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Research paper

Effect of climatic and soil moisture conditions on mushroom productivity and related ecosystem services in Mediterranean pine stands facing climate change

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ABSTRACT

Wild mushrooms contribute to a variety of ecosystem services. The expected warmer and drier conditions for the Mediterranean region as a consequence of climate change, are raising concerns about future mushroom productivity due to potential reduction of soil water availability for fungi. The aim of this study was to increase our understanding of the interaction between climate and soil moisture in relation to their impact on mushroom productivity in Mediterranean forests. Mushroom yield data were obtained from 28 permanent mushroom inventory plots intensively monitored in Maritime pine (*Pinus pinaster* Ait.) stands of northeastern Iberian Peninsula. Annual productivity of total, edible and marketed mushrooms was obtained from measurements conducted every week during the autumn fruiting season for years 2008–2015. Historical weather conditions were obtained through data interpolation from meteorological stations. Soil moisture data were obtained from continuous plot-level measurements. A process-based soil water balance model was used to predict soil moisture under two climate change scenarios, using the predictions of two different regional climate models. Mixed-effects models using either precipitation or soil moisture as predictors, in combination with other weather variables, were fitted to annual mushroom occurrence and yield data. Mushroom yield was primarily dependent on weather and soil moisture conditions during the same month, with the exception of precipitation, whose effects exhibited a one-month delay. High temperatures limited mushroom yield at the beginning of the fruiting season, but tended to enhance it towards the end. The analysis revealed no apparent negative effect of climate change on long-term mushroom productivity, but rather the opposite (i.e., predicted median productivity of marketed mushrooms for 2016–2100 was 23–93% higher compared to the current yield), mainly due to an elongation of the fruiting season arising from the combined effect of increased precipitation at the beginning of the season and warmer temperatures at the end.

1. Introduction

Wild mushrooms contribute to a variety of provisioning, cultural and supporting ecosystem services in the Mediterranean Basin and worldwide. On one hand, wild edible mushrooms represent an important food source and may be regarded as a key non-wood forest product (NWFP), especially in the Mediterranean basin where NWFPs are of particular socioeconomic importance (Boa, 2004; Croitoru, 2007). Indeed, in Mediterranean forests, the economic value of mushroom-based ecosystem services, can be much higher than the economic profit traditionally obtained from timber-oriented forestry (Palahí et al., 2009; Martínez de Aragón et al.,2011). Forest fungi also play a critical role in forest ecosystem functioning through their contribution to nutrient and carbon cycles (Mohan et al., 2014; Stokland et al., 2012).

Mushroom yield varies dramatically between years due to variation in the environmental factors that determine the duration of the fruiting season and the frequency of mushroom emergence (Alday et al., 2017; Boddy et al., 2014). Climate arises as the foremost important factor, with precipitation and temperature (and their interaction) having a major impact on mushroom phenology, yield and diversity (Bonet et al.,

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2012; Büntgen et al., 2015; Kauserud et al., 2008, 2012; Ogaya and Peñuelas, 2005; Taye et al., 2016). However, the effect of climate on mushroom productivity is further modulated by the combined effect of site and soil characteristics and forest stand structure (Martínez-Peña et al., 2012; de-Miguel et al., 2014; Tomao et al., 2017). The interaction between these factors determines soil moisture, which may be regarded as an integrative driver of mushroom fruiting accounting for different processes resulting in a given mushroom productivity level.

Since fungal fruiting is mainly enhanced by humid and warm conditions, recent trends of temperature increase driven by climate change have been found to enhance yield and earlier mushroom emergence in humid temperate regions, while decreasing and delayed productivity has been observed under drier Mediterranean conditions (Boddy et al., 2014). Future hotter and drier conditions predicted by climate change models for the Mediterranean region (Allen et al., 2014), and the subsequent expected reduction in soil water availability, are likely to enhance drought stress and aridity in forest ecosystems, eventually affecting negatively mushroom productivity (Ágreda et al., 2015; Büntgen et al.,2015). Yet, given the uncertainty about precipitation patterns in climate change scenarios, the reverse could occur if early-autumn drought were not enhanced and the duration of the fruiting season were expanded due to increasing temperature in late autumn.

Climate-sensitive mushroom yield models are in short supply largely due to the lack of long-term monitoring of mushroom yield, especially in drought-prone environments such as the Mediterranean forests (Mohan et al., 2014), although some examples can be found in the literature (e.g., Bonet et al., 2012; Martínez-Peña et al., 2012; Hernández-Rodríguez et al., 2015). Moreover, mushroom yield models considering weather variables only, may fail to capture the actual water availability in the soil as they ignore soil water fluxes, especially those driven by evapotranspiration demands (Ágreda et al., 2015). Nevertheless, long series of soil moisture records in mushroom monitoring plots within forest ecosystems are scarce, since most studies on mushroom productivity are usually lacking such intensive measurements (Boddy et al., 2014). This may constitute a major drawback to our understanding of productivity patterns since modelers are then forced to use precipitation as a surrogate for a more proximal driver. Therefore, in view of the ecological and socioeconomic importance of mushrooms in the Mediterranean basin, a better understanding of the drivers of mushroom productivity is required in order to forecast the provision of the ecosystem services provided by mushrooms, especially within the context of climate change.

