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The MIMOSE Approach to Support Sustainable Forest Management Planning at Regional Scale in Mediterranean Contexts

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Abstract: In recent decades, Mediterranean landscapes have been affected by human-induced drivers, such as land use and climate change. Forest ecosystems and landscapes have been particularly affected in mountainous regions due to limited management and stewardship, especially in remote areas. Therefore, there is a need to set up new strategies to enhance ecosystem services in forested areas which, in turn, will benefit local communities and economies. In this study, we implemented a new approach—Multiscale Mapping of Ecosystem Services (MIMOSE)—to assess ecosystem services in Mediterranean forests located in a mountainous region of Italy. We spatially assessed timber provision and carbon sequestration according to three forest management strategies: business-as-usual, maximizing economic values, and prioritizing conservation. Sustainable strategies for forest planning were identified at the landscape scale. We found that (i) timber provision is a conflicting service, especially when adaptation strategies are promoted; (ii) the most balanced set of forest ecosystem services is achieved through prioritizing conservation; and (iii) the ecosystem services availability is enhanced by optimizing the spatial allocation of different management strategies. Our approach is suitable to support landscape planning for balancing forest ecosystem potentialities while respecting local community needs and promoting sustainable development goals in the Mediterranean area.

Keywords: carbon storage and sequestration; forest ecosystem services; forest management planning; MIMOSE; total ecosystem services value; wood production

1. Introduction

Forest ecosystems provide a large set of goods and services (hereafter referred to as forest ecosystem services, FES) from the global to the local scale, such as timber and non-timber products, habitats for wildlife, sinks to regulate and mitigate chemical and hydrological regimes, and cultural and historical heritages [1,2]. In recent decades, FES have been formally recognized in some countries (e.g., UK; [3]), and their associated benefits to communities have increased [4]. FES availability depends on the resilience, health, and stability of forest ecosystems [5]. However, the most recent changes in land use and climate have strongly altered the capacity of forest ecosystems to guarantee future human well-being, especially in partly degraded and fragmented landscapes, such as those in the Mediterranean region [6]. The forest ecosystems in the Mediterranean region have suffered the abandonment of traditional silvicultural practices, localized overexploitation and, consequently, a reduction in stand productivity [7]. Considering these challenges, forest management and planning are called to balance FES availability with ecological and socio-economic aspects at the local scale in European forests [8,9]. In the spatial and temporal distribution and allocation of management interventions across the forest area, forest management planning needs to be primarily oriented towards sustainability at a broader scale (e.g., the landscape or regional levels). In other words, forest management planning should enhance the social and economic well-being of local communities by considering the anthropogenic effects on FES flows, such as land use change or forestry interventions. As a consequence, assessing the impact of alternative forest management strategies on the capacity of forests to provide FES is increasingly required to better direct decision-making processes towards improving the resilience of integrated ecological and socio-economic systems, especially at the landscape scale [10].

The acquisition of more detailed data on forest structure and soil, and their integration with additional information (e.g., remotely-sensed) may support forest management planning in better detecting changes in forest ecosystems and related services at both the spatial and temporal scale. In recent decades, very few models/systems have been adopted or implemented in Mediterranean forest landscapes as decision support tools, for example, to evaluate trade-offs and flows of timber and cork and pinecone supplies, and carbon stocks in Portugal [11–13], to address the joint production of timber and mushrooms in Turkey [14], and to facilitate predictions on wildfire management [15,16]. The role of the available models and decision-support systems to operationalize the concept of ecosystem services at local and regional scales is largely debated [13,17]. For instance, regional differences in terms of FES provision at EU scale were recently assessed by combining decision support systems with scenario-building processes [18]. However, the implementation of targeted policies (e.g., the EU Biodiversity Strategy to 2020; COM(2011)244), as well as a multi-sectorial perspective in assessing ecosystem services, are still required in spatial planning [17]. On the contrary, the so-called "model suites" have been shown to provide multiple approaches to decision-making issues [17]. For example, the "Integrated Valuation of Ecosystem Services and Trade-offs" (InVEST) and "Artificial Intelligence for Ecosystem Services" (ARIES) models have been proven effective in several cases [19,20]. Outside of Europe, the InVEST model was shown to be flexible in estimating, in a spatially explicit way, both the biophysical and economic values of ecosystem services at the landscape or watershed scale, and for forest management planning purposes [21]. In the Mediterranean region, the InVEST model was adopted to analyze the sediment dynamics and habitat quality in two forested watersheds in Spain [22,23]. Nevertheless, to our knowledge, very few studies have examined the implications of forest management planning on FES provision. For example, the Multiscale Mapping of Ecosystem Services (MIMOSE) approach was adopted to simulate the effects of management strategies on FES in Central Italy [24].

