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Research paper

Forest management scenarios to reduce the fire risk in chestnut coppices in the Mediterranean area

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ABSTRACT Chestnut coppices are among the formation most affected by fires in the Mediterranean environment. In the absence of cultivation treatments, the structure of the stands appears without vertical and horizontal interruptions in the canopy, with a considerable expansion of the fuel load. In this study, we showed the importance of silvicultural interventions on the mitigation of the fire in the chestnut coppices of southern Italy. In the study sites, we estimated the pyrological potential in terms of heat energy produced per surface unit and the variation in the critical surface intensity. Following silvicultural interventions, the reduction of heat energy is between 12.5 and 50%, and the extinguishing water saving are between 270 and 1,157 Mg·ha^{-1}. The reduction of the probability of the passage of the surface fire to a crown fire can be up to 375%. With the same environmental conditions and dendro-structural characteristics, most effective interventions were observed for rotation cycles of 30 years, compared to shorter rotation cycles. This study showed the importance that silvicultural interventions, such as cleaning and bottom-up thinning, have at both the stand and territorial level on fire risk mitigation.

KEYWORDS: Heat energy, critical surface intensity, water saving, cleaning and thinning, fuel load reduction, intervention planning.

Introduction

In Mediterranean European countries, the chestnut tree (*Castanea sativa* Mill.) is the only native species of the genus, and it is spread in agricultural and forest landscapes of many hilly and mountain areas, covering more than 2.5 million hectares (Conedera et al. 2016). Chestnut has been intensively cultivated for centuries as a monoculture, even at the limits of its ecological range, both for wood production (coppice and high forest) and for fruit production (Pitte 1986, Cutini 2001, Manetti et al. 2001, Marcolin et al. 2020), including a broad range of secondary products and ecosystem services. The resulting geographic distribution, silvicultural system and structure of chestnut forests are the results of humanity's interest in its multiple uses (Bernetti 1995, Gomes-Laranjo et al. 2009).

However chestnut forests over the last century have been progressively abandoned or managed as coppices for timber production due to changing social needs (Vogt et al. 2006, Conedera et al. 2004, Venanzi et al. 2020).

Consequently, the current surface of chestnut forests is almost all coppice forests, and only a small part is made up of high forest stands (Conedera et al. 2016, Bruzzese et al. 2020). Today, many chestnut coppices have aged beyond the normal cultivation cycle and are frequently affected by pests or diseases (Manetti et al. 2017), as well as being particularly vulnerable to fires. In addition, in the absence of management, over time, chestnut stands become unstable and tend to uproot (Vogt et al. 2006). This has caused a severe decrease in biodiversity in these forest ecosystems (Gondard et al. 2006, Obrist et al. 2011, Parisi et al. 2020) and reduced ecosystem service (San Roman Sanz et al. 2013).

In recent years, current European and national strategies to reduce the use of fossil fuels and the related increasing demand of renewable bio-energy sources have given a new boost to the coppice system, so that the need for improved management of these stands is emerging (Cutini et al. 2018, Marcolin et al. 2020). In addition, the valorisation of chestnut coppices is also important for the survival of biodiversity heritage, traditional landscapes and cultural and economic models linked to the chestnut (Bounous 2002), thus contributing to the provision of several environmental services still relevant today, such as water regulation, protection of the territory, landscaping, recreational activities (Manetti et al. 2017). This restoration of chestnut coppices is also necessary because chestnut coppices supply wood products that are today widely used and requested by the market. On the other hand, the good technological characteristics of chestnut wood make the assortments obtainable an ecologically sustainable product, replacing other climate-altering materials.

However, the renewed interest in coppice wood products increased the need for a solid knowledge of the most suitable restoration practices of overaged and abandoned coppices (Marcolin et al. 2020). Generally, almost all the chestnut coppices are managed with a rotation cycle of 15-25 years (Del Favero 2010), no thinning and 50-80 standards (reserve trees) per hectare (Manetti et al. 2001).

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Nevertheless, the absence of thinning in Mediterranean coppice forests may led to degradation and higher vulnerability to fires, which are always very frequent in such environments (Iovino et al. 2021). Furthermore, chestnut sprouts have a rather thin bark that can lead to serious damage due to the action of the fire. The vulnerability of coppice chestnut forests to fire can be attributed to *(i)* the typical Mediterranean climactic environment (hot and dry for a long time); *(ii)* the absence of cultivation treatments, which favours a forest structure characterised by an intricate set of stems and branches, without vertical and horizontal interruptions in the canopy. These two factors result in an increase in the fuel load, which makes these formations even more sensitive to fire risk. The land abandonment in recent decades has also increased the fire frequency in chestnut woods, so much so that the chestnut coppice forests are among the most affected forest categories by fires in many European regions. In Italy for example, fire incidence in chestnut formations is almost 21% of the total forest area affected by fires (INFC 2007).

Fortunately, chestnut coppices forests regenerate more easily after fire passage, than other forest types. The rapid after fire vegetative resprouting is the fire defence strategy which characterises these forest formations and which makes it easier to regenerate the forest after the fire (Ciancio and Nocentini 2004). Maringer et al. (2012) reported that chestnut was the only species that emitted a significant number of shoots after a high-intensity fire that occurred in a mixed forest of chestnut trees (*Castanea sativa* Mill.), beech (*Fagus sylvatica* L.) and deciduous oaks (*Quercus spp.*) in the Swiss canton of Ticino.

However, since the high frequency of fires in the Mediterranean basin, fire protection based on an integrated approach to fire planning, with fighting systems and prevention activities, is essential to mitigate the effects of fires on fauna, vegetation, soil and the atmosphere (Johnson and Miyanishi 2001, Keller et al. 2002, Romeo et al. 2020).

Fire prevention activities include all those silvicultural operations (thinning, cleaning, pruning, prescribed burning) that affect the composition and structure of the forests (Corona et al. 2015). These activities can be classified with the term “fire smart management of forest landscapes” (Fernandes 2008, 2013) since the approach is based on the management of fuels in the most at-risk areas and on their overall reduction at the landscape level.

The usefulness of forest management activities in fire prevention and forest fuel reduction has already been highlighted in several studies (McKelvey et al. 1996, Graham et al. 1999, Allen et al. 2002, Pollet and Omi 2002, Agee and Skinner 2005, Skog et al. 2006, Reinhardt et al. 2008, Foresta et al. 2016, Moreira et al. 2020).

In recent years, several authors have carried out studies on the management methods of chestnut coppices (Menéndez-Miguélez et al. 2015, Mattioli et al. 2016, Pinchot et al. 2017, Manetti et al. 2018, Beccaro et al. 2019, Marcolin et al. 2020, Venanzi et al. 2020). However, there is a lack of studies regarding *(i)* the economic effects in terms of silvicultural prevention, *(ii)* the effects on the reduction of the fuel load, *(iii)* the horizontal and vertical continuity of fuels, *(iv)* the fire propagation.

To assess the appropriateness and effectiveness of preventive management measures (e.g. thinning) in such stands, particularly vulnerable as chestnut coppices, it is necessary to first assess the fuel load and its potential impact on wildfire. Subsequently, it is crucial to investigate the amount of fuel and the respective heat energy that can be potentially removed through these interventions.

