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

Koma, Z.V.

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CHAPTER 1.

General introduction

Importance of habitat structure in animal ecology

The habitat-heterogeneity hypothesis is one of the cornerstones of ecology which assumes that structurally more complex habitats increase the species diversity (Bazzaz, 1975; MacArthur and MacArthur, 1961; Simpson, 1949). The complexity of habitats can be described by the vertical and horizontal distribution of the plant communities (Tews et al., 2004) and habitat structure plays an important role in better understanding of animal-habitat relationships. For instance, in 1961 the first quantitative approach to measure species diversity in relation to habitat structure proved that, in deciduous forests, bird diversity is determined by the vertical distribution of foliage diversity rather than tree species composition (MacArthur and MacArthur, 1961). Since then, many follow-up studies have analyzed how habitat structure shapes animal communities in different ways by providing more niche space (Müller et al., 2014), affecting the resource availability (Cody, 1985) and altering the climate conditions (Zellweger et al., 2019). However, current studies often use 2D categorical land cover and habitat maps and the 3D physical structure of vegetation and small and scattered habitats are generally not well represented (Kissling et al., 2017). For a better understanding of animal-habitat relationships, the quantification of habitat structure (e.g. height, cover, horizontal and vertical variability) is required. However, the measurement of habitat structure in spatially contagious and broad extents in animal ecology remains an ongoing challenge.

The habitat structure is often measured by field ecologists who focus on describing the plant species composition within vegetation plots (Schaminée et al., 2009). In animal ecology studies, local field observations are carried out to describe specialized structural habitat needs of a focal species. For example, previous studies have measured reed stem thickness, the ratio between old and new shoots or litter thickness during monitoring of wetland bird breeding habitats (Dyrcz, 1981; Neto, 2006; van der Hut, 1985). Even though direct field measurements are considered to be the most precise methods, quantifying vegetation structure within field plots is labor-intensive, time-consuming and expensive and thus limited in spatial extent. Therefore, the development of quantitative, accurate and spatially continuous indicators for reconstructing vegetation structure over a broad scales are needed. One of the most promising technologies for this purpose is remote sensing which can provide data products to quantify habitat structure (Skidmore et al., 2021, 2015).

Remote sensing products for quantifying habitat structure

The growing availability of spaceborne and airborne remote sensing products offers new opportunities for quantifying fine-scale habitat structure at high resolutions across broad spatial extents (Pettorelli et al., 2014a; Davies and Asner, 2014; Valbuena et al., 2020). Remote sensing acquires information about the Earth’s surface by measuring the biophysical characteristics of the surface from a distance using reflected or emitted radiation e.g. (Pettorelli et al., 2014a). Different remote sensing techniques and products capture different types of information about the vegetation. Active remote sensing techniques use an artificial source of radiation that can scatter back to the sensor after interacting with the measured objects (Andersen et al., 2006). In contrast, passive remote sensing relies on solar radiation as an illumination source, where the sensor detects a specific parts of the electromagnetic spectrum (Awange and Kiema, 2013). Although various remote sensing products are available to provide information about different habitats, the maturity of remote sensing products can differ considerably (Skidmore et al., 2021). While categorical land cover maps are routinely produced even at the global scale such as MODIS (https://modis.gsfc.nasa.gov/data/dataprod/mod12.php) or CORINE land cover products (https://land.copernicus.eu/pan-european/corine-land-cover), the characterization of a fine-scale habitat structure is still subject of ongoing research (Kissling et al., 2017).

LiDAR as a promising technology for reconstructing habitat structure

Light Detection And Ranging (LiDAR) technology obtains direct information about vegetation structure (Davies and Asner, 2014; Lefsky et al., 2002; Valbuena et al., 2020; Vierling et al., 2008). This remote sensing technology uses a laser scanner that emits laser pulses which are then reflected back from different parts of the vegetation (e.g. leaves, branches and stems) or from the terrain surface. The sensor captures the time difference between the emitted laser pulse and the returned signal as well as the intensity of the reflected energy (Shan and Toth, 2018). Based on the returned signal the x,y,z coordinates of the objects can be calculated and thus result in a 3D point cloud which represents the 3D vegetation structure. LiDAR technology can be operated from different platforms. At the local to landscape scale, Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle Laser Scanning (ULS) is often applied using tripods or drones as a platform for carrying the scanner. From local to regional scale, Airborne Laser Scanning (ALS) can provide point cloud datasets where the scanner is mounted on airplanes or helicopters. Additionally, at the continental scale the spaceborne LiDAR mission, Global Ecosystem Dynamics Investigation (GEDI), collects data about the vegetation structure (Dubayah et al., 2020). In this thesis, I mainly focus on using ALS data to capture information about the habitat structure.

