity signals, however, at the same time, the approach risks overemphasizing spectrally dominant characteristics that can overshadow the elements of plant diversity that we are actually interested in. While the 'spectral variability hypothesis' based on Sentinel-2 observations was able to predict taxonomic diversity, chapter two also exemplified the risks that the spectral diversity signal to be dominated by other factors. At the time of writing, several studies came to similar conclusions regarding a range of factors that may confound the spectral diversity-biodiversity relationship using airborne remote sensing, including the fraction of bare soil (Gholizadeh et al., 2018), biomass/vegetation density (Villoslada et al., 2020; Wang et al., 2016), and litter and dead biomass (Rossi et al., 2021). Given that these studies use hyperspectral airborne observations, chapter two is unique at this point in providing a characterization of the spectral diversity derived from Sentinel-2 multispectral satellite observations highlighting the dominance of vegetation cover in the spectral diversity patterns.

Our ability to account for spectrally dominant confounding factors, such as vegetation cover and soil, could improve the robustness and relationship of spectral diversity approaches to in-situ plant diversity across spatial, spectral, geographic, and temporal resolutions. Several approaches are already in place to assist in further dissection of the spectral signal to isolate plant diversity (Musavi et al., 2015). Chapter three explored the application of a physics-based RTM inversion to dissect the spectral signal and derive multiple relevant plant traits to quantify community patterns of functional diversity across a heterogeneous and biodiverse (semi-)natural landscape. The approach presented in chapter three could help to account for the canopy and vegetation cover dominance that can confound the spectral diversity-plant diversity relationship.

6.1.2. Physics-based estimation of functional diversity

Physics-based approaches are appealing given its theoretical universal applicability as opposed to statistical learning approaches and/or spectral indices that heavily depend on comprehensive field measurements for training and that have been found to be site- and time-specific (Verrelst et al., 2015; Clevers, 2014; Ali et al., 2020a). Physics-based approaches using RTMs have two major advantages over spectral diversity applications (as applied in chapter two); 1) RTM inversion allows to break down the spectral signal into multiple relevant canopy and leaf traits while accounting for soil, canopy, angular and other parameters, and 2) the spectrally derived traits relate directly to measurable, and thus verifiable, in-situ ecological field data. While for spectral diversity the link to plant diversity remains relatively abstract, a physics-based remotely sensed functional diversity links spectra to verifiable optical traits before quantifying diversity estimates. The downside is that these physics-based approaches require an additional and challenging step compared to direct use of spectral diversity metrics; the inversion of spectra through Look-up Tables (LUTs) or hybrid emulation of RTMs. Such inversion is challenging as RTMs are subject to strong assumptions, heavy parameterization, and ill-posedness (Combal et al., 2003; Koetz et al., 2007; Musavi et al., 2015), especially for multispectral observations (Brede et al., 2020; de Sá et al., 2021). Likewise, the choice of RTM holds implications of what biophysical parameters can be retrieved and its underlying assumptions, inversion complexity, and ill-posedness.

In addition, active decisions need to made on a set of spectrally derived traits retrievable through RTM emulation/inversion that hold ecological relevance to study plant biodiversity. Trade-offs between the number and selection of traits is difficult considering spectral limitations, ill-posedness, and ensuring relevant functional differentiation in plant community. Yet, these choices are highly influential to the patterns observed. In the end, functional diversity patterns are dictated by the functional traits selected that make up the diversity metrics (Legras et al., 2020).

Using the physics-based approach, chapter three examined our ability to retrieve multiple traits simultaneously to estimate community plant functional diversity in heterogeneous (semi-)natural landscapes from Sentinel-2 observations. At the time of writing, the presented two-fold multivariate validation of plant traits as well as community functional diversity at the scale of satellite remote sensing was completely novel. Strong performance is demonstrated in characterizing leaf area index (LAI; R^2= 0.58 - 0.63, RMSE= 0.49 - 0.51 m^2/m^2), a key biophysical parameter that relates to the canopy architecture and vegetation cover density. Beyond the canopy, leaf biophysical and biochemical traits were estimated focusing on leaf mass per area (LMA) and leaf chlorophyll (CAB). Chapter three demonstrates the utility of RTM-based retrieval of LMA (R^2 = 0.66 - 0.68, RMSE = 6.36 - 31.06 mg/cm^2) in a forest and shrubland ecosystem at canopy scale. Notably, very few studies have evaluated the RTM-based retrieval of LMA, particularly at the canopy level in forest ecosystems using satellite remote sensing (Gara et al., 2021). Besides trait means, the analysis included an assessment of our ability to estimate trait variability within the 20m adjacent plots which is rarely seen in validation studies and highlighted the challenges to predict local trait variability.

Combining the retrieved traits in diversity metrics, the implemented inversion approaches demonstrated a general performance and applicability of RTM-based functional diversity estimates when compared against in-situ estimates of functional diversity. The remotely sensed functional diversity estimates exhibited a degree of robustness against biases in individual mean trait retrievals and the variability thereof. Despite biases, relatively robust estimates of functional diversity from Sentinel-2 were predicted especially when using convex hull volume calculations to quantify the diversity. This robustness is largely attributable to the distance-based (relative) nature of the metrics applied. Our results showed that relatively simplistic and assumption-bound RTMs and general inversion algorithms (e.g. SNAP) can already produce maps indicative of coarse relative spatial patterns of plant diversity (Table 3.3).

The functional diversity estimates captured from satellite remote sensing were also in agreement with in-situ community taxonomic diversity (Fig. 6.1). In particular, I found that leaf-level traits, biophysical (e.g. LMA) and biochemical (chlorophyll) properties, were effective in estimating both taxonomic and functional plant diversity, whereas the inclusion of canopy trait LAI somewhat weakened the former relation (Fig. 6.1). Further testing across different ecosystem types and larger sample sizes will be necessary.

