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Testing an expanded set of sustainable forest management indicators in Mediterranean coppice area

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ABSTRACT

Although coppice forests represent a significant part of the European forest area, especially across southern Countries, they received little attention within the Sustainable Forest Management (SFM) processes and scenarios, whose guidelines have been mainly designed to high forests and national scale. In order to obtain "tailored" information on the degree of sustainability of coppices on the scale of the stand, we evaluated (i) whether the main coppice management options result in different responses of the SFM indicators, and (ii) the degree to which the considered SFM indicators were appropriate in their application at stand level. The study considered three different management options (Traditional Coppice TC, coppice under Natural Evolution NE, and coppice under Conversion to high forest by means of periodical thinning CO). In each of the 43 plots considered in the study, which covered three different European Forest Types, we applied a set of eighteen "consolidated" SFM indicators, covering all the six SFM Criteria (FOREST EUROPE, 2020) and, additionally, tested other sixteen novel indicators shaped for agamic forests and/or applicable at stand level. Results confirmed that several consolidated indicators related to resources status (Growing stock and Carbon stock), health (Defoliation and Forest damage), and socio-economic functions (Net revenue, Energy and Accessibility) were highly appropriate for evaluating the sustainability of coppice at stand level. In addition, some novel indicators related to resources status (Total above ground tree biomass), health (Stand growth) and protective functions (Overstorey cover and Understorey cover) proved to be highly appropriate and able to support the information obtained by the consolidated ones. As a consequence, a subset of consolidated SFM indicators, complemented with the most appropriate novel ones, may represent a valid option to support the evaluation of coppice sustainability at stand level. An integrated analysis of the SFM indicators showed that NE and CO display significant higher environmental performances as compared with TC. In addition, CO has positive effects also on socio-economic issues, while TC -which is an important cultural heritage and a silvicultural option that may help to keep local communities engaged in forestry – combines high wood harvesting rates with dense understory cover. Overall, each of the three management options showed specific sustainability values; as a consequence, their coexistence at a local scale and in accordance with the specific environmental conditions and the social-economic context, is greatly recommended since it may fulfill a wider array of sustainability issues.

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1. Introduction

Coppice forests cover about 23 million hectares in the Mediterranean area and represent a significant part (14%) of European forests. The share of forests under this management system varies a lot at a national and geographic level, from a negligible amount up to 50% (Balkans) of total forested area. Coppice forests coverage is considerable (exceeding 1,000,000 ha) in nine European Countries (France, Turkey, Spain, Italy, Greece, Bulgaria, Ukraine, Serbia, Bosnia & Herzegovina) (Unrau et al., 2018).

Coppice is a traditional forest management system exploiting the ability of many broadleaved tree species to regenerate new shoots from the stool after cutting (coppicing). It is usually characterized by short rotations, ranging from 15 to 20 years up to 50–60 years, depending on the tree species and the site conditions (Unrau et al., 2018). Cultivation techniques have been well documented since the Middle Ages (Piussi, 1982; Szabó et al., 2015; Piussi and Stiavelli, 1986; Piussi and Zanzi Sulli, 1997). Coppice has imprinted the broadleaved forest landscape across Europe since the establishment of the early human settlements, with important changes in terms of extention from 1600 to now (McGrath et al., 2015). The main products - firewood and charcoal - experienced an increasing global use because they met people's common daily needs, such as cooking food and domestic heating, whilst industrial development produced a further, huge demand for energy over the last centuries (Nocentini, 2009). The peak of coppice exploitation took place during the first industrial revolution whilst its role decreased due to the diffusion of fossil fuels since the mid-1900s (Fabbio, 2016). Former coppice areas developed therefore into a more composite panorama, with stands still managed under the traditional coppice regime, stored coppice developing without any practice of silviculture and coppice stands under conversion to high forest by the periodical thinning of standing crop (Fabbio and Cutini, 2017).

This background is nowadays changing again, as a consequence of global drivers and the general awareness that an increased use of renewable energy sources is necessary (Marchetti et al., 2014; Erni et al., 2020).

Several ecological and economical features meet the forthcoming role of this system under the new scenario: the short rotation periods, the resprouting ability of the agamic system, the prompt and high carbon sequestration rates after cutting, the higher ecological tolerance to drought because of the pre-formed root system, the flexibility and reversibility of the system, the variability of habitats and ecosystem services, from the initial to the late stand cycle (Espelta et al., 1999; Konstantinidis et al., 2006; Lopez et al., 2009; Splichalova, 2015; Holisova et al., 2015; Pietras et al., 2016; Bisi et al., 2018). The above mentioned features make coppices potentially helpful to counteract the risk associated with climate change (unpredictability, rainfall reduction, higher temperature, prolonged droughts, water stress, extreme events, fire risk), although the effect of the different coppice management practices and their interaction with e.g. changes in precipitation regime are not yet fully understood (e.g. Cotillas et al., 2009).

Despite the considerable amount of coppices in, at least, two of five reporting regions of Forest Europe (2020), and despite the inherent characteristics reported above, coppice forests received little attention in the Sustainable Forest Management (SFM) assessments and scenarios. Moreover, the set of SFM Criteria and indicators (Forest Europe, 2020) and the relevant guidelines have been mainly designed to favor national reporting at the European level and - as such – are inherently more relevant to high forests. The extent to which the set of indicators can also capture sustainability issues related to coppice and to the traditionally small sized coppice ownerships and management units across southern Europe is unclear. This is especially relevant to Italy, where coppice forests cover >3.6 million hectares and the average size of properties is roughly 3 ha (Gasparini and Tabacchi, 2011). Obtaining "tailored", still comparable, information on the levels and types of sustainability achievable for the different options at the scale of the operational management unit (the stand) is therefore essential to inform forest owners, resource managers and decision-makers.

The aims of this study are to evaluate (i) whether the different coppice management options actually result in different responses of SFM indicators, and (ii) the degree to which the considered SFM indicators were actually applicable at stand level. We considered three European Forest Types (EFTs) and the three main management options (traditional coppice, natural evolution, conversion; see below) as the full range of choices adopted for coppice forests. These options are associated with different degrees of wood exploitation, from the lowest (natural evolution) up to the highest (traditional coppice) with inherent consequences on all stand parameters and sustainability issues. We applied a large set of the "consolidated" SFM indicators (FOREST EUROPE, 2020), integrated by novel indicators intended to be functionally oriented, well tailored to agamic forest features and/or applicable at the stand level. We assessed all indicators on a network of permanent experimental plots established and monitored by CREA since the '60s; this made it possible to operate at stand level, this scale allowing a more detailed evaluation of management options' sustainability with respect to the forest district scale (Mendoza and Prabhu, 2000; Islam et al., 2010, Santopuoli et al., 2015). This approach was meant to strengthen the knowledge for an effective system of SFM indicators, to promote their use, to inform decision-makers, and to favor an operational evaluation of forest management sustainability into the coppice area. At a more general level, this will promote the understanding of the potentiality and limits of forest management measures like, for instance, the regeneration of "full grown coppice forest areas with more productive and climate adapted species" (Nabuurs et al., 2017) suggested to implement Climate Smart Forestry. Moreover, results could be considered useful for EU environmental monitoring and reporting.

2. Materials and methods

2.1. Study areas and sampling design

We considered stands of three European Forest Types (EFTs; Barbati et al., 2014) located in forested areas of Tuscany (central Italy) and Sardinia (Fig. 1).

These stands have been monitored since the late 1960s (Cutini, 1996; Amorini et al., 1998a; Amorini et al., 1998b; Cutini et al., 2015; Chianucci et al., 2016). EFTs and tree species composition were as follows:

(i) Mountainous Beech Forests (MBF; EFT code 7.3), dominated by European beech (Fagus sylvatica L.), in two sites: Buca Zamponi and Eremo della Casella (Tuscany);
(ii) Thermophilous Deciduous Forests (TDF; EFT code 8.2), dominated by Turkey oak (Quercus cerris L.), in three sites: Caselli, Poggio Pievano and Valsavignone (Tuscany);
(iii) Evergreen Broadleaved Forests (EBF; EFT code 9.1), dominated by holm oak (Quercus ilex L.), in three sites: Alberese (Tuscany), Is Cannoneris and Settefratelli (Sardinia).

These coppices have been managed under different options: Traditional Coppice (TC; rotation = 30–35 yrs), Natural Evolution (NE; no silviculture applied), and Conversion to high forest (CO; by means of periodical thinning). For each site and related management options, data were collected on one 40x20 m randomly selected plot. Forty-three plots were considered as a whole in this study (Table 1; see for more details Fig. 1 of Supplementary Material). For the assessment of a few biodiversity indicators, a 10 × 10 m sub-plot was randomly selected within each plot. A synthesis of the main characteristics for each EFT and management option level is reported in Table 1. The Traditional Coppice option was not available for the Evergreen Broadleaved Forest (EFT 8.2).