In this framework, the present study has considered chestnut coppices of different ages located in two regions of southern Italy (Campania and Calabria) with the following objectives:

- *(i)* quantify the above-ground phytomass which could potentially be eliminated with the cleaning and thinning operations in chestnut coppices
- *(ii)* estimate the reduction in pyrological potential following these operations
- *(iii)* estimate the amount of water, pre and post intervention, necessary for extinguishing
- *(iv)* quantify the effects of such interventions on reducing the propagation of fires at the landscape scale
- *(v)* identify the most effective management model for silvicultural prevention

Materials and Methods

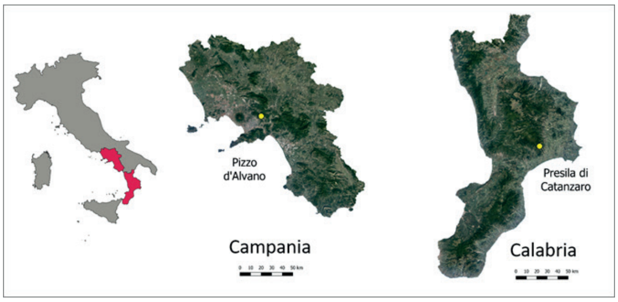
Study area and field survey

The examined chestnut coppices are in two regions of southern Italy: Calabria and Campania. These regions represent 8.8% (69,370 ha) and 6.7% (53,200 ha), respectively (MIPAAFT 2019) of the total area occupied by chestnut woods at the national level. In these regions two peculiar territorial contexts were identified due to the presence of chestnut coppices.

In Calabria the study areas fall within Presila di Catanzaro (between 39°01’ and 39°03’ N; 14°42’ and 14°46’ E) (Catanzaro Province), at altitudes between 800 and 1,200 m above sea level. In Campania the study area falls within the area of Pizzo d’Alvano (between 40°47’ and 40°52’ N; 14°35’ and 14°44’ E) (Salerno and Avellino Provinces), at altitudes between 170 and 1,100 m above sea level (Fig. 1).

The study area in Calabria covers a total surface of 1,002 ha (1.4% of the regional chestnut area) made

Figure 1 - Location of study areas: 1. Chestnut coppices at Pizzo d'Alvano (Campania); 2. Chestnut coppices at Presila di Catanzaro (Calabria).



up of coppices with a maximum age of 50 years. Furthermore, the area in Campania covers a total surface of 2,232 ha (4.2% of the regional chestnut area) made up of coppices with a maximum age of 30 years. These stands have never been subjected to cleaning or thinning.

The climatic context for both areas is the Mediterranean climate with differences in precipitation and the thermal conditions linked to the variations in altitude and the macro-exposure of the slopes. In the Campania area the average annual rainfall varies from 1,012 to 1,359 mm, with 68% of rainfall concentrated in the autumn-winter period and 10% in the summer. The average annual temperature is between 17°C in the lower part (100 m a.s.l.) and 10°C in the higher part (1,134 m a.s.l.). At the same levels the average temperature of the coldest month is respectively 8.8 and 0.5°C, while that of the hottest month is 25.1 and 18.8°C. In the study area of Presila di Catanzaro, the average annual temperature is between 11 and 12°C, that of the coldest month varies from 1 to 3°C, with an absolute minimum of -14°C. The average annual rainfall amounts to 1,195 mm.

The lithologic substratum of the Campania area consists of carbonate rocks and the soil, according to the Soil Taxonomy (USDA 1998), belongs to the order of Andisols, which developed from pyroclastic flow and fall material coming from the nearest eruptive centres. These soils are characterised by considerable fertility and thickness. The Calabrian area is instead characterised by a lithologic substratum consisting of metamorphic rocks (gneiss, schists and phyllites) from which soils were formed, according to the Soil Taxonomy, by the large group of Dystrudepts. The soils are well-structured, moderately deep and with frequent skeletons.

The fire regime is characterised, on average, by 2,882 fire, 5,827 ha of total annual burnt area and 2 ha of average fire size in Campania (Regione Campania 2020) and by 957 fires, 12,485 ha of total annual burnt area and 14 ha of average fire size in Calabria (Regione Calabria 2018). In both areas, the fire season is between July and September.

Analyses and data processing

Colour orthophotos with 10x10 resolutions were consulted for each area, available online on the national geoportal (http://www.pcn.minambiente.it/GN/). A total of 63 circular plots of 400 m^2 each were realized in the two areas (15 in Calabria and 48 in Campania), positioned through a systematic sampling system and representative of the different dendro-structural characteristics of the stands. In each plot, the diameter at breast height (*DBH*) of all trees with a diameter ≥ 1 cm was measured and, on each stump, the total height (*Ht*) and height of insertion of the crown (*Hc*) of the dominant shoot were measured. The age of the shoots with *DBH* > 5 cm was determined by counting the rings present in the cores extracted at the base of the stem using a Pressler's increment borer. For shoots with a diameter less than 5 cm, the age was estimated by breaking down, 5 shoots for each diameter class in each plot, and subsequently counting the rings present at the base of the stem.

The maps of the chestnut coppices of the two study areas were carried out fusing photo-interpretation, dividing the areas with homogeneous characteristics in terms of texture and structure and subsequent verification of the dendro-structural characteristics in the field.

Each of the two maps consists of a geodatabase in which a basic cartographic unit is a coltural unit (compartment), which in the Calabria area has an average size of 20.9 ha (SD ±18.3) and in Campania has an average size of 5.1 ha (SD ± 9.3). Each plot was homogeneous in terms of the age and composition of the stand and for site ecological conditions.

The data collected in the plots allowed defining the total distribution of the shoots as a function of age and, through the average value of diameter by age class and the relative standard deviation, the normal diametric distribution of shoots for each age class, both alive and dead, was defined for both study areas. This allowed defining the variation of the total number of living and dead shoots over time.

The above-ground phytomass (AGP_{tot}) (Mg ha^{-1}) of the trees, divided between stem and large branches (branches with a diameter > 5cm) (AGP_{slb}) and small branches (diameter < 5cm) (AGP_{sb}) was estimated with the following models defined for the National Italian Forest Inventory (INFC 2005, Tabacchi et. 2011)

$$AGP_{slb} = -9.5407 \cdot 10^{-1} + 1.8335 \cdot 10^{-2} \cdot DBH^2 \cdot H_t + 1.9237 \cdot 10^{-1} \cdot H_t \quad \text{(eq. 1)}$$

$$AGP_{sb} = -7.9938 \cdot 10^{-1} + 2.6769 \cdot 10^{-1} \cdot DBH^2 \cdot H_t + 6.9544 \cdot 10^{-1} \cdot H_t \quad \text{(eq. 2)}$$

where:

AGP_{slb} = above-ground phytomass of the stem and large branches (kg)

AGP_{sb} = phytomass of the small branch (kg)

DBH= diameter at 1.30 m (cm)

H_t = total height (m)

