Reconstructing the fine-scale habitat structure of wetlands for animal ecology using remote sensing

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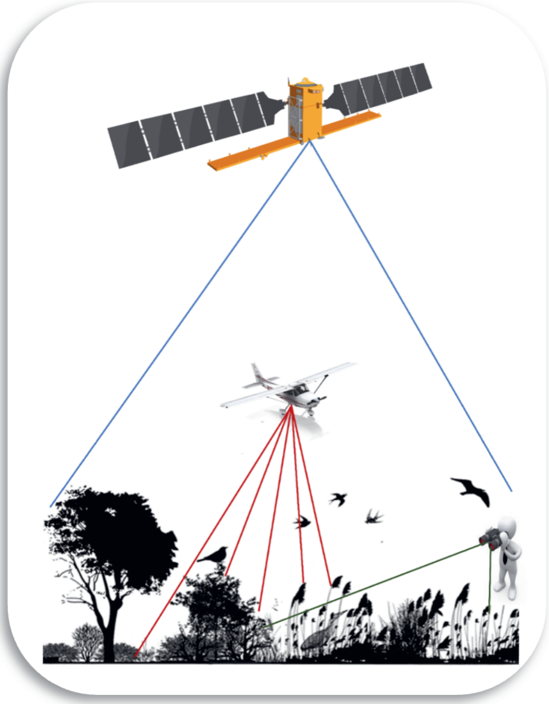
CHAPTER 6.

Synthesis



The development of remote sensing-based metrics for describing habitat structure is an important step towards a better understanding of animal-habitat relationships (Bakx et al., 2019; Davies and Asner, 2014). Former studies mainly relied on climate and land cover-related information in modelling the distribution and diversity of animal species (Kissling et al., 2017). Predictor variables related to climate and land cover types can be easily retrieved from official open source databases, e.g. the bioclimatic variables (https://www.worldclim.org/data/index.html) or CORINE land cover products (https://land.copernicus.eu/pan-european/corine-land-cover). In contrast, quantification of habitat structure is still limited to local scale case studies (Bakx et al., 2019) and development of standardized remote sensing-based products is still a subject of ongoing research, e.g. within the GEOBON framework (Pereira et al., 2013; Skidmore et al., 2021). In this thesis, I explored various ecological applications using metrics derived from remote sensing — especially from country-wide ALS — to reconstruct fine-scale habitat structure within wetlands. In this chapter, I discuss recommendations for future work based on my thesis to establish remote sensing-based ecological indicators for quantifying and monitoring habitat structure at broad spatial scales.

LiDAR metrics for quantifying habitat structure in animal ecology

One of the main challenges of applying LiDAR metrics to animal ecology is that the calculated metrics should reflect the relevant home range characteristics of the animal species. Many studies only use a few commonly applied LiDAR metrics, such as vegetation height and vertical variability, to characterize habitat structure relevant for animals (Bakx et al., 2019). My thesis suggests that in addition to these commonly used LiDAR metrics, horizontal variability (e.g. proportion of predominantly reed vegetation) plays an important role in animal ecological applications (**chapter 3-5**). For instance, I showed that horizontal variability metrics can be used for differentiating reed bed types **(chapter 3**), habitat niches (**chapter 4**) and predicting habitat suitability (**chapter 5**) of wetland birds. Other studies have also indicated that horizontal variability metrics are powerful predictor variables for estimating the species distribution of certain forest bird species (Zellweger et al., 2013) and threatened butterfly species (Vries et al., 2021). These types of metrics can be used to quantify landscape structure (Turner and Gardner, 2015) with high spatial detail which is particularly useful for describing the home range environment of focal species. Future studies should investigate applying horizontal variability metrics to quantify and better understand the effect of landscape structure, such as habitat connectivity or linear vegetation elements (e.g. tree lines, hedgerows), on animal species.

A general bottleneck in the application of LiDAR metrics to animal ecology is the limited availability of sufficient and standardized *in-situ* field measurements of habitat structure at broad spatial scales (e.g. across Europe). In **chapter 3**, I used a highly detailed expert-based digitized map as an annotation. This type of data is only accessible for one particular lake in the Netherlands and upscaling is only possible if similar types of expert-based maps are available across several lakes in the country. In addition to the limited availability of field measurements, in **chapter 2**, I show that standardized field measurements of vegetation structure need to be simultaneously collected alongside ALS datasets, otherwise estimation of complex vegetation structural parameters such as biomass and leaf area index are limited. Therefore, future studies should develop standardized *in-situ* field databases for validating ALS measurements (e.g. simultaneous field measurements at a broad spatial scale). An alternative solution is, intead of directly validating the ecological meaning of the LiDAR metrics, interpret them using the observed habitat requirements of a bird species, as I did in **chapter 4 and 5**. This type of interpretation works at broad scales, because bird observation datasets covering large areas are available (e.g. European Breeding Bird Atlas (https://www.ebcc.info/) or the GBIF database (https://www.gbif.org/)). However, the interpretation of the LiDAR metrics remains indirect and requires in-depth ecological knowledge of the focal bird species being used.