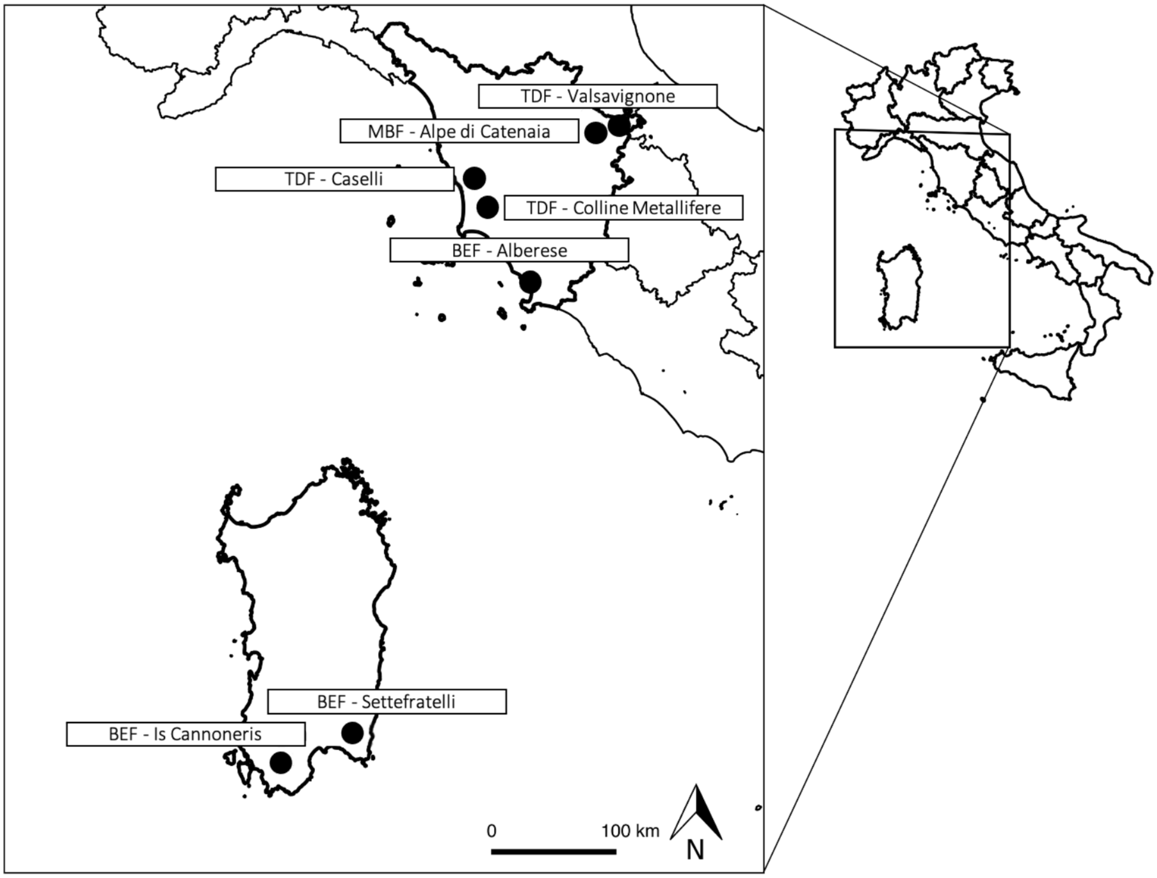

Fig. 1. Study forest areas (Mountainous Beech Forests: MBF; Thermophilous Deciduous Forests: TDF; Evergreen Broadleaved Forests: EBF).

Table 1
List of the European Forest Types (EFTs) and forest sites considered. The geographical position is also reported. Stand age, density and mean height are the average values (year 2016) for each management option and EFT.

EFT	Forest sites	Management option	Age (yrs)	Stem Number per ha	Basal Area (m^2 ha^{-1})	Mean height (m)
Mountainous Beech Forests MBF(7.3)	Buca Zamponi (43.65 N 11.62E) Eremo della Casella (43.66 N 11.62E)	Conversion (n = 5)	72 ± 1	400 ± 83	34.3 ± 4.43	24.7 ± 1.6
		Natural Evolution (n = 1)	71	1900	48.11	19.9
		Traditional Coppice (n = 4)	20 ± 0	1960 ± 435	17.0 ± 2.74	12.9 ± 1
Thermophilous Deciduous Forests - TDF (8.2)	Caselli (43.24 N 10.70E) Poggio Pievano (43.15 N 10.90E) Valsavignone (43.74 N 12.04E)	Conversion (n = 12)	65 ± 3	1595 ± 899	33.4 ± 5.43	19.5 ± 3.2
		Natural Evolution (n = 6)	64 ± 4	1817 ± 488	37.2 ± 4.68	16.9 ± 2.3
		Traditional Coppice (n = 2)	22 ± 0	4882 ± 981	22.6 ± 0.42	9.3 ± 0.2
Evergreen Broadleaved Forests BEF (9.1)	Alberese (42.65 N 11.10E) Is Cannoneris (39.05 N 8.84E) Sette Fratelli (39.27 N 9.43E)	Conversion (n = 9)	71 ± 6	838 ± 298	28.4 ± 10.18	13.5 ± 1.6
		Natural Evolution (n = 4)	72 ± 9	3888 ± 276	48.1 ± 6.95	10.1 ± 0.7

2.2. SFM indicators

The full list of the 33 SFM indicators (numbered) (FOREST EUROPE, 2020) is shown in Table 2. The indicators adopted in this study are written in black (n = 20); the indicators in grey (n = 13) were not used, because they were considered not applicable at stand scale (i.e. the spatial scale here). The consolidated SFM indicators were complemented with novel indicators (n = 16) proposed by the multidisciplinary project team for the purpose of adding information besides the consolidated set. The variable used is also reported for each indicator, followed by the unit (in brackets) and by a short description and/or specific attributes of the novel indicators. The reference method is also reported. The novel indicator Tree growth was included under Criterion 2, because it was considered as a proxy of tree vitality and of tree ability to buffer environmental constraints (Dobbertin, 2005), and sensitive to the impact of abiotic and biotic agents.

Data for consolidated indicators were collected according to standard methods; specific field protocols were developed and applied on a sub-set of plots (n = 18 out of 43) for the novel indicators. Data were collected in 2016 and 2017.

Table 2
Forest Europe Criteria and Indicators (numbered) for Sustainable Forest Management (SFM) (https://foresteurope.org/sfm-criteria-indicators/) and novel indicators (not numbered) selected for this study. Thirteen SFM indicators were not applied (i.e., in grey) because not suitable at the stand scale (i.e. the spatial scale in this study). For each indicator a short description, the variable(s) considered and related unit, the significance (especially for novel indicators), the main reference(s) are reported.