The development of the total height (H_t) and the height of insertion of the crown (H_c) was carried out by applying a single model in which the total number of trees per hectare (N_t), age (AGE) and DBH are considered as independent variables. On the other hand, height–diameter relationships with a combination of these variables have been included in several modelling approaches of tree growth (Clutter et al. 1983, Corona et al. 2002, Marziliano et al. 2019). The model coefficients were defined through stepwise regression. For the total height (H_t) the height of all the trees of the stand was estimated, while for the height of insertion of the crown (H_{bc}), it was sufficient to only estimate the heights of the tree of the average diameter. The following models were used:

$$H_t = e^{\left[3.142+1.01\cdot10^{-6}\cdot N_t+2.12\cdot10^{-5}\cdot\frac{1}{AGE}-6.058\cdot\frac{1}{DBH}+10.358\cdot\frac{1}{DBH\cdot AGE}\right]} \quad \text{(eq. 3)}$$

R^2 = 0.64, RMSE = 0.36

$$H_{bc} = e^{\left[1.728-5.564\cdot10^{-5}\cdot N_t-0.402\cdot\frac{1}{AGE}+2.436\cdot\frac{1}{DBH}-11.110\cdot\frac{1}{DBH\cdot AGE}\right]} \quad \text{(eq. 4)}$$

R^2 = 0.61, RMSE = 0.42

Once the age, diameters distribution of the shoots and above-ground phytomass were known, the pyrological potential was estimated in terms of the amount of heat energy theoretically produced per surface unit, in the case of total combustion of the above-ground phytomass. The heat energy was estimated using the following formula (Corona et al. 2015):

$$HE_T = AGP_{slb}\cdot HV_{slb} + AGP_{sb}\cdot HV_{sb} \quad \text{(eq. 5)}$$

where:

HE_T = total heat energy (MJ·ha^{-1});

AGP_{slb} = stem and large branches phytomass (Mg·ha^{-1});

AGP_{sb} = small branches phytomass (Mg·ha^{-1});

HV_{slb} = heating value of stem and large branches equal to 18,810 MJ·Mg^{-1} (Hellrigl 2004)

HV_{sb} = heating value of the branchwood equal to 19,750 MJ·Mg^{-1} (Hellrigl 2004)

The interventions hypothesised for the reduction of above-ground phytomass, aimed at reducing the risk of fire, refer to the cultivation algorithms defined by Ciancio and Nocentini (2004) for the chestnut tree and appropriately adapted to local conditions. Depending on the maximum age recorded in each territorial context, the following two cultivation algorithms based on the cutting cycle were considered for the Campania area: (1) 18-year cutting cycle (T18) and (2) 30-year cutting cycle (T30); one only cultivation algorithm for the Calabrian area: (3) 50-year cutting cycle (T50) (Tab. 1). The algorithms refer to the customary rotation cycles of private properties (T18) and customary rotation cycles of public properties (T30 and T50).

The percentages of cleaning and thinning were defined based on the variation of the total number of living and dead shoots over time. Through the cleaning, an intervention was simulated where dead and excess shoots were eliminated, starting from the smallest diameters, and bringing the number of shoots to the number of live shoots that the stand would have at 10 years (for T18) and 15 years (for T30 and T50) respectively. The same intervention modalities for thinning at 15 years in T50, reducing the number of shoots to that which the stand would have at 30 years, as well as at 10 (T18), 15 (T30) and 30 (T50) years, bringing the number of shoots to that which they would have respectively had at the end of the rotation cycle (Fig. 2).

Figure 2 - Example of the sequence of interventions: rotation cycle T=30 yrs. Variation of the number of trees per hectare according to age (Cl: cleaning; Th: thinning; Har: harvesting).

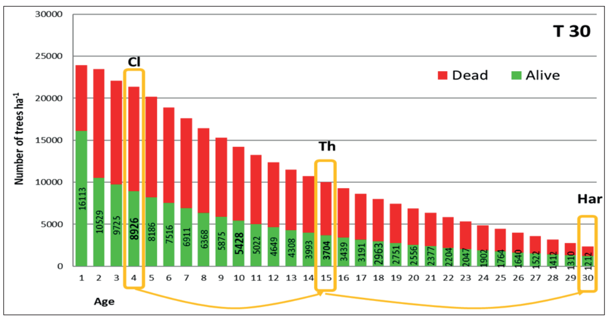


Table 1 - Characteristics of cultivation interventions.

Site	Rotation cycle years	N° of intervention	Type of intervention	Year of intervention
Pizzo d'Alvano (T18)	18	2	1 cleaning and 1 thinning	4 and 10
Pizzo d'Alvano (T30)	30	2	1 cleaning and 1 thinning	4 and 15
Presila di Catanzaro (T50)	50	3	1 cleaning and 2 thinning	4, 15 and 30

The variation of the critical surface intensity (CSI - kW·m^{-1}) was also estimated, before and after the intervention, for the passage from surface fire to crown fire, applying the equation of Van Wagner (1989) in which account is taken of the height of insertion of the crown (H_{bc}) and the relative foliar moisture content (FMC). The FMC varies between 60 and 140% (Cruz and Alexander 2010) but, as considered acceptable by several authors (Agee et al. 2000, Scott and Reinhardt 2001), was set at 100%.

$$CSI = 0.001 \cdot (H_{bc})^{1.5} \cdot (460+25.9 \cdot FMC)^{1.5} \qquad \text{(eq. 6)}$$

Moreover, although with a margin of error due to the complexity of the variables that influence the phenomenon, the quantities of water necessary for extinguishing were determined, before and after the silvicultural interventions hypothesised for the coppices in the case of total combustion of the above-ground phytomass.

The following formula was used to estimate the water quantities (Marotta and Mossa Verre 1998)

$$W_{H2O} = \frac{HE}{\beta \cdot \Delta h_w} \qquad \text{(eq. 7)}$$

where:

W_{H2O} = quantity of water necessary for the absorption of the heat energy developed in the combustion (Mg·ha^{-1});

HE = heat energy (MJ·ha^{-1});

β = efficiency coefficient equal to the ratio between the quantity of water poured on the fire and which undergoes complete vaporisation and the total quantity of water supplied; this coefficient represents the yield of the extinguishing process. Practical and experimental considerations (Delle Chiaie 1976) led to estimating rather low values of probably less than 0.6-0.7. According to the literature (Marotta and Mossa Verre 1998) and in our case was assumed to be 0.4.

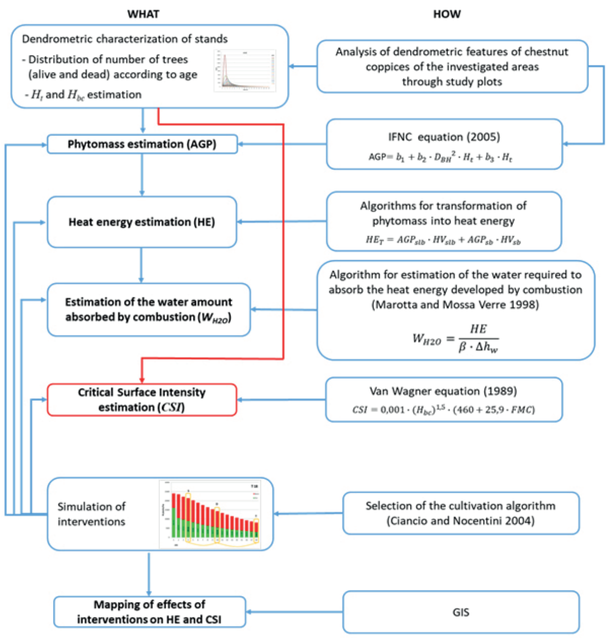
Δh_w = latent heat of water evaporation at 100°C (2,440 MJ·Mg^{-1}).

