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Yield models for ectomycorrhizal mushrooms in *Pinus sylvestris* forests with special focus on *Boletus edulis* and *Lactarius* group *deliciosus*

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ABSTRACT

Mushrooms in general, and *Boletus edulis* and *Lactarius deliciosus* in particular, are important non-wood forest products worldwide. Despite their economic and ecological importance, models that describe the influence of different factors on mushroom yield are few. These models would support multi-objective forest management and planning that takes into account mushroom production. This study aims at providing models for predicting the total yield of wild ectomycorrhizal mushrooms and, especially, of *L.* group *deliciosus* and *B. edulis*. Mushroom data were collected in 18 permanent plots in pure even-aged *Pinus sylvestris* stands during fifteen consecutive years. Variables describing weather conditions, stand structure and local site characteristics were used as predictors in the modeling process. Rainfall and temperature were significant predictors in all the fitted models. In addition, the total yield of ectomycorrhizal fungi was significantly affected by dominant height and stand age. The production of *L.* group *deliciosus* was influenced by dominant height and stand basal area. The equation fitted for *B. edulis*, to our knowledge, is the first model for this species. It shows that stand basal area is a strong factor influencing the yield. The equations presented in this study enable predictions of mushroom yield under different forest management schedules and climatic scenarios.

1. Introduction

Wild edible fungi are valuable non-wood forest products throughout the world and have a clear potential for commercial use (Boa, 2004). Some fungi such as boletes (*Boletus edulis*) or saffron milk caps (*Lactarius* group *deliciosus*) are specially valued in many countries, and their trade has become an important complementary economic activity in many regions (Voces et al., 2011; Cai et al., 2011; Martínez de Aragón et al., 2011). The socioeconomic relevance of non-wood resources coupled with the low profitability of timber production in many areas is driving a change in forest management paradigms and practices, switching from traditional forest planning focused on timber production to more complex multifunctional silvicultural schemes. One of these new schemes is the so-called mycosilviculture, which attempts to integrate timber and mushroom production (Martínez-Peña et al., 2011).

Sound forest planning for the joint production of wood and mushrooms requires predictions of both mushroom and wood production (Palahí et al., 2009). For that, detailed information on the main variables affecting mushroom yield is needed. However, predicting mushroom yields is not an easy task. In addition to the difficulty associated with mushroom inventories (Calama et al., 2010), a wide range of factors have been recognized as influencing fruit-body emergence. These factors can be classified into three main groups: (a) local site characteristics (e.g. altitude, slope, aspect); (b) stand structure (e.g. tree species, stand density, stand age); and (c) weather variables (e.g. precipitation, temperature). Since most of the collected mushroom species establish mycorrhizal symbioses with trees, it may be expected that stand structure, which can be modified through forest management, as well as soil properties, affect mushroom production. Moreover, it is well known that weather, together with other environmental factors, also affect mushroom dynamics. In addition, the local site characteristics have been repeatedly mentioned in the literature to have an impact on mushroom yield (Egli, 2011). The large amount of potential variables related to mushroom productivity and their interdependence makes it difficult to give clear recommendations for managing mushroom yields. Systematic quantitative analyses on the effect of different variables are required.

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Modeling techniques are a valuable tool that allows to identify factors most relevant for predicting mushroom yield. Forest management oriented models based on long historical data series of annual measurements in many locations can be used to model mushroom yield as a function of different types of predictors. These kinds of studies are rather recent, and only a few models for mushroom yield have been published so far. Bonet et al. (2008) developed a model for predicting the total, edible and marketable mushroom yield and species richness as a function of site and forest stand variables based on a three-year mushroom inventory in 24 Scots pine plots in north-eastern Spain. They showed that basal area was the most important growing stock characteristic for mushroom production with maximum mushroom yields at stand basal areas of approximately 20 m^2 ha^{-1}. Additional studies based on 21 plots established in *Pinus sylvestris*, *Pinus nigra* and *Pinus halepensis* forests in the same region also found that the maximum mushroom productivity corresponded to stands where the basal area ranged from 15 to 20 m^2 ha^{-1}. Site variables such as aspect, slope and elevation also had an important influence on annual mushroom yield (Bonet et al., 2010).

Between-region differences in site characteristics, weather and forest structure prevent a straightforward application of the above-mentioned results for north-eastern Spain in other regions. The ecological conditions in north-central Spain differ from those in the other parts of Spain. North-central Spain, where mushroom collection is an important activity, has a more continental climate, larger average tree size, higher stand volumes, different soil types and, partly, different mushroom species.

The aim of this study was to develop empirical models for predicting the total annual yield (fresh mass of sporocarps) of wild ectomycorrhizal mushrooms with a special focus on the most valuable species (*L.* group *deliciosus* and *B. edulis*) in Scots pine forests in north-central Spain.