Criterion	Indicator	Definition	Variables considered in this study (unit) – description	Note
C1: Forest Resources & Global Carbon Cycles	1.1 Forest area	Area of forest and other wooded land, classified by forest type and by availability for wood supply, and share of forest and other wooded land in total land area		
	1.2 Growing stock	Growing stock on forest and other wooded land, classified by forest type and by availability for wood supply	Growing stock (m^3 ha-1) - descriptor of woody biomass per unit area and time (year). The stem volume of living trees.	
	1.3 Age structure and/or diameter distribution	Age structure and/or diameter distribution of forest and other wooded land, classified by availability for wood supply	Diameter distribution (n) - this indicator concerns the age-class structure of forests and, for uneven-aged forests, their diameter distributions	Qualitative indicator, no further considered in data analysis
	1.4 Carbon stock	Carbon stock and carbon stock changes in forest biomass, forest soils and in harvested wood products	Carbon stock of woody biomass (Mg ha-1) - carbon content allocated in the standing tree biomass (current biomass) in dry weight.	
	Growth efficiency		Growth efficiency_Litter [(Mg ha^{-1} yr^{-1})/ (Mg ha^{-1} yr^{-1}) - ratio between the increment of epigeous woody biomass and average dry weight of foliar biomass produced within the same time. Growth efficiency_LAI [(Mg ha-1 yr-1)/(m2/m2)]- ratio between the increment of epigeous woody biomass and (i) average Leaf Area Index (LAI) .	The indicator, being a ratio between the increment and foliar biomass which generated it, is able to go further productivity and to give back a picture of stand efficiency and so allowing comparison among different stands.. (Waring, R.H., 1983; Chianucci and Cutini, 2013)
	Total above ground tree biomass		Total above ground tree biomass (Mg ha^{-1}) – it accounts for total tree biomass produced over the stand permanence time. It summarizes and makes comparable all the management options because it takes into account also the intermediate removals periodically harvested (thinnings) and deadwood	The quality of the proposed indicator lies in the concept of overall productivity, independently of any management option applied. The value of Total above ground tree biomass may be easily changed into carbon content and indicate the stock and substitution ability (intermediate removals) of fossil fuels. (Chiarello et al., 1989; Bertini et al., 2016)
C2 : Forests Health & Vitality	2.1 Deposition and concentration of air pollutants	Deposition and concentration of air pollutants on forest and other wooded land		
	2.2 Soil condition	Chemical soil properties (pH, CEC, C/N, organic C, base saturation) on forest and other wooded land related to soil acidity and eutrophication, classified by main soil types	pH (a.u.)	
	2.3 Defoliation	Defoliation of one or more main tree species on forest and other wooded land in each of the defoliation classes	Defoliation (%) - reduced density of the tree crown (needle/leaf loss) in the assessable crown when compared both to absolute and relative (local reference tree) reference standards	Eichhorn et al., 2016; Ferretti, 1994; Mueller and Stierlin, 1990
	2.4 Forest damage	Forest and other wooded land with damage, classified by primary damaging agent (abiotic, biotic and human induced) and by forest type	Causal agent or factors (n) – number of main categories of causal agents (i.e. game and grazing, insects, fungi, abiotic agents, direct action of man, fire, atmospheric pollutants, other factors, investigated but unidentified) detected	Eichhorn et al., 2016
	Chlorophyll content		Chl_{SPAD} (a.u.) - estimate of the leaf chlorophyll content obtained by non-destructive measures carried out with a portable chlorophyll meter	The leaf chlorophyll content is an indicator of photosynthetic capacity and provides indirect information on tree vitality;
				can be altered by biotic and abiotic stress factors (Jangpromma et al., 2010)
	Leaf traits		Specific leaf area, SLA=LA/DW (mm^2 mg^{-1}), where LA is the leaf area (mm^2) and DW is the dry weight (mg)	SLA is a proxy of plant growth (Pérez-Harguindeguy et al., 2013)
	Chlorophyll *a* fluorescence		F_V/F_M (a.u.) - maximum quantum yield of primary photochemistry, which expresses the probability that an absorbed photon be trapped by the PSII reaction center .	The analysis of the Chl *a* fluorescence transient and related indicators is useful in providing information on physiological aspects of photosynthesis and to assess plant stress conditions (Kalaji et al., 2016)
	Stand growth		Stand growth biomass (Mg ha^{-1} y^{-1})	Tree size change over time (tree/stand growth), can be used as response variables to environmental stressors and as explanatory variables of other variables measured. It has been considered a proxy of tree vitality. (Dobbertin, 2005)
C3: Productive Functions of Forests	3.1 Increment and fellings	Balance between net annual increment and annual fellings of wood on forest available for wood supply	Increment and fellings (%) - it refers to the balance between woody increment and periodical harvesting at the stand level, calculated from mensurational inventories (dbh and tree height) and allometric relationships. It is the percentage ratio volume of wood harvesting to volume increment of standing trees over the reference period reported on an annual basis	
	3.2 Roundwood	Quantity and market value of roundwood	Roundwood = firewood (m^3 ha^{-1}) - is the wood productivity in terms of volume or dry weight at stand level of firewood	

(continued on next page)

Table 2 (*continued*)

	3.3 Non-wood goods	Quantity and market value of non-wood goods from forest and other wooded land	Marketed mushrooms production (€ ha^{-1}) - assessed by three harvestings within the autumn months. The survey consists of the mushroom harvesting by people with expertise and/or mycologists which identify and count all the epigeous marketable bodies, in a good status, larger than 2 cm. Mushrooms are then dried up to constant weight. The local market survey is then undertaken	
	3.4 Services	Value of marketed services on forest and other wooded land		
C4: Forest Biological Diversity	4.1 Tree species composition	Area of forest and other wooded land, classified by number of tree species occurring	Woody species richness (n)/ plot	
	4.2 Regeneration	Total forest area by stand origin and area of annual forest regeneration and expansion		
	4.3 Naturalness	Area of forest and other wooded land by class of naturalness		
	4.4 Introduced tree species	Area of forest and other wooded land dominated by introduced tree species	Introduced tree species richness (n)	
	4.5 Deadwood	Volume of standing deadwood and of lying deadwood on forest and other wooded land	Total deadwood: lying deadwood volume + standing deadwood volume (m³ ha-1)	
	4.6 Genetic resources	Area managed for conservation and utilisation of forest tree genetic resources (in situ and ex situ genetic conservation) and area managed for seed production		
	4.7 Forest fragmentation	Area of continuous forest and of patches of forest separated by non-forest land		
	4.8 Threatened forest species	Number of threatened forest species, classified according to IUCN Red List categories in relation to total number of forest species	Threatened forest species richness (n)/plot	
	4.9 Protected forests	Area of forest and other wooded land protected to conserve biodiversity, landscapes and specific natural elements, according to MCPFE categories		
	4.10 Common forest bird species	Occurrence of common breeding bird species related to forest ecosystems	Forest breeding bird richness (n)/plot	Not further applied due the structure of sampling design
	Forest herbaceous species		Forest herbaceous species richness - number of herbaceous species strictly linked to forest habitats (n/plot)	They are strictly related to the age and the conservation status of the forest (Eleman, 2004)
	Native herbaceous species		Herbaceous species richness - number of herbaceous species in the understorey (n/plot)	Herbaceous plant species in forests is higher than those of shrubs and woods and they are sensitive to environmental and dynamic changes (Campetella et al. 2004)
	Wood decaying fungi		Wood decaying fungi richness - number of wood decaying fungi (n/plot)	Fungi play an important role as indicators of the health of forest ecosystems (Hainaut Développement, 2004).
	Epiphytic lichens		Epiphytic lichen species richness - number of Epiphytic lichen species (n/plot)	Epiphytic lichens have been widely used as indicators of forest continuity especially with respect to impacts determined by silvicultural practices (Nascimbene et al., 2013; Brunialti et al. 2020) Simplified monitoring method: only foliose and fruticose species considered (Brunialti et al. 2020)
	Edible mushrooms		Edible mushrooms species richness (n/plot)	
C5 Protective Function (Soil & water)	5.1 Protective forests – soil, water and other ecosystem functions – infrastructure and managed natural resources	Area of forest and other wooded land designated to prevent soil erosion, preserve water resources, maintain other protective functions, protect infrastructure and managed natural resources against natural hazards		
	Bryophyte cover		Bryophyte cover (0;1) - estimates bryophytes cover based on presence (1)/absence (0) observations of the litter layer	Chianucci et al. 2016a
	Ground litter depth		Ground litter depth (cm) - estimates bryophytes cover based on the depth (cm) of the litter layer	Chianucci et al. 2016a
	Flood retention		Flood retention (0.1-1) - Indicator based on the Flood retention Index by Kennessey (1930), modified to downscale its applicability at the stand level	Chianucci et al. 2016a
	Overstorey cover		Overstorey cover (0;1) - the average proportion of ground surface covered by the vertical projection of tree crowns and expressed as relative value (0: no cover; 1: full overstorey cover = 100%) estimated using a restricted digital cover photography and a nearly-zenith view angle method; it can be easily obtained from field-based optical instruments like canopy photography	Chianucci et al 2016a
	Understorey cover		Understorey cover (0;1) - the average proportion of ground surface covered by the vertical projection of understorey and it is expressed as relative value (0: no cover; 1: full overstorey cover = 100%). The determination of undestorey is generally more complex than overstorey; the indicator can easily be obtained from field-based optical instruments like downward-looking digital photography	Chianucci et al. 2014b

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Table 2 (*continued*)

