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Research article

Combined impact of forest management and climate change on Boletus edulis productivity: may mycosilviculture mitigate the effects of climate extremes?

Elena Salerni[1], Luca Paoli[2], Claudia Perini[1]

[1] Department of Life Sciences, University of Siena, Via Mattioli 4, 53100 Siena, Italy.
[2] Department of Biology, University of Pisa, Via Ghini 13, 56126 Pisa, Italy.

Corresponding author e-mail: elena.salerni@unisi.it

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Abstract
Climate change can affect forest ecosystems, especially through an increase of extreme events. In order to verify whether mycosilvicultural practices could mitigate the effects of climate change, productivity of *Boletus edulis* in *Abies alba* managed plantations was correlated to intense rainfall and temperature peaks during three years. Fungal productivity in each of the 21 days following an extreme climatic event was considered. Results showed that sudden increases in maximum temperature seemed to have an inhibitory effect on *B. edulis* productivity in sites with no or modest thinning. In sites with heavy thinning, productivity seemed to be favoured by high temperatures, starting from the twentieth day following the extreme event. Mycosilviculture may mitigate the climate change effects; however, further studies are needed to verify how climate-dominated effects can be altered by local factors and how ecological relationship between *B. edulis* and forest ecosystem will be affected.

Keywords
ectomycorrhizal fungi, wild edible mushrooms, coniferous plantations, extreme precipitation, extreme temperature, forest thinning, Italy

Introduction

The *Boletus edulis* species complex (penny bun mushroom, cep, cèpe de Bordeaux, porcino, Steinpilz) includes four European species (*Boletus edulis* Bull., *Boletus aereus* Bull., *Boletus pinophilus* Pilát & Dermek and *Boletus reticulatus* Schaeff.) whose molecular identification is based on ITS specific primers developed by Mello et al. (2006). They are rich in dietary minerals, like sodium, iron, calcium, and magnesium and have therapeutic effects, which are useful in preventing many health issues due to their antibacterial, antimutagenic and antiviral activities (Zubaidi et al., 2021).

The *Boletus edulis* species complex belongs to ectomycorrhizal (ECM) fungi producing edible mushrooms highly prized worldwide (Boa, 2004; Bonet et al., 2010; Martínez-Peña et al., 2012a; García-Bustamante et al., 2021), associated with various trees and shrubs (Fagales, Malvales, Malpighiales, Ericales, Pinales, ecc.). These fungal species are collected exclusively from wild (Cannon and Kirk, 2007), and their cultivation is a challenging target for many agro-food biotech

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companies. Up to now, a major problem is that only a few ECM fungal species can be induced to fruit in co-culture in interaction with their hosts. These difficulties, the socio-economic relevance of mushrooms picking (e.g., Bonet et al., 2010; Alonso Ponce et al., 2011; Martínez de Aragón et al., 2011; Martínez-Peña et al., 2012b; Diez et al., 2013; Leonardi et al., 2017) coupled with the low profitability of timber production 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 (e.g., Salerni and Perini, 2004; Palahí et al., 2009; Bonet et al., 2012; Pierangelo and Rolland, 2013; Lin et al., 2015; Cantiani, 2016; Leonardi et al., 2017; Salerni et al., 2020). One of these practices 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 knowledge of both mushroom ecology and forestry techniques useful for wood production (Palahi et al., 2009). In general, the main factors affecting mushroom production are local site characteristics (e.g., altitude, exposition, slope, soil characteristics), stand structure (e.g., tree species composition, stand density and age, basal area, standing volume, mean height), climatic variables (e.g., precipitation, temperature, CO_2 concentration) and anthropogenic factors (e.g., pollution, forest management). Land plot basal area (Salerni and Perini, 2004; Martínez-Peña et al., 2012b), age category (Salerni and Perini, 2004; Martínez-Peña et al., 2012b), rainfall (Salerni and Perini, 2004; Parladé et al., 2017; García-Bustamante et al., 2021) and air temperature (Hernández-Rodríguez et al., 2015) have been identified as some of the relevant factors influencing *B. edulis* basidioma production.