To derive ecologically relevant information from ALS datasets, 3D point cloud data need to be further processed, for example, into metrics that statistically aggregate the 3D point cloud information within raster cells (Bakx et al., 2019; Davies and Asner, 2014). These LiDAR metrics can then be used to model the habitat suitability of various animal species such as birds, mammals and invertebrates by quantifying the vertical and horizontal variability of the vegetation (Davies et al., 2018; Vries et al., 2021; Zellweger et al., 2013). For instance, one of the most widely used LiDAR metrics, the canopy height, allows the prediction of, for example, the breeding success of great tits (*Parus major*) and blue tits (*Cyanistes caeruleus*) in the UK (Hill et al., 2014; Hinsley et al., 2002). Furthermore, the quantification of vertical variability of the canopy structure can identify suitable habitats of e.g. the hazel grouse (Zellweger et al., 2013) as well as the beta diversity of birds in Switzerland (Zellweger et al., 2017). The ALS flight campaigns were generally organized for specific local scale studies, but in recent years country-wide ALS datasets increasingly become available which capture data across the whole country (Valbuena et al., 2020). So far, only a few studies have processed and used country-wide ALS data at the national level (Moeslund et al., 2019), therefore, the data processing workflows and analyses of LiDAR metrics at the national-scale in animal ecology are still missing (Kissling et al., 2017; Meijer et al., 2020). Furthermore, most studies have quantified the 3D vegetation structure for animals within forested ecosystems (Bakx et al., 2019) and the usage of LiDAR in low vegetation remains little explored.

Possibilities of reconstructing habitat structure using other type of remote sensing techniques

Satellite remote sensing technologies, such as multispectral and Synthetic Aperture Radar (SAR), offer data products with different spatial, temporal and radiometric resolutions (Skidmore et al., 2021). In animal ecology, multispectral imaging sensors (e.g. LANDSAT, MODIS and Sentinel-2) are often used to derive various vegetation indices such as the Normalized Difference Vegetation Index (NDVI) (Drusch et al., 2012). Recent studies have also shown that textural metrics derived from multispectral imagery can provide useful information on habitat heterogeneity to predict bird species richness (Farwell et al., 2021; St-Louis et al., 2014). However, the reconstruction of habitat structure from this type of data is still limited, because the retrieved information only relates to the top of the canopy and does not represent the full 3D habitat structure (Valbuena et al., 2020). In contrast, SAR data such as Sentinel-1 products, can be used for deriving information related to habitat structure, since the SAR signal is sensitive to orientation, volume and roughness of the surface (e.g. plants) (Torres et al., 2012). SAR data is often used to quantify biomass (Sinha et al., 2015) or other vegetation structural parameters such as vegetation height and complexity (Bae et al., 2019; Bruggisser et al., 2021). Overall, SAR data has potential for quantifying habitat structure, however, compared to ALS the vegetation structural information retrieved under the canopy is relatively limited.

Wetlands as a breeding habitat for birds

Wetlands are among the most productive ecosystems present on the Earth and comprise a wide variety of habitats, including meadows and wet grasslands formed by herbaceous vegetation (e.g. grasses, sedges and bulrush), patches of trees and shrubs (e.g. European alder, and willows), and reedbeds (i.e. mono-dominant stands of the common reed *Phragmites australis*) (Leisler and Schulze-Hagen, 2011; Weller, 1999). Wetlands have been in rapid decline, therefore international agreements such as the Ramsar Convention on Wetlands (https://www.ramsar.org/) urge monitoring and mapping of wetlands for effective planning and natural resource management.

As the plants in wetlands vary in life form and physical stature, they form a structurally complex habitat type that is important for many wetland animals, including migratory and breeding birds (Leisler and Schulze-Hagen, 2011). For instance, the great reed warbler (*Acrocephalus arundinaceus*), Eurasian reed warbler (*Acrocephalus scirpaceus*) and Savi's warbler (*Locustella luscinioides*) are specialized and exclusively breed in reedbeds. Within reedbeds, vegetation structure and composition typically varies with distance to water (Leisler and Schulze-Hagen, 2011). Close to the water edge, reed vegetation grows tall and is denser (water reed) than in reedbeds that are located in the drier parts of a wetland (land reed) (Kleefstra et al., 2016). All three warbler species have distinct habitat preferences in terms of vegetation structure and types of reedbeds. The great reed warbler breeds in areas close to open water (e.g. 5 m away from the water edge) (Báldi and Kisbenedek, 1999). In contrast, the Savi's warbler prefers large contiguous reedbeds mixed with other herbaceous perennial plants such as the bulrush (*Typha* spec.) and sedges (*Carex* spec.), with a few trees and bushes interspersed (Báldi, 2006). The Eurasian reed warbler is abundant in small patches of reed (Dyrcz, 1981; Graveland, 1998).

Quantitative methods for linking field observations to remote sensing data

Field observation data often consist of either quantitative values (e.g. percentage of cover or biomass measured in g/m^2) or categorical classes (e.g. name of land cover or habitat type). Statistical modelling methods are used to link different types of field observations to remote sensing-based metrics. For instance, multivariate regression methods (James et al., 2013) measure the degree at which predictor variables (e.g. remote sensing metrics) and a response variable (e.g. height of the reed) are statistically related. More advanced modelling methods such as machine learning (Rebala et al., 2019) offer to model more complex statistical relationships between predictor and response variables. One of the most favorably used methods in remote sensing is the Random Forest (Breiman, 2001) which is a supervised, ensemble learning method. This algorithm constructs a number of decision trees by randomly splitting training data into internal training and validation sets, then merges the predictions for each individual decision tree to get a final prediction. This type of algorithm can be used either as a classifier (e.g. classifying the derived remote sensing metrics into specified classes such as habitat types), or in a regression analysis to estimate quantitative information such as the biomass within wetlands (Mutanga et al., 2012).