A dendro-auxometric approach was adopted to evaluate the quantity of standing phytomass on a territorial basis, with the variation of the age and the applied cultivation algorithms. Starting from the age attributed by photo-interpretation, and verified in the field, and the relative normal diametric distribution of the shoots and the above-ground phytomass present based on the INFC 2005 model was estimated (Tabacchi et al. 2011). Subsequently, starting from the distribution of the stands according to actual age, cleaning and thinning interventions were simulated (cleaning at 4 years and thinning at 10-15-30 years, depending on the duration of the rotation cycle), during an entire rotation cycle: 18 and 30 years in Pizzo d'Alvano and 50 years in Presila di Catanzaro. In this way it was possible to derive the effects of the silvicultural interventions on the pyrological potential.

At a territorial level, the CSI values were calculated according to the age of the stands (before and after silvicultural interventions envisaged by the different cultivation algorithms) and were evaluated by calculating the weighted averages based on the surfaces available for each age class.

In this way, maps were obtained that, for each year of the crop cycle, show the distribution of the heat energy subtracted, the amount of water saved and the critical surface intensity. The conceptual scheme of the procedure followed Figure 3.

Figure 3 - Adopted protocol flowchart.



Results

Stand level

The chestnut coppices located in Presila di Catanzaro have ages varying from less than 10 years up to 50 years (Fig. 4), with a greater concentration (48%) in the last age class (Tab. 2), while those in Campania have ages varying from less than 10 years up to 30 years (Fig. 5), with a greater concentration (58%) in the age group between 10 and 20 years (Tab. 2).

The parameters characterising the stands before and after the silvicultural interventions (cleaning and thinning) are shown in Table 3. In both localities the number of shoots was reduced from a minimum of 72% to a maximum of 82% with the cleaning interventions (Fig. 4÷6) (Tab. 3). In addition, there was a further reduction with the thinning ranging between

Figure 4 - Chestnut coppice in Presila di Catanzaro at the age of 3 years.

Figure 5 - Chestnut coppice in Pizzo d'Alvaro at the age of 15 years.

Table 2 - Surface of the investigated chestnut coppices according to age.

Age years	Pizzo d'Alvano ha – (%)	Presila di Catanzaro ha – (%)
<10	601 (27%)	112 (11%)
10 to 20	1,306 (58%)	98 (10%)
20 to 30	325 (15%)	314 (31%)
30 to 50		478 (48%)
TOTAL (Ha)	2,232	1,002

28% and 67%, bringing the number of shoots to 1,051 and 1,212 per hectare in Presila di Catanzaro and in Pizzo d'Alvano respectively (Fig. 4÷6) (Tab. 3).

After the silvicultural interventions there was a considerable increase in the average diameter of the shoots (*Dm*), as well as the total height (*Hm*) and height of insertion of the crown (H_{bc}) (Tab. 3). This parameter, of particular interest for the prevention of crown fires, shows a substantial increase, especially in the 4-year cleaning phase, ranging between

Table 3 - Stand characteristics pre- and post-intervention.

Site		Pizzo d'Alvano		Pizzo d'Alvano		Presila di Catanzaro		
Rotation cycle (years)		T18		T30		T50		
Year of intervention		4	10	4	15	4	15	30
Nt	Pre	21,343	5,428	21,343	3,704	8,200	2,296	1,462
	Post	5,428	2,963	3,704	1,212	2,296	1,462	1,051
	%_ΔNt	*-74.6%*	*-45.4%*	*-82.6%*	*-67.3%*	*-72.0%*	*-36.3%*	*-28.1%*
Dm (cm)	Pre	2.59	6.69	2.59	9.33	3.07	13.12	20.03
	Post	4.23	8.40	4.62	10.34	5.93	14.74	22.81
	%_ΔDm	*63.5%*	*25.6%*	*78.6%*	*10.8%*	*93.0%*	*12.4%*	*13.9%*
Hm (m)	Pre	6.18	10.98	6.18	13.07	7.55	15.41	17.43
	Post	10.25	12.77	10.97	13.79	12.92	16.11	18.04
	%_ΔHm	*65.7%*	*16.3%*	*77.3%*	*5.5%*	*71.3%*	*4.5%*	*3.5%*
Hbc (m)	Pre	1.36	4.87	1.36	5.35	2.89	5.49	5.68
	Post	3.47	5.37	3.85	6.04	4.23	5.67	5.74
	%_ΔHbc	*155.2%*	*10.2%*	*182.8%*	*12.9%*	*46.5%*	*3.3%*	*1.0%*
AGPtot ($Mg \cdot ha^{-1}$)	Pre	64.99	122.35	64.99	157.57	27.26	138.98	268.43
	Post	47.41	100.27	36.97	98.39	13.55	107.67	234.91
	%_ΔAGPtot	*-27.1%*	*-18.0%*	*-43.1%*	*-37.6%*	*-50.3%*	*-22.5%*	*-12.5%*
HE ($MJ \cdot ha^{-1}$)	Pre	1,250,224	2,335,819	1,250,224	3,000,593	527,320	2,644,878	5,094,745
	Post	911,912	1,912,007	710,623	1,871,035	263,877	2,049,001	4,458,563
	%_ΔHE	*-27.1%*	*-18.1%*	*-43.2%*	*-37.6%*	*-50.0%*	*-22.5%*	*-12.5%*
CSI ($kW \cdot m^{-1}$)	Pre	267.3	1812.7	267.3	2083.5	826.1	2,166.0	2,278.2
	Post	1,089.7	2,095.8	1,271.3	2,497.8	1,465.3	2,273.0	2,313.8
	%_ΔCSI	*307.6%*	*15.6%*	*375.6%*	*19.9%*	*77.4%*	*4.9%*	*1.6%*
W_{H2O} (Mg·ha-1)	Pre	1,281	2,393	1,281	3,074	540	2,710	5,220
	Post	934	1,959	728	1,917	270	2,099	4,568
	%_ΔW_{H2O}	*-27.1%*	*-18.1%*	*-43.2%*	*-37.6%*	*-50.0%*	*-22.5%*	*-12.5%*

Nt= number of trees; Dm= mean diameter; Hm= mean height; Hbc= height of crown insertion; AGPtot= total above-ground phytomass; HE= heat energy; CSI= Critical Surface Intensity; W_{H2O}= water quantity

Figure 6 - Pizzo d'Alvano: rotation cycle = 18 yrs. Distribution of the number of trees before and after the Interventions (Cl: cleaning; Th: thinning).