Chapter three demonstrates that different inversion methods produce acceptable results. However, optimized look-up tables, and predefined trait ranges enhanced performance noticeably which is in line with earlier studies showing that *a priori* information can reduce ill-posedness of retrievals (Combal et al., 2002; Dorigo et al., 2009). When such *a priori* knowledge is absent, trait databases (e.g. TRY of s-Plot) and active learning approaches can prove helpful to add constraints to inversion space and facilitate intelligent sampling for the training of retrieval algorithms to overcome some of the ill-posedness (Berger et al., 2021; Bruelheide et al., 2019; Kattge et al., 2020).

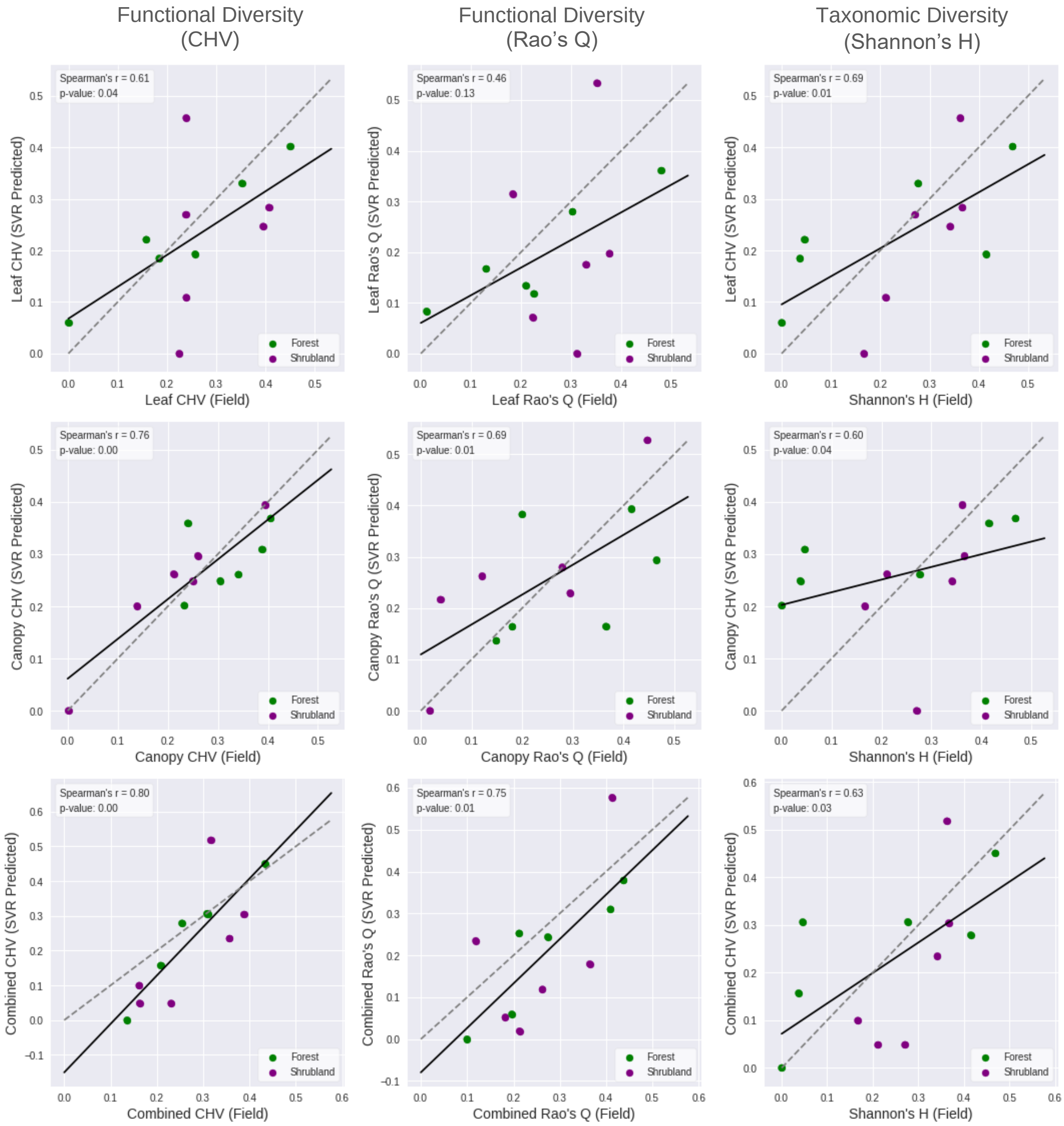

*Fig. 6.1: Remotely sensed functional diversity estimates (CHV and Rao's Q) calculated from Sentinel-2 derived traits through the Support Vector Regression (SVR) hybrid inversion compared against in-situ functional diversity measurements (left and center columns). The rightmost column compares SVR-derived remotely sensed functional diversity (CHV) against in-situ taxonomic diversity (Shannon's H). Comparisons are made across different scales; Leaf-level traits (leaf LMA and leaf CAB), Canopy-scaled trait (LAI*LMA, LAI*CAB), and combined canopy and leaf traits (LAI, leaf LMA, and leaf CAB). The grey dotted line shows the 1:1 relationship, whereas the black line indicates the linear relationship between the remotely sensed estimates and field data. Purple and green points represent shrubland and forested locations, respectively.*

Hybrid modeling approaches, such as the PROSAIL-D Support Vector Regression approach (SVR) presented in chapter three amongst others, are potentially superior to lookup-table (LUT) based inversion strategies through the hybrid combination of the generic capabilities of physics-based methods (theoretical foundations, interpretable compartments) and the versatility of machine learning (data-adaptiveness and computationally efficient) (Reichstein et al., 2014; Verrelst et al., 2015). An added benefit of hybrid models is the ability to propagate uncertainties and estimate confidence intervals through Bayesian/probabilistic inference (Reichstein et al., 2014; Verrelst et al., 2015). Moreover, the next generation of hybrid retrieval algorithms can integrate active learning (AL) heuristics to optimize training datasets (Berger et al., 2021). The key idea behind AL is that the hybrid model can obtain higher accuracy with fewer training data if it is allowed to choose the data from which it learns through an iterative procedure (Settles, 2009). The extension of AL approaches in hybrid retrieval methods offers adaptive solutions to overcome the genericity and assumptions of RTM models when held against noisy satellite-inferred spectra and the trait-based particularities of the real-world ecosystems under study.