C6: Socioeconomic Functions	6.1 Forest holdings	Number of forest holdings, classified by ownership categories and size classes		
	6.2 Contribution of forest sector to Gross Domestic Product	Contribution of forestry and manufacturing of wood and paper products to gross domestic product	Forest contribution to GDP (%) - percentage of the contribution of the forest sector in terms of added value compared to the added value of agriculture of Tuscany	
	6.3 Net revenue	Net revenue of forest enterprises	Net revenue (€ ha^{-1} $year^{-1}$) - based on stumpage value, also considering discount rate and turnover of different treatments	
	6.4 Expenditures for services	Total public and private investments in forests and forestry		
	6.5 Forest sector workforce	Number of persons employed and labour input in the forest sector, classified by gender and age group, education and job characteristics	Workforce (Specialization index). This indicator is based on the ratio between forestry workers and agricultural workers at the provincial and regional level	
	6.6 Occupational safety and health	Frequency of occupational accidents and occupational diseases in forestry		
	6.7 Wood consumption	Consumption per head of wood and products derived from wood		
	6.8 Trade in wood	Imports and exports of wood and products derived from wood	Wood market (m^3year^{-1}). This indicator measures the contribution in terms of forest utilization at the level of the single district defined within the project. Partially measures timber trade in terms of quantity and stumpage value	
	6.9 Energy from wood resources	Share of wood energy in total primary energy supply, classified by origin of wood	Energy (MW ha^{-1} $year^{-1}$) - assesses the renewable energy that can be obtained from the residues of forest utilization. More specifically, it refers to the thermal hourly megawatts produced by the forest residues available from coppice forest exploitation. The wood	
			residues (Bernetti et al., 2009) obtained by forest utilization is multiplied by the specific calorific value	
	6.10 Accessibility for recreation	The use of forests and other wooded land for recreation in terms of right of access, provision of facilities and intensity of use	Recreation (€ $year^{-1}$) - calculated through the contingent valuation method (CVM) which aims to analyze consumers' choice regarding environmental goods. Through the use of questionnaires and interviews, willingness to pay to maintain a specific management option has been calculated	

(See above-mentioned references for further information.)

2.3. Data analysis

Thirty-four SFM indicators (18 consolidated and 16 novel) were considered in the data analysis as a whole. Two (i.e. 1.3 and 4.10) out of 20 consolidated indicators were not included in the analyses (see Table 2 for details).

To give an overall information on the distribution of each indicator in the three European Forest Types, we elaborated boxplots with the variability of most of the indicators.

Data were then aggregated and processed at the plot level. Descriptive statistics (mean ± standard deviation) of each indicator were calculated for the different management options and EFTs. When feasible in terms of data availability and sampling number, the statistical differences between management options were tested using the non-parametric Mann-Whitney test. Statistical analyses were carried out with the statistical open software R (R Core Team, 2020).

We tentatively evaluated each SFM indicator in relation to its appropriateness for coppice forest stands. Appropriateness was evaluated by a composite score based on an eight-point scale (from min 2 to max 9): 2–4, low total score; 5–6, medium total score; 7–9, high total score. The total score resulted from the sum of the partial scores attributed to each of the following characteristics:

(i) Discriminative ability - capability to discriminate among different management options at the stand level, as resulted from their application in this study; based on a quantitative evaluation, the following partial scores were adopted:

- Null discriminative ability, score = 0: no significant differences among management options within any EFT;

- Low discriminative ability, score = 1: at least one significant difference among management options for one EFT;

- Medium discriminative ability, score = 2: at least one significant difference among management options for two EFTs;

- High discriminative ability, score = 3: at least one significant difference among management options for three EFTs.

(ii) Replicability - possibility to replicate consistently the use of the indicator at the stand level; based on a qualitative evaluation, the following partial scores were adopted:

- Low replicability, score = 1: very complex measurement procedures and/or protocols, sophisticated instruments needed, and/or the need for long monitoring period, and/or highly qualified expertise;

- Medium replicability, score = 2: standard but complex procedures, protocols and/or sophisticated instruments and qualified expertise needed;

- High replicability, score = 3: standard simplified procedures and/or protocols, without the need for sophisticated instruments and/or long monitoring period, and/or highly qualified expertise.

(iii) Cost - expenditures in terms of personnel, instruments and consumables needed for the indicator assessment at the stand level; based on a qualitative evaluation, the following partial scores were adopted:

- Low cost, score = 3: low relative estimated expenditures for personnel, due to the need for medium–low personnel skill, customary instruments or/and low time-consuming surveys and monitoring activities;

- Medium cost, score = 2: medium relative estimated expenditures for personnel, due to the need for personnel with expertise, specific instruments or/and time-consuming surveys and monitoring activities;

- High cost, score = 1: high relative estimated expenditures for personnel, due to the need of personnel with high skill and expertise, sophisticated instruments or/and very time-consuming surveys and

Table 3
Mountainous Beech Forests: SFM indicators with own descriptive statistics (mean ± SD) in the three management options and results of pair comparisons (Mann-Whitney test; 1 df) between the two management options with sufficient sampling size (Conversion vs Traditional Coppice; only one plot for Natural Evolution). n.d.: not detected value. n.a.: statistical test not applicable due to the lack of data. n.s.: not significant ($p > 0.05$).

Criterion	Indicator	Variable, unit	Conversion (n = 5)	Natural Evolution (n = 1)	Traditional Coppice (n = 4)	Mann-Whitney test
C1	1.2 Growing stock	$m^3\ ha^{-1}$	366.7 ± 38.80	505.2	101.6 ± 27.67	p < 0.05 (n = 9)
	1.4 Carbon stock	$Mg\ ha^{-1}$	152.1 ± 16.09	209.6	42.1 ± 11.47	p < 0.05 (n = 9)
	Growth efficiency	litter, $(Mg\ ha^{-1}\ yr^{-1})/\ (Mg\ ha^{-1}\ yr^{-1})$	3.2	2.7	n.d.	n.a.
	Total above ground tree biomass	$Mg\ ha^{-1}$	477.9 ± 73.44	419.1	220.4 ± 21.89	p < 0.05 (n = 9)
C2	2.2 Soil condition	pH 0–10 cm, a.u.	4.9 ± 0.06	5.2	4.6 ± 0.18	p < 0.05 (n = 9)
	2.3 Defoliation	%	25.7 ± 1.80	22.4	37.5 ± 3.51	p < 0.05 (n = 9)
	2.4 Forest damage	causal agent or factors, n	2.4 ± 0.13	2.0	3.4 ± 0.37	p < 0.05 (n = 9)
	Chlorophyll content	Chl_{SPAD}, a.u.	36.1 ± 1.35	37.5	n.d.	n.a.
	Leaf traits	SLA, $mm^2\ mg^{-1}$	14.9 ± 2.40	12.3	n.d.	n.a.
	Chlorophyll *a* fluorescence	FV/FM, a.u.	0.83 ± 0.006	0.83	n.d.	n.a.
	Stand Growth	tree biomass, $Mg\ ha^{-1}\ y^{-1}$	6.9 ± 0.87	5.4	4.2 ± 2.05	p < 0.05 (n = 9)
C3	3.1 Increment and fellings	%	46.0 ± 3.83	n.d.	64.5 ± 7.52	p < 0.05 (n = 7)
	3.2 Roundwood	firewood, $m^3\ ha^{-1}$	261.1 ± 24.06	n.d.	164.1 ± 19.53	p < 0.05 (n = 7)
	3.3 Non-wood goods	marketed mushrooms production (€ ha^{-1})	59.8 ± 74.75	0.0	n.d.	n.a.
C4	4.1 Tree species composition	woody species richness, n	1.3 ± 0.52	2	1 ± 0	n.a.
	4.4 Introduced tree species	species richness, n	0.0	0.0	0.0	n.a.
	4.5 Deadwood	$m^3\ ha^{-1}$	n.d.	93.3	n.d.	n.a.
	4.8 Threatened forest species	species richness, n	0.0	0.0	0.0	n.a.
	Forest herbaceous species	species richness, n	2 ± 0.0	1	n.d.	n.a.
	Native herbaceous species	species richness, n	5.3 ± 4.57	1	n.d.	n.a.
	Wood decaying fungi	species richness, n	9.5 ± 2.38	15.0	n.d.	n.a.
	Epiphytic lichens	species richness, n	3 ± 0.8	4	n.d.	n.a.
	Edible mushrooms	species richness, n	2.3 ± 0.96	0.0	n.d.	n.a.
C5	Bryophyte cover	0;1	0.01 ± 0.01	0.0	n.d.	n.a.
	Ground litter depth	cm	2.0 ± 0.48	2.9	n.d.	n.a.
	Flood retention	score (0.1–1)	0.36 ± 0	0.36	0.42 ± 0.00	p < 0.05 (n = 9)
	Overstorey cover	0;1	0.93 ± 0.02	0.95	0.58 ± 0.04	p < 0.05 (n = 9)
	Understorey cover	0;1	0.03 ± 0.01	0.05	0.3 ± 0.06	p < 0.05 (n = 9)
C6	6.2 Contribution of forest sector to GDP	%	0.02 ± 0.01	−0.02	0.02 ± 0.002	n.s. (n = 9)
	6.3 Net revenue	€ $ha^{-1}\ year^{-1}$	46.9 ± 2.07	−39.8	30.7 ± 5.10	p < 0.05 (n = 9)
	6.5 Forest sector workforce	specialization index	1.7 ± 0	1.7	1.7 ± 0	n.a.
	6.8 Trade in wood	$m^3\ year^{-1}$	15797 ± 0	15,797	15797 ± 0	n.a.
	6.9 Energy from wood resources	$MW\ ha^{-1}\ year^{-1}$	1.7 ± 0.14	−1.49	1.1 ± 0.14	p < 0.05 (n = 9)
	6.10 Accessibility for recreation	€ $year^{-1}$	8.8 ± 0	8.64	7.55 ± 0	n.a.

monitoring activities.

