

Impact of forest management intensity on landscape-level mushroom productivity: A regional model-based scenario analysis



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ABSTRACT

The aim of this study was to predict the effect of forest management intensity on mushroom productivity at the landscape level by means of a model-based scenario analysis. The study area was Catalonia region, north-eastern Iberian Peninsula. Mushroom yield models were developed for the most common pine-dominated forest ecosystems. The models accounted for the effect of site and stand structure on mushroom occurrence and yield. The mushroom yield models and individual-tree growth models were used in continuous cover forestry simulation and optimization to assess the impact of alternative regional forest management intensity scenarios on landscape-level mushroom productivity. The baseline scenario was defined as the estimated current forest harvesting intensity in Catalonia (i.e., 25% of annual forest growth). The time frame was 30 yr. The current average productivity of valuable mushrooms is 14 kg ha⁻¹ yr⁻¹ (4600 tonnes yr⁻¹). Under the current forest management intensity, a loss of 220 tonnes yr⁻¹ (5%) in mushroom production at the regional level can be expected. In the absence of forest management, the loss in productivity can attain almost 500 tonnes yr⁻¹ (11%). With forest harvesting intensity similar to the average in Europe, an increase of 100 tonnes yr⁻¹ (2%) in mushroom production could be expected. If forest harvesting was equal to 100% of annual forest growth, an increase of 262 tonnes yr⁻¹ (6%) could be expected. Mushroom productivity increases with increasing forest management intensity. Low forest management intensities may result in a progressive reduction in mushroom yield. Intermediate management intensities would maintain the current mushroom productivity. Sustained yield harvesting policy would contribute to increasing mushroom productivity in continuous cover forestry.

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1. Introduction

Wild mushrooms are important non-wood forest products all over the world. As food or condiment, they are often considered a delicacy and their nutritional value is comparable to many vegetables. Owing to their medicinal properties, they are also important for human health and they are often used as traditional medicine (Boa, 2004). In this regard, Catalonia (north-eastern Iberian Peninsula) represents a paradigmatic case of a long tradition of mushroom picking and trade. Hundreds of tonnes of edible forest mushrooms annually sold in local markets contribute to a significant economic activity of several million euros. The Central Market of Barcelona, the capital city of Catalonia, is the most important market of wild edible mushrooms in Spain (Voces et al., 2012). In

the current context of low profitability of timber-oriented forestry arising from the high harvesting costs compared to the income from wood products, the economic benefit of mushroom harvesting can be clearly higher than the economic profit obtained from timber production (Alexander et al., 2002; Palahí et al., 2009). Furthermore, the deep-rooted tradition of mushroom picking for self-consumption gives additional value to wild mushrooms as a recreational and environmental service (Martínez de Aragón et al., 2011; Schulp et al., 2014).

Forest stand characteristics, coupled with the strong influence of climatic and site variables (e.g., precipitation, temperature and aspect), determine the productivity of wild mushrooms (Bonet et al., 2008, 2010). Stand basal area, stand age and dominant height have been found to have a significant effect on mushroom production (Bonet et al., 2012; Martínez-Peña et al., 2012). Although weather and site conditions cannot be controlled by forest managers, mushroom yield can be affected by means of forest

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management (Bonet et al., 2012; Egli et al., 2010; Pilz et al., 1999). It can be therefore expected that management intensity has an impact on mushroom productivity.

Forest management intensity can be described by the ratio between annual felling and annual volume increment (so-called felling rate). Sustainable forest management partly relies on the concept of maximum sustained yield, which implies that wood harvesting should be approximately equal to forest growth (Luckert and Williamson, 2005; Elbakidze et al., 2013; Helms, 1998). While the average felling rate in Europe is around 65% (Forest Europe et al., 2011), the estimated current wood harvesting in Catalonia represents only 20–30% of annual forest growth (Levers et al., 2014). A gradual decline of the forest sector has occurred in Catalonia during the last decades, which has resulted in a progressive abandonment and reduction of forest management practices and harvesting operations. If such a trend persists, the forests of the region might be increasingly unmanaged in the coming decades. On the other hand, utilization of forest biomass for bioenergy and new applications of forest products in emerging sectors arising from innovations in the forest industry may boost forest management in the future. Whatever the evolution of forest management intensity, it is likely to affect mushroom productivity, the economic value of forests (Pilz et al., 1999) and the socio-economic activity based on mushroom picking.

The assessment of the impact of forest management on landscape-level mushroom productivity can be tackled from a modelling and simulation perspective. In combination with forest growth models for the simulation of stand dynamics, mushroom yield equations can be used to predict mushroom productivity under different stand structures and silvicultural regimes (Palahí et al., 2009). Mushroom yield models based on permanent sample plots have been previously fitted for Catalonia by Bonet et al. (2008, 2010). Since this sampling effort has continued over time and has been significantly expanded to additional plots and forest ecosystems (i.e., including mixed and pure stands), models based on new and improved data can bring deeper insight into the influence of forest stand structure and management on mushroom yield (Pilz and Molina, 2002). Although previous research has analyzed the effect of forest management on mushroom productivity at the stand level (Alexander et al., 2002; Palahí et al., 2009), so far no studies have dealt with the impact of forest management intensity at the landscape or regional level, which is crucial in large-scale forest policy making.

The aim of this study was to analyze alternative regional forest management intensity scenarios in relation to their impact on the landscape-level mushroom productivity based on new and improved mushroom yield models.

2. Material and methods

2.1. Modelling mushroom yield

Yield models were developed for the fresh mass of total, edible and marketed mushrooms based on data obtained from the weekly monitoring of permanent sample plots in stands representing most pine forest ecosystems found in Catalonia. The sampling started with the measurement of 24 plots between 1995 and 1997. Since then, new plots have gradually been established, the number of additional plots measured in 2012 being 83. In total, measurements have been done in 107 plots. The plots represent pure and mixed pine stands. The number of sample plots in pure *P. sylvestris*, *P. nigra*, *P. halepensis* and *P. pinaster* stands was 43, 14, 8 and 30, respectively. The number of plots in mixed *P. sylvestris*-*P. nigra* and *P. nigra*-*P. halepensis* stands was 7 and 5, respectively (Table 1).