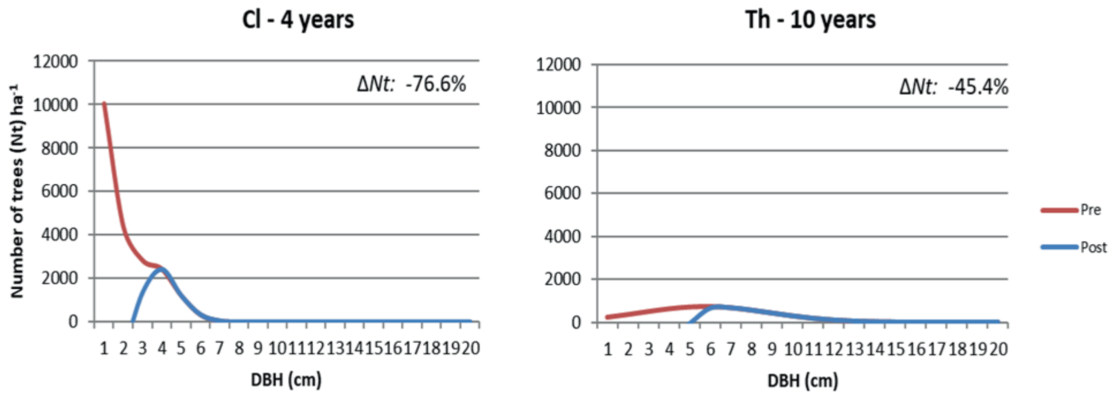


Figure 7 - Pizzo d'Alvano: rotation cycle = 30 yrs. Distribution of the number of trees before and after the Interventions (Cl: cleaning; Th: thinning).

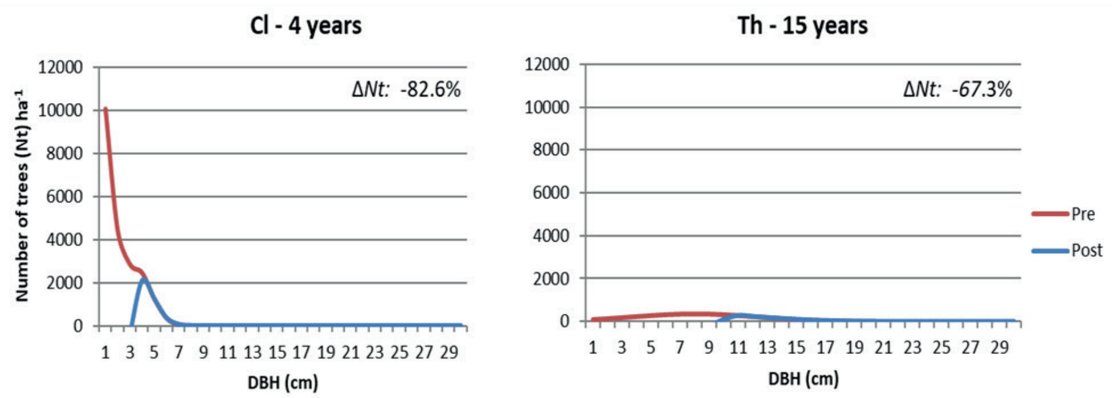
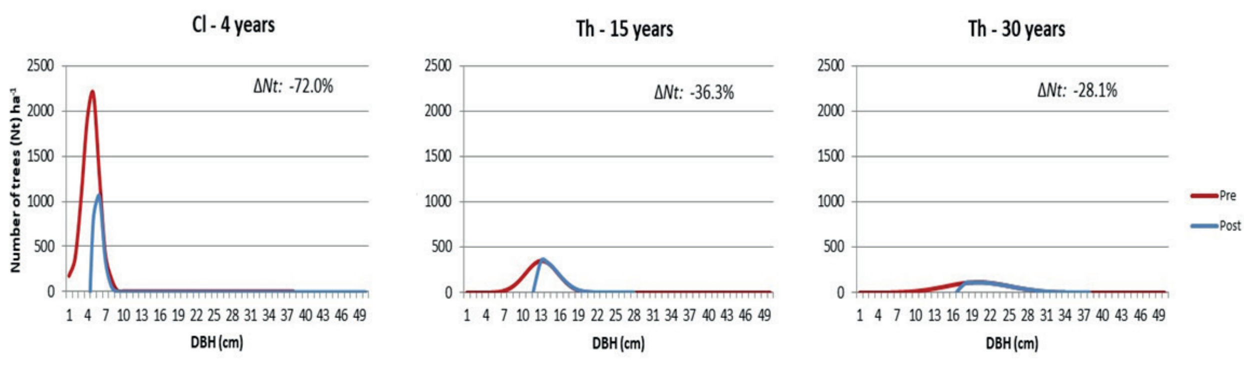


Figure 8 - Presila di Catanzaro: rotation cycle = 50 yrs. Distribution of the number of trees before and after the interventions (Cl: cleaning; Th: thinning).



46 and 182% (Tab. 3). In terms of above-ground phytomass (AGP_{tot}), there was a reduction between about 50% at 4 years and almost 13% at 30 years with the cleaning and thinning interventions (Tab. 3).

The variation of the heat energy (HE) theoretically produced by the total combustion of the standing phytomass, being closely connected to the latter, had a substantially identical trend (Tab. 3). In absolute terms, the minimum pre-cleaning and pre-thinning values were recorded in Presila di Catanzaro respectively with 52,7320 MJ·ha^{-1} at 4 years and maximum at 30 years with 5,094,745 MJ·ha^{-1}. Post-cleaning the minimum was 26,3877 MJ·ha^{-1} and post-thinning the maximum was 4,458,563 MJ·ha^{-1} (Tab. 3).

The variation of the critical surface intensity (CSI), linked to the variation of the height of insertion of the crown, showed considerable increases especially following the cleaning interventions at 4 years (up to about 375%), while after the thinning the increases were more contained (up to about 20%) (Tab. 3).

Finally, the estimate of the quantity of water needed (W_{H2O}) to absorb the heat energy produced (HE) before and after the intervention showed interesting data in terms of absolute values. In Presila di Catanzaro, the respective minimum and maximum values before the intervention were 540 and 5,220 Mg·ha^{-1}, and the minimum and maximum values post-intervention were 270 and 4,568 Mg·ha^{-1}, respectively. The percentage reduction was between 12.5% and 50%. At the same site, the largest percentage reduction was recorded following the 4-year cleaning (Tab. 3).

Territorial level

At the territorial level, the analysis concerned (1) the total variation of the aboveground phytomass (*AGP*), (2) the heat energy subtracted (*HE*), (3) the critical surface intensity (*CSI*), (4) the reduction of the quantity of water needed (W_{H2O}) for the dissipation of the heat energy produced in the case of total combustion of the standing phytomass on the entire surface of the areas considered.

Three of the variables considered (*AGP*, *HE* and W_{H2O}), being mutually correlated, had the same variation trend for the same rotation cycle duration (Fig. 9÷11). The widest range of variation was observed for Pizzo d'Alvano (T30) while the smallest was observed in Presila di Catanzaro (T50) (Fig. 9÷11). In percentage terms, the total changes during the entire rotation cycle were quite limited and ranged from -0.7% to -1.9% respectively in Presila di Catanzaro (T50) and Pizzo d'Alvano (T30) (Tab. 4).

