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Mapping a 'cryptic kingdom': Performance of lidar derived environmental variables in modelling the occurrence of forest fungi

Maiju Peura [a,b,*], Ramiro Silveyra Gonzalez [a,c], Jörg Müller [a,d], Marco Heurich [a], Lee A. Vierling [e], Mikko Mönkkönen [b], Claus Bässler [a]

[a] Bavarian Forest National Park, Freyunger Str. 2, 94481 Grafenau, Germany
[b] University of Jyvaskyla, Department of Biological and Environmental Sciences, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland
[c] University of Freiburg, Chair of Remote Sensing and Landscape Information Systems, Tennenbacherstrasse 4, Freiburg D-79106, Germany
[d] Field Station Fabrikschleichach, Biozentrum University of Würzburg, Glashüttenstraße 5, 96181 Rauhenebrach, Germany
[e] University of Idaho, Department of Natural Resources and Society, 875 Perimeter Drive, Moscow, ID 83844-1139, USA

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ABSTRACT

Fungi are crucial to forest ecosystem function and provide important provisioning, regulating, supporting, and cultural ecosystem services. As major contributors to biomass decomposition, fungi are important to forest biogeochemical cycling and maintenance of vertebrate animal diversity. Many forest plant species live in a symbiotic relationship with a fungal partner that helps a host plant to acquire nutrients and water. In addition, edible fungi are recreationally as well as economically valuable. However, most fungi live in very cryptic locations (e.g. in soils and interior plant tissues) and are only visible when their ephemeral fruiting bodies are produced, making fungal occurrence difficult to detect and predict. While remote sensing has been used increasingly to identify and scale many forest characteristics (e.g. structure, function, and species diversity) related to myriad ecosystem services, the use of remotely sensed data in modelling the occurrence of fungi is largely unknown. We compared the performance of airborne lidar derived structural variables, including those associated with single tree detection, with variables derived from field inventories to model overall fungal species abundance as well as specific fungal guilds (i.e. a range of edibility from highly edible to very poisonous, and the number of fruiting bodies of saprotrophic and mutualistic ectomycorrhizal species) based on fruiting body sampling in a low range mountain forest (Bavarian Forest National Park). Lidar derived variables performed better than variables derived from field measurements to explain the abundance of all guilds combined, as well as the guilds of soil saprotrophic and ectomycorrhizal fungi, and the yield of highly edible fungi. Variables derived from field measurements performed better than lidar derived variables in explaining the yield of very poisonous fungi. Upscaling of yield and abundance of fruiting bodies to the whole study area opens the avenue for managers to identify areas of high interest by mushroom pickers, as opposed to those of potential danger to people and those that co-occur with sensitive species and habitats of conservation relevance. Moreover, the strong, guild-specific relationships found between the occurrence of fungi and lidar derived variables opens new avenues for scaling to large areas the occurrence of members of this cryptic kingdom.

1. Introduction

Ecosystem services are benefits that people obtain from nature, such as climate regulation, timber, food, and recreational values (MEA, 2005). Ecosystem services can be divided into four categories: provisioning, regulating, supporting and cultural services. Fungi in forests provide services from all of these categories (Pringle et al., 2011; Heilmann-Clausen et al., 2015) while also maintaining or augmenting the biodiversity of other taxa that underpin all ecosystem services (Müller and Bütler, 2010; Cockle et al., 2012).