The trees of the sample plots have been measured once or twice for diameter at breast height and height. To be able to relate annual mushroom yield to the stand structure in a given year, the stand characteristics were updated for each year using individual-tree growth models for pine stands in Catalonia (e.g., Palahí, 2002; Trasobares, 2003; Trasobares et al., 2004). Alternatively, linear interpolation was used in some plots where trees had been inventoried at two different measurement occasions with a few years difference.

Mixed-effects models, which can account for the spatial and temporal correlation among observations and can deal with unbalanced data (Pinheiro and Bates, 2000), were used to predict annual mushroom yield. This methodological choice is justified since the number of sample plots varied between forest ecosystem types and, furthermore, because mushroom yield data from permanent sample plots established in different pine ecosystems are expected to be spatially and temporally correlated. This is because stands belonging to a given forest ecosystem and sharing similar ecological conditions are more likely to present similar yields than stands from different forest types. Similarly, a given stand is more likely to present similar mushroom productions over time.

An additional feature of mushroom yield data is the high occurrence of “zero” production in many sample plots over time arising from small plot sizes and the stochasticity of sporocarp emergence. Thus, the stochastic nature of mushroom yield was taken into account by using a two-stage modelling approach that accounts for two separate states (Hamilton and Brickell, 1983; Vanclay, 1992). The first stage aimed at predicting the probability of occurrence of mushroom production based on binomially distributed data (i.e., absence or presence) by means of mixed-effects logistic regression (Eq. (1)) using a logit link function (Eq. (2)). The second stage involved linear mixed-effects modelling aiming at predicting mushroom yield in log scale conditional on the occurrence of sporocarp emergence in the first stage (Eq. (3)). Snowdon’s bias correction factor (Snowdon, 1991) was used to correct the predictions for the back-transformation bias to the original scale. Final mushroom yield estimations were computed as the product of the probability of occurrence and the conditional yield estimate (Eq. (4)):

$$p(y = 1|x) = \pi(x) = \frac{1}{1 + e^{-[(\beta_0 + b_0) + (\beta + b)x_1]}} \quad (1)$$

$$g(x) = \log \left[\frac{\pi(x)}{1 - \pi(x)} \right] = (\beta_0 + b_0) + (\beta + b)x_1 \quad (2)$$

$$\ln(\text{yield}_c) = (\beta_{n+1} + b_{n+1}) + (\beta_k + b_k)x_2 + \varepsilon \quad (3)$$

$$\text{yield} = \pi(x) \times CF \times e^{\ln(\text{yield}_c)} \quad (4)$$

where $p(y = 1|x)$ is probability of total, edible or marketed mushroom occurrence of stand i in pine ecosystem j and year k , yield_c is total, edible or marketed mushroom yield conditional on mushroom occurrence, yield is total, edible or marketed mushroom yield ($\text{kg ha}^{-1} \text{yr}^{-1}$), β denotes fixed-effects model parameters, b denotes random effects, x_1 and x_2 are vectors of independent variables, CF is bias correction factor and ε is residual following a normal distribution with mean equal to zero and variance equal to σ^2 .

Model evaluation and selection was based on fitting statistics, i.e., statistical significance of model parameters (t -value > 2 , p -value < 0.05), residual standard error and likelihood-ratio tests, as well as on the agreement with current scientific knowledge on forest and mushroom ecology.

Table 1Summary of the data used to model mushroom yield in pine forest ecosystems (Ps: *P. sylvestris*, Pn: *P. nigra*, Ph: *P. halepensis*, Pp: *P. pinaster*).

Forest type	Temporal data series	Range	Stand basal area, m ² ha ⁻¹	Altitude, m	Orientation, °	Slope, %	Mushroom yield, kg ha ⁻¹ yr ⁻¹		
							Marketed	Edible	Total
Ps	13 yr	Min.	1.0	684.0	4.0	4.0	0.0	0.0	0.0
	1995–2001	Mean	29.8	1197.0	189.2	23.1	26.3	62.3	91.3
	2007–2012	Max.	58.0	1615.0	356.0	38.0	260.5	563.0	743.5
Pn	11 yr	Min.	11.4	397.0	13.0	5.0	0.0	0.0	0.0
	1997–2001	Mean	27.4	763.6	210.0	16.2	12.6	42.2	55.2
	2007–2012	Max.	50.0	1040.0	357.0	32.0	144.2	332.3	365.2
Ph	11 yr	Min.	3.44	355.0	70.0	8.0	0.0	0.0	0.0
	1997–2001	Mean	24.18	548.3	229.6	15.8	14.8	45.6	53.9
	2007–2012	Max.	41.46	661.0	310.0	34.0	137.4	403.7	420.6
Pp	5 yr	Min.	15.3	594.0	10.0	3.0	0.0	0.0	0.0
	2008–2012	Mean	38.04	767.3	127.3	15.6	44.5	74.7	83.5
		Max.	82.3	1013.0	360.0	23.0	441.7	448.9	449.8
Ps–Pn	6 yr	Min.	11.3	1030.0	4.0	8.0	0.0	0.0	0.0
	2007–2012	Mean	24.7	1085.0	72.1	23.9	30.2	79.8	101.6
		Max.	34.3	1148.0	202.0	31.0	196.1	410.6	472.1
Pn–Ph	6 yr	Min.	17.3	390.0	108.0	9.0	0.0	0.0	0.0
	2007–2012	Mean	22.9	459.4	216.0	11.4	4.4	31.0	36.1
		Max.	30.5	577.0	296.0	13.0	41.4	377.8	405.0

2.2. Simulation of landscape-level forest dynamics

The plots of the Third Spanish National Forest Inventory (NFI) (DGCN, 2003) constituted the basic calculation units and starting point for simulation in the design of alternative landscape-level forest management intensity scenarios. The NFI is based on systematic sampling throughout a grid of forest inventory plots separated by one kilometer covering the whole territory of Catalonia, so that every plot represents one squared kilometer of forest area. Both stand and site characteristics can be retrieved from the NFI plots.

