LiDAR derived forest structure data improves predictions of canopy N and P concentrations from imaging spectroscopy

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ABSTRACT

Imaging spectroscopy is a powerful tool for mapping chemical leaf traits at the canopy level. However, covariance with structural canopy properties is hampering the ability to predict leaf biochemical traits in structurally heterogeneous forests. Here, we used imaging spectroscopy data to map canopy level leaf nitrogen (N_{mass}) and phosphorus concentrations (P_{mass}) of a temperate mixed forest. By integrating predictor variables derived from airborne laser scanning (LiDAR), capturing the biophysical complexity of the canopy, we aimed at improving predictions of N_{mass} and P_{mass}. We used partial least squares regression (PLSR) models to link community weighted means of both leaf constituents with 245 hyperspectral bands (426–2425 nm) and 38 LiDAR-derived variables. LiDAR-derived variables improved the model's explained variances for N_{mass} (R^2_{cv} 0.31 vs. 0.41, % $RSME_{cv}$ 3.3 vs. 3.0) and P_{mass} (R^2_{cv} 0.45 vs. 0.63, % $RSME_{cv}$ 15.3 vs. 12.5). The predictive performances of N_{mass} models using hyperspectral bands only, decreased with increasing structural heterogeneity included in the calibration dataset. To test the independent contribution of canopy structure we additionally fit the models using only LiDAR-derived variables as predictors. Resulting R^2_{cv} values ranged from 0.26 for N_{mass} to 0.54 for P_{mass} indicating considerable covariation between biochemical traits and forest structural properties. N_{mass} was negatively related to the spatial heterogeneity of canopy density, whereas P_{mass} was negatively related to stand height and to the total cover of tree canopies. In the specific setting of this study, the importance of structural variables can be attributed to the presence of two tree species, featuring structural and biochemical properties different from co-occurring species. Still, existing functional linkages between structure and biochemistry at the leaf and canopy level suggest that canopy structure, used as proxy, can in general support the mapping of leaf biochemistry over broad spatial extents.

1. Introduction

Plant traits are important indicators of ecosystem functioning and are widely used in ecological research to detect responses to environmental change (Chapin, 2003; Garnier et al., 2007; Kimberley et al., 2014) or to quantify ecosystem services (Lamarque et al., 2014; Lavorel

et al., 2011). Biochemical traits like leaf nitrogen and phosphorus content respond to changing environmental conditions, such as soil nutrients or climate (Di Palo and Fornara, 2015; Sardans et al., 2015) and are key factors related to important ecological processes including net primary production and litter decomposition (Melillo et al., 1982; Ollinger et al., 2002; Reich, 2012). Temporal trends, like increasing N:P ratios caused by nitrogen deposition can serve as indicators for ecosystem health and sustainability (Jonard et al., 2015; Talkner et al., 2015). Using leaf traits to answer questions related to ecosystem functioning often requires scaling from the leaf to the plant community or ecosystem level (Masek et al., 2015; Suding et al., 2008). Due to the fact that certain leaf biochemical traits are closely linked to the reflectance signature of leaves (Kokaly et al., 2009) the use of imaging spectroscopy has proved to be an efficient method for scaling and the prediction of these traits across large spatial scales (Homolová et al., 2013). By far, most studies relating foliage biochemistry to airborne imaging spectroscopy data focused on leaf nitrogen (e.g. Dahlin et al., 2013; Huber et al., 2008; Martin and Aber, 1997; Wang et al., 2016). But also other biochemical leaf ingredients like chlorophyll, cellulose and lignin (Curran et al., 1997; Schlerf et al., 2010; Serrano et al., 2002) and even micronutrients like iron and copper (Asner et al., 2015; Pullanagari et al., 2016) have been successfully related to imaging spectroscopy data. Compared to leaf nitrogen, mapping of leaf phosphorus concentrations received less attention (but see Asner et al., 2015; Porder et al., 2005; Pullanagari et al., 2016).

The link between leaf biochemistry and reflectance established in optical remote sensing applications strongly depends on the observational level. At the leaf level, nitrogen concentrations, for example, are directly expressed in the spectral signal. For dried and ground samples, characteristic absorption features can be found in the shortwave infrared (SWIR) region of the electromagnetic spectrum. The absorption of radiation in the SWIR can be attributed to nitrogen bonds in organic compounds primarily of leaf proteins (Kokaly et al., 2009). In fresh leaves the nitrogen concentration is additionally strongly related to absorption in the visible part of the spectrum (VIS) (Asner and Martin, 2008), which can be attributed to the correlation between chlorophyll and leaf nitrogen (Homolová et al., 2013; Ollinger, 2011). At the canopy level, spectral reflectance is strongly influenced by canopy structure (Asner, 1998; Gerard and North, 1997; Rautiainen et al., 2004). Thus, the estimation of leaf traits from canopy reflectance is more complex due to the confounding effects of structural properties like crown morphology, leaf area index (LAI), leaf clumping or stand height (Ali et al., 2016; Simic et al., 2011; Xiao et al., 2014). Consequently, variability in canopy structure can strongly influence the accuracy of nitrogen estimations from remote sensing (Asner and Martin, 2008). On the other hand, canopy structure has been found to explain part of the relation between reflectance and canopy nitrogen. This relation is revealed by a strong importance of reflectance in the near infrared (NIR) for mapping canopy nitrogen reported by previous studies (Martin et al., 2008; Ollinger et al., 2008). Reflection in the NIR region is dominated by multiple scattering between leaves of the canopy, and thus very sensitive to variation in canopy structure (Knyazikhin et al., 2013; Ollinger, 2011). Covariation between canopy structure and nitrogen was found across different types of forest ecosystems and hence points at the existence of a functional link between canopy structure and biochemical composition. However, the foundation of this functional link has not been fully understood.

