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Optimizing the bioindication of forest soil acidity, nitrogen and mineral nutrition using plant species

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ABSTRACT

Soil moisture and nutritional characteristics are frequently assessed using plant species and community bioindication, e.g., the Ellenberg system of species indicator values. This method, based on complete inventories of plant species present in plots, is time-consuming, which could prevent its general use for forest or other natural land management. Our aim was to determine the impact of a reduction in the time spent to carry out a floristic inventory on the quality of soil characteristic assessment using plant bioindication. We compared the measurements of soil pH-H_2O (pH), organic carbon to total nitrogen ratio (C:N) and base saturation (BS) in the 0–5 cm soil layer of 470 plots with the same variables estimated from floristic inventories of increasing duration, using plant indicator values (IV) from the EcoPlant database. The performance of predictions was evaluated by the square of the linear correlation coefficient between measured and predicted values (R^2) and the root mean square error (RMSE) of predictions.

The number rather than the percentage of total plot species used for the estimations was determinant for the prediction of soil pH quality. Performance of bioindication of pH, BS and C:N reached the maximum R^2 using the first 20–25 species recorded per plot, corresponding to a 14-min-long floristic inventory in comparison to a mean of 28 min spent to carry out a complete floristic inventory. A precision of prediction of 80% of the maximal precision was obtained after 4–5 min (6–12 inventoried species) for the three studied variables. These results are independent of the nutritional capability of the soils and were similar at the national and local scales. In order to estimate soil nutritional resources by plant bioindication, it is feasible to significantly reduce the time spent on floristic inventories and, thus, their cost. This is especially useful when the goal is to map the soil quality for decision-making in forest management.

1. Introduction

Forest management of temperate forests requires a detailed ecological characterization of forest sites. Bioindication of soil moisture and soil nutrition by the "presence" and "absence" of plant species at a site has long been used for this purpose (Duchaufour, 1948; Host and Pregitzer, 1991; Ponette et al., 2014; Wilson et al., 2001). Bioindication by plant species has also been used to predict the productivity of forest stands in Europe (Bergès et al., 2006; Nieppola, 1993; Proll et al., 2011; Seynave et al., 2005, 2008) and in Northern America (Wang, 1995; Strong et al., 1991; Host and Pregitzer, 1991), or the probability of presence of individual species in European forests (Dupre and Diekmann, 1998; Coudun et al., 2006; Bertrand et al., 2012; Piedallu et al., 2016). In a global change context, plant species have been used to assess long-term changes in soil characteristics (Falkengren-Grerup, 1989; Ewald et al., 2013; Payne et al., 2013; Thimonier et al., 1994; Riofrio-Dillon et al., 2012; Verstraeten et al., 2013).

Using plants as bioindicators has several advantages in comparison to soil measurements conducted in the laboratory: (i) a lower

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cost and time; (ii) the possibility to predict several soil parameters from the same floristic survey; (iii) the fact that the floristic community represents the integrated expression of values of abiotic variables that can vary at high frequency in time and space (e.g., soil nitrogen) (Zonneveld, 1983); and (iv) in the absence of old direct soil measurements, bioindication becomes essential to evaluate long-term environmental changes when numerous old floristic inventories are available (e.g. Diekmann and Dupré, 1997; Falkengren-Grerup, 1989; Lameire et al., 2000; Thimonier et al., 1994). Among bioindication systems, the Ellenberg species indicator values (IV), based on the ecological optimum of vascular plants, has been the most frequently used (Ellenberg et al., 1992). More recently, new sets of IV have been established for France based on soil measurements and formalized methods of estimation (see Gégout (2008) for pH). They have been effectively used to predict species distribution (Pinto and Gégout, 2005; Coudun et al., 2006; Piedallu et al., 2016) and tree species productivity (Seynave et al., 2005; Charru et al., 2014). In a climatic change context, the applicability at the local scale of formalized bioindication methods that link site environmental variables to tree-species distributions and productivity models became especially relevant to forest decision-makers in order to help them in the choice of more adapted tree species or provenances. However, bioindication using plants commonly relies on complete floristic surveys, inventorying the maximum possible number of species present in the studied site. This requires a major effort in terms of time and has limited applicability in forest management.

The purpose of this study was to assess the relationship between the time investment in plant surveys and the quality of bioindication of a site's nutritional characteristics, in order to make bioindication methods more accessible to forest managers. We hypothesized that bioindication performance increased with the number of species used for bioindication and the time spent in the field for flora inventory. Since the species with higher cover in the plot are recorded first and the proportion of misidentifications increases with the time spent since the start of the inventory (Archaux et al., 2006), we also hypothesized that bioindication performance decreased with the rank order in which species were surveyed in the field. We thus addressed the following questions: (i) To what extent does the number and the proportion of species per plot used for bioindication influence the quality of the assessment? (ii) What is the effect of increasing time inventories on bioindication quality? (iii) Is this effect the same for different predicted soil variables? (iv) To what extent does the rank order of species acquisition affect the quality of prediction? (v) Does the spatial scale at which the predictions are made (national v/s local) have any influence on the quality of the results? In order to analyze this scale effect, we compared the relationship between inventory time and quality of prediction at the national and local (forest) scales. The goal was to ensure the applicability of results to local management practices.