To be consistent with the mushroom yield models, only those NFI plots that represented pure *P. sylvestris*, *P. nigra*, *P. halepensis* and *P. pinaster* stands as well as mixed *P. sylvestris*–*P. nigra* and *P. nigra*–*P. halepensis* stands were selected. Pure stands were defined as those in which at least 80% of stand basal area corresponded to one of the abovementioned pine species (Helms, 1998). Similarly, mixed stands were defined as those in which at least 80% of stand basal area corresponded to the aforesaid pine mixtures. The application of these criteria resulted in the selection of 3272 NFI plots representing 327,200 hectares of pure and mixed pine forests.

Many pine stands in Catalonia are characterized by multilayered or semi-even-aged structures as a result of past management and stand dynamics. Current forest management is also based on continuous cover forestry. Previous research has found that using growth models capable of simulating uneven-aged stand dynamics may be more suitable when dealing with such stand structures (de-Miguel et al., 2012). Therefore, existing growth models for uneven-aged Catalanian pine stands (e.g., Trasobares, 2003; Trasobares et al., 2004) were used to simulate the stand dynamics of each NFI plot. Pine ecosystem-specific predictions of mushroom yield for a typical year (i.e., without considering the annual random variation) were produced for every NFI plot using the models developed in this study.

2.3. Simulation of landscape-level forest management intensity scenarios

The following scenarios were considered in the quantification of the impact of regional forest management intensity on landscape-level mushroom productivity:

- Scenario 1 or baseline: the approximate current forest management intensity in Catalonia, felling rate equal to 25%.
- Scenario 2: absence of forest management, felling rate equal to 0%.

- Scenario 3: average forest management intensity in Europe, felling rate equal to 65%.
- Scenario 4: maximum sustained yield, felling rate equal to 100% (annual timber harvesting equal to annual forest growth).

The time frame of each scenario was 30 yr, i.e., from 2013 to 2043, subdivided into three 10-yr periods. The assessment of the impact of forest management intensity on mushroom productivity focused on a group of nineteen edible mushroom species of high social and market value in Catalonia (henceforth referred to as marketed or commercially important mushrooms) since they constitute the most relevant group of mushrooms as non-wood forest product and an environmental service (Table 2).

The simulation of forest management alternatives for the NFI plots was based on continuous cover forestry since selective cuttings and natural regeneration has been the common practice in Catalonia. Selective cuttings were simulated by thinning larger diameter classes more heavily than the small ones. Since stand basal area affects the timing of the thinning treatments, different management schedules were obtained by varying the stand basal area required for thinning and the intensity of thinning. One of the simulated schedules was always a no treatment alternative.

The four alternative forest management intensity scenarios were then developed by formulating and solving four optimization problems by means of combinatorial optimization using simulated annealing algorithm (Dowsland, 1993). The total growing stock volume at the end of the 30-yr period was maximized in all problems with the constraints that the 10-yr harvest had to be 0, 1.7, 4.3 and 6.6 million m³, which corresponded to the intended forest harvesting intensities of 0, 25, 65 and 100%. The utility-theoretic formulation of the problem was as follows:

Maximize

$$U = \sum_{i=1}^I w_i u_i(q_i)$$

subject to

$$q_i = Q_i(\mathbf{x}) \quad i = 1, \dots, I$$

$$\sum_{k=1}^{N_n} x_{kn} = 1 \quad n = 1, \dots, N$$

$$x_{kn} \in \{0, 1\}$$

Table 2

Group of mushroom species of high social and market value (marketed mushrooms) and the pine forests ecosystems where they are found according to the inventory data of the 107 permanent sample plots. The coding of pine species is as follows: *P. sylvestris* (Ps), *P. nigra* (Pn), *P. halepensis* (Ph), *P. pinaster* (Pp).

Scientific name	Ps	Pn	Ph	Pp	Ps–Pn	Pn–Ph
<i>Boletus aereus</i> Bull.	*					
<i>Boletus edulis</i> Bull.	*				*	
<i>Boletus pinophilus</i> Pil. & Derm.	*					
<i>Cantharellus lutescens</i> Fr.	*	*	*		*	*
<i>Hydnum repandum</i> L. var. <i>albidum</i>	*	*	*		*	
<i>Hydnum repandum</i> L. var. <i>rufescens</i>	*	*				
<i>Hygrophorus agathosmus</i> (Fr.) Fr.	*	*				
<i>Hygrophorus eburneus</i> (Bull.) Fr.	*				*	
<i>Hygrophorus latitabundus</i> Britz.	*	*	*		*	*
<i>Hygrophorus russula</i> (Sch.) Quél.	*					
<i>Lactarius deliciosus</i> (L.) S. F. Gray	*	*	*	*	*	*
<i>Lactarius deliciosus</i> (L.) S. F. Gray x <i>Hypomyces lateritius</i>	*				*	
<i>Lactarius sanguifluus</i> (Paul.) Fr.	*	*			*	*
<i>Lactarius sanguifluus</i> var. <i>violaceos</i>	*	*		*	*	*
<i>Lactarius semisanguifluus</i> Heim & Lecl.	*	*	*	*	*	
<i>Lactarius vinosus</i> Quél	*			*		
<i>Suillus luteus</i> (L.) Roussel.	*	*	*	*	*	*
<i>Suillus variegatus</i> (Swartz) Rich. & Roze.	*	*			*	
<i>Tricholoma terreum</i> (Sch.) Kumm.	*	*	*	*	*	*

where U is the total utility, I is the number of management objectives, w_i is the importance (weight) of management objective i , u_i is a sub-utility function for objective i , and q_i is the value of objective variable i . Q_i is an operator that calculates the value of objective i , x is a vector of binary decision variables (x_{kn}) that indicate whether stand n is treated according to schedule k , N_n is the number of alternative treatment schedules in stand n , and N is the number of stands. The management objectives were the harvested volumes of the three 10-yr periods and the ending growing stock volume. The sub-utility functions for the harvested volumes had an ascending-descending shape so that the target value of the harvest maximized the sub-utility.