Figure 9 - Above-ground phytomass removed (ΔAGP) according to the different protocols. The midlines of the boxplots are the median, the boxes show the 1st and 3rd quartiles and the whiskers extend up to 1.5 times the interquartile range, while values exceeding this threshold are considered as outliers and plotted as open circles.

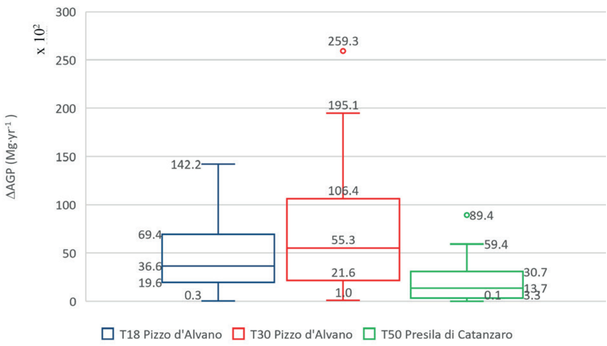


Figure 10 - Reduction of heat energy (ΔHE) according to the different protocols. The midlines of the boxplots are the median, the boxes show the 1st and 3rd quartiles and the whiskers extend up to 1.5 times the interquartile range, while values exceeding this threshold are considered as outliers and plotted as open circles.

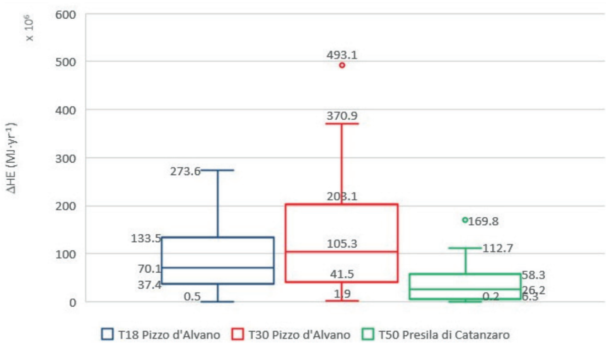
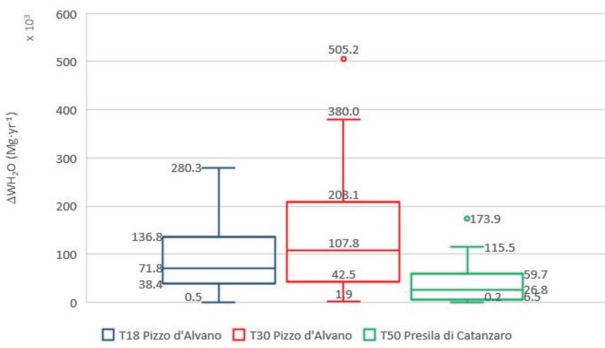


Figure 11 - Reduction of water amount (ΔW2O) according to the different protocols. The midlines of the boxplots are the median, the boxes show the 1st and 3rd quartiles and the whiskers extend up to 1.5 times the interquartile range, while values exceeding this threshold are considered as outliers and plotted as open circles.



The highest average annual total phytomass removed (ΔAGP_TOT_m) was recorded in Pizzo d'Alvano (T30) with 6,656 Mg·year^{1} while the lowest was in Presila di Catanzaro (T50) with 1,612 Mg·year^{1} (Tab. 4). During the entire rotation cycle the total phytomass removed varies from a minimum of 0.3·10^{2} to a maximum of 259.3·10^{2} Mg·year^{1} in Pizzo d'Alvano and between 0.1·10^{2} and 89.4·10^{2} Mg·year^{1} in Presila di Catanzaro (Fig. 9). On average, for every hectare and year from 1.6 to 3 Mg·ha^{-1}·year^{1} were removed (Tab. 4).

The average annual heat energy subtracted with the interventions (ΔHE_TOT_m) was the greatest in Pizzo d'Alvano (T30) with 127.0·10^{6} MJ·year^{1} and the least in Presila di Catanzaro with 30.7·10^{6} MJ·-year^{1} (Tab. 4). The total heat energy subtracted varied during the entire rotation cycle, from 0.5·10^{6} and 493.1·10^{6} MJ·year^{1} in Pizzo d'Alvano and between 0.2·10^{6} and 169.8·10^{6} MJ·year^{1} in Presila di Catanzaro (Fig. 10). On average, for each hectare and year from 30,590 to 56,899 MJ·ha^{-1}·year^{1} were subtracted (Tab. 4).

As regards the variation of the average annual water quantity ($\Delta W_{H2O}\_TOT_m$) the highest value was observed in Pizzo d'Alvano (T30) with 130,122 Mg·year^{1} and the lowest was in Presila di Catanzaro with 31,405 Mg·year^{1} (Tab. 4). During the entire rotation cycle the amount of water saved varied from 0.5·10^{3} and 505.2·10^{3} Mg·year^{1} in Pizzo d'Alvano and between 0.2·10^{3} and 173.9·10^{3} Mg·year^{1} in Presila di Catanzaro (Fig. 11). On average, from 31 to 58 Mg·ha^{-1}·year^{1} were saved per hectare every year (Tab. 4).

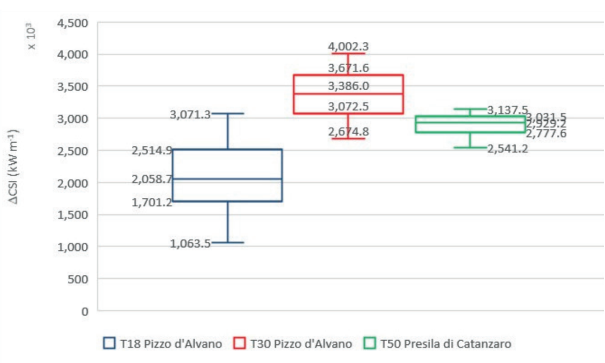
Finally, the increase in the average annual critical surface intensity (ΔCSI_TOT_m) was greatest in Pizzo d'Alvano (T30) with 3,347,424 kW·m^{-1}·year^{1} while the lowest was in Presila di Catanzaro with 872,941 kW·m^{-1}·year^{1} (Tab. 4). The increase in critical sur-

Table 4 - Phytomass (AGP), heat energy (HE), critical surface intensity (CSI) and water amount (H2O) necessary for the absorption of heat energy, pre- and post-intervention on a territorial scale in a complete rotation cycle.