In this study, we aim at shading light on the climatic and soil moisture conditions driving mushroom productivity under typical Mediterranean conditions. Moreover, we intend to better understand the role of precipitation *vs* soil moisture in the development of predictive mushroom yield models, in particular: (a) which of the two factors results in models with higher predictive ability; and (b) how mushroom productivity predictions of models using either precipitation or soil moisture differ when projected towards future climates. We address these questions using data from a network of permanent mushroom inventory plots intensively monitored in northeastern Iberian Peninsula, and combining a process-based soil water balance model with mushroom yield statistical models. Analyses were done for three mushroom categories accounting for several ecosystem services; total mushrooms to deduce on the overall productivity (i.e., regulating/supporting services), and edible and marketed mushrooms to deduce on food supply and socioeconomic activity (i.e., provisioning and cultural ecosystem services). All models were projected to future climate conditions using downscaled, bias-corrected climate model predictions.

2. Materials and methods

2.1. Study area and mushroom inventory plots

The study area is located in the Natural Park of Poblet in Catalonia, North-East Spain (41° 21′ 6.4728 latitude and 1° 2′ 25.7496 longitude). The area is characterized by a coastal Mediterranean climate, with mean annual temperature of 11.8 °C, annual rainfall of 665 mm and a pronounced summer drought usually extending from mid-June to mid-September. A set of 28 permanent plots was established between 2008 and 2009 in 50-year-old, even-aged Maritime pine (*Pinus pinaster* Ait.) stands, representing a range of different conditions in stand structure, i.e., stand density from 446 to 2657 trees ha^{-1} and basal area from 20.9 to 81.7 $m^2 ha^{-1}$, as well as in elevation (594–1013 ma.s.l), slope (2–13%) and aspect. Mushroom inventory plots were 100 m^2 (10 m × 10 m) in size. Soil is siliceous and has franc-sandy texture. All trees were measured for diameter at 1.3 m breast height (DBH) in December 2010 and re-measured in August 2013.

2.2. Mushroom productivity sampling

In each plot, all mushrooms were collected every week between 2008 and 2015 (15 plots) and between 2009 and 2015 (13 plots) during the autumn fruiting season, i.e., from the beginning of September to the end of December, with the majority of the yield being concentrated in October and November. Mushrooms were species-identified, counted and weighted. Total annual yield was classified according to mushroom edibility and marketability categories. Edible mushrooms represented 87% of total mushroom yield, and marketed mushrooms represented, respectively, 43% and 50% of total and edible mushroom production. Marketed mushrooms consisted of seven species, 80% percent of the fresh biomass being represented by *Lactarius* group *deliciosus.* and 13% by *Macrolepiota procera*.

2.3. Meteorological data and climate change scenarios

Plot-specific daily weather variables were interpolated from Spanish meteorological stations [1990–2011], and from both Catalan and Spanish stations [1990–2015] following the DAYMET methodology (Thornton and Running, 1999; Thornton et al., 2000), as implemented in the R package ‘meteoland’ (De Cáceres et al., 2017). Daily precipitation, temperature (min, max and average) and relative humidity (min, max and average) were estimated for each plot by averaging the values of several meteorological stations with weighting factors that depended on the geographic proximity to the target plot. The estimate from each meteorological station was further corrected for differences in elevation between the station and the target plot. The high dependence of precipitation on local topography and the distance from weather stations might result in false-predictions of rain events that have not reached the plot, or miss-predictions of rain events which occurred locally at the plot but did not reach the weather stations. This may have an influence on both the estimated probability of occurrence for rain and the intensity of rain events.

Climatic projection data for the period 2016–2100 were obtained from the EU-CORDEX project, available at Earth System Grid Federation (ESGF; http://esgf.llnl.gov/). Daily precipitation, min/max temperature, relative humidity, radiation and wind speed data were assembled according to predictions of the CNRM-CERFACS-CNRM-CM5 global model under representative concentration pathways (RCPs) 4.5 and 8.5, later regionalized to Europe (at 11-km resolution) using CCLM4-8-17 and RCA4 regional dynamic models. As a result, we obtained four alternative climate change scenarios based on the combinations between the two RCPs and the two regional climate models. These predictions were downscaled by correcting for local topography using the 1990–2015 period as reference. Future projected values were corrected for biases calculated monthly for the reference period. In the case of precipitation, correction involved quantile mapping (Gudmundsson et al., 2012). All corrections were conducted using the package ‘meteoland’ (De Cáceres et al., 2017).