Human influence on the climate system is evident: as a known example, recent anthropogenic emissions of greenhouse gases reached the highest peaks in history. By 2100, the atmospheric concentration of CO_2 is predicted to rise between 540–970 ppm above the current concentration. Together with other greenhouse gases such as CH_4, this may lead to a predicted global increase of temperatures from 1.1 °C up to 6.4 °C, depending on different predictive models used and the region of the world concerned (IPCC AR4, 2007). As a reciprocal consequence, recent climate change has widespread impact on humans and natural systems (IPCC AR5, 2014) and thus, the interest in its mutations on a large and local scale has expanded far beyond the scientific community. There are evidences that a negative influence on the production of mushrooms can be attributed to global climate change and local effects on the alteration of climatic parameters, also in the Mediterranean area (Kauserud et al., 2012; Boddy et al., 2014; Büntgen et al., 2015; Ágreda et al., 2015; 2016). The IPCC AR5 report (2014) underlines how climate change has affected climatic extremes and, in the future, the severity and frequency of extreme events are expected to be exacerbated. In the Mediterranean area, according to the report aimed at identifying and evaluating the extent of variations in climatic extremes in Italy over the last half century (Fioravanti et al., 2013), all parameters linked to temperature extremes show a warming trend, while less marked are those associated with the reduction of extremes of cold. Concerning precipitation extremes, an increase in intense rainfall is reported especially in southern Italy and on the islands.

In the present paper, a previously collected dataset (Salerni and Perini, 2004) was updated and reworked in order to verify whether mycosilvicultural practices are able to mitigate the effects of the variability of climatic parameters, especially those related to temperature and rainfall. For this reason, data related to the productivity of *B. edulis* in managed plantations of *Abies alba* Mill. were investigated in relation to precipitation events and temperature peaks occurred during the sampling period.

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Material and Methods

The study was carried out in artificial fir woods of Mt. Amiata in the municipality of Abbadia San Salvatore (Siena, Italy) (42°51'57''N, 11°39'03''E, mean elevation 1,050 m a.s.l.). Mt. Amiata is an isolated outcrop (1,738 m a.s.l.) in southern Tuscany, consisting of volcanic rocks deposited on allochthonous substrates of Cretaceous and early Cenozoic Ligurian facies (Giannini et al., 1972). The study sites are in the petrographic province of quartz porphyrites of ignimbrites (Carta Geologica d'Italia, 1965). Mean annual temperature is 11.4 °C (max: 27.2 °C in August; min: 5.9 °C in January). Mean annual rainfall is 1,210 mm, with November as the rainiest month (Centro Funzionale Regione Toscana: http://www.sir.toscana.it). Further information on the study sites is reported in Salerni and Perini (2004). The plantation is dominated by 33-year-old *A. alba*, followed by a minority of *Picea abies* (L.) H. Karst. and clusters of *Pinus nigra* J.F. Arnold and broadleaved trees such as *Acer monspessulanum* L., *Castanea sativa* Mill. and *Prunus avium* (L.) L. (Salerni and Perini, 2004).

Mycological observations were made in 36 plots (each one of 250 m^2) in three different woody areas (12 plots each) and very close to each other. In 1999, one third of the plots was subjected to medium thinning, one third to heavy thinning and one third considered as a control with no thinning. Based on the principal dendrometric approach (Salerni and Perini, 2004), the thinning was carried out taking tree base area (G m^2 ha^{-1}) as standard. In this study a mean removal of 20% of trees with respect to the standard area is intended as medium thinning, while removal of 40% as a heavy one. Around each plot, buffer areas were marked out. Furthermore, in half of the plots for each forest treatment (n = 6), the litter layer was manually removed to assess the effects of dead plant organic material present on top of the mineral soil surface on the fungal fruiting process (Fig. 1).