The assessment of the appropriateness represents a synthesis of the scores provided by the team of experts involved in field data collection in the 43 permanent experimental plots and data analysis; thus, it is not possible to exclude a certain subjectivity in the qualitative evaluation of the indicators and in the score assignment. As far as possible, subjectivity inherent to the qualitative analysis of indicators and to the score assignment is controlled by the expertise of the team.

3. Results and discussion

3.1. SFM indicators, EFT and management options

Giving the nature of the study and related data collected, the EFT was firstly considered as one of the key factors driving the variability of the indicators. The distribution of values of each indicator in the three EFTs is reported in Supplementary Material, Fig. 2 (with the exception of tree species composition, introduced tree species, and threatened species, with low or without variability, and deadwood, measured only in NE).

Statistical test among management options showed that seventeen out of the 34 indicators applied were significantly different, at least for one EFT (Table 3–5). These 17 indicators were distributed across all the Criteria, although significant responses were more frequent for Criteria 1, 2 and 6, and for Mountainous Beech Forests (14 indicators) rather than for Evergreen Broadleaved Forests (8 indicators) and Thermophilous Deciduous Forest (4 indicators). Overall, the proportion of indicators showing significant response was higher among the consolidated set than among the novel set (69% vs. 31%).

Differences between management options were not tested because of the low number of replicates (i.e. plots) for 16 indicators (seven consolidated and nine novel). This cannot exclude the possibility of divergent patterns, suggesting the need for further investigations.

3.1.1. Criterion 1

Three out of the four indicators tested pointed out better performances of environmental SFM indicators such as Growing stock and C stock and Total above ground tree biomass in stands managed with CO and/or NE, rather than with TC. Even if it was not possible to test the

Table 4
Thermophilous Deciduous Forests: SFM indicators with own descriptive statistics (mean ± SD) in the three management options and results of pair comparisons (Mann-Whitney test; 1 df) between the two management options with sufficient sampling size (Conversion vs Natural Evolution; only two plots for Traditional Coppice). n.d.: not detected value. n.a.: statistical test not applicable due to the lack of data. n.s.: not significant ($p > 0.05$).

Criterion	Indicator	Variable, unit	Conversion (n = 12)	Natural Evolution (n = 6)	Traditional Coppice (n = 2)	Mann-Whitney test
C1	1.2 Growing stock	$m^3\ ha^{-1}$	283.5 ± 73.28	357.5 ± 98.09	113.2 ± 6.34	n.s. (n = 18)
	1.4 Carbon stock	$Mg\ ha^{-1}$	120.3 ± 31.09	151.7 ± 41.62	50.6 ± 4.48	n.s. (n = 18)
	Growth efficiency	litter, $(Mg\ ha^{-1}\ yr^{-1})/(Mg\ ha^{-1}\ yr^{-1})$	4.0 ± 2.43	1.6 ± 0.74	n.d.	n.a.
	Total above ground tree biomass	$Mg\ ha^{-1}$	362.5 ± 68.32	303.4 ± 83.25	160.2 ± 10.32	n.s. (n = 18)
C2	2.2 Soil condition	pH 0–10 cm, a.u.	5.8 ± 0.86	5.8 ± 0.92	6.1 ± 0.87	n.s. (n = 18)
	2.3 Defoliation	%	12.6 ± 3.06	12.9 ± 1.82	11 ± 1.68	n.s. (n = 18)
	2.4 Forest damage	causal agent or factors, n	1.2 ± 0.46	1.2 ± 0.37	1.3 ± 0.32	n.s. (n = 18)
	Chlorophyll content	$Chl_{SPAD,}$ a.u.	41.5	38.8	41.5 ± 0.65	n.a.
	Leaf traits	SLA, $mm^2\ mg^{-1}$	9.7	11.9	10.6 ± 0.88	n.a.
	Chlorophyll *a* fluorescence	FV/FM, a.u.	0.83	0.83	0.83 ± 0.008	n.a.
	Stand Growth	tree biomass, $Mg\ ha^{-1}\ y^{-1}$	5.7 ± 1.53	4.3 ± 2.45	4.6 ± 0.29	n.s. (n = 18)
C3	3.1 Increment and fellings	%	50.8 ± 21.56	n.d.	90.4 ± 6.22	n.a.
	3.2 Roundwood	firewood, $m^3\ ha^{-1}$	150.7 ± 54.09	n.d.	171.0 ± 22.73	n.a.
	3.3 Non-wood goods	marketed mushrooms production (€ ha^{-1})	4.4	17.2	131.5 ± 33.99	n.a.
C4	4.1 Tree species composition	woody species richness, n	2.5 ± 1.17	2.3 ± 1.03	1.5 ± 0.71	n.a.
	4.4 Introduced tree species	species richness, n	0.0	0.0	0.0	n.a.
	4.5 Deadwood	$m^3\ ha^{-1}$	n.d.	70.5 ± 4.26	n.d.	n.a.
	4.8 Threatened forest species	species richness, n	0.0	0.0	0.0	n.a.
	Forest herbaceous species	species richness, n	9	12	14 ± 1.41	n.a.
	Native herbaceous species	species richness, n	24	26	25.5 ± 3.54	n.a.
	Wood decaying fungi	species richness, n	10.0	13.0	7.5 ± 2.12	n.a.
	Epiphytic lichens	species richness, n	8	5	9 ± 0.0	n.a.
	Edible mushrooms	species richness, n	2	1	4.5 ± 0.71	n.a.
C5	Bryophyte cover	0;1	0.03	0.09	0.08 ± 0.01	n.a.
	Ground litter depth	cm	1.6	1.4	1.3 ± 0.26	n.a.
	Flood retention	score (0.1–1)	0.29	0.29	0.29 ± 0	n.a.
	Overstorey cover	0;1	0.78	0.81	0.81 ± 0.01	n.a.
	Understorey cover	0;1	0.19	0.10	0.13 ± 0.002	n.a.
C6	6.2 Contribution of forest sector to GDP	%	0.03 ± 0.004	−0.03 ± 0.001	0.02 ± 0.001	$p < 0.001$ (n = 18)
	6.3 Net revenue	€ $ha^{-1}\ year^{-1}$	39.01 ± 5.89	−39.8 ± 4.40	49.8 ± 12.34	$p < 0.001$ (n = 18)
	6.5 Forest sector workforce	specialization index	1.2 ± 0.37	1.05 ± 0.38	0.5 ± 0	n.a.
	6.8 Trade in wood	$m^3\ year^{-1}$	7338 ± 7878.9	6056 ± 7064.7	4975 ± 0	n.a.
	6.9 Energy from wood resources	MW $ha^{-1}\ year^{-1}$	1.21 ± 0.13	−1.17 ± 0.08	0.9 ± 0.06	$p < 0.001$ (n = 18)
	6.10 Accessibility for recreation	€ $year^{-1}$	8.2 ± 0.39	7.2 ± 0.26	7.6 ± 0	$p < 0.001$ (n = 18)

differences between management options, higher values of Growth efficiency were detected in CO than in NE.

In detail, significant differences were observed in Mountainous Beech Forests (TC vs. CO) (Table 3), while no significant differences were registered in Thermophilous Deciduous Forests (Table 4). Significant differences for Growing stock and C stock between CO and NE were recorded in Evergreen Broadleaved Forests and the highest values shown were in NE (Table 5). Several studies reported that the "no harvest" option commonly produces the highest forest carbon stocks (Gratani et al., 2018) and that managed stands typically have lower levels of forest biomass than unmanaged stands (Nunery and Keeton, 2010; McKinley et al., 2011).

The values of Growing stock in NE and CO were largely higher than the average value for European forests (169.1 $m^3\ ha^{-1}$) (FOREST EUROPE 2020), while in TC they were lower. The same pattern occurred at the Italian level (145.0 $m^3\ ha^{-1}$) (FOREST EUROPE, 2020). A similar pattern was clearly recorded for Carbon stock. NE and CO were largely higher than the average value (64 $Mg\ ha^{-1}$) at the Italian level (FOREST EUROPE, 2020), while TC was lower.