More specifically, in animal ecology, field monitoring data often contain quantitative values about species occurrences such as presence-absence or presence-only observations of the focal animal species in a given area (Guisan et al., 2017). This type of field observation data is used in combination with a special type of modelling technique called species distribution modeling (SDM) or environmental niche modelling (Araújo et al., 2019; Elith et al., 2006; Guisan and Thuiller, 2005; Guisan and Zimmermann, 2000; Soberón and Nakamura, 2009). This method quantifies the statistical relationship between measured species occurrences and environmental conditions to predict the habitat suitability of the focal species. SDMs play a fundamental role in conservation ecology to provide information about the geographic distribution of a species. Other types of analyses focus on describing the ecological niche to understand how populations of species can persist (Holt, 2009) or how species' respond and adapt to different environmental conditions (Pearman et al., 2008; Schurr et al., 2012). The environmental conditions related to vegetation types and structure characterize the habitat niche of the species (Grinnell, 1917; Soberón, 2007), which can be used to analyze the similarities and differences in habitat requirements of e.g. closely related species (Broennimann et al., 2012; Brown and Carnaval, 2019; Warren et al., 2008).

Research objectives and structure of the thesis

In this thesis, I analyze how high-resolution remote sensing-based metrics can be used to reconstruct the fine-scale habitat structure within wetlands for animal ecology. In this context, my thesis predominantly focuses on developing applications of country-wide ALS data to different animal ecology settings, as ALS is a promising remote sensing technology for describing fine-scale habitat structure from local to regional scales. The following are the specific research questions related to each chapter:

(1) How can LiDAR metrics obtained from different ALS flight campaigns be used to quantify the physical structure of vegetation within reedbeds?

(2) Can LiDAR metrics derived from country-wide ALS data identify fine-scale habitats within wetlands?

(3) Can LiDAR metrics derived from country-wide ALS data separate the fine-scale habitat niches of closely related wetland birds?

(4) What is the added value of country-wide ALS data compared to other high-resolution remote sensing products for describing the fine-scale habitat suitability of wetland birds?

Overall, my thesis includes four chapters (**chapter 2-5**) to answer these questions. In **chapter 2**, I statistically relate various ALS datasets to a standardized set of field measurements (height, biomass and leaf area index) of vegetation structure within reedbeds. The field measurements and ALS flights were conducted at three Hungarian lakes. Using these different ALS datasets and a standardized set of field measurements I developed multivariate regression models to quantify vegetation height, biomass and leaf area index, and analyzed how the characteristics of ALS data and the discrepancies between field and ALS data (spatial resolution, temporal offset and seasonality) affect the quantification of 3D structure of vegetation within reedbeds.

In **chapter 3**, I present an open-source workflow to classify land cover and fine-scale habitats within wetlands by using country-wide ALS data. I test the workflow using a wetland area in the Lauwersmeer wetland located in the northern part of the Netherlands. I derive LiDAR metrics to quantify the 3D structure of the vegetation by quantifying aspects related to vegetation cover, 3D shape, vertical variability, horizontal variability and height, as well as fine-scale topographic variability to classify the land cover types and fine-scale habitats at different hierarchical levels within wetlands.

In **chapter 4**, I use country-wide ALS data in combination with presence–absence observations of birds from a national monitoring scheme in the Netherlands to separate the fine-scale breeding habitat niches of closely related reed warbler species (great reed warbler, Eurasian reed warbler and Savi’s warbler). The general breeding habitat niche of the three selected warblers is highly overlapping (i.e. all species are breeding in reedbeds), however, various field studies have suggested that they separate their niches at a finer scale along different gradients of vegetation structure. I derive various LiDAR metrics to capture these vertical and horizontal structural variations in vegetation to quantify niche filling, niche overlap and niche separation of the closely related warbler species.

In **chapter 5**, I assess the potential of different high resolution remote sensing data products next to the country-wide ALS to map the habitat suitability of wetland birds. I use the species presence-absence observations of wetland birds (great reed warbler and Savi’s warbler) within the northeastern part of the Netherlands together with metrics derived from national land cover maps, country-wide ALS data, and SAR and multispectral imagery obtained from the Sentinel-1 and Sentinel-2 satellites. These remote sensing products capture the habitat types, structure, heterogeneity and seasonal variability of wetland vegetation. Using the derived metrics I compare achieved model accuracies, relative feature importances and the response curves of the most important metrics when using different types and combinations of land cover, LiDAR and Sentinel-based metrics.

In **chapter 6**, I combine the results obtained from different chapters to discuss recommendations for future work based on my thesis for quantifying and monitoring habitat structure from local to continental scale.