In this study, we aim at scaling leaf level measurements of mass based leaf nitrogen (N_{mass}) and phosphorus content (P_{mass}) to the canopy level for a temperate mixed forest. To capture the forest's diversity in terms of tree species, age distribution and canopy structure we propose to explicitly integrate information on forest structure derived from airborne laser scanning (Light Detection And Ranging, LiDAR) into the empirical models. Airborne LiDAR data can depict the 3D structure of the vegetation and has been successfully used to map forest attributes like the leaf area index and standing biomass (Fassnacht

et al., 2014; Korhonen et al., 2011; Zolkos et al., 2013). We argue that the integration of structural properties allows for a better acquisition of leaf chemical traits in heterogeneous forests canopies. We furthermore expect that LiDAR data can help to understand expected covariation between canopy structural properties and biochemical leaf traits. Specifically, we aim at: (1.) improving predictions of N_{mass} and P_{mass} using imaging spectroscopy through the integration of LiDAR-derived information on forest structure and (2.) finding out which structural canopy properties correlate with N_{mass} and P_{mass} in canopies of mixed forests.

2. Materials and methods

2.1. Study area

The study area is the forest of Compiègne (northern France, coordinates: 49.370° N, 2.886° E), covering an area of 144.2 km². This lowland forest is located in the humid temperate climate zone with a mean annual temperature of 10.3 °C and mean annual precipitation of 677 mm. The soils cover a range from acidic nutrient-poor sandy soils to basic and hydromorphic soils (Closset-Kopp et al., 2010). The forest mainly consists of even-aged managed stands of beech (*Fagus sylvatica*), oaks (*Quercus robur*, *Quercus petraea*) and pine (*Pinus sylvestris*) growing in mono-culture as well as in mixed stands, frequently intermingled with European hornbeam (*Carpinus betulus*) and ash (*Fraxinius excelsior*) (Chabrerie et al., 2008). Stands are covering a range from early pioneer stages to > 200-year-old mature forests. As a result of thinning activities and windthrow the forest is characterized by frequent canopy gaps which are often filled by the American black cherry (*Prunus serotina*), an alien invasive tree species in central Europe. *Prunus serotina* is in some parts also highly abundant in the upper canopy of earlier pioneer stages.

2.2. Field data

Field data were acquired from 50 north-facing field plots (25 m × 25 m) established in July 2014. Of those plots, 44 plots were randomly selected from an initial set of 64 field plots established in 2004 during a previous field study by Chabrerie et al. (2008). Six additional plots were selected to include stands in earlier stages of forest succession, aiming to cover the entire range of structural canopy complexity. The plots covered all main forest stand types including mixed tree species stands in different age classes (supplementary material, Table S1). In each plot we recorded the diameter at breast height for all trees and shrubs higher than 2 m.

In July 2015, we sampled leaves from the most abundant tree species making up at least 80% of the basal area in one plot. This resulted in up to five sampled species per plot. For each species in each plot, we took three independent samples, if possible from different individuals. Taller trees were sampled by shooting branches using shotguns (Marlin Model 55 Goose, Marlin Firearms Co, Madison, USA and Winchester Select Sporting II 12 M, Winchester, Morgan, USA) with Buckshot 27 ammunition (27 × 6.2 mm pellets), aiming at single branches (Aerts et al., 2017). Samples from smaller trees were taken using a pole clipper. In both cases leaves from the upper part of the crown were preferably chosen. Trees growing in canopy gaps were sampled in the center of these gaps, in order to collect the most sunlit leaves from these individuals. For broadleaved trees, each sample consisted of 10 to 15 undamaged leaves, depending on leaf size. The samples of the only coniferous tree species *P. sylvestris* consisted of at least 20 needles from both the current and the last growing season. In total, we collected 328 leaf samples from nine different tree species. Leaves were put in sealed plastic bags and stored in cooling boxes. At the end of each field day samples were weighed, and then dried at 80 °C for 48 h.

Back from the field, leaves were milled prior to the analysis. N_{mass} was measured applying the Dumas method using a vario MACRO