Some fungal species are consumed as food or medicine, and picking edible fungi is a popular recreational activity important in many cultures (Boa, 2004). In Central Europe, information on the regional economic value of mushroom picking is still largely missing despite the fact that annual average yields of all fungal species can reach as high as 29 kg/ha (fresh weight) with edible species comprising over 50% of the yield (Martínez de Aragón et al., 2007). The economic value of edible fungi can be even higher than the value from timber revenues in some

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* Corresponding author at: Department of Biological and Environmental Sciences, University of Jyvaskyla, P.O. Box 35, FI-40014 University of Jyvaskyla, Finland.
E-mail addresses: maiju.h.peura@jyu.fi (M. Peura), rasilgon@gmail.com (R. Silveyra Gonzalez), joerg.mueller@npv-bw.bayern.de (J. Müller), marco.heurich@npv-bw.bayern.de (M. Heurich), leev@uidaho.edu (L.A. Vierling), mikko.monkkonen@jyu.fi (M. Mönkkönen), claus.baessler@npv-bw.bayern.de (C. Bässler).

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forests, thus ranking fungi among the most economically important forest services (Palahí et al., 2009).

The roles fungi play in ecosystem functioning are diverse yet fundamental. Soil saprotrophic fungi are major decomposers of organic litter and important in regulating biogeochemical cycles (Carlile et al., 2001). Most plant species (90%) have a mutualistic relationship with mycorrhizal fungi; these fungi assist in water and nutrient uptake of host species, which in turn provide photosynthate to the fungi (van der Heijden and Horton, 2009; Courty et al., 2010). In addition, mutualistic fungi are important for soil chemical weathering (Hoffland et al., 2004) and can provide resistance against e.g. pathogen- (Sikes et al., 2009) or drought- (Augé, 2001) induced stress. Finally, some fungi are parasites, and are thus harmful to their host plants but benefit organisms dependent on weakened plants or dead organic matter (Carlile et al., 2001).

Many of the ecosystem processes facilitated by fungi occur through mycelia that thread their way, unseen, through soil, litter, and internal plant organs. In contrast, fungal fruiting bodies (i.e. sexual production organs) are immediately visible and attract much more attention than mycelia, with their ephemeral beauty (Boa, 2004). Moreover, fruiting bodies provide a major link between carbon fixed by primary producers (due to ectomycorrhizal fungi) or from decomposition of soil organic matter (due to soil saprotrophic fungi) and other trophic levels in the ecosystem (Carlile et al., 2001). For example, fungal fruiting bodies comprise up to 90% of the dietary intake for several rodent species (Maser et al., 1978).

In larger field studies, occurrence of fungal species is typically inferred from the sampling of fruiting bodies (Halme et al., 2012). However, detecting fruiting species can be challenging, first because fruiting bodies can be highly ephemeral (Straatsma et al., 2001), and second because the appearance of fruiting bodies is dependent on many critical environmental factors such as macro- and microclimate (e.g., precipitation) and soil conditions (e.g., moisture content) (Kües and Liu, 2000; Straatsma et al., 2001; Bonet et al., 2008; Moore et al., 2008; Bonet et al., 2010; Pinna et al., 2010; Martínez-Peña et al., 2012) causing much annual and random variation in occurrence data. Not surprisingly, collecting and monitoring these kinds of data is expensive and time consuming. In recent years, remote sensing techniques such as lidar have provided new methods to acquire information from ecosystems with lower cost and more comprehensive coverage relative to field surveys (Lefsky et al., 2002).

Lidar data have been used in many facets of ecology and forestry. For example, it has been shown that lidar derived variables can be used to model forest habitat types and also have high utility in biodiversity research (Vierling et al., 2008; Davies and Asner, 2014). However, lidar derived variables are generated as a function of instrument technical characteristics convolved with ecosystem physical structural characteristics. Therefore, while these variables may not have uniformly direct ecological interpretations, phenomenological models based on such data have enormous heuristic value (Müller and Brandl, 2009). Despite the central roles that fungi play in forest ecosystems, no studies have explored how lidar derived variables can be applied to model the occurrence of fungal species, their yields or abundances.