3. Results

3.1. Mushroom yield models

Crossed (or main) random effects accounting for spatial and temporal correlation among the mushroom yield observations were included in the selected models. The models were ecosystem- and year-specific. The fitted models for total, edible and marketed mushroom yield were as follows (Tables 3 and 4):

$$p(y_{ijk} = 1) = \frac{1}{1 + e^{-(\beta_0 + b_{0j} + b_{0k} + \beta_1 \ln(G_{ijk}) + \beta_2 \sqrt{G_{ijk}} + \beta_3 \cos(Asp_{ij}) \ln(Slo_{ij} + 1))}} \quad (5)$$

$$\begin{aligned} \ln(tot_{ijk}) = & \beta_4 + b_{4j} + b_{4k} + \beta_5 \ln(G_{ijk}) + (\beta_6 + b_{6j}) \sqrt{G_{ijk}} \\ & + (\beta_7 + b_{7j} + b_{7k}) \sqrt{Alt_{ij}} + \beta_8 Alt_{ij} \\ & + \beta_9 \cos(Asp_{ij}) \ln(Slo_{ij} + 1) + \varepsilon_{ijk} \end{aligned} \quad (6)$$

$$\begin{aligned} \ln(ed_{ijk}) = & \beta_4 + b_{4j} + b_{4k} + \beta_5 \ln(G_{ijk}) + (\beta_6 + b_{6j}) \sqrt{G_{ijk}} + \beta_7 \ln(Alt_{ij}) \\ & + \beta_9 \cos(Asp_{ij}) \ln(Slo_{ij} + 1) + \varepsilon_{ijk} \end{aligned} \quad (7)$$

$$\begin{aligned} \ln(mk_{ijk}) = & \beta_4 + b_{4j} + b_{4k} + \beta_5 \ln(G_{ijk}) + (\beta_6 + b_{6j}) \sqrt{G_{ijk}} + \beta_7 \sqrt{Alt_{ij}} \\ & + (\beta_8 + b_{8j} + b_{8k}) Alt_{ij} + \varepsilon_{ijk} \end{aligned} \quad (8)$$

where $p(y_{ijk} = 1)$ is probability of total, edible or marketed mushroom occurrence of stand i in pine ecosystem j and year k , tot_{ijk} , ed_{ijk} and mk_{ijk} are, respectively, total, edible and

Table 3

Parameter estimates and Snowdon's bias correction factors (CF) of the models for marketed, edible and total mushroom yield. Symbol $s()$ refers to standard deviation, β denotes fixed-effects model parameters, b denotes random effects and ε_{ijk} is residual. Subscript j refers to ecosystem-specific random effects and subscript k refers to year-specific random effects.

Model parameters	Marketed	Edible	Total
β_0	-0.858	1.455	1.538
β_1	1.988	1.670	2.988
β_2	-0.846	-0.871	-1.512
β_3	0.171	0.458	0.719
β_4	-8.313	-1.602	-4.064
β_5	1.849	1.642	1.866
β_6	-0.913	-0.986	-1.016
β_7	0.575	0.626	0.382
β_8	-0.009	0.000	-0.006
β_9	0.000	0.073	0.092
$s(b_{0j})$	0.505	1.058	1.655
$s(b_{0k})$	1.382	1.181	1.322
$s(b_{4j})$	2.104	2.448	1.503
$s(b_{4k})$	1.504	0.848	2.429
$s(b_{6j})$	0.348	0.510	0.547
$s(b_{7j})$	0.000	0.000	0.064
$s(b_{7k})$	0.000	0.000	0.078
$s(b_{8j})$	0.002	0.000	0.000
$s(b_{8k})$	0.001	0.000	0.000
$s(\varepsilon_{ijk})$	1.489	1.548	1.419
CF	2.301	2.124	1.857

marketed mushroom yield conditional on mushroom occurrence ($\text{kg ha}^{-1} \text{yr}^{-1}$), β_0 to β_9 are fixed effects, b_{0j} , b_{4j} , b_{6j} , b_{7j} and b_{8j} are random pine ecosystem effects, b_{0k} , b_{4k} , b_{7k} and b_{8k} are random year effects, G_{ijk} is stand basal area ($\text{m}^2 \text{ha}^{-1}$), Alt_{ij} is altitude above sea level (m), $\cos(Asp_{ij})$ is a dimensionless predictor denoting north-south aspect (from 1 to -1), Asp_{ij} is orientation (radians), Slo_{ij} is slope (%), and ε_{ijk} is residual.

Random effects only affect the intercept of the logistic models for the probability of mushroom production (Eq. (5)) whereas they affect both the intercept and some of the slopes in the conditional yield models (Eqs. 6–8). If random effects are assumed to be zero, Eqs. 5–8 provide predictions for a typical pine forest ecosystem and year. Mushroom productivity as predicted by the two-stage models is the highest in stands where *P. sylvestris* is dominant or co-dominant (Fig. 1).

Table 4
Pine ecosystem random effects of the two-stage mushroom yield models for predicting the probability of mushroom occurrence and the mushroom yield conditional on the probability of mushroom occurrence. The pine species abbreviations are as follows: *P. sylvestris* (Ps), *P. nigra* (Pn), *P. halepensis* (Ph), *P. pinaster* (Pp).