2. Materials and methods

2.1. Sampling sites and data collection

At the large scale, 304 plots were carried out by the French National Forest Inventory (NFI) over the entire French territory via a random selection of NFI plots carried out from May to September 2013, with plots located in mountains mainly inventoried during the summer period (see Robert et al. (2010) and for a presentation of the NFI method of survey). At the local scale, three forests were surveyed by the two research laboratories involved in the study using a systematic sampling grid of 250 m × 250 m to survey 58, 52 and 56 plots in the Villey-le-Sec, Rupt-sur-Moselle and Xonrupt forests, respectively (Fig. 1). The resulting forest network, located in northeastern France, consists of a mature lowland forest (Villey-le-Sec) with broadleaved stands of *Fagus sylvatica* L., *Quercus petraea* Liebl. and *Carpinus betulus* L., located on the Lorraine Plateau, and mountain to subalpine forests (Rupt-sur-Moselle and Xonrupt) with mature broadleaved-coniferous stands composed mainly of *Fagus sylvatica*, *Abies alba*, *Picea abies* and *Acer pseudoplatanus,* located in the Vosges mountains. Geological substrates are calcareous limestone and marls covered by Tertiary and Quaternary acidic alluvia for Villey-le-Sec, whereas they are neutral to rich granitic rocks covered by poor sandstone in the Rupt-sur-Moselle forest, and poor granitic substrates adjacent to rich sedimentary substrates in the Xonrupt forest. These varied geological substrates lead to a broad variation of soil acidity and nutrient status in the sampled forests (Table 1).

In each of the 400-m^2 (local scale) or 700-m^2 (national scale) plots, vascular species in the understory layer and terricolous bryophytes were recorded. The understory layer comprised all species below 7 m in height at local scale. At national scale, it included all herbaceous and shrubby species, and tree species below 7.5 cm in diameter. The time at which species were sighted was recorded. The cover of each species in the plot was visually assessed using the Braun-Blanquet approach (Braun-Blanquet, 1932), after completion of the timed inventory. The total number of species recorded per plot was, on average, 32.9, 38.4, 26.3, 36.1 for the plots surveyed at the national level, Villey-le-Sec, Rupt-sur-Moselle and Xonrupt, respectively. The total inventory time per plot was, on average, 27.8′, 22.3′, 22.3′ and 26.9′ for the NFI dataset, Villey-le-sec, Xonrupt and Rupt-sur-Moselle, respectively.

In addition to the floristic inventory, one composite sample of the 0–5 cm soil layer (A-horizon) was obtained in each plot from five soil cores of 5 cm in depth, collected systematically within each plot. Soil analyses were conducted at the INRA-Arras laboratory and included soil pH-H_2O (1:5 in water, ISO 10390:1994), total nitrogen (N) and organic carbon (C) measured by dry combustion, which made it possible to calculate the C:N ratio, an indicator of nitrogen availability (Andrianarisoa et al., 2009). Protons were measured by titration and exchangeable Ca, Mg, K, and Al were extracted with cobaltihexamine at soil pH and measured by spectrometry. Base saturation (BS) was defined as: (Ca + Mg + K)/(Ca + Mg + K + Al + H).

2.2. Species indicator values

EcoPlant (Gégout et al., 2005), a phytoecological database for French forests that contains more than 3000 plots with complete floristic inventories and soil chemical analyses, was used to compute the indicator values (IV) of the most common forest species in France for acidity (3835 plots used), nitrogen (3547 plots) and mineral nutrition (2670 plots). Each species' probability of occurrence along each of the three environmental gradients was modeled using a logistic equation. The gradient value of higher probability of occurrence was used as the species IV (Ter Braak and Looman, 1986; Gégout et al., 2003). The efficiency of this IV system was compared to measurements (Gégout, 2006; Andrianarisoa et al., 2009) and was used to predict soil nutrients (Bergès et al., 2006), as well as to develop and spatialize models of species distribution (Pinto and Gégout, 2005; Coudun et al., 2006; Bertrand et al., 2012; Piedallu et al., 2016) and growth (Seynave et al., 2005, 2008; Charru et al., 2014).

2.3. Estimation by indicator values (IV)

Using the EcoPlant indicator values (see Section 2.2 for description), the pH-H_2O, C:N ratio and BS variables were estimated for each plot of the studied datasets by calculating the mean IVs over all species present in the plot or over selected subsets of species (see