Another particular issue with the application of country-wide ALS to animal ecology is the seasonal discrepancy between the ALS flights and bird observations. The country-wide ALS data campaigns are measured in the leaf-off season with the purpose of terrain mapping (Reutebuch et al., 2005), whereas bird observations are carried out during the breeding season e.g. (Vergeer et al., 2016). It is therefore expected that ALS data captured in winter months may not fully and accurately represent the variability of habitat structure in the breeding season. This could introduce potential biases and errors in quantifying the habitat niche (**chapter 4**) and in predicting habitat suitability (**chapter 5**) of wetland bird species. For instance, the location of the reed-water boundary can change up to several meters during the year (Zlinszky, 2013) and the reed cutting can affect the extent of the reedbeds (Vadász et al., 2008). In **chapter 2**, our analysis estimating leaf-area index within reedbeds was not substantially affected by the seasonality of the ALS data. A few other studies suggest that leaf-off data can better capture the structure under the canopy compared to measurements carried out in leaf-on season where penetration of the laser pulse through dense canopy is limited (Næsset, 2005; Ørka et al., 2010). Overall, future studies need to report and quantify the potential effects and errors caused by seasonal discrepancies between ALS and field datasets for each LiDAR metrics within different land cover types.

An additional important aspect of future research is the analysis of the robustness of derived LiDAR metrics across different ALS datasets. Country-wide ALS are typically measured using slightly different data acquisition parameters per country, and ALS datasets from different countries can differ considerably in the characteristics and quality of the measured ALS datasets (e.g. average point density in the Netherlands is 10 pt/m^2 versus 5 pt/m^2 in Denmark). In **chapter 2**, I found that ALS datasets with different characteristics can affect the estimation of vegetation structural parameters within wetlands. Studies using ALS in forestry indicate that, for example, flying altitude, scanning angle and pulse repetition frequency can affect the accuracy of the estimated forest inventory parameters (Hopkinson, 2007; Keränen et al., 2016; Nasset, 2004), which can also be true within wetlands. However, quantifying the robustness of LiDAR metrics is difficult because of high cost of carrying out ALS measurements at the same study area and with various data acquisition parameters at the same time. Future studies should investigate this using LiDAR simulation softwares packages such as HELIOS (Bechtold and Höfle, 2016; Winiwarter et al., 2021). This software allows for the simulation of various ALS acquisition parameters which can then be used to test the robustness of the derived LiDAR metrics for animal ecology.

From ecological applications to monitoring change in habitat structure from local to continental scale

Monitoring changes in habitat structure at a continental scale remains a challenging task (Skidmore et al., 2021; Valbuena et al., 2020). This is because no single LiDAR technique can provide sufficient spatial and temporal resolution for monitoring habitat structure. For instance, my thesis showed various successful ecological applications (**chapter 2-5**) within wetlands using country-wide ALS to quantify habitat structure. However, when it comes to upscaling the ecological applications from national to continental scale, the availability of this type of ALS datasets are still spatially patchy and temporarily scarce. Country-wide ALS data is only collected within specific countries (e.g. Netherlands, Denmark, England and Spain) and the measurements are not repeated, e.g. annually. Other LiDAR measurements such as Terrestrial Laser Scanning (TLS) can provide high temporal resolution e.g. with sub-hourly intervals over periods of months using an automated scanner (Anders et al., 2021; O’Dea et al., 2019; Puttonen et al., 2016) or with annual or monthly repeated field campaigns (Hoffmeister et al., 2016; Srinivasan et al., 2014), but spatial coverage still remains limited to local scales. The recent launch of the spaceborne LiDAR mission (GEDI) aims to address some of these challenges by measuring LiDAR data at a continental scale (Dubayah et al., 2020), but it does not provide information in a spatially continuous way (only within 25 m footprints) and the temporal frequency remains insufficient for monitoring, since it is only planned as a 2-year mission. Therefore, the analysis of synergy between various types of LiDAR datasets and other satellite remote sensing products is required for establishing a framework for monitoring habitat structural changes across space and time (Valbuena et al., 2020).