Mushroom group	Random effects	Ps	Pn	Ph	Pp	Ps–Pn	Pn–Ph
Marketed	b_{0j}	0.657	0.094	–0.222	–0.269	0.238	–0.577
	b_{4j}	–1.199	0.562	2.824	–2.266	0.585	–0.506
	b_{6j}	0.103	0.103	–0.437	0.354	–0.190	0.068
	b_{8j}	0.001	–0.002	–0.001	0.001	0.001	0.001
Edible	b_{0j}	0.924	–0.346	0.029	1.015	–0.281	–1.749
	b_{4j}	–0.601	–2.230	3.268	–1.860	0.662	0.761
	b_{6j}	0.134	0.453	–0.702	0.393	–0.126	–0.154
	b_{8j}	1.379	–0.925	–0.548	1.624	0.362	–2.660
Total	b_{0j}	–1.193	–1.085	2.096	–0.404	0.162	0.424
	b_{4j}	0.149	0.396	–0.889	0.409	0.005	–0.070
	b_{6j}	0.021	–0.034	0.090	–0.066	–0.008	–0.004
	b_{8j}						

Both the occurrence of sporocarp emergence and the amount of mushroom production depend significantly on stand basal area. The effect of stand basal area on mushroom yield follows an increasing-decreasing trend with an optimum dependent on the pine forest ecosystem. For the group of marketed mushroom species, this optimum ranges from 10 to 15 m² ha^{–1} in pure *P. halepensis* stands to 35–40 m² ha^{–1} in pure *P. pinaster* stands (Fig. 1c). A similar trend showing even greater difference between the minimum and maximum optimal stand basal areas was also observed for edible and total mushroom yield.

The probability of mushroom occurrence was higher with increasing northness, whereas sporocarp emergence was less probable in south-facing slopes. The differences between northern and southern aspects were exacerbated as slope increased. Mushroom yield was slightly enhanced with increasing slope in north-facing aspects and clearly decreased with increasing slope in south-facing aspects (Fig. 1a and b). A similar effect of aspect was also found for the conditional models for edible and total mushroom yield.

Altitude above sea level did not have a statistically significant influence on the probability of mushroom occurrence, but it was

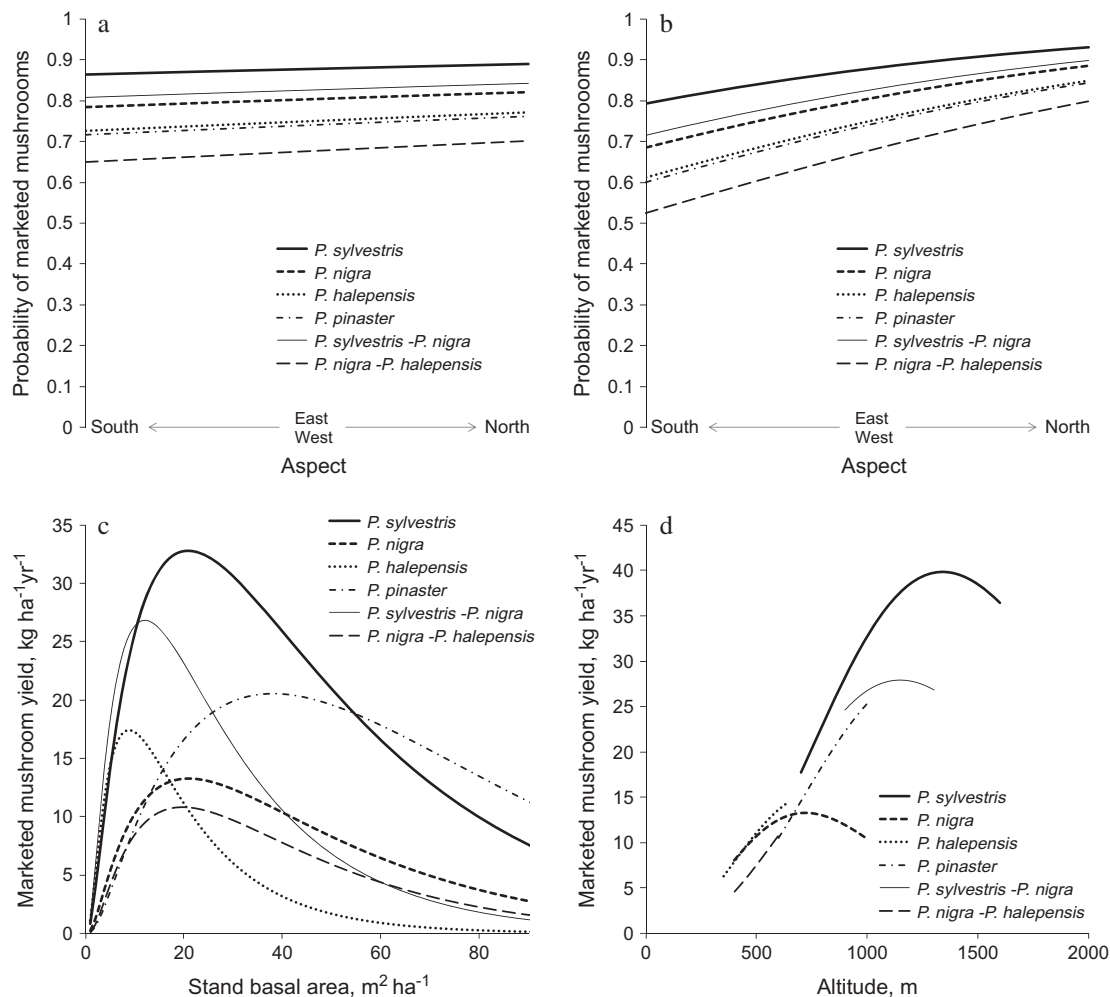


Fig. 1. Effect of aspect on the probability of mushroom occurrence with 1% (a) and 40% (b) slope, and influence of stand basal area (c) and altitude (d) on the yield, i.e., probability (Eq. (5)) multiplied by conditional yield (Eq. (8)) of commercially important mushrooms. The values assigned to the predictors correspond approximately to the mean values in the modelling data.

a significant predictor of the amount of mushroom production in the conditional yield models. The effect of altitude is ecosystem- and/or year-specific depending on the modelled group of mushroom species. Since the distribution of pine forest ecosystems in Catalonia partly follows an altitudinal gradient (see Table 1), the effect of altitude on mushroom yield can be considered from two complementary perspectives. On one hand, the models predict higher mushroom yield for those pine ecosystems which are present at the upper bound of the overall altitudinal range (i.e., *P. sylvestris* growing in pure stands or associated with *P. nigra* in mixed stands, as well as pure *P. pinaster* stands). On the other hand, elevation above sea level plays itself a significant role in determining within-pine-ecosystem differences in mushroom productivity along the altitudinal range of each forest type (Fig. 1d). While the effect of elevation is positive for those pine forests typical of lower altitudes (i.e., *P. halepensis* growing in pure stands or associated with *P. nigra* in mixed stands), it shows an increasing-decreasing trend with an optimum altitudinal range for those pine forests typical of higher elevations, except for *P. pinaster*.