Chapters two and three present two complementary approaches. Our analyses suggest that RTM-based approaches are more robust to predict in-situ plant functional and taxonomic diversity as compared to using spectral diversity directly based on Sentinel-2 observations. Yet, the latter has the advantage that less technical and methodological steps are needed. To further understand the pros and cons, comparative studies are needed. Such studies would implement different approaches to quantify plant diversity from satellite remote sensing to compare performances to assess plant diversity in reproducible and transferable workflows. Future work on this should also compare the presumed transferability of spectral diversity and RTM-based approaches against the use of vegetation indices (Schneider et al., 2017), fully data-driven approaches, and could include alternative approaches such as the spectral species concept (Féret and Asner, 2014). Improved sensors (e.g. PRISM, CHIME; Cavender-Bares et al., 2020; Ustin and Middleton, 2021), optimized state-of-the-art RTMs, advanced inversion techniques (e.g. deep learning and AL) (Berger et al., 2021; Reichstein et al., 2014), and multi-source data assimilation can further enhance the performance of the presented RTM approach across ecosystems (Lahoz and Schneider, 2014; Lewis et al., 2012).

6.1.3. Validation of satellite remotely sensed plant diversity

Maturation and the widespread application of remote sensing approaches for biodiversity and conservation studies are still in dire of proper and in-depth validation (O'Connor et al., 2015). Validation campaigns help to understand the accuracy and uncertainties tied to remotely sensed plant diversity products, and to gain acceptance of remote sensing products in the field of ecology and among practitioners and relevant decision-makers. So far, most validation studies focused on agricultural applications rather than natural areas (Berger et al., 2018a; Djamai et al., 2018; Jacquemoud et al., 2009; Lu et al., 2019). And, if done in natural areas, validation is mostly done for remotely sensed estimates of single trait mean values in relatively homogeneous (semi-)natural environments set in relatively small study areas (e.g. Ali et al., 2020a; Brede et al., 2020; Brown et al., 2019; Darvishzadeh et al., 2019a, 2019b; Padalia et al., 2020; Rossi et al., 2020; Vinué et al., 2018). Combined validation studies on plant diversity metrics and multiple underlying optical traits were not done thus far for scalable physics-based retrieval approaches of satellite remote sensing. Moreover, many of the large-scale remotely-sensed trait validation studies heavily depend on interpolation or extrapolation of spatially and temporally fragmented in-situ data points (Ma et al., 2019; Moreno-Martínez et al., 2018; Serbin et al., 2019). In many other cases, accuracy assessment is missing or unusual, often not having independent validation data.

Building upon these insights, chapter three provides a thorough validation study for functional diversity metrics derived from satellite remote sensing. It presents a validation exercise in its simplest form: pixel-wise comparison of presumably high accuracy in-situ data with the remotely sensed data (Richter and Hank, 2021). Despite its simplicity in theory, actual sampling proved to be a challenging undertaking to ensure representative areas of individual plants with individual leaf samples to align with the Sentinel-2 imagery and spatial scale (spatial resolution) and orientation (raster). The study presented validation both at the pixel level (N=115), aggregate average trait values of the representative canopy, and at the community-level of clusters of pixels in terms of functional and taxonomic diversity. Unique to this study and lacking in current validation literature was the validation of our ability to estimate individual trait means but also local trait variability between adjacent plots.

Chapters two and three rely on a relatively small yet carefully sampled and scaled dataset for validation that comprises a heterogeneous ecosystem in the Northern Mediterranean mountainous region surrounding the Montesinho national park. More studies and large sample sizes will be needed across different ecosystem types to study the transferability of physics-based satellite remotely-sensed derived functional diversity. At the same time, the small sample presented here speaks of the labour-intensiveness of validating functional diversity at the scale of satellite pixels.

6.1.4. Large-scale spatially continuous application

To investigate satellite remote sensing as an operational tool for monitoring biodiversity at large continuous spatial extents, chapter four and five presents wall-to-wall retrieval of spectral trait indicators over the vast and biodiverse Sabah region, Northern Borneo, Malaysia. Based on Sentinel-2 retrieved spectral trait indicators, the study mapped functional diversity estimates over the region's diverse landscape consisting of intact forests, logged forests, and oil-palm plantations. For qualitative assessment, the derived functional diversity maps were held against a human disturbance of land use, historic trait measurements, and across spatial scales. The remotely sensed functional diversity estimates based on Villeger's (2008) metrics indeed reflected ecological expectations across land use (chapter 4), elevational gradients and spatial scale through functional richness-area relationships (Chapter 5). The qualitative assessment signalled a responsiveness of satellite remotely sensed functional diversity metrics to differences in land use and plot area size. However, the lack of quantitative error estimates limits our ability to draw conclusions beyond descriptive patterns. The spatially continuous nature of satellite remote sensing did lend itself particularly well for iterative multi-scale analyses of plant functional diversity estimates across increasingly large areas as representatives of differently sized functional communities which gives new insights in the role of spatial scaling in how we observe plant diversity patterns (section 6.2.1).

For future studies, a two-tier validation approach linking in-situ measurements with satellite remote sensing through airborne, unmanned aerial vehicles *(*UAV*)/*drone observations may facilitate validation campaigns that are more feasible in terms of spatial scales (Almeida et al., 2021b). Drones and other UAVs tend to present higher spatial resolutions, and therefore, may help serve as a bridge to scale up field observations to aggregated satellite remote sensing scales (Almeida et al., 2021b). In addition, the establishment of repeatedly sampled field laboratories such as the US National Ecological Observatory Network (NEON) (Kampe, 2010), the

Laegeren forest site in Switzerland (Morsdorf et al., 2020; Schneider et al., 2017), and the 'Data pool initiative for the Bohemian Forest Ecosystem' (Latifi et al., 2021). These sites can serve as natural biodiversity observatories presenting harmonized data pools for repeated detailed validation and training/calibration for optimizing retrieval algorithms.