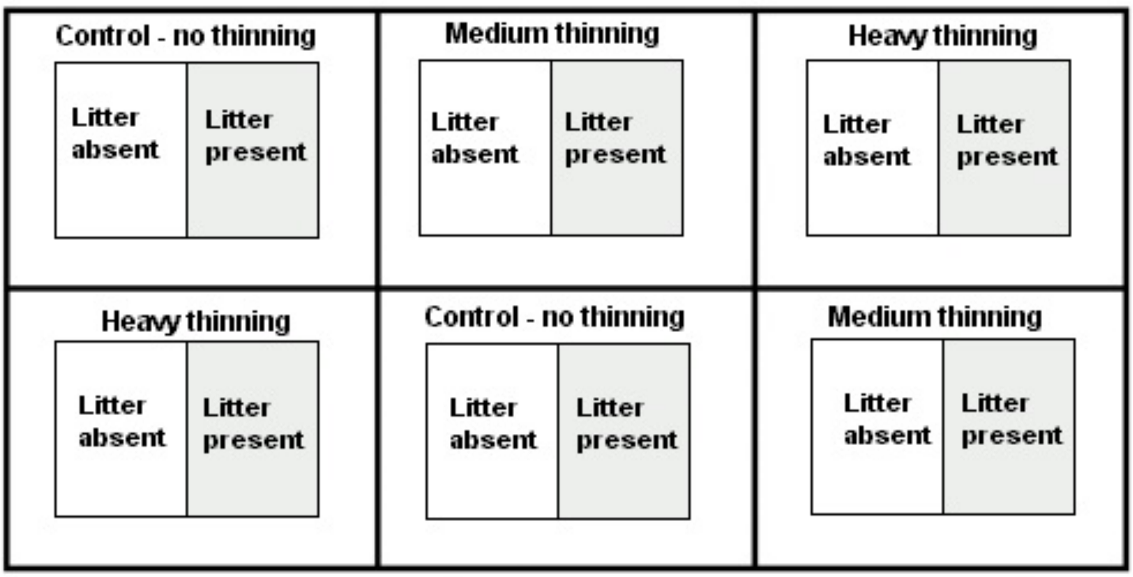

Fig. 1 - Experimental design realized in the study areas.

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Data on occurrence of basidiomata of *B. edulis* species complex in the study sites were gathered for 3 years (2000–2002) after forest management. The data of 2002 were elaborated for the first time in this study, while those of 2000 and 2001 were retrieved from Salerni and Perini (2004). Observations were made on daily basis by local mycologists during major fruiting periods (mostly August–November). During each survey, all basidiomata of *B. edulis* s.l. were collected to simulate what happens during the harvest period and then counted.

To assess climate influence on the fruiting process of *B. edulis* s.l., climatic parameters were obtained from a nearby weather station (Santa Fiora), 7 km away from the study sites. A primary dataset consisted of daily averages of air temperature and vertical atmospheric precipitation. Primary data were subsequently summarized as means, minimum and maximum values of monthly, seasonal and annual rainfalls and temperatures. Moreover, since it is indicated that extreme climatic events may cause serious consequences on the environment, additional climatic parameters were selected following the recommendations of the Expert Team on Climate Change Detection and Indices (ETCCDI) of the CLIVAR Working Group on Climate Change Detection (Commission for Climatology of the World Meteorological Organization), who has defined a set of 27 indices suitable for describing the extremes of temperature and precipitation in terms of frequency, intensity and duration (Fioravanti et al., 2013). Among these, the index for precipitation (R20 - number of days with very intensive precipitation, i.e. ≥ 20 mm) and two absolute temperature indices (TXx – maxima of daily maximum temperature; TNn - minima of daily minimum temperature) were selected for this study. Correlations between values of climatic parameters and number of basidiomata were analysed by Pearson's linear coefficient.

Results

In the period 2000–2002, basidiomata of two species of *B. edulis* complex were collected: *B. edulis sensu stricto* was abundantly occurring in the study area, while the sporadic findings belonging to *B. pinophilus* reported only six times in three years were here not considered. The number of basidiomata increased in all sampling sites during the study period (Fig. 2). In those plots where the litter was removed, the number of basidiomata was lower in comparison with litter present plots (Fig. 2).

The highest increase in production was observed in areas subjected to medium thinning where the litter was maintained (Fig. 2b). Compared to the control (Fig. 2a), the number of basidiomata decreased by about one third in the areas treated by heavy thinning (Fig. 2c). The number of basidiomata found in relation to mean monthly temperature and total monthly rainfall is shown in Figure 3.

During the first two years of the study, the maximum productivity was recorded during autumn, in particular in October (338 basidiomata in 2000 and 584 in 2001), while in the following year, the maximum production (574 basidiomata) shifted in August, two months earlier. This trend is in line with values of mean monthly temperatures. In the first two years, the highest temperatures were measured in August, while in 2002 in June, followed by a rainy sum0mer (Fig. 3). Table 1 shows the values of these variables calculated both annually and seasonally for all three years of study.