A number of additional predictors accounting for stand and site characteristics (e.g., site index, dominant height, number of trees per hectare) were also tested but they did not have significant and logical relationships with mushroom yield.

3.2. Impact of forest management intensity on landscape-level mushroom productivity

At the landscape-level, most mushroom production is concentrated in pine forests of central and northern Catalonia, where *P. sylvestris* and *P. nigra* are the dominant pine species (Fig. 2).

The scenario analysis showed that landscape-level mushroom productivity improves with increasing forest management intensity (Figs. 3–5). Currently, the expected average productivity of marketed mushrooms from pine ecosystems in Catalonia is approximately $14 \text{ kg ha}^{-1} \text{ yr}^{-1}$ (4600 tonnes yr^{-1} at the regional level). If the current forest management intensity continues during the next three decades (Scenario 1 or baseline), a progressive loss in mushroom productivity can be expected as a consequence of a reduction in mushroom yield affecting 65% of the Catalanian pine forest area. After thirty years the loss in productivity may be almost $0.7 \text{ kg ha}^{-1} \text{ yr}^{-1}$. At the regional level, this would represent a decline of 220 tonnes per year (5%) in mushroom production from pine forests.

In the absence of forest management (Scenario 2), a decrease in productivity of commercially important mushrooms of approximately $0.5 \text{ kg ha}^{-1} \text{ yr}^{-1}$ every ten years (i.e., $1.5 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in

30 yr) could be expected. At the regional level this means a drop in production of 163 tonnes per year every ten years, that is, 490 tonnes per year (11%) at the end of the 30-yr period as compared with the current production. Such a loss in mushroom yield arises from an expected loss in mushroom productivity in 76% of the pine forest area.

The models predict that, in a landscape-level felling rate scenario of 65% (Scenario 3), the average mushroom productivity would increase by approximately $0.3 \text{ kg ha}^{-1} \text{ yr}^{-1}$ arising from a rather even distribution of positive and negative changes in mushroom yield. At the regional level, this represents an increase in mushroom production of approximately 100 tonnes per year (2%) after thirty years.

If wood felling was equal to annual forest growth (Scenario 4), the models predict an increase of $0.8 \text{ kg ha}^{-1} \text{ yr}^{-1}$ of commercially important mushrooms in the coming thirty years, representing a positive shift in production of 262 tonnes per year (6%) at the regional level. This change in mushroom yield arises from an overall increase in mushroom productivity in 58% of Catalanian pine forest as a result of managing forests for maximum sustained timber yield.

The effect of increasing forest management intensity (Scenarios 3 and 4) on mushroom productivity mainly occurs during the first ten years of the 30-yr time frame considered in the scenario analysis, after which mushroom productivity tends to stabilize.

4. Discussion

4.1. Conditional mushroom yield models

This study analyzed the impact of regional forest management intensity on the landscape-level productivity of economically important wild mushrooms based on modelling and simulation techniques. The models reflect the relationships between mushroom yield and stand and site characteristics in accordance with current scientific knowledge (Bonet et al., 2004, 2010, 2012; Martínez de Aragón et al., 2007; Martínez-Peña et al., 2012). The models account for between-ecosystem and between-year variation of mushroom productivity.

Stand basal area is the most relevant predictor in terms of forest management since site characteristics (i.e., altitude, aspect and slope) remain constant over time and cannot be modified by means of silviculture. Our results suggest that the optimal stand basal area at which mushroom production is maximized is forest ecosystem-specific (Fig. 1c). The magnitude of the optimal stand basal areas for different pine forests is consistent with previous research

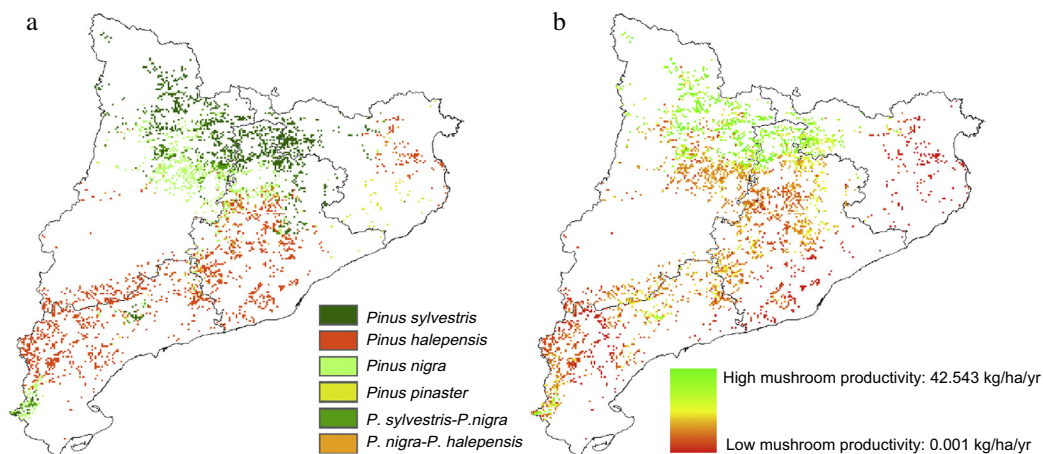


Fig. 2. Geographical distribution of pine forests (a) and predicted current mushroom productivity (year 2013) (b) in Catalonia.