	Site Surface (ha) Rotation cycle (years)	Pizzo d'Alvano 2,232 18	Pizzo d'Alvano 2,232 30	Presila di Catanzaro 1,002 50
AGP	TOT Pre *(Mg)*	4,643,105	10,613,561	11,188,277
	TOT Post *(Mg)*	4,573,852	10,413,895	11,107,670
	ΔAGP_TOT (Mg)	*69,252*	*199,667*	*80,607*
	ΔAGP_TOTm year (Mg· yr-¹)	3,847	6,656	1,612
	% ΔAGP_TOT	*-1.5%*	*-1.9%*	*-0.7%*
	AGPm ha *(Mg·ha-¹)*	*31*	*89*	*80*
	AGPm ha year *(Mg·ha-1·yr-¹)*	*1.7*	*3.0*	*1.6*
HE	*TOT Pre (MJ)*	88,584,144,127	201,870,962,594	212,337,853,884
	TOT Post (MJ)	87,257,581,154	198,061,004,464	210,805,299,806
	ΔEE_TOT (MJ)	1,326,562,973	3,809,958,129	1,532,554,078
	$ΔHE\_TOT_m$ year (MJ· yr-¹)	73,697,943	126,998,604	30,651,082
	% ΔHE_TOT	*-1.5%*	*-1.9%*	*-0.7%*
	HE_m ha *(MJ·ha-¹)*	594,338	1,706,970	1,529,495
	HE_m ha year *(MJ·ha-¹·yr-¹)*	*33,019*	*56,899*	*30,590*
CSI	TOT Pre *(kW· m-¹)*	31,686,505	87,760,478	101,136,606
	TOT Post *(kW· m-¹)*	69,185,448	188,183,184	144,783,641
	ΔCSI_TOT (kW· m-¹)	37,498,943	100,422,706	43,647,035
	$ΔCSI\_TOT_m$ year (kW· m-¹·yr-¹)	2,083,275	3,347,424	872,941
	% ΔCSI_TOT	*+118.3%*	*+114.4%*	*+43.2%*
	CSIm ha *(kW m-¹ ha-¹)*	16,801	44,992	43,560
	CSIm ha year *(kW· m-¹ ha-¹·yr-¹)*	*933*	*1,500*	*871*
W_{H2O}	TOT Pre *(Mg)*	90,762,443	206,835,003	217,559,277
	TOT Post *(Mg)*	89,403,259	202,931,357	215,989,037
	$ΔW_{H2O}$_TOT (Mg)	1,359,183	3,903,646	1,570,240
	$ΔW_{H2O}$_TOTm year (Mg· yr-¹)	75,510	130,122	31,405
	% $ΔW_{H2O}$_TOT	*-1.5%*	*-1.9%*	*-0.7%*
	W_{H2O}m ha *(Mg·ha-¹)*	609	1,749	1,567
	W_{H2O}m ha year *(Mg·ha-¹·yr-¹)*	*34*	*58*	*31*

TOT Pre = total pre-intervention; TOT Post = total post-intervention; ΔAGP_TOT = total above-ground phytomass variation; ΔAGP_TOTm = variation of mean annual total phytomass; ΔHE_TOT = variation of total heat energy; ΔHE_TOTm = variation of mean annual total heat energy; ΔCSI_TOT = variation of total critical surface intensity; ΔCSI_TOTm = variation of mean annual total critical surface intensity; $ΔW_{H2O}$_TOT = variation of total water quantity; $ΔW_{H2O}$_TOTm = variation of mean annual total water amount; AGPm = average phytomass subtracted; HEm = average heat energy subtracted; CSIm = average increase of critical surface intensity; W_{H2O}m = average amount of water subtracted.

Figure 12 - Critical Surface Intensity (ΔCSI) according to the different protocols. The midlines of the boxplots are the median, the boxes show the 1st and 3rd quartiles and the whiskers extend up to 1.5 times the interquartile range.



face intensity varied from a minimum of $1{,}063.5 \cdot 10^3$ to a maximum of $4002.3 \cdot 10^3$ in Pizzo d'Alvano and between $2{,}541.2 \cdot 10^3$ and $3{,}137.5 \cdot 10^3$ in Presila di Catanzaro (Fig. 12). On average, for each hectare and year, there was an increase of between 871 and 1,500 $kW \cdot m^{-1} \cdot year^{1}$ (Tab. 4). In percentage terms, the total increase during the entire rotation cycle ranged from 43.2% to 118.3% respectively in Presila di Catanzaro (T50) and Pizzo d'Alvano for T30 (Tab. 4)

Discussion

The socio-economic changes that occurred in the Mediterranean basin after the Second World War (i.e. abandonment of traditional forest ecosystem management practices and uses), along with climate change and other factors, led to a greater probability of large forest fire occurrence (Fernandes et al. 2013). Currently, many scientists and managers are increasingly concerned about the resilience of existing chestnut landscapes to new fire regimes, particularly considering climate change and the lack of management practices (Grund et al. 2005, Krebs et al. 2012, Pezzatti et al. 2013, San Roman Sanz et al. 2013, Zlatanov et al. 2013).

In light of this and to mitigate the risk of "larger fires", landscape managers now seem to face a choice between increased fire suppression and silvicultural interventions of preventions (Fernandes et al. 2013, Khabarov et al. 2016).

Our study has demonstrated that cleaning and thinning carried out during the rotation cycle of chestnut coppices, can be an effective preventive silvicultural technique to reduce the occurrence of forest fires and mitigate their effects. However, a divergence emerges between the two investigated sites with respect to the average fire size (2 hectares in Campania vs 14 hectares in Calabria). In light of this, and also considering the expected fire regime trends towards greater average fire size, it may be necessary to intensify frequency and magnitude of silvicultural management interventions.

The results of the analyses carried out for chestnut coppices with three different rotation cycles (18, 30 and 50 years) showed the variations of the different parameters (AGP_{tot}, HE, CSI, W_{H2O}) at stand level and on a territorial scale, following simulated of silvicultural interventions of cleaning at 4 years and thinning at 10, 15 and 30 years.

At 4 years, the number of shoots was substantially different between Pizzo d'Alvano coppices, with higher density, and Presila di Catanzaro coppices, with lower density (Tab.3). Consequently, the relative above-ground phytomass was greater in the first locality than the second, despite the greater average diameter and the average height of the latter. However, it was in Presila di Catanzaro that the greatest percentage of reduction of phytomass carried out with cleaning was observed.

The number of shoots also affects the standing present at 15 years in coppices with rotation cycles of 30 and 50 years. In the coppices with 50-year rotation cycles, the number of shoots and the potentially flammable total phytomass is lower than in coppices with 30-year rotation cycles, despite the average diameter and average height being greater than those with 30-year rotation cycles are. With the same initial density (Pizzo d'Alvano) there was a greater phytomass removed for rotation cycles of 30 years, both at 4 and 15 years, compared to the 18-year rotation cycle, with cleaning and thinning interventions at 4 and 10 years (Tab. 3).

The amount of phytomass removed changes relative to the initial density, diameter, height and rotation cycle duration. However, what the different areas have in common is emphasised by the greater percentage of phytomass removed during the four-years compared to subsequent thinnings. This aspect is of particular importance as it is at the very beginning of the rotation cycle that the stands are more susceptible to fires due to a large number of small trees, both in diameter and in height, with crowns not far from the ground, and with a considerable quantity of deadwood relative to the dead shoots still standing (Marziliano et al. 2013).