Total above ground tree biomass showed significant differences between CO and TC for Mountainous Beech Forests only (Table 3). The highest values were recorded in CO plots, while the lowest in TC plots. This novel indicator summarizes the overall productivity (and therefore the full carbon sequestration and stock ability) into one value and makes the performance of all the concerned forest management options comparable.

3.1.2. Criterion 2

Criterion 2 SFM indicators were significantly different for each management option for Mountainous Beech Forests only, where Defoliation and Forest damage (number of damage attributable to different causal agents) were significantly higher in TC than in CO (Table 3). Soil

Table 5
Evergreen Broadleaved Forests: SFM indicators with own descriptive statistics (mean ± SD) in the two management options and results of pair comparisons (Mann-Whitney test; 1 df) for the indicators with sufficient sampling size. n.d.: not detected value. n.a.: statistical test not applicable due to the lack of data. n.s.: not significant ($p > 0.05$).

Criterion	Indicator	Variable, unit	Conversion (n = 9)	Natural Evolution (n = 4)	Mann-Whitney test
C1	1.2 Growing stock	$m^3\ ha^{-1}$	159.9 ± 84.63	313.0 ± 85.24	p < 0.05 (n = 13)
	1.4 Carbon stock	$Mg\ ha^{-1}$	72.5 ± 36.66	132.8 ± 36.17	p < 0.05 (n = 13)
	Growth efficiency	litter, $(Mg\ ha^{-1}\ yr^{-1})/(Mg\ ha^{-1}\ yr^{-1})$	2.6 ± 0.05*	n.d.	n.a.
	Total above ground tree biomass	$Mg\ ha^{-1}$	275.3 ± 61.0	265.6 ± 72.34	n.s. (n = 13)
C2	2.2 Soil condition	pH 0–10 cm, a.u.	5.8 ± 0.42	6.0 ± 0.61	n.s. (n = 13)
	2.3 Defoliation	%	16.4 ± 4.16	15.7 ± 8.26	n.s. (n = 13)
	2.4 Forest damage	causal agent or factors, n	0.6 ± 0.30	0.6 ± 0.47	n.s. (n = 13)
	Chlorophyll content	Chl_{SPAD}, a.u.	46.8 ± 1.25	46.8 ± 1.14	n.a.
	Leaf traits	SLA, $mm^2\ mg^{-1}$	6.1 ± 0.69	6.1 ± 0.40	n.a.
	Chlorophyll *a* fluorescence	FV/FM, a.u.	0.83	0.78	n.a.
	Stand Growth	tree biomass, $Mg\ ha^{-1}\ y^{-1}$	8.5 ± 2.69	4.4 ± 1.21	p < 0.05 (n = 13)
C3	3.1 Increment and fellings	%	105.1 ± 11.22	n.d.	n.a.
	3.2 Roundwood	firewood, $m^3\ ha^{-1}$	211.8 ± 25.94	n.d.	n.a.
	3.3 Non-wood goods	marketed mushrooms production (€ ha^{-1})	297.1 ± 328.57	0.0	n.a.
C4	4.1 Tree species composition	woody species richness, n	1.4 ± 0.53	2.4 ± 0.55	n.a.
	4.4 Introduced tree species	species richness, n	0.0	0.0	n.a.
	4.5 Deadwood	$m^3\ ha^{-1}$	n.d.	49.8 ± 2.56	n.a.
	4.8 Threatened forest species	species richness, n	0.0	0.0	n.a.
	Forest herbaceous species	species richness, n	3 ± 0.89	2.3 ± 0.58	n.s. (n = 9)
	Native herbaceous species	species richness, n	16.2 ± 6.34	5.3 ± 2.31	p < 0.05 (n = 9)
	Wood decaying fungi	species richness, n	3.5 ± 1.76	4.0 ± 2.00	n.a.
	Epiphytic lichens	species richness, n	5.2 ± 2.79	2.0 ± 2.00	n.a.
	Edible mushrooms	species richness, n	0.8 ± 0.75	0.0 ± 0.00	n.a.
C5	Bryophyte cover	0;1	0.18 ± 0.06	0.14 ± 0.02	n.a.
	Ground litter depth	cm	1.6 ± 0.44	1.9 ± 0.13	n.a.
	Flood retention	score (0.1–1)	0.24 ± 0.02	0.23 ± 0.01	n.s. (n = 9)
	Overstorey cover	0;1	0.77 ± 0.08	0.89 ± 0.04	p < 0.05 (n = 9)
	Understorey cover	0;1	0.04 ± 0.02	0.07 ± 0.01	n.s. (n = 9)
C6	6.2 Contribution of forest sector to GDP	%	0.02 ± 0.01	−0.02 ± 0.001	p < 0.01 (n = 13)
	6.3 Net revenue	€ $ha^{-1}\ year^{-1}$	35.5 ± 4.36	−35.6 ± 0.51	p < 0.01 (n = 13)
	6.5 Forest sector workforce	specialization index	0.43 ± 0.03	0.44 ± 0.05	n.a.
	6.8 Trade in wood	$m^3\ year^{-1}$	2518 ± 820.8	2677 ± 1215.5	n.a.
	6.9 Energy from wood resources	$MW\ ha^{-1}\ year^{-1}$	0.8 ± 0.51	−0.94 ± 0.76	p < 0.01 (n = 13)
	6.10 Accessibility for recreation	€ $year^{-1}$	8.7 ± 0.56	7.0 ± 0	n.a.

pH was lower in TC.

Even if it was not possible to test the differences between management options for leaf traits and Chlorophyll-related indicators, FV/FM values did not evidence stress conditions (reference values for healthy C3 plants: 0.83–0.84; Kalaji et al., 2016), except for Evergreen Broadleaved Forests under NE (i.e. 0.78; Table 5).

Mean defoliation was higher than the average value reported for beech at the European level in 2016 (22.5%) (Timmermann et al., 2017), both in CO (25.7%) and TC (37.5%) and above the traditional warning stage value of 25% (FOREST EUROPE, 2020). In NE plots, defoliation was almost the same (22.4%) as the average value at European level. The novel indicator Stand growth (biomass) showed significantly higher values in CO than in TC for Mountainous Beech Forests (Table 3), and in NE for Evergreen Broadleaved Forests (Table 5).

Thus, CO seems to promote health and vitality of beech forests, with concurrently lower defoliation, damage and higher tree biomass values than TC and NE (Mattioli et al., 2015).

3.1.3. Criterion 3

Criterion 3 indicators, often reported to be useful in describing the sustainability of the different management options both in ecological and economical terms (EEA, 2017; Lassere et al., 2011; Pra and Pettenella, 2016), showed different patterns among the three EFTs in our study (Tables 3–5).

Increment and fellings was significantly higher in TC than in CO for Mountainous Beech Forests (Table 3). The observed value (64.5%) was over the Italian benchmark for Increment and fellings (39.2%), but lower than the benchmarks at the European level, which are around 73%, relatively stable and under 80% for most countries across Europe (FOREST EUROPE, 2020). This utilization rate has allowed the forest stock to increase. However, a value of approximately 70% is recommended to ensure the sustainable management of forests (EEA, 2017).

Roundwood values were significantly higher in CO than in TC for Mountainous Beech Forests (Table 3). In our context, this indicator is used to evaluate the economical sustainability of firewood harvesting in the coppice system and in coppice under conversion into high forest. As a rule, the main performances of this indicator were recorded within the coppice system. Here, an optimized arrangement of thinning repetitions, thinning intensity and incremental response of the standing crop, allowed sound performances of Roundwood in the case of CO, too. Similarly, in a study on the treatment-dependency of ecosystem services provision carried out at the European level, Biber et al. (2015) reported that, as expected, the ecosystem services associated with wood production display a close dependency on management intensity and a clear and opposite trend to those related to carbon storage and standing volume. Values generally tend to increase with stand age, i.e. with standing volume.

3.1.4. Criterion 4

Analyses were possible only for Evergreen Broadleaved Forests and two indicators, Native Herbaceous Species richness and Forest Herbaceous Species richness. Native Herbaceous species richness was significantly higher in CO than in NE ($p < 0.05$; Table 5). Forest Herbaceous Species richness was similar in CO and NE ($p > 0.05$).

Our results confirm that CO can favor herbaceous species (Beatty, 2003, Vockenhuber et al., 2011; Campetella et al., 2016). Indeed, even if forest management has direct effects on the overstory layer, which is mainly represented by woody species, it also has indirect effects on the understorey species, modifying light availability, microclimate and ventilation (Neufeld and Young, 2003). Nevertheless, this effect is limited to more generalist herbaceous species, because the ones typical of forests were not affected by the management options under comparisons.