6.2. Considerations of scale dimensions

Discussions of scale have a rich history in both ecology and remote sensing. Thus far, the majority of the literature on remote sensing of plant biodiversity relies on the use of hyperspectral airborne remote sensing (Asner and Martin, 2009; Durán et al., 2019; Féret and Asner, 2014; Schneider et al., 2017) or emphasizes the need and potential of forthcoming high-resolution hyperspectral satellite remote sensing to conduct biodiversity assessments (Hill et al., 2019; Jetz et al., 2016). Rightfully so, higher spatial and spectral resolutions present more opportunities to assess plant canopies in detail. Nevertheless, this thesis has focused on the potential of currently available satellite remote sensing by a thorough examination of the use of Sentinel-2 for estimating functional and taxonomic diversity through spectral diversity and physics-based approaches. Integral to this is the examination of the spectral and spatial opportunities and limitations in capturing patterns of plant diversity. The derived findings hold new lessons on the effects of scale, relevant for its interpretation, and for guiding the future developments in satellite remote sensing for plant diversity observations.

6.2.1. Spatial scale and resolution

The spatial resolution of remote sensing instruments, i.e. pixel size, is shown to be highly influential but thus far mostly studied using airborne/drone remote sensing (Gholizadeh et al., 2019; Wang et al., 2018b). I encountered throughout the four research chapters that the coarse and geometric nature of pixel-based satellite remote sensing challenges traditional ecological interpretation. While Sentinel-2 provides improved spatial and spectral resolutions compared to most of its publicly available space-borne predecessors, its spatial resolution is still relatively coarse for ecological interpretations. With the majority of bands scaled at 10-20m spatial resolution, pixels observed from Sentinel-2 are too large for delineation of individual vegetation canopies. Even in the case of relatively large tree canopies, such pixels will aggregate several individual plants. Hence, individual trait observations such as those traditionally collected in the field are not easily compared to the satellite remote sensing spatial scale. Generally, each pixel will consist of multiple aggregated canopies inapt to delineate individual canopies, complicating straightforward interpretation of ecological measures of functional and/or taxonomic diversity that are traditionally based on diversity between individuals and/or discrete 'communities' of individuals (Laliberté et al., 2019; Schleuter et al., 2010). Additionally, pixel-wise aggregation of plant canopies does neither account for the effects of density of individual plants as an important variable related to diversity, nor for canopy size which affects the number of individuals aggregated within a pixel (Magurran, 2003; Zheng et al., 2021).

The challenges of scale become amplified when looking at diversity, given that a combination of multiple pixels is required to assess spectral or functional (information) entropy. Chapter three's calculations were scaled at functional "communities" of 8 pixels covering pixel-based communities of 3200m^2. These geometric pixel-based clusters further raise challenges for ecological interpretation. In particular, what type of diversity are we looking at; alpha or beta-diversity? Clarifying and disentangling the combined and separate effects of α and β diversity on satellite-based observations is a remaining challenge. The disparity between remote sensing observations and the scale of individual organisms in field sampling muddles the separation of traditional additive α or β diversity. Not all individual differences will be captured given the coarseness of individual pixels while the community concept is arbitrarily captured through a cluster of pixels. Therefore, it remains unclear how much of the alpha diversity is captured through relatively coarse aggregations of multiple canopies. Some studies have simply assumed that every single pixel equals an ecological community (Hoffmann et al., 2019; Khare et al., 2021, 2019; Rossi et al., 2020). In the case of grasslands, for instance, such assumptions can be understood and/or justified given the small canopy crown size and a large number of canopies aggregated in a single pixel observation. However, for larger tree and shrub canopies, such assumptions are likely inadequate. Logically, the coarser the satellite spatial resolution compared to the grain and delineation of field data (i.e. in-situ canopies), the more spatial heterogeneity with sub-pixel plant diversity remains concealed (Khare et al., 2019; Rocchini, 2007). In other words, part of the alpha diversity is happening sub-pixel and is lost through pixel aggregation. At the same time, coarser resolutions and larger clusters of pixels are more likely to be composed of beta diversity.

Chapter five particularly looked into the role of area, i.e. the number of adjacent pixels, used to calculate functional diversity patterns over a large spatial extent covering Sabah, Malaysian Borneo. Firstly, the study confirms the common law that diversity increases with increasing area. Chapter five is novel in demonstrating this through satellite remote sensing observations, estimating functional diversity based on spectral trait indicators at large observational scales ranging from 0.4 to 60 ha single land use plots. The curvature of the functional richness-area relationship (FARs) reveals a pattern typically found in field and airborne studies conducted at much smaller scales (Durán et al., 2019; Karadimou et al., 2016; Schneider et al., 2017; Smith et al., 2013). The curvature follows exponential increases up to 5ha plots. From 10ha plots onwards, increases in diversity shift from exponentiality to linearity. The fast increases observed at small scales may be attributable to high variation in stochastic species occupancy patterns among sampling units, and variation through species responses to competition and niche occupancy. Such shapers of variation are commonly attributable to alpha diversity drivers (Field et al., 2009).

At larger sampled scales (> 5ha), increases of diversity per area attenuate leading to saturation in variation. Particularly at larger scales, a larger share of the explained variance could be explained by landscape heterogeneity, for which I used morphology (slope and elevation) as an indicator. The increasing explanatory role of landscape morphology at bigger (intermediate) scales suggests the increasing importance of beta diversity drivers that require communities to adapt to different environmental conditions (Barton et al., 2013; Weiher and Keddy, 1995). In combination, chapter five shows how discrete concepts of alpha and beta diversity are expressed in a continuous transition when observed from spatially explicit satellite remote sensing. This challenges the applicability of discrete alpha and beta concepts and raises the question of whether we need new more continuous concepts, and illustrates how multi-scale analyses can unveil the compound role of different drivers at different spatial scales.