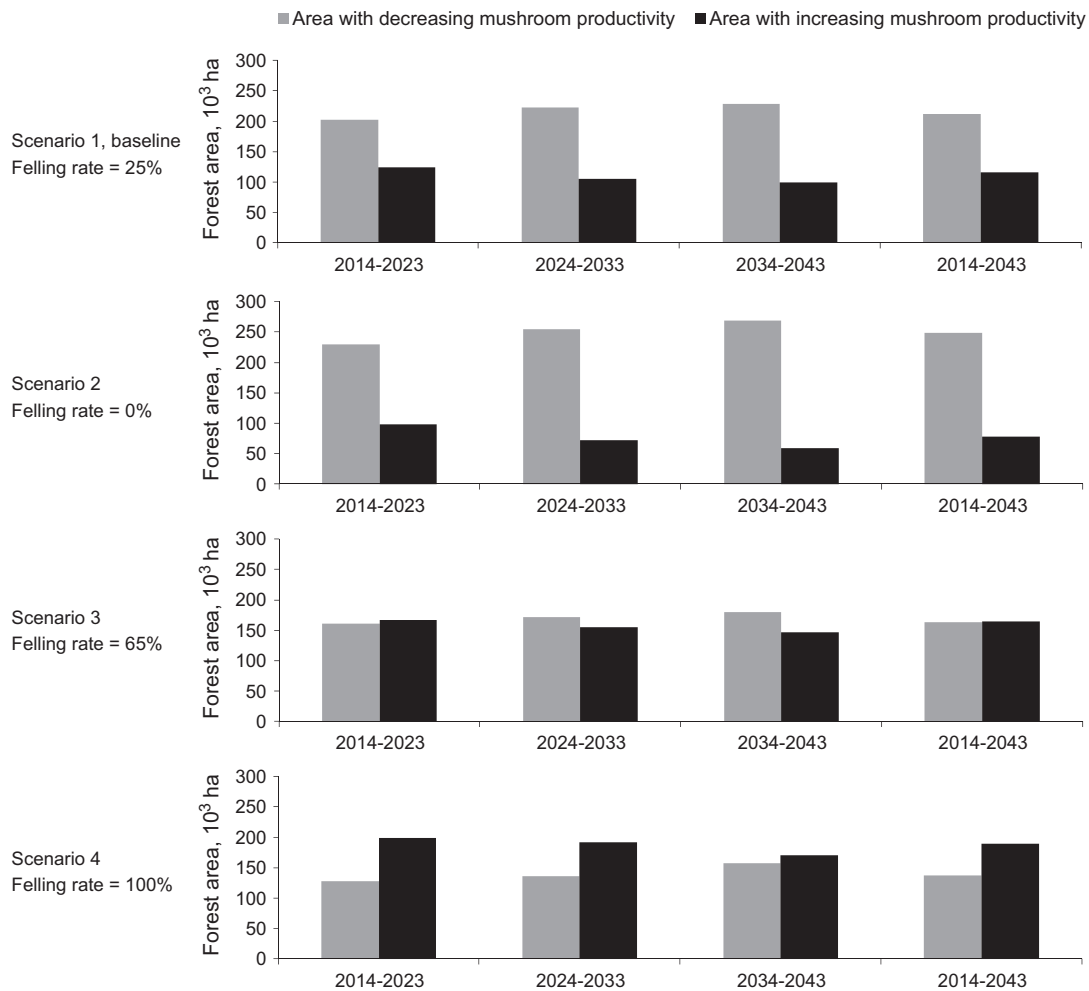


Fig. 4. Temporal evolution of the regional pine forest area (in thousands of hectares) affected by a decrease or an increase in mushroom productivity as a result of applying alternative forest management intensities.

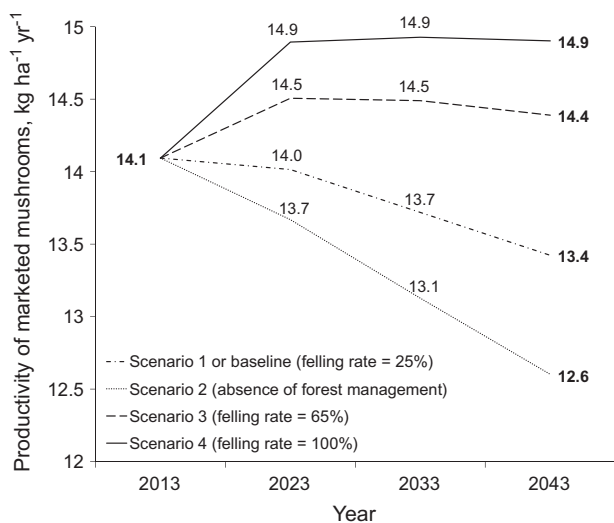


Fig. 5. Evolution of the average productivity ($\text{kg ha}^{-1} \text{yr}^{-1}$) of valuable mushrooms in Catalonia during the next 30 yr under alternative regional forest management intensity scenarios.

temperature is not constant over time but it experiences interannual variation, which explains the year-specific effect of altitude in the conditional yield models.

The mushroom yield models developed in this study are of higher resolution than those fitted in previous research. Therefore, the new models enable predictions of mushroom productivity for most pine forest ecosystems of Catalonia by taking into account ecosystem-specific effects of stand structure and site characteristics on mushroom yield. Moreover, the random year effects may be used in combination with climatic information in further research to inspect the impact of long-term climate change on mushroom yield. The two-stage modelling approach used in this study is capable of accounting in more detail for the processes leading to sporocarp emergence and determining the amount of mushroom production as compared with single-model functions (Hamilton and Brickell, 1983). Thus, while stand basal area seems to play a key role in determining both the probability of mushroom occurrence and the amount of yield, aspect seems to be more important in determining the probability of mushroom occurrence. Altitude seems to play a more important role in determining the amount of yield.

Differences in mushroom productivity among different forest types may arise from between-ecosystem variation in both mushroom diversity and yield of one or several mushroom species. Pure *P. sylvestris* forests host the highest species richness of socially and economically important mushrooms followed by mixed stands of *P. sylvestris* and *P. nigra* and pure *P. nigra* forests (Table 2). A similar gradient can be observed among these pine ecosystems in terms of mushroom productivity. In contrast, *P. pinaster* forests are more

productive than pure *P. nigra* stands occurring at similar elevation despite hosting lower diversity of valuable mushrooms (Table 2 and Fig. 1). Further research should be devoted to further inspect the relationship between mushroom yield and diversity in different forest ecosystems.