Following the selection induced by silvicultural interventions, the density reduction determines not only a decrease in the potentially ignitable phytomass, but also modifications of the height of insertion of the crowns and, consequently, of the critical surface intensity (*CSI*) to which it is related. The cleaning interventions had a significant effect in raising the height of insertion of the crown: from just under 50% to over 180%; the thinning, on the other hand, had little impact on this parameter (Tab. 3). This led to a marked increase in *CSI* values. In fact in percentage terms, there was always a greater increase for cleaning ranging from 77% to 375% and more limited for thinning with values between 2% and 20% (Tab. 3). These results clearly show the greater effectiveness of the cleaning interventions compared to the thinning interventions in the reduction of the probability of the transition from surface fire to crown fire. Furthermore, even if late thinning can contribute to the creation of stands of high landscape value able to exercise good soil protection, it does not induce appreciable improvements from a production point of view (Macchioni and Pividori 1996, Fonti et al. 2009, Romagnoli et al. 2014, Manetti et al. 2017). Conversely, cleaning and thinning carried out on time contribute to reducing vulnerability to fires, as well as having a positive effect on stems quality (Fioravanti et al. 2002), vascular flora diversity (Gondard et al. 2006, Mattioli et al. 2008, Mattioli et al. 2016) and stands stability (Amorini et al. 2001, Manetti et al. 2017). Therefore, the fuel quantity reduction through silvicultural prevention interventions (e.g. prescribed burning, cleaning and thinning), allows for limiting catastrophic fires (Covington and Moore 1994), increasing the ecosystem resilience to future disturbances (Crotteau et al. 2016) and facilitating extinguishing interventions (Moghaddas and Craggs 2007) with relative cost reduction (Duguy et al. 2007). Among the different types of thinning, the type from below, compared to selective thinning from above, is the most suitable for fire prevention (Agee and Skinner 2005, Leone and Lovreglio 200, Corona et al. 2015).

The results obtained at the stand level have also allowed for verifying the extent to which the effects of the cleaning and thinning can make entire forest areas less vulnerable to fires. The results of our analyses showed that the amount of above-ground phytomass removed during the period of an entire rotation cycle duration at the territorial level (18, 30 or 50 years) reached 2%. These are fairly moderate values, but close (5%) to those reported by Cochrane et al. (2012), which can influence the behaviour of fires and therefore their final size. Therefore, to make the forest areas less vulnerable to the spread of flames, the effects that occur at the stand level must be amplified on a territorial scale through an adequate spatial distribution of the treated stands (Finney et al. 2007, Benali et al. 2021). Indeed, as reported by some authors (Agee et al. 2000, Fernandes 2010, 2013), silvicultural interventions carried out on entire surfaces in different areas of the wooded complex can act as fuel breaks. Furthermore, they hinder the propagation of fire and reduce its intensity (Finney 2001), resulting in more efficiency than linear interventions such as firebreaks (Fernandes 2013, Benali et al. 2021).

Finally, the values of the heat energy subtracted and the quantities of water necessary for extinguishing showed the same percentage variations of the removed phytomass, as the three variables were mutually correlated, for the same rotation cycle duration. However, in absolute terms, the amount of water that could be saved on average each year is not negligible. Indeed, an average annual reduction is estimated, varying according to rotation cycle duration, as between 31 and 58 Mg·ha^{-1}·year^{1}. With the same stand characteristics, the greatest savings are obtained for the 30-year rotation cycle, as the phytomass quantity removed is greater.

However, the two study areas have different characteristics relative to the fire regime. In recent decades, the area of Pizzo d'Alvaro has had a greater economic development than the Presila di Catanzaro area. This led to the abandonment of chestnut coppices management practices in Pizzo d'Alvaro, resulting in a greater accumulation of phytomass. Furthermore, in this area many chestnut coppices are found at lower altitudes (100-300 m a.l.s.) with higher temperatures than the Presila di Catanzaro area, and a greater probability of large forest fires. As shown in Pausas and Fernandez-Muñoz (2012), fire regimes in this type of landscapes tend to be increasingly "climate-driven" in contrast to the pre-industrial past when fire regimes were "fuel-limited". This hypothesis is also supported by Seijo et al. (2017) who states that the fire regime seems to be coupled with climate in site of a more economically developed area than in a less developed area.

The enhancement activities in chestnut coppices for increasing their resistance and resilience to natural and anthropic disturbances are also due to the considerable social, historical, environmental and landscape value of the chestnut stands. In addition, a strategy based on a high level of knowledge and a consolidated Traditional Ecological Knowledge (TEK; Berkes et al. 2000) in the use of the chestnuts, can promote forest management of chestnut stands as a possible tool to mitigate the effects of climate change on forest resources (Seijo et al. 2017, Bruzzese et al. 2020).

Finally, thinning could also be effectively combined with prescribed burning. Iovino et al. (2014) adopted an integrated approach of thinning and prescribed fire in a *Pinus halepensis* Mill. forest, highlighting the effectiveness of this coupling. Particularly, when carried out before thinning, the prescribed fire acts above all on the consumption of litter fuels and fine necromass. When carried out after thinning, the prescribed fire contributes to reducing the larger necromass (diameter between 0.6 and 7 cm) resulting from the cut (Iovino et al. 2014).

Furthermore, as shown in recent paper by Seijo et al. (2017), the fire seasonality linked to "Traditional Fire Knowledge"-based (TFK; Seijo et al. 2015) fire use practices result in a decreased burned area in the vegetative season. In this scenery, the use of prescribed burn in the non-vegetative season could be an effective fire management action in chestnut woodland landscapes (Seijo et al. 2017). Finally, a controlled low intensity fire with straw or chestnut leaf burns can also result in the control of fungal pests and insects, while simultaneously curbing understory fuel accumulation (Seijo et al. 2015).

Conclusions

In the Mediterranean environment, chestnut coppices are among the forest stands most affected by fires. This forest typology is characterised by a very high emission of shoots after coppicing, followed by considerable mortality in the following years. In the absence of silvicultural treatments, the structure of these stands often appears as an intricate set of stems and branches without vertical and horizontal interruptions in the canopy, and with an expansion of the fuel load that facilitates fire spread.

This study showed the importance that silvicultural interventions, such as cleaning and bottom-up thinning, have at both the stand and the territorial level on fires risk mitigation. In particular, the heat energy reduction subtracted in the event of total combustion, the water economy for extinguishing and the probability reduction of the passage of surface fire to a canopy fire, proved by the increase in critical surface intensity (*CSI*) was highlighted. The increase of *CSI* is particularly evident after the cleaning interventions which when carried out early (4 years), had a significant effect on the phytomass quantity eliminated and on raising the insertion base of the crown, causing a greater heat energy reduction. Therefore, forest management can also be very useful as fire prevention, reducing the risk of canopy fire, with a significant amount of water saved in case of surface fire and therefore with a considerable reduction in fire-fighting costs. With the same environmental conditions and dendrostructural characteristics, the most effective interventions were observed for the 30-year rotation cycle.

In geographic contexts where the risk of forest fires is high, it is more important than ever that fuel management, aimed at reducing the severity of fires and reducing large catastrophic events, is appropriately included in planning. The interventions must be distributed on the territory in space and time, with cleaning and thinning to interrupt vertical continuity (*ladder fuel*).

However, all the interventions must find the right balance (trade-off) between effectively combating fires and ecosystem services. It is also useful to remember that above all thinning can favour the entry and the speed of the wind, facilitating the drying up of the surface fuel and increasing the flame intensity as well as the rapid spread of the fire, with a consequent increase in the damage severity. Furthermore, the density reduction could cause an increase in surface fuels derived from slash and the possible development of herbaceous and shrubby layers. In these cases, it could be useful to apply prescribed fire for the elimination of surface fuel, to further reduce the fire risk.

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