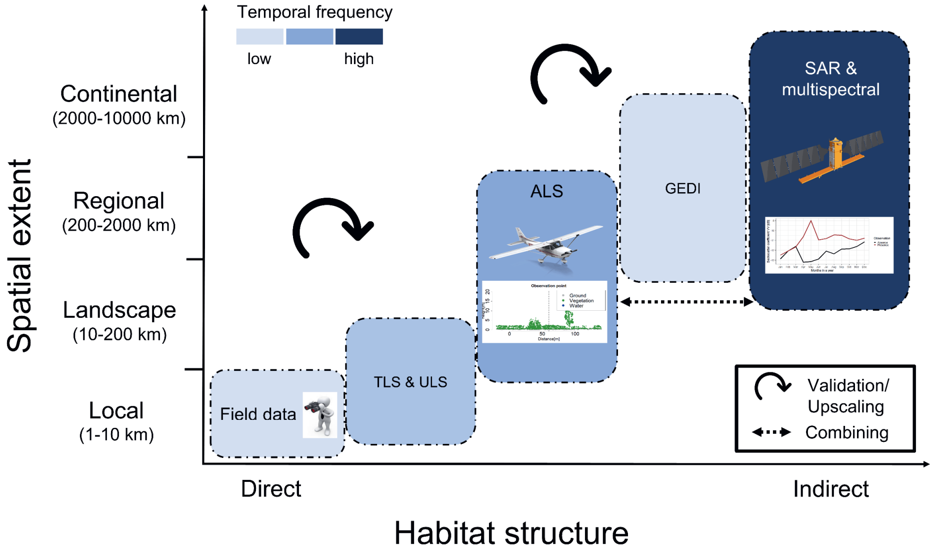


Figure 6.1. A schematic exemplary framework for synergistic and complementary use of ecological field observation data, different types of LiDAR and Synthetic Aperture Radar and multispectral remote sensing technologies for reconstructing and monitoring habitat structure from local to continental scale. The x axis indicates the directness which habitat structure is measured with each remote sensing technology. Color reflects the temporal frequency of measurements, where light blue indicates that the dataset was measured only once, and dark blue indicates frequently repeated measurements e.g. weekly basis. The validation and upscaling of different data products can be carried out using various statistical or machine learning methods, whereas the combination of different ALS and SAR or multispectral imagery datasets can be used by either combining derived metrics from different remote sensing products independently or with the application of data fusion techniques. TLS = Terrestrial Laser Scanning, ULS = Unmanned Aerial Vehicle Laser Scanning, ALS = Airborne Laser Scanning, GEDI = Global Ecosystem Dynamics Investigation, SAR = Synthetic Aperture Radar.

The synergistic use of different remote sensing technologies (also called remote sensing data fusion) is a rapidly evolving research direction (Ghamisi et al., 2019; Joshi et al., 2016; Zhang, 2010). Based on my thesis, I have outlined a possible data processing framework to establish synergistic use of different data products for reconstructing habitat structure for animal ecology applications (Fig. 6.1.). In this framework, I suggest using ecological field observations together with high resolution TLS or Unmanned Aerial Vehicle Laser Scanning (ULS) measurements to capture the key vegetation structural indicators at a local scale. This data can then be used as annotation datasets for validating and calibrating LiDAR metrics derived from country-wide ALS datasets. The validated country-wide habitat structure maps will provide sufficient training and validation data for machine learning approaches to upscale the information using temporally dense open-source satellite remote sensing datasets (e.g. multispectral and Synthetic Aperture Radar (SAR) datasets from different sensors such as Sentinel and LANDSAT). Furthermore, SAR and multispectral imagery datasets can not only be used to upscale habitat structural information, but also to enhance the information about seasonal dynamics of vegetation which could improve e.g. habitat suitability modelling of wetland birds, as I showed in **chapter 5**. Future studies still need to invest in the development of adequate data fusion techniques to integrate LiDAR information efficiently with other imagery datasets, to take advantage of and optimaly use the different types of spatial, spectral, temporal and radiometric resolutions (Ghamisi et al., 2019).

Concluding remarks

The reconstruction of habitat structure from local to continental scale is important for improving the understanding of species diversity and distribution of animals. My thesis shows that metrics derived from country-wide ALS data can be used to quantify habitat structure at a national scale. For instance, in **chapter 2,** I show that LiDAR metrics can estimate vegetation height robustly within reedbeds across ALS datasets that were measured differently. In **chapter 3**, I found that fine-scale habitats within wetlands can be classified with high overall accuracies using LiDAR metrics together with a high resolution digitized expert-based map as an annotation dataset. These classification results could be upscaled, if this type of expert-based map becomes more available across different lakes within the Netherlands. In **chapter 4**, I show that LiDAR metrics calculated at a country-wide scale can be used to separate the fine-scale habitat niches of closely related wetland birds, which can be used to reconstruct the habitat structural preference of the species with unprecedented detail. Finally, in **chapter 5**, I demonstrate that country-wide ALS provides a useful additional value for describing fine-scale habitat suitability of wetland birds, and alongside other remote sensing products it can improve understanding of habitat-animal relationships. Overall, my thesis also suggests that the quantification of habitat structure from regional to continental scale still remains challenging. To overcome this challenge, future work should focus on developing a standardized guideline and framework for processing, validating and combining remote sensing-based metrics for quantifying habitat structure across space and time.