4.2. Regional forest management intensity and landscape-level mushroom yield

The mushroom yield models fitted in this study were used to quantify the current mushroom yield of pine forests in Catalonia (Fig. 2b) and the change in mushroom productivity at the landscape level under alternative regional forest management intensity scenarios (Figs. 3–5). The spatial distribution of mushroom production as predicted by the models is consistent with empirical evidence and previous estimations (Bonet et al., 2014). Since wild mushrooms also grow in Catalonian forest ecosystems other than the pine forests considered in the present study, the regional mushroom production (i.e., in tonnes per year) of all Catalonian forests is much higher than the values obtained in this research. Accordingly, the absolute changes in regional mushroom production under different forest management intensity scenarios will also be larger than reported in this study.

Our model-based scenario analysis suggests that, given the current state of Catalonian forests, landscape-level mushroom productivity may be enhanced by increasing forest management intensity (Scenarios 3 and 4). On the contrary, maintaining or reducing the current management intensity may result in a progressive reduction of mushroom yield during the next decades (Scenarios 1 and 2). In the absence of forest management, the expected decrease in the annual mushroom production at the regional level in thirty years is equivalent to the average annual sales of *Lactarius deliciosus* at the main Spanish Central Markets (Voces et al., 2012) as well as to the annual mushroom exports in Catalonia (IDESCAT, 2009). These results suggest that forest management should be intensified in Catalonia if current mushroom yields are to be maintained. A gradual convergence to the current European average felling rate would represent a reasonable intensification in the use of forest resources that would contribute to preserve the provision of socially and economically important mushroom species.

The results of the scenario analysis must be framed within the context of uneven-aged forest management which relies on the maintenance of a continuous forest cover over space and time (Pukkala and von Gadov, 2012). The complete removal of tree cover, as it is often the case for even-aged forestry and which is not currently applied in Catalonia, would most probably set the production of marketed mushrooms to almost zero for several years as marketed mushrooms are mycorrhizal symbionts of forest trees (Table 2). Therefore, simulations of even-aged forest management intensity scenarios would most probably lead to lower estimations of the landscape-level mushroom production. On the other hand, the impact of even-aged forest management based on the shelter-wood method on mushroom productivity may not necessarily deviate much from the results obtained in this study.

The effect of simulating alternative forest management intensities on the spatial changes in mushroom productivity arises only from the modification of stand basal area in 1-km² area units according to the predicted forest stand dynamics based on growth models as well as on optimized thinning schedules based on management instructions for uneven-aged forestry. Previous research conducted by Bonet et al. (2012) in Catalonian *P. pinaster* forests has, however, shown that moderate thinning intensity may immediately boost the productivity of most mushroom species considered in this study (i.e., *Lactarius* group *deliciosus*). Kropp and Albee (1996) also found a similar trend for the same mushroom species in *P. contorta* stands. Having included such thinning effects

would probably had led to even more favorable results in terms of mushroom production for those scenarios representing more intense forest management. Nonetheless, such results may not be extrapolated to other forest ecosystems since other studies have reported a negative thinning reaction of mushroom yield with a subsequent recovery of the productivity after 3–6 yr (Pilz et al., 2006; Egli et al., 2010) most probably arising from soil disturbance caused by forest harvesting operations. In the absence of conclusive information concerning the thinning effects for all pine ecosystems involved in this scenario analysis, we applied the precautionary principle and assumed that, in simulation, mushroom yield was neutral to thinning reaction.

In this study, landscape-level mushroom productivity was predicted by assuming the environmental conditions of a typical year according to the modelling data. A relationship between climatic variables and the random year effects of the mushroom yield models could be used to calibrate the predictions for changing climatic conditions. Although long-term changes in climatic conditions may scale up or down the mushroom productivity estimates provided in this article, the time frame used in the simulated scenarios involves short- to medium-term projections (i.e., 10–30 yr) for which climate change may not have much effect. On the contrary, short- to medium-term projections are meaningful to the objectives of this study since they account for the typical time frame used in the design of forest management plans and policies.

By assuming that maximum sustained yield cannot support diverse forest functions and sustain the provision of non-timber values, some authors (e.g., Luckert and Williamson, 2005) have concluded that in the pursuit of sustainable forest management it may be necessary to abandon maximum sustained yield. Conversely, other authors (e.g., Elbakidze et al., 2013) defend that the contribution of sustained yield to sustainable forest management depends on the socioeconomic, ecological and cultural context, which in turn determines maximum sustained yield forestry in a particular region. Our results show that, within the framework of continuous cover forestry, maximum sustained yield may enhance the provision of wild mushrooms, which represent both an economically important non-wood forest product and an environmental service of high socio-cultural value (Martínez de Aragón et al., 2011; Schulp et al., 2014). These results are consistent with previous research on economically and socially relevant non-wood forest goods (i.e., wild mushrooms and berries) and suggest that the provision of such goods may be better assured in managed stands rather than in unmanaged forests (Titus et al., 2006; Guariguata et al., 2010; Palahí et al., 2009; Miina et al., 2010). In this context, increasing forest management intensity might entail a number of synergies favouring the sustainability of forest ecosystems as compared with the current trend towards increasingly unmanaged forests. Additional research should focus on further integrating the complex interactions and trade-offs in the provision of multiple forest goods and services (e.g., non-timber values, fire risk reduction, climate change mitigation and adaptation, green economy) in relation to forest management practices. Since changes in the climatic conditions may affect not only mushroom productivity at the stand level (Bonet et al., 2012; Martínez-Peña et al., 2012), but also the spatial distribution of forest ecosystems at the landscape level (Carnicer et al., 2013), climate change scenarios and their impact on mushroom productivity at multiple scales should be also addressed in further research.

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