In our analyses across the four research chapters, the pixel size remained invariant at 20m spatial resolution following the majority of Sentinel-2 bands. For future development and application of satellite remote sensing, it is important to increase understanding of how both grain (spatial resolution) and the number of pixels (spatial 'window', plot area to capture a 'community', chapter 5) in functional diversity assessments done from space-borne instruments affect the patterns observed. This requires expanding the analysis of chapter five by including both variant pixel sizes and the number of pixel observations for remotely sensed functional diversity estimates. Various combinations of changing grain and plot area (changing grain while maintaining plot area, changing plot area while maintaining grain, changing grain and plot area) could be examined to explore scaling relationships like discussed conceptually by Barton et al. 2013.

In terms of spatial extent, future attempts can be expanded to the scales of cross-biome and latitudinal gradients by mosaicking images and data assimilation principles to overcome cloud cover and temporal mismatches (Lahoz and Schneider, 2014; Lewis et al., 2012). Satellite remote sensing of plant diversity over large spatial extents (cross-biomes and continental) could help allow us to validate and calibrate large-scale ecological models of biodiversity with observational data.

In terms of grain, the integration of multi-platform remote sensing, most notably drones, can be valuable to inform on the sub-pixel heterogeneity not captured at satellite earth observation scales (Almeida et al., 2021b). Additionally, even within the capacity of Sentinel-2, recent developments relying on pan-sharpening, Bayesian frameworks and machine learning techniques have resulted in algorithms to enhance or resolve Sentinel-2's spatial resolution (Brodu, 2017; Lanaras et al., 2018). Rather than resampling all bands to 20m for spatial consistency as done in our current analyses, future studies could explore either Sentinel-2's original four 10m bands or a super-resolved spatial resolution of 10m across all bands (e.g. Brodu, 2017) to assess (artificially) enhanced spatial resolution to capture sub-pixel (20m) heterogeneity. Fig. 6.2 provides an example of such a potential analysis. In this preliminary analysis, 10m resolved bands did not significantly differ in terms of prediction of our in-situ measurements of taxonomic diversity. Still, resampling at 10m would offer advantages for validation as representative sampling campaigns become more manageable at 10m plots.

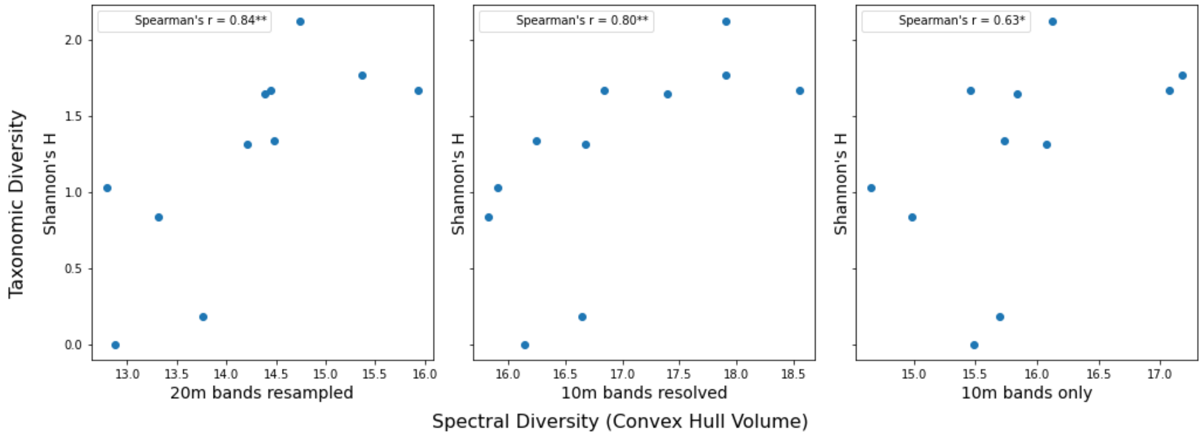

Fig. 6.2: Preliminary analysis examining the relationship between spectra diversity calculated by convex hull volume to predict in-situ taxonomic diversity (Shannon's H) measured in the Montesinho (PT) national

park region across three different spatial-spectral configurations derived from Sentinel-2 observations; i) nine resampled 20m bands (left), ii) nine resolved 10m bands (following Brodu et al., 2017) (middle), iii) and four original 10m bands.

6.2.2. Spectral resolution

Approaches for optical detection of plant diversity, i.e. spectral diversity (chapter two), physics-based approaches (chapters 3-5), depend on the information content of the spectra themselves. The spectral layout of sensors can influence plant diversity detection in complex ways (Nagendra et al., 2010; Rocchini, 2007). Therefore, attention is required to how the spectral resolution and spectral range of the instruments influence the derived observations. Both chapters two and three suggest that the Sentinel-2 sensor's multispectral broadband setup may increase the dominance of canopy, soil, and biomass signals as opposed to expressions of biochemical and biophysical leaf traits found in narrower ranges of the electromagnetic spectrum that benefit from hyperspectral measurements (Durán et al., 2019; Schneider et al., 2017; Schweiger et al., 2018).

The forthcoming launch of hyperspectral satellite imagers (e.g. EnMAP, SBG, CHIME; Cavender-Bares et al., 2020) offers more spectral detail and versatility that can benefit plant diversity assessments. For instance, satellite-based imaging spectroscopy offers new potential to retrieve traits that are hard to detect from multi-spectral setups, such as leaf and canopy contents of nitrogen (Verrelst et al., 2021), anthocyanin, anthocyanin, carotenoid content, and carbon-based constituents (Féret et al., 2021). Additionally, hyperspectral observations potentially offer additional input information to improve the ill-posedness experienced in the inversion of RTMs using few multi-spectral bands. Hyperspectral imaging might offer benefits for spectral diversity approaches too; the few studies conducted on spectral resolution and plant biodiversity thus far state that more spectral information is generally better than less (e.g., Asner et al. 2012).