2. Material and methods

2.1. Permanent plots for mushroom inventory

Eighteen permanent plots were established in pure even-aged stands of *P. sylvestris* L. forests, located within the "Pinar Grande" area, in the Iberian System Mountains of the province of Soria. The plots were randomly established in different locations so as to capture high variation in stand age (from 7 to 122-year-old *P. sylvestris* stands). Site variables (altitude, slope and orientation) were measured in every plot. Detailed soil analyses considering physical and chemical properties were carried out for every plot. Soils were acid (pH between 4 and 5) with a sandy-loam to sandy texture. The understory was mainly composed of *Erica vagans* and *Nardus stricta*. The mean monthly temperature and total monthly precipitation were also recorded during the inventory period.

Each of the 18 mushroom plots, 175 m^2 in size, was subdivided into 6 sub-plots of 5 m × 5 m for mushroom measurement, which resulted in a total sampled area of 150 m^2 per plot. All the plots were fenced in order to prevent uncontrolled mushroom harvesting. The inventory was carried out annually since 1995 until 2009. In every plot, all the sporocarps of ectomycorrhizal species having a diameter larger than 1 cm were collected at 1-week intervals during weeks 35–50.

The collected mushrooms were identified and classified in the laboratory according to their edibility and marketability. Afterwards, fresh weight was calculated for all the sampled mushrooms. This study focused on the total yield of ectomycorrhizal mushrooms (72 species, see Martínez-Peña et al. (2012)), *L.* group *deliciosus* and *B. edulis*. *Lactarius* yield refers to *L.* group *deliciosus*, which comprises three species (*L. deliciosus*, *L. quieticolor* and *L. sanguifluus*) all of which are commonly sold together in the markets. Additional information concerning the study area and the permanent plots can be found in Martínez-Peña (2009).

2.2. Temporary plots for forest inventory

Eighteen temporary forest inventory plots, each centered on one permanent mushroom inventory plot, were also measured to characterize the forest stands. The forest stand plots were measured only once; plots 4–18 in the beginning of the mushroom inventories, and plots 1–3, which were young seedling stands in 1995, at the end of the mushroom inventories (in 2010). In order to reduce the sampling error of the stand variables, the forest inventory plots were larger, 800 m^2 (20 m × 40 m). In each plot, every tree was measured for diameter at 1.3 m. In addition, tree height was measured for a minimum of 10 trees. Table 1 summarizes the forest inventory data. Plot number 4 was thinned in 2006 according to the established management plan of the forest. The other plots were not treated during the period of mushroom measurements (1995–2009).

The site index of every plot was calculated on the basis of stand age and dominant height (mean height of 100 largest trees per hectare) using the model of Palahí et al. (2003). Site index is equal to dominant height at 100 yr. The stand characteristics of plots 4–18 were updated for each mushroom inventory year by simulating the stand development using the above-mentioned dominant height model and the individual tree models of Pukkala (2008) for diameter increment, tree height, and tree survival. The stand characteristics of plots 1–3 were back-tracked to years 1995–2009 using the dominant height model to obtain the stand dominant height for different years. The measured stand characteristics of all plots were used to fit a model that gives the quadratic mean diameter as a function of dominant height, stand age, and number of trees per hectare. The stand basal area for different years was then calculated from the quadratic mean diameter and the number of trees per hectare. It was assumed that the number of trees per hectare remained unchanged during 1995–2010, which is a reasonable assumption taking into account the still low basal area of plots 1–3 in 2010 (Table 1).

2.3. Model fitting

The dataset contained variables describing mushroom yield, monthly and annual weather conditions (temperature and rainfall), forest stand (age, basal area, dominant height, etc.) in different years and site characteristics (altitude, aspect, slope), as well as physical and chemical soil properties of each stand. Different transformations of these variables were tested when modeling the annual yield of ectomycorrhizal mushrooms, *L.* group *deliciosus* and *B. edulis*. The models were fitted using nonlinear regression analysis and fixed-effects modeling approach. A correlation analysis was used to find out whether mushroom yield was related to soil characteristics.

Based on the fitted equations, predictions were calculated using alternative weather scenarios typical to the region in order to show the model behavior and to facilitate a graphical comparison among the predictions of the different models. Based on the recorded data of a central meteorological station, dry and wet autumn conditions were calculated as the mean inter-annual autumn precipitation ± 30% (115 mm and 215 mm to simulate dry and wet autumns, respectively).

The following criteria were considered in model evaluation: (a) agreement with current biological knowledge, (b) logical behavior of the model set in extrapolations, (c) simplicity and robustness, (d) statistical significance (p-value < 0.05), (e) non-biasness, and (f) homocedasticity and normal distribution of residuals.