Most previous work in developing predictive models for fungal occurrence and yield have focused on edible fungi, such as *Boletus edulis* (Martínez-Peña et al., 2012). Less attention has been given to model larger fungal groups of broad importance to ecosystem functioning (Straatsma et al., 2001; Straatsma and Krisai-Greilhuber, 2003). In addition, in only a few cases have the spatial distribution of fruiting body production been explored. A recent study by Kucuker and Baskent (2015) was one of the first to tackle this challenge. In particular, when considering multiple use of forests and non-timber forest products, the spatial distribution of forest products must be evaluated at broad spatial scales (*FAO*, 2002).

Airborne lidar data offer the prospect of modelling and evaluating the large-scale spatial variance of fungal occurrence. Airborne lidar enables ecosystem structural data to be collected at broad spatial extents (yet with fine grain size) to derive environmental variation in a continuous manner at relatively low cost. When combined with field-based species occurrence records, which often cover a much more limited spatial extent but convey direct ecological information, lidar derived data can provide an efficient method for species distribution modelling (Bradley and Fleishman, 2008). To test the potential for modelling the probability of the occurrence of fungal species using lidar derived environmental variables, we collected location data on fungal fruiting bodies over three years, categorizing each species relative to the different ecosystem services provided. We compared the performance of models based on airborne lidar derived structural variables against models based on environmental data collected from field inventories in modelling overall fruiting body abundance, the yield of various guilds of fungal fruiting bodies (ranging from “highly edible” to “very poisonous”), and the abundance of soil saprotrophic and ectomycorrhizal fungal fruiting bodies.

2. Methods

2.1. Study area

We sampled fungi along an elevational gradient within the Bavarian Forest National Park (48°54′N, 13°29′E) that covers approximately 24,000 ha in south-eastern Germany (Fig. 1). The Bavarian Forest lies in the south-western part of the Bohemian Massif, which is formed of granite and gneiss (Bässler et al., 2008). Acidic sand and loamy soils prevail. Elevations range between 650 and 1350 m a.s.l. At 650 to 1150 m a.s.l., forests are dominated by Norway Spruce (*Picea abies*) admixed with European Beech (*Fagus sylvatica*) and Silver Fir (*Abies alba*). Above 1150 m, forests are dominated by Norway Spruce and Mountain Ash (*Sorbus aucuparia*). Depending on elevation, the mean annual temperature (1972–2001) varies from 3.5 to 7.0 °C, and the total annual precipitation varies from 1300 to 1900 mm (Bässler et al., 2008).

2.2. Fungal data

From 2009 to 2011, we sampled soil-related (terricolous) macrofungi from 48 circular plots covering the elevational gradient (Fig. 1). Selected plots were a subset of a larger biodiversity survey project within the national park (comprising approximately 300 plots in total, see Bässler et al., 2008 for more details). We used a pre-stratified random sampling scheme for subsetting plots, to both balance the number of plots sampled across the elevational gradient available in the park (minimum 5 plots per 100 m elevational belt) while also balancing the sampled tree species composition (mainly spruce with admixed beech and fir, see also Section 2.1 and Bässler et al., 2016). Each plot had an area of 200 m^2 and was surveyed at weekly intervals to cover all phases of fruiting between June and November, i.e. during the main period of fruiting body production in the study region. We counted fruiting bodies at the species level and removed all fruiting bodies from the plots after each survey, which has been shown to have no effect on fruiting body productivity (Egli et al., 2006). We categorized fungi based on their edibility, using 5 different edibility classes from the literature (e.g. Breitenbach and Kränzlin, 1984–2000): (i) highly edible, (ii) edible, (iii) inedible (without edible value, not poisonous), (iv) poisonous and (v) very poisonous species. Of 340 species, 44 species were not assigned because of lack of information in the literature. In this study, we focused on highly edible fungi as the most informative category in terms of provisioning ecosystem services. We however additionally considered the category “very poisonous” as the competing guild of the highly edible guild and to evaluate whether these guilds respond to environmental variation in similar ways in our study area. In addition, we categorized fungi based on the main fungal functional groups: soil saprotrophic (SS) and ectomycorrhizal fungi (EM).