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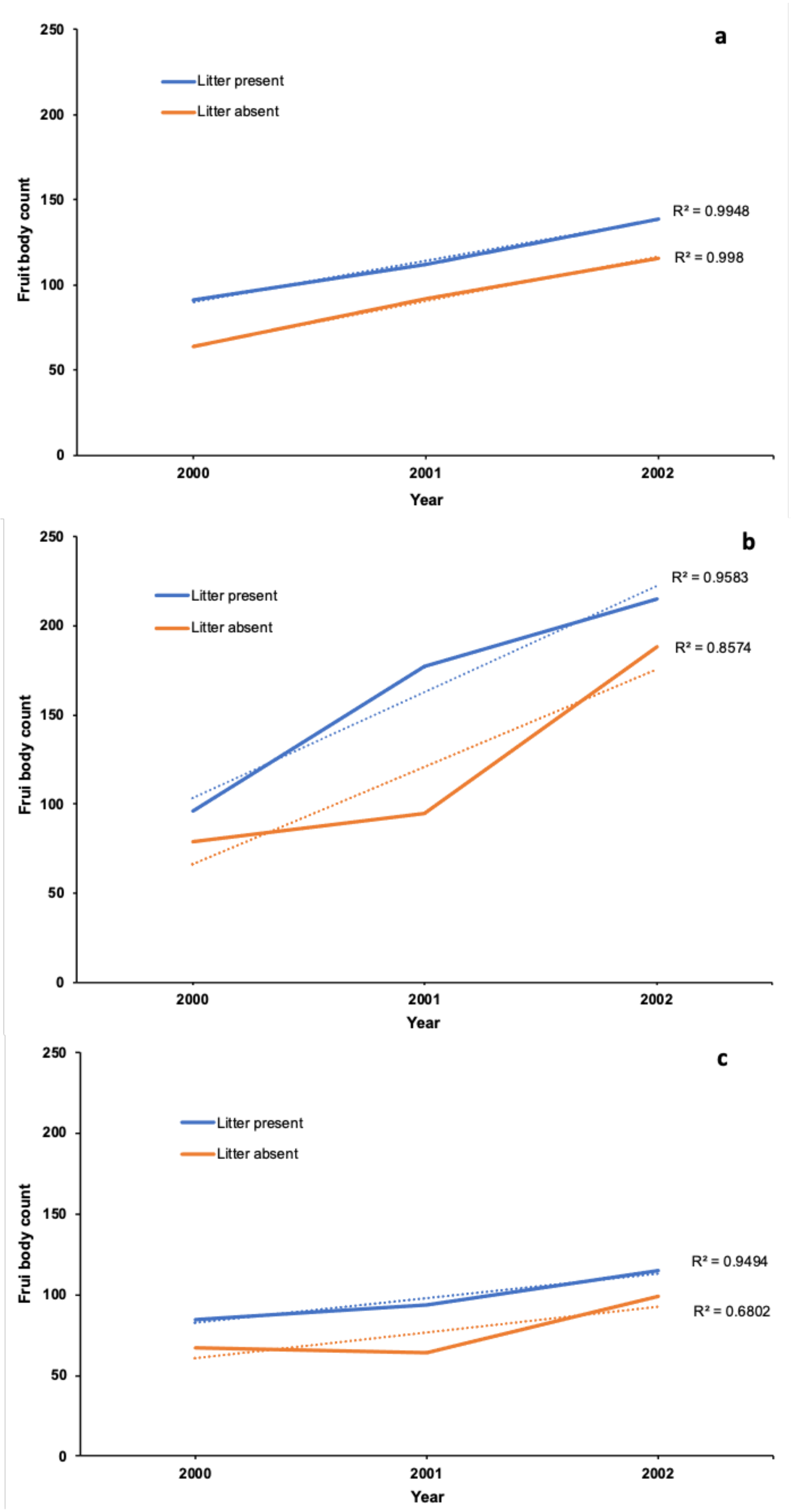

Fig. 2 - Total count of *B. edulis* basidiomata in all plots subjected to different silvicultural treatment - control no thinning (**a**), medium thinning (**b**), heavy thinning (**c**) - during the study period (2000-2002). In each treatment, half plots were subjected to litter removal, N = 12.