On the other hand, hyperspectral imagery is not always significantly better. Hyperspectral narrowbands tend to be highly correlated resulting in high redundancy in spectral information (Hakkenberg et al., 2018). Rocchini (2017) concluded that more bands are not necessarily better but the placing of bands is crucial as the study shows that ASTER images, having a better spectral resolution, yielded worse results than LandSAT images, in estimating species diversity. Using airborne remote sensing, Lu et al. (2019) concluded that the extra bands in the hyperspectral image did not substantially improve chlorophyll estimation in vegetation. Gholizadeh et al. (2019) showed that the standard deviation of NDVI (two bands) performs well among other spectral diversity metrics (multi- and hyperspectral derivatives). Wang et al. (2018b) found no additional benefit of using full-range spectrometer data in quantifying plant diversity versus dimension reduction techniques. Using UAV imagery, Rossi et al. (2021) stress the overriding importance of high spatial resolution in comparison to high spectral resolution in predicting plant diversity using spectral diversity metrics. Across these studies the spatial resolution appears the limiting factor. Spectral resolution does affect the spectral diversity-biodiversity relationship, yet higher spectral resolutions cannot replace or compensate for the lack of high spatial resolution (Gholizadeh et al., 2019; Rocchini, 2007; Rossi et al., 2021; R. Wang et al., 2018a).

Current momentum emphasizes the development of hyperspectral sensors and the need for satellite-based imaging spectroscopy (Ustin and Middleton, 2021). Due to technical constraints, a trade-off exists between spatial and spectral resolution to ensure adequate signal-to-noise ratios which determines the sensor design of space-borne instruments (Rossi et al., 2021). The planned hyperspectral satellite missions present sensors with 30m spatial resolution at best, slightly worse than Sentinel-2 (10-20m). With an eye on the application for biodiversity studies, the question arises whether a tradeoff to more spectral resolution and less spatial resolution is the most beneficial investment for mapping plant diversity.

Research chapters two to five reveal that Sentinel-2's relatively simple multi-spectral and 20m spatial resolution can predict coarse community plant diversity patterns, even despite strong assumptions in retrieval algorithms, and challenging interpretation of mixed alpha and beta diversity. While Sentinel-2's spectral capabilities allowed for an estimation of multivariate functional diversity and spectral covariates of taxonomic diversity, this thesis highlights that interpretation and validation of these diversity patterns is challenged by especially its spatial resolution. To advance the detection of plant diversity from space and advance beyond Sentinel-2's capabilities, smart trade-offs are needed to facilitate continuous improvements in both spectral resolution and spatial resolution (working towards <5-10m resolution). Therefore, with eyes on mapping plant biodiversity, an overemphasis on hyperspectral sensors may be unwanted. Rather, we should seek technical trade-offs that lead to spectral advances without compromising the spatial resolution. At the same time, data assimilation techniques and multi-sensor constellations will continue to advance and open new venues to combine the strengths of space-borne hyperspectral imagers to complement pre-existing multi-spectral sensors and future high spatial resolution sensors.

6.2.3. Temporal dimension

Satellites in orbit offer the advantage of frequent revisit times. In the case of the Sentinel-2a/b constellation, inferences of the same region of interest can be as frequent as every five days. These repeated measurements offer the potential to closely study changes and dynamics over time as well as the phenology of traits and the diversity thereof. Within the four research chapters of this thesis, the temporal element of mapping functional diversity has unfortunately not been analyzed. Yet, obviously, ecological processes are subject to microclimatic properties, phenology, management strategies, grazing, or nutrient availability that occur over the course of time and seasons. Ultimately, when working towards the maturation of approaches in mapping plant diversity through satellite remote sensing, we need to account not only for spatial patterns but also temporal spectral variation.

Plant diversity is shaped by temporal trends and dynamics. Single inferences in time are simply a snapshot and are inferior to more robust multi-temporal assessments and time series to capture spectrally-derived estimations of plant diversity patterns. Time series analysis will improve the confidence in patterns observed through temporal cross-validation and can overcome temporal fluctuations in noise and retrieval accuracies (Hauser et al., 2020). Moreover, combining temporal observations can help us overcome cloud, cloud shadow and atmospheric contamination often encountered in optical imagery. The assimilation of multi-temporal observations, potentially combined with ancillary ecological, and phenological datasets, will enable us to study changes in functional diversity over time while overcoming data gaps and inference intervals (e.g. gap-filling approaches such as implemented by Belda et al., 2020). Ultimately, temporal dynamics will be a key factor in understanding changes in plant (functional) biodiversity.

Temporal variability also influences our ability to capture relevant elements of plant diversity from spectral reflectance. For spectral trait indicators, Schiefer et al. (2021) show that accuracies vary during the growing season for both RTM-based and statistical (Partial Least Squares Regression) retrieval. The study concludes that for the application of PROSAIL, the highest accuracies are reached when canopy conditions are closest to the model assumptions. Therefore, the RTM traits were better estimated towards the middle or end of the growing season when plant canopies were fully developed and corresponded most to a turbid medium. The exception is LAI which is better retrieved at the beginning of the growing season as dense canopies suffer from saturation effects for LAI retrieval. These findings could be relevant for the retrieval accuracies presented in Chapter 3.: which marked superior retrieval of LAI compared to leaf chlorophyll conducted before the peak of the growing season (early-mid June). It remains to be seen how fluctuations in temporal accuracy will affect functional diversity metrics as distance-based calculations exhibit a degree of robustness against structural biases (Chapter 3.:).

These findings are also relevant for estimating plant diversity through the ‘spectral variability hypothesis’. Denser ecosystem types tend to allow for multiple-scattering, enhancing the contribution coming from leaf-level biochemical and biophysical information within canopy scale reflectance (Asner, 1998; Baret et al., 1994). Temporally, this could translate to a superior ability to pick up leaf traits and the diversity thereof during seasonal peak biomass. In line with this, in Torresani et al. (2019)’s temporal study in an alpine conifer forest, the highest correlations between spectral diversity and in-situ plant diversity were found at the peak of the growing season in June and July.