Introduced tree species and Threatened forest species (Tables 3–5) were not present.

3.1.5. Criterion 5

As for the protective function of forests, we considered a different set of indicators for which soil coverage by canopy (overstorey and understorey), bryophytes, and litter are the key characteristics. It was not possible to test differences between management options for Bryophyte cover and Ground litter depth due to the reduced number of observations.

For Mountainous Beech Forests (Table 3) and Evergreen Broadleaved Forests (Table 5) Overstorey cover was significantly higher in CO than in TC for the former and in NE than in CO for the latter. The opposite occurs for Understorey cover, which goes in parallel with Flood retention for Mountainous Beech Forests (Table 3) with values significantly higher in TC than in CO.

Flood retention was able to discriminate TC in Mountainous Beech Forests but was not effective in the other forest types. Another potential limitation is that the flood retention indicator also considers geomorphological attributes, which potentially reduce the contribution of treatment on the indicator value.

Understorey cover observed in the beech plots under different management options is comparable with that observed by Kermavnar et al. (2019) in beech forests under different felling intensity.

Given that the estimate of understorey cover at plot scale is seldom made in forestry, due to the only recent release of effective measurement tools (Chianucci et al., 2014a), we advocate the need to make understorey cover measurements more conventionally considered in forest inventory and monitoring programs (Chianucci, 2020).

3.1.6. Criterion 6

Indicators under Criterion 6 consistently pointed out that CO is the most economically rewarding option in terms of Net Revenue, Contribution to GDP and Energy, while it was not possible to test differences between management options for Forest sector workforce and Trade in wood due to the lack of data.

In detail, Net Revenue and Energy show significant differences between CO and TC in Mountainous Beech Forests (Table 3), with the higher values in CO. Forest contribution to GDP, Net Revenue and Energy show significant differences between CO and NE for Thermophilous Deciduous Forests (Table 4) and Evergreen Broadleaved Forests (Table 5), with higher values in CO. These results are consistent with other outcomes: Net Revenue can be compared with that reported by FOREST EUROPE (2020), where data are referred to large areas of Europe: South East-E. 43.1 € ha-1, South West E. 212 € ha-1, Central East-E. 47.6 € ha-1, Central West E. 131.8 € ha-1, North E. 80 € ha-1, average value for Europe (28 countries) 94.7 € ha-1. The indicator values are comparable with those for South East-E. In other European areas, the difference is mainly due to the predominance of the high forest system compared to the coppice system.

The indicator Accessibility for recreation was significantly higher in CO than in NE for Thermophilous Deciduous Forests only (Table 4). This could be related to the fact that NE is perceived as impenetrable scrub, while CO is more suitable for recreational activities and at the same time is more appealing from an aesthetic point of view.

We underline that the indicators Net Revenue and Energy showed significant differences among the management options for all the EFTs: they were the two indicators, out of the whole tested set, able to discriminate significantly each management option.

3.2. SFM indicators appropriateness

According to the eight-point scale used to assess the overall appropriateness of SFM indicators, 11 of them (seven consolidated and four novel) turned out to be highly appropriate, and 7 (four consolidated and three novel) resulted medium appropriate (Tables 6a and 6b). No SFM indicator was evaluated as inappropriate. The appropriateness of sixteen indicators could not be assessed in full, because of the lack of scores on their discriminative ability (see also Tables 3–5); nevertheless, they were assessed for replicability and cost, at least providing detailed information on these two characteristics, which are potentially useful in other contexts and sites/species.

A detailed evaluation for each Criterion is reported below.

3.2.1. Criterion 1

Overall, three out of the four indicators were deemed to be highly appropriated (Table 6a). The consolidated indicators Growing stock and Carbon stock and the novel Total above ground tree biomass showed the highest score. They can be calculated easily using the conversion factors in the literature. Standard technical tools are generally certified by the National Forest Inventories. These are the reasons why the above-mentioned SFM indicators can be considered highly discriminative, replicable and low-cost. They are well suited to describe forest dynamics, and the stand level monitoring allows their periodical updating.

The appropriateness of Growth Efficiency could not be assessed in full because of the lack of the score on its discriminative ability among management options, although it was characterized by medium replicability and cost.

3.2.2. Criterion 2

Overall, three out of the four evaluable indicators were considered highly appropriated. The consolidated indicators Defoliation and Forest damage were considered to be highly appropriate, particularly because of their ease in replicability and low cost (Table 6a). These indicators have been well known for providing information on tree condition at different spatial scales for several decades (Ferretti, 1997); they can discriminate between management options in coppice forests at the stand level for Mountainous Beech Forests. The low costs (i.e. 3) are mainly due to the fact that no expensive instruments are required; anyway, well-trained personnel is needed for the visual assessment of the tree condition. As for Soil condition, the medium score (i.e. 2) assigned to the costs is due to the quite expensive chemical analyses

Table 6a
SFM Criteria 1 – 3: SFM indicators appropriateness.

Criterion	Indicator	Discriminative ability	Replicability	Cost	Appropriateness at stand level	
					Total score	Qualitative rating
Criterion 1 – Carbon stock	1.2 Growing stock	2	3	3	8	High
	1.4 Carbon stock	2	3	3	8	High
	Growth Efficiency	n.a.	2	2	Not fully evaluated	
	Total above ground tree biomass	1	3	3	7	High
Criterion 2 – Forest health and vitality	2.2 Soil condition	1	3	2	6	Medium
	2.3 Defoliation	1	3	3	7	High
	2.4 Forest damage	1	3	3	7	High
	Chlorophyll content	n.a.	2	2	Not fully evaluated	
	Leaf traits	n.a.	2	2	Not fully evaluated	
	Chlorophyll a fluorescence	n.a.	2	2	Not fully evaluated	
	Stand growth	2	3	3	8	High
Criterion 3 – Productive functions	3.1 Increment and fellings	1	3	2	6	Medium
	3.2 Roundwood	1	3	2	6	Medium
	3.3 Non-wood goods	n.a.	1	2	Not fully evaluated	

required at the stand level.

The novel indicator Stand growth was considered highly appropriate, due to its medium discriminating ability among management options, high replicability and low costs. The appropriateness of the three novel indicators measured at leaf level (i.e. Chlorophyll content, Leaf traits and Chlorophyll *a* fluorescence) could not be fully assessed because of the lack of the score on discriminative ability between management options (see Tables 4–6). Their replicability is also a potential issue, even if several non-destructive measurements can be easily taken at leaf level in a short time, making it possible to perform detailed and informative analyses that can support tree health assessment. For example, defoliation in European beech at our plots was accompanied by several significant differences at leaf level (i.e., leaf damage, leaf volume, dry weight, carbon/nitrogen ratio and photosynthetic efficiency) (Gottardini et al., 2020). The costs for measuring Leaf traits and Chlorophyll *a* fluorescence were considered to be quite high because of the time required for leaf image analysis, and because of the instrument (fluorimeter), the time and expertise required for data analysis, respectively.

3.2.3. *Criterion 3*

Both Increment and fellings and Roundwood resulted medium appropriate, while Non-wood Goods (Marketed mushrooms production) was not fully evaluable because of the lack of the score on discriminative ability among management options (Table 6a). The calculation of Increment and fellings and Roundwood makes use of mensurational variables inventoried during the periodical surveys at the time of each removal. For the above mentioned reasons, the replicability is highand the cost is medium.

The Marketed mushrooms production indicator is potentially important for assessing non-woody production and for its contribution to socio-economic and environmental sectors (Dettori et al., 2009). We found that it is characterized by low replicability and medium cost. The need for expert collectors and the high variability linked to the value of each species (marketed price) and its fluctuation, to the seasonality of production and number of species collected, as well as to animal and human predation, affected the indicator performance so that it was considered to be less reliable and informative, making it largely dependent on a multi-yearly monitoring.

3.2.4. *Criterion 4*

Out of the nine indicators considered for this Criterion, only two showed a medium level of qualitative rating, namely, the Species richness of native and Forest herbaceous vascular plants (Table 6b), with a total score of 6 and 5, respectively. These two indicators have a particular relevance, considering the role of herbaceous plants in providing a physical structure for other organisms. For these reasons, they are traditionally considered a key surrogate group in different habitats (e.g. Bagella, 2014; Bagella et al., 2014; Burrascano et al., 2018; Brunialti et al., 2020). The high level of knowledge of vascular plants favors the indicator applicability and replicability and contributes to limit the costs of their assessment.