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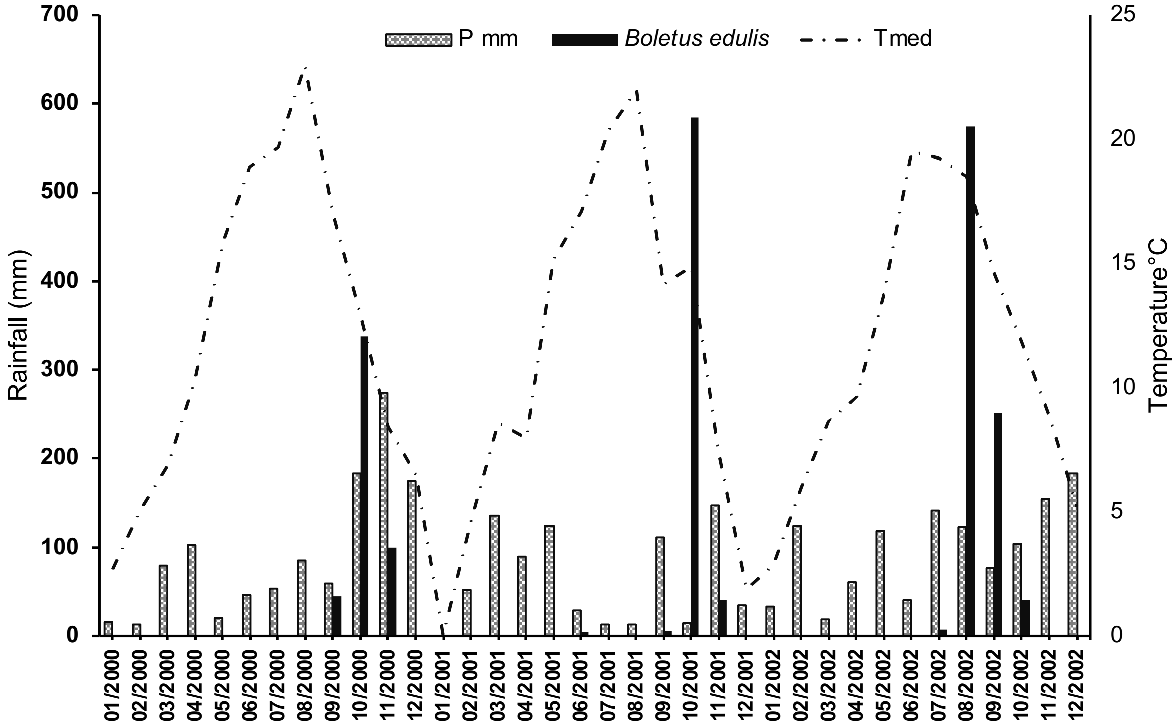

Fig. 3 - Mean monthly temperature (Tmed), total monthly rainfall (P mm) and total monthly number of *B. edulis* basidiomata in the study period (2000-2002).

Table 1 - Summary of climatic parameters on seasonal basis during the study period (2000–2002) (RT - number of rainy days; Tmax - maximum temperature; Tmin - minimum temperature; Tmean - mean temperature; TXx - maxima of daily maximum temperature; TNn - minima of daily minimum temperature; R20 - days with intensive precipitation, i.e. ≥ 20 mm). Annual referred to the time range between 1st January and 31st December; while winter, spring, summer and autumn referred to the first and the last day of each season in the traditional Gregorian calendar, respectively.

		RT	**T max**	**T min**	**T mean**	***R20***	***TXx***	***TNn***		
		n. days	(°C)	(°C)	(°C)	n. days	(°C)	n. days	(°C)	n. days
2000	*Annual*	122	16.07	7.65	12.29	14	20.43	125	2.62	82
	Winter	18	7.93	0.81	4.61	1	11.67	5	-4.57	3
	Spring	33	17.63	8.72	13.65	2	21.55	21	3.65	10
	Summer	20	25.36	13.88	20.21	1	28.03	21	9.68	8
	Autumn	43	13.51	7.22	10.78	6	18.60	9	4.25	17
2001	*Annual*	87	16.66	7.87	12.26	12	22.02	86	2.72	67
	Winter	15	8.83	2.40	5.61	3	14.00	1	-4.00	4
	Spring	33	16.67	7.88	12.28	4	21.83	12	3.45	15
	Summer	13	25.16	13.70	19.43	1	28.53	18	9.18	9
	Autumn	22	13.31	5.80	9.55	3	18.10	26	1.15	14
2002	*Annual*	126	15.54	7.59	11.57	14	20.52	96	2.80	70
	Winter	17	8.91	1.59	5.25	2	14.83	9	-1.77	10
	Spring	32	17.09	7.78	12.44	2	23.33	9	3.05	12
	Summer	27	23.39	13.82	18.60	6	27.75	9	10.35	6
	Autumn	44	14.11	7.46	10.78	4	16.63	11	2.08	17