6.3. Future outlook

Crisis-level losses of biodiversity are requiring action right now. To protect the ecosystems on which our lives depend, public and private commitments have been voiced to halt current declines as evidenced by the establishment of the Aichi targets and the post-2020 Convention on Biological Diversity (CBD) (IPBES, 2019; Skidmore et al., 2021). Nevertheless, significant challenges currently remain to monitor progress towards commitments, and to quantify the impact of human actions and interventions from local to global scales (Pettorelli et al., 2016). For countries to deploy cost-effective systems to monitor the post-2020 goals and targets, the integration of satellite remote sensing with models will be essential. Satellite earth observation approaches can fill data gaps, facilitate transparency, open-source data access, and repeatable workflows (Latifi et al., 2021).

Plant functional and taxonomic diversity observations from space have the potential to provide a global context for biodiversity research, and link plant diversity at local scales to ecosystem functioning around the globe (Jetz et al., 2016; Rocchini et al., 2015). Moreover, such observations would help map spatio-temporal plant biodiversity dynamics in relation to human interventions. Despite the anticipation of future satellite missions, research on currently operational sensors cannot be overlooked, especially considering the urgency of current biodiversity declines, and the value of such research as a learning curve for the development of future sensors and methodologies. The quantitative and qualitative assessments of this thesis outline the capabilities and opportunities for assessing plant biodiversity from space using Sentinel-2, while acknowledging spectral and spatial limitations and implications for the ecological interpretation.

These limitations affect the patterns we can and cannot observe and the confidence margins that are realistically possible. A more detailed understanding of how spectral, temporal, and spatial resolutions affect our capability to monitor plant diversity from space is still needed and can be achieved through multi-sensor or multi-platform analyses. Furthermore, a wider range of validation campaigns is needed to assess the robustness of different spectral approaches across different ecosystem types and scales and to facilitate the propagation of uncertainties of plant diversity estimates. Quantitative approaches (Chapter 3.:) are more difficult to acquire, yet more valuable than qualitative assessments (Chapter 4).

The importance of data assimilation has been highlighted in this discussion chapter. To overcome shortcomings, data gaps, signal-to-noise ratios, and trade-offs between different sensors, we need to advance towards the assimilation of multi-sensor, multi-temporal, multi-scale remote sensing observations. Similarly, data assimilation and gap-filling will need to look beyond the horizon of earth observation datasets. The ingestion of in-situ trait/taxonomic measurements, innovative techniques (e.g. eDNA), and ancillary environmental and phenological datasets can help us to study changes in plant biodiversity across hierarchical levels and over space and time. Ultimately, temporal and spatial continuity is a key factor in understanding changes in plant biodiversity.

The thesis also highlights that different operationalization and workflow choices will impact the observed patterns of plant diversity. Academics have proposed ‘Essential Biodiversity Variables (EBVs)’ to help structure and harmonize biodiversity monitoring globally (Skidmore et al., 2021; Pereira et al., 2013). Satellite remote sensing has been designated as an important instrument for the derivation of a selection of EBVs. Indeed, satellite remote sensing EBVs (SRS-EBVs) have been conceptualized as the subset of EBVs whose monitoring relies largely or wholly on the use of satellite-based data (Jetz et al., 2016; Pettorelli et al., 2016). However, so far, there has been little agreement on what these SRS-EBVs should be and what reproducible workflows are needed (Skidmore, 2015).

For the metrics used in this thesis to be included within a suite of SRS-EBVs, agreement on reproducible workflows is important (Skidmore, 2015). Justified and well-understood decisions underlie the design of such workflows and metrics. This thesis exemplifies the importance of underlying decisions; what sensors to use, what scales to apply, what traits to consider, what inversion and retrieval algorithms to run. This thesis also reveals that a degree of robustness and ‘surrogacy’ occurs in terms of scale (taxonomic versus functional), metrics (spectral diversity versus functional diversity), and inversion algorithms. Extrapolation of the findings is still needed at a cross-ecosystem scale. In terms of scaling up current efforts to global observations, cloud computing infrastructures, e.g. Google Earth Engine and DIAS, will play a key role when combined with the aforementioned data assimilation principles into harmonized workflows (Campos-Taberner et al., 2018; Moreno-Martínez et al., 2018). Moreover, further test cases are necessary to assess the sensitivity and suitability of plant diversity metrics to study ecological phenomena and gradients, and including; community assembly (chapters 4-5), elevation (Durán et al., 2019, chapter 4), productivity (Durán et al., 2019), post-fire recovery (chapters two and three), invasive species (Khare et al., 2021, 2019), protected areas, rewilding and legislative efforts (Lausch et al., 2016).

To further understanding on the human impact on plant biodiversity, environmental footprints of human intervention and consumption are becoming increasingly relevant (Marques et al., 2017). Chapter four has shown distinct patterns between land use types (oil-palm plantations versus logged and intact forests) in terms of plant functional diversity observed from Sentinel-2 spectral reflectance. These findings are relevant given that land use change for agricultural expansion like oil-palm remains the most detrimental driver of biodiversity declines (IPBES, 2019). Agricultural expansion serves human consumption and is largely driven global commodity supply chains. A fundamental modelling technique to evaluate and quantify environmental impacts of products, processes or services across entire supply chains is Life Cycle Assessment (LCA; e.g. Guinée and Lindeijer, 2002). LCA models can help quantify the impact of human consumption on biodiversity, yet current methodologies are hampered by data gaps and quality relying on highly aggregated, limited, and static characterization factors (Ahmed et al., 2018; Chaudhary et al., 2015; Curran et al., 2016).

Current state-of-the-art LCA modelling approaches that seek to evaluate the biodiversity impacts of human consumption through commodities and sourcing regions tend to rely on (self-disclosed) national or regional characterization of species losses as model input through classification schemes based on land use (Jaroenkietkajorn et al., 2021) or ecoregions (Olson et al., 2001). The implemented datasets require spatio-temporal interpolation, use one or few key indicative taxa, and tend to rely on heavy assumptions for extrapolation across large spatial extents (Winter et al., 2017). Satellite-based estimates of plant diversity could complement current model input simplifications with considerably more spatial detail, overcome field inconsistencies among observers (Takashina and Economo, 2021), and provide global representativeness in observational data (Rocha et al., 2021). Local and spatially explicit estimates of plant diversity from satellite remote sensing would allow for local characterization of plant diversity impacts as opposed to regional or national aggregates. Moreover, local characterization can go beyond taxonomic indicators and include estimated plant functional diversity impacts which tend to respond more consistently to environmental drivers (Ahmed et al., 2018; de Souza et al., 2013; Scherer et al., 2020).