Table 6b
SFM Criteria 4 – 6: SFM indicators appropriateness.

Criterion	Indicator	Discriminative ability	Replicability	Cost	Appropriateness at stand level	
					Total score	Qualitative rating
Criterion 4 – Forest biodiversity	4.1 Tree species composition	n.a.	3	3	Not fully evaluated	
	4.4 Introduced tree species	n.a.	3	3	Not fully evaluated	
	4.5 Deadwood	n.a.	3	3	Not fully evaluated	
	4.8 Threatened forest species	n.a.	3	3	Not fully evaluated	
	Forest herbaceous species	0	3	2	5	Medium
	Native herbaceous species	1	3	2	6	Medium
	Wood decaying fungi	n.a.	3	2	Not fully evaluated	
	Epiphytic lichens	n.a.	3	2	Not fully evaluated	
	Edible mushrooms	n.a.	1	2	Not fully evaluated	
Criterion 5 – Protective functions	Bryophyte cover	n.a.	1	3	Not fully evaluated	
	Ground litter depht	n.a.	1	3	Not fully evaluated	
	Flood retention	1	2	3	5	Medium
	Overstorey cover	2	3	2	7	High
	Understorey cover	1	3	3	7	High
Criterion 6 – socio economic functions	6.2 Contribution of forest sector to GDP	2	2	2	6	Medium
	6.3 Net revenue	3	3	2	8	High
	6.5 Forest sector workforce	n.a.	3	3	Not fully evaluated	
	6.8 Trade in wood	n.a.	3	1	Not fully evaluated	
	6.9 Energy from wood resources	3	3	2	8	High
	6.10 Accessibility for recreation	1	3	3	7	High

3.2.5. *Criterion 5*

Overstorey cover and Understorey cover turned out to be highly appropriate indicators (Table 6b). Overstorey cover, also known as canopy cover, is a variable commonly used in forestry (Angelini et al., 2015; Jennings et al., 1999), as well as in land-use and land-cover (LULC) studies (Chianucci, 2020). In addition, this variable is often included in national forest inventories (McIntosh et al., 2012). Canopy cover is often used as a measure of stand density, and it is an important indicator of wildlife habitats (Johnson and O'Neil, 2001), tree vitality and forest pest damage monitoring (O'Brien, 1989). This variable can be easily assessed with field-based optical instruments such as digital canopy photography (Chianucci, 2020), which makes rapid, robust and cost-effective measures of canopy cover possible. While measurements of overstorey cover are widespread in forestry, understorey cover measurements were made accessible only relatively recently, thanks to the advancement in digital canopy photography technology (Chianucci et al., 2014b; Chianucci, 2020). While complementary to overstorey cover, understorey cover measurements are also useful for designing silvicultural systems aimed at promoting natural tree regeneration (Caccia and Ballarè, 1998; Chianucci et al., 2014b), for understanding energy and mass exchange processes (Xue et al., 2011), and for understanding the relationships between plants and other organisms growing on the forest floor (Brunialti et al., 2020).

Flood retention showed medium appropriateness, due to its low discriminative ability at the considered fine spatial scale and its dependence on soil and slope properties.

In addition, the appropriateness of Bryophyte cover and Ground litter depth could not be assessed in full because of the lack of the score on discriminative ability among management options.

The data on the presence-absence of the Bryophyte cover indicator added limited information about the protective role of forest, considering the modest contribution of bryophyte to the forest ecosystem cover. Conversely, the ecological importance of this taxon implies that bryophyte information has a greater importance for the biodiversity

Criterion.

The Ground litter depth low appropriateness may be due to the fast leaf decomposition and thus mineralization, which characterize coppice woods in comparison with high forests, which often results in a relatively low accumulation in the topsoil horizon (Bruckman et al., 2011). Alternative methods based on collecting annual leaf litter using litter traps (Chianucci et al., 2019; Cutini et al., 2015) may be more useful to discriminate between different annual litter productions according to different coppice management systems.

3.2.6. Criterion 6

Net Revenue and Energy from wood resources showed the highest discriminative ability among the whole set of tested indicators and resulted highly appropriate together with Accessibility for recreation (Table 6b). Trade in wood and Forest sector workforce were not fully evaluable because of the lack of the score on discriminative ability among management options, while Forest contribution to GDP resulted medium appropriate due to its medium discriminative ability, replicability and cost.

More in detail, Net Revenue, based on stumpage value, also considering the discount rate and turnover of the different treatments, resulted highly appropriate in analyzing and evaluating the sustainability with a special reference to the economic context. It was highly able to discriminate among management options and to be replicated in any context where mensurational and economic data are available; it was characterized by medium costs concerning the basic forest surveys

The Energy from wood resources indicator assessed the renewable energy obtained from the residues of forest harvesting (Bernetti et al., 2009). It was highly appropriate for its discriminative ability among coppice management options and generally for high forests. It was also important from an environmental point of view, given the renewable energy production. It was easily replicable and the costs were medium due to the quite common availability of data needed.

The Accessibility for recreation indicator took into account an important forest service from both an economic and social point of view (Pearce, 2001; Wegner and Pascual, 2011; Bernetti et al., 2013; Riccioli et al., 2019). In this context, it was interpreted as the willingness to pay to maintain a specific management option (Riccioli et al., 2019; Riccioli et al., 2020a; Riccioli et al., 2020b). It was characterized by the lack of discriminative ability, high replicability and low cost, resulting highlyappropriate. Data collection, by means of the online distribution of questionnaires, contributed to lower the cost of the survey.

4. Conclusions

The novelty of this study was to test an adjusted and expanded set of consolidated and novel SFM indicators at the stand scale (i.e. at the management unit level), and their ability to document how coppice forests react to the different management options on the floor. Our results confirmed that – in the examined stands - several consolidated indicators related to resources status (Growing stock and Carbon stock), health (Defoliation and Forest damage), and socio-economic functions (Net revenue, Energy from wood resources and Accessibility for recreation) resulted highly appropriate to evaluate the sustainability at stand level. In addition, some novel indicators related to resources status (Total above ground tree biomass), health (Stand growth) and protective functions (Overstorey cover and Understorey cover) resulted highly appropriate and able to support the information obtained by the consolidated ones, thus allowing the possibility of an integrated evaluation of the sustainability of coppice forests. Some other indicators, especially those related to biodiversity, even if known for their relevance in SFM reporting, here resulted not fully evaluable because of constraints inherent to the spatial–temporal scale of the study.

We conclude that, according to the European Forest Type and management option, a subset of consolidated SFM indicators supplemented with the most appropriate novel ones, may represent a valid support for local resource managers, owners and decision-makers in their evaluation of coppice forest management. Case by case, decision makers may select those indicators that displayed responsiveness, ease of application, and reasonable costs. Moreover these indicators can be used to set targets in coppice forest related EU strategies, action plans and programmes to secure an appropriate monitoring, assessment and reporting of the respective achievements (Lier et al, 2021).

On the other hand, the implementations of geostatistically based methods for investigations of forest ecosystems using remote sensing imagery (Zawadzki et al., 2005) may allow further applications of the selected subset of SFM indicators by means of integration of ground-data and ground-data derived indicators with satellite observations.

In addition, some of the highly suitable SFM indicators could be usefully considered in national and international environmental monitoring programs (i.e. UNECE ICP Forests Level I and Level II network).

When considering the three management options examined, the picture resulting from our assessment is rather complex. In general, SFM indicators showed that coppice stands left to natural evolution or under conversion to high forest display significantly higher environmental performances in terms of growth and contribution to the carbon cycle, with values over the benchmarks for the European forests (FOREST EUROPE, 2020), as compared to traditional coppices.

The conversion of coppice to high forest has comparatively high values of standing biomass and provides the possibility to exploit wood resources by means of thinning, with positive effects also on the socio-economic aspects. Moreover, an optimized arrangement of the thinning repetitions and intensity over the rotation period, allows sound performances of Criterion 3 indicators, Roundwood especially. Further, it enhances the recreational function as highlighted by the higher values of “willing to pay”.

Traditional coppice combines dense understory cover with high values of wood harvesting rate; anyway, the harvesting rate was lower than the benchmark for the European forests and the one recommended to ensure their sustainable management (EEA, 2017).

In addition, it is an important cultural heritage, and may help keep local communities engaged in forest management.

Since each analyzed management option can provide specific aspects of sustainability, their coexistence - on a local scale and in accordance with the specific environmental conditions and the social-economic context - is greatly recommended, since it may fulfill a wide array of sustainability issues. Concurrently, it may represent a sound Climate Smart Forestry option in mitigating the risk associated with climate change and providing complementary ecosystem benefits.

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CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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