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During the study period, about 12% of rainy days were characterized by very intense precipitation (R20 ≥ 20 mm). These events concerned in particular way the productive seasons of *B. edulis* (as said above autumn 2000-2001 and summer 2002), where the percentage of days with R20 ≥ 20 mm increased by 14% (6 days out of 43 in the 2000 and 3 days out of 22 in 2001) and over 20% (6 days out of 27 in 2002) (Table 1). In 2000, the annual TXx value (20.43 °C) was exceeded for 125 days, and in particular, during autumn 2001, the TXx value (18.10 °C) was exceeded for 26 days (Table 1).

To verify whether and how the various silvicultural treatments affected the productivity of *B. edulis* in relation to the selected climatic parameters, a correlation analysis (linear Pearson coefficient) was performed between the productivity of *B. edulis* observed in the different pattern of treatments in each of the 21 days following an extreme climatic event (R20, TXx and TNn) and the climatic values of the same extreme events during the overall study period. The results, with 12 days with significant values out of 21 considered, are shown in Table 2.

In the case of very intense rain phenomena (R20 ≥ 20 mm), the rainfall had a positive effect on the productivity of *B. edulis*, in particular on the twelfth day following the event (Table 2). Most of significant values, here presented, are in areas where the litter layer was not removed. In plots subjected to medium intensity thinning, this positive effect was also observed on the second day. On the contrary, in plots where the thinning was more intense heavy rains seemed to have an inhibitory effect on species productivity the thirteenth and nineteenth day (Table 2). Statistically significant negative correlations were found between TXx values and productivity in control plots on days 4, 14 and 19 and in plots with medium thinning on days 1, 7, 14, 15 and 19. In the heavily thinned plots, a statistically significant positive correlation was detected on the twentieth day (Table 2). Concerning the parameter TNn, a statistically significant negative correlation with the production of *B. edulis* was found only in heavily thinned plots with litter present on the fourth day following the occurrence of the climatic event.

Discussion

Various studies highlighted the relationship between mushroom production, climatic parameters (e.g., Salerni et al., 2002; Alonso Ponce et al., 2011; Martínez-Peña et al., 2012a; Boddy et al., 2014; Ágreda et al., 2015; Büntegen et al., 2015; Primicia et al., 2016; Andrew et al., 2018; Collado et al., 2019; García-Bustamante et al., 2021) and silvicultural treatments (Salerni and Perini, 2004; Bonet et al., 2012; Castaño et al., 2018; Karavani et al., 2018; Sánchez-González et al., 2019; Salerni et al., 2020). Only in a few cases the production of basidiomata has been related with climatic instability (Kauserud et al., 2008; Ágreda et al., 2015; Alday et al., 2017) and, as far as we know, it has not been evaluated whether silvicultural treatments (beyond influencing the production) can also mitigate the effects of climate instability. The present research, integrating the study carried out by Salerni and Perini (2004), confirms medium thinning (removal of approximately 20% of the stand basal area) as the most effective silvicultural treatment to enhance the production of *B. edulis*, with respect to heavy thinning (40%) or no thinning. Similarly, Egli and Ayer (1997) showed that the production of edible mushrooms in mixed forests in Switzerland increased by removing about 35% of the stand basal area, while more intensive thinning (40–75%) inhibited the production of various edible fungal species (Pilz et al., 2006; Bonet et al., 2012).