Similarly, accurate characterization of plant functional diversity for Earth system models would greatly improve our ability to model and understand the effects of global change on the cycling and storage of carbon, water, energy, and ecosystem functioning (Serbin et al., 2019). However, current analyses are hampered by data gaps and the use of aggregated, interpolated, and third-party data (e.g. IUCN threat categories or indicator species inventory data) which is overly coarse, taxonomy-dominated, high-level aggregated, and/or not spatially explicit. Over time, with growing validation and methodological improvements, satellite remote sensing estimates of plant functional diversity can address major data gaps, contribute to posterior models, and overcome the widespread lack of national biodiversity monitoring systems. Specifically, once spatially explicit and validated land use impacts on plant biodiversity can be mapped confidently, we can integrate these estimates in models to quantify the impacts of human intervention and consumption (de Souza et al., 2013).

6.4. Conclusions

This thesis addressed current knowledge gaps in remote sensing applications for studying large-scale terrestrial plant diversity patterns regarding the understudied role of currently operational satellite earth observation and physics-based methods to estimate plant functional diversity patterns. The analyses presented relied on Sentinel-2's multispectral imager and reveal a promising ability to estimate plant diversity from physics-based RTM inversion for functional diversity as well as based on spectral diversity metrics for taxonomic diversity.

Validity of both was tested empirically against in-situ field measurements on taxonomic and functional plant diversity derived from a dedicated field campaign scaled to Sentinel-2's pixel-based raster as well as against large-scale gradients of land use, elevation and spatial scaling. The approximation of the satellite-based estimates to actual in-situ plant diversity suggests a sufficient spectral differentiation in Sentinel-2's broadband multi-spectral lay-out supportive of estimating functional/taxonomic diversity across aggregate plant canopies and the traits studied. A degree of robustness was observed in the distance-based diversity metrics deployed, in particular the Convex Hull Volume, to quantify the information entropy found in the observations. These metrics were not impaired by the observed estimation errors and biases found in the different RTM inversion methods or the signal-to-noise ratios of remote sensing observations but remained relatively effective in estimating plant diversity patterns.

The 'spectral variability hypothesis' when tested with Sentinel-2 in the presented case study held its presumed validity in estimating coarse taxonomic plant diversity patterns. However, the application of spectral diversity metrics will require caution given the potentially strong (orthogonal) dominance of vegetation cover, i.e. canopy architecture and density, over functional and taxonomic diversity in spectral diversity signals. Therefore, methods that can isolate functional and taxonomic diversity in the spectral signal are preferred despite generally requiring a more complex data processing chain. Functional and taxonomic diversity based on RTM inversion of spectral observations allowed for a two-fold validation of both the estimated individual plant traits as well as the diversity thereof. Using three different inversion techniques, the findings suggest a promising performance in estimating plant functional and taxonomic diversity based on three RTM-derived plant traits (LAI, LMA, and CAB). Inversion techniques that allow for locally optimized trait ranges performed best in the analyses exhibiting a 20-21% (nRSME) deviation and a strong rank-based relationship (Spearman's ρ: 0.76-0.80) to plant functional richness (CHV) patterns.

The PROSAIL RTMs implemented in the retrieval techniques offer a simplified representation of heterogeneous canopies. Therefore, future improvements in the accuracy of plant functional diversity estimates may be achieved by RTMs better-equipped to the ecosystems under study, or the use of more versatile hybrid inversion methods such as the implementation of active learning heuristics and deep learning. A major advantage of the presented physics-based methods lies in its foundation in the universal principles of light-vegetation interaction which should theoretically be scalable and applicable across ecosystems types without a heavy reliance on a priori field measurements or ancillary data. However, its actual scalability across different study sites, ecosystems and vegetation types remains to be thoroughly tested, preferably at large continuous scales.

The spatial scaling of Sentinel-2 at 20m spatial resolution leads to challenges in how to apply and interpret plant diversity patterns observed. Its spatial resolution is ill-equipped to delineate individual canopies. Instead, it presents an aggregation of individual species and canopy traits at rasterized scales that are difficult to validate in the field given its size, geometry, and mixing of canopy and background signals. This aggregation leads to a mixing of both alpha and beta diversity scales that are traditionally instrumental to the ecological interpretation of spatial plant diversity patterns. Future studies that seek to overcome such challenges may want to rely 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. Moreover, multi-sensor approaches can offer adaptability to address the spatial irregularities found in ecological phenomena, including the heterogeneous canopy sizes found in ecosystems and abstract ecological community sizes to which coarse satellite-based rasterized pixels are ill-equipped and single sensors applications lack versatility.

The spatial continuity or spatial explicitness of satellite inference offers an unprecedented readiness to conduct analyses of diversity patterns across a wide range of multiple scales. The multi-scalar analyses presented in this dissertation illustrate the gradual transition of what are traditionally considered separate drivers of alpha versus beta diversity while omitting the need for arbitrary decisions of a fixed optimal plot area. Subsequently, these findings question whether the traditional ecological focus of discrete ‘within’ versus ‘between’ community diversity (alpha vs beta) should be maintained or whether we need new more continuous concepts.

Further validation of plant diversity estimates from satellite remote sensing will remain necessary with the inclusion of large sample sizes, more ecosystem and vegetation types, a wider range of traits to ensure adequate functional differentiation and multi-temporal analyses. With growing adequate validation, ongoing advances in sensors, and methodological improvements, the large-scale repeated and spatially explicit monitoring of plant diversity patterns through remote sensing techniques is going to become an integral part of global biodiversity observatory systems and planetary models to quantify our impacts and monitor Earth’s ecological healthspan.