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Table 2 - Significant Pearson correlations between the number of basidiomata of *B. edulis* observed in each of the 21 days following an extreme climatic event (R20 - days with intensive precipitation, i.e. ≥ 20 mm; TXx - maxima of daily maximum temperature; TNn - minima of daily minimum temperature) and the climatic values of the same extreme events throughout the overall study period (2000-2002). Different treatment types (control no thinning, medium thinning, heavy thinning, with litter present or absent) were also considered.

day	Control-no thinning						Medium thinning						Heavy thinning					
	Litter present			*Litter absent*			*Litter present*			*Litter absent*			*Litter present*			*Litter absent*		
	R20	*TXx*	*TNn*	*R20*	*TXx*	*TNn*	*R20*	*TXx*	*TNn*	*R20*	*TXx*	*TNn*	*R20*	*TXx*	*TNn*	*R20*	*TXx*	*TNn*
1								-,397*			-,431*							
2							,612*											
3																		
4		-,381*									-,397*				-,720*			
5											-,372*							
6																		
7								-,389*			-,384*							
8																		
9																		
10																		
11																		
12	,623*						,605*									,593*		
13													-,716*					
14		-,395*						-,431*										
15								-,389*										
16																		
17																		
18					,634**													
19		-,413*						-,412*			-,402*		-,652*					
20					,477*									,665**				
21																		

Statistical significance: * $p \leq 0.005$; ** $p \leq 0.001$

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Kavarani et al. (2018) highlighted the link between mushroom production and temperature and reported that extreme values (minimum and maximum) have greater influence on fruiting processes. Moreover, according to Andrew et al. (2018), temperature is the most influencing parameter for the beginning of fruiting, by anticipating or postponing it. These evidences also agree with the results of our study. Furthermore, the interaction between silvicultural treatments (thinning and litter removal) and climatic parameters highlighted the role of rain on the production of *B. edulis*, especially after the tenth day following a high intensity phenomenon (R20 ≥ 20 mm). This timing was already noticed by Salerni et al. (2002) studying the fruiting processes of various fungal communities in the Mediterranean area, where the greatest number of species fruited just 10 days after the rain. In the case of *B. edulis*, the influence of precipitation on fruiting processes seems to be linked both to the rain recorded in the period preceding the fruiting season (García-Bustamante et al., 2021) and to that of the production period itself (Parladé et al., 2017).

As regards the possibility of silviculture to mitigate the effects of climate extremes, our results showed that sudden increases in maximum temperature (here about 8 °C) compared to the average of the period seemed to have an inhibitory effect on the productivity of *B. edulis* in those experimental plots affected by no treatments (i.e., no-thinning and no litter removal). Such phenomenon was also noticeable in sites treated by medium thinning (removal of approximately 20% of the stand basal area) and with litter present, while it appeared attenuated in sites with heavy thinning (removal of approximately 40% of the stand basal area), where fruiting processes seemed to be favoured by high temperatures, starting from the twentieth day following the event.

According to some studies, the removal of herbaceous vegetation, litter, or humus may have positive effects on species richness of ECM fungi (Baar and Kuyper, 1998; Smit et al., 2003), also in coniferous forests (Baar and Kuyper, 1993; Baar and Ter Braak, 1996). On the other hand, in general, soil litter is considered an ecologically relevant part of the terrestrial compartment and its vital importance for maintaining biological communities and their large biodiversity is highlighted by many other works (Savoie and Largeteau, 2011 and references therein). In line with this and as also previously observed by Salerni and Perini (2004), our results show that an intensive litter removal can have negative effects on the fruiting process of *B. edulis*. The variable outcomes related to litter removal on ECM productivity suggest that the interactions between forest management and mushroom ecology and production is much more complex and need to be better understood (Tomao et al., 2017) also in relation to climatic variability. Several authors hypothesized an impact on production of mushrooms linked to global climate change, especially in the Mediterranean area (Kauserud et al., 2012; Boddy et al., 2014; Büntgen et al., 2015; Ágreda et al., 2015; 2016). This scenario has prompted interest in the development of methods for cultivating ECM (Savoie and Largeteau, 2011) and since forest practices can affect the occurrence, productivity, and reproduction of mushrooms, they should also consider the actual influence and risks associated to climatic variability.

The results of our survey suggest that mycosilviculture may mitigate the effects of environmental variability caused by climate change. However, further studies are necessary to verify whether such indications are related exclusively to local and/or temporal factors, as well as to clarify to which extent the intricate network of relationships between *B. edulis* and the surrounding environment will be affected.

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