In Italy, the weak integration between the information made available by the national forest inventory and the current management and socio-economic conditions, as well as the overlap of responsibilities in forest planning have limited the long-term functionality and resilience of forest landscapes [25]. Similarly, the implementation of scenario-based solutions (i.e., models and tools) at the operational scale for maximizing FES provision in forest management planning contexts is still lacking in many parts of Italy. Although several studies have attempted to combine decision support systems with participatory processes (Basilicata region; [26]) and addressed the multi-functionality of forest landscapes (Molise region; [27]), many more efforts are still needed to consider FES in a spatially-explicit way and their related trade-offs in forest management planning in Italy.

To address these challenges, our study aims to: (i) implement the MIMOSE approach in Southern Italy to highlight the potentialities and constraints of assessing FES for forest planning in both biophysical and economic terms; (ii) propose alternative spatially-explicit strategies for improving sustainable forest management planning; and (iii) assess the implications of different forest management strategies on the total ecosystem services value, as well as their effects on incomes and social well-being. Firstly, timber provision and carbon sequestration were assessed and mapped over a 20-year simulation period (2015–2035) according to three forest management strategies; Secondly, the FES obtained were then used to compare the implications of the three alternative management strategies; Lastly, an optimized forest management plan was hypothesized by merging the three alternative management strategies in order to maximize the total ecosystem services value at the landscape scale and ultimately support sustainable large-scale forest management planning.

2. Materials and Methods

2.1. Study Area and Data

The study was carried out in the region of Sicily (Southern Italy), the largest island in the Mediterranean Sea. The study area covers 962,300 ha in the northeastern part of Sicily and reaches an altitude ranging between sea level and 3350 m a.s.l. at Mount Etna, the tallest active volcano in Europe (Figure 1). The climate is Mediterranean-type in the coastal belts and littoral plains and temperate in the mountainous inland [28]. The soils are classified as Entisols, Inceptisols, Mollisols, Alfisols, Vertisols, and Andisols [29], according to the USDA soil taxonomy system [30]. Almost 21% of the study area (approximately 200 thousand ha) is covered by forests and other woodlands (Figure 1). The most common forest categories and their percentage of total forest cover, respectively, are Downy oak (*Quercus pubescens* Willd.; 35%), Turkey oak (*Q. cerris* L.; 13%), European beech (*Fagus sylvatica* L.; 9%), and plantations (17%) [31]. Protected areas, such as regional parks, regional nature reserves, and Sites of Community Importance of the Natura 2000 network cover 60% of the total forest area. According to the currently available forest management regulations, silvicultural interventions are applied on 53% of the forest landscape, both in coppices (20%) and high forests (33%). The remaining forest area (47%) is not actively managed because it is mostly covered by degraded forests, young stands in early secondary evolution stages, and coppice stands exceeding the standard rotation age; these are abandoned and usually left to evolve spontaneously.

We used a map of forest categories [31], a growing stock map and a forest age map to create a forest management unit (FMU) map, in which all polygons are homogeneous in terms of forest category, age, and forest management system (see Chirici et al. [32] for more details on the approach used to create the FMU map). The methodology proposed by Frate et al. [33] was used to map forest age. We employed the *k*-nearest neighbour (k-NN) algorithm to estimate growing stock volume by combining the field data obtained from a local forest inventory with multispectral satellite images, as described in Chirici et al. [34]. Specifically, we used 829 inventory plots (each 530 m^2 in size) and the IRS LISS-III P6 (pixel size = 20 × 20 m) multispectral bands (green, red, near infrared, and short-wave infrared). The k-NN algorithm was configured as follows on the basis of the leave-one-out procedure: $k = 8$ and the Mahalanobis distance weighted with fuzzy weights [34] as multidimensional distance measures; the spectral feature extraction was performed using a 3 × 3 window generated around the field plots. The k-NN growing stock volume pixel level estimates had a root mean square error (RMSE) of 61.1 $m^3 \cdot ha^{-1}$ and a coefficient of determination (R^2) between predicted and observed values was 0.62. We set the size of FMUs to a minimum of 0.5 ha and a maximum of 15 ha according to local forest regulations. The FMU map contains 44,467 FMUs, with an average size of 4.5 ha (SD ± 3.5). Table 1 summarizes the main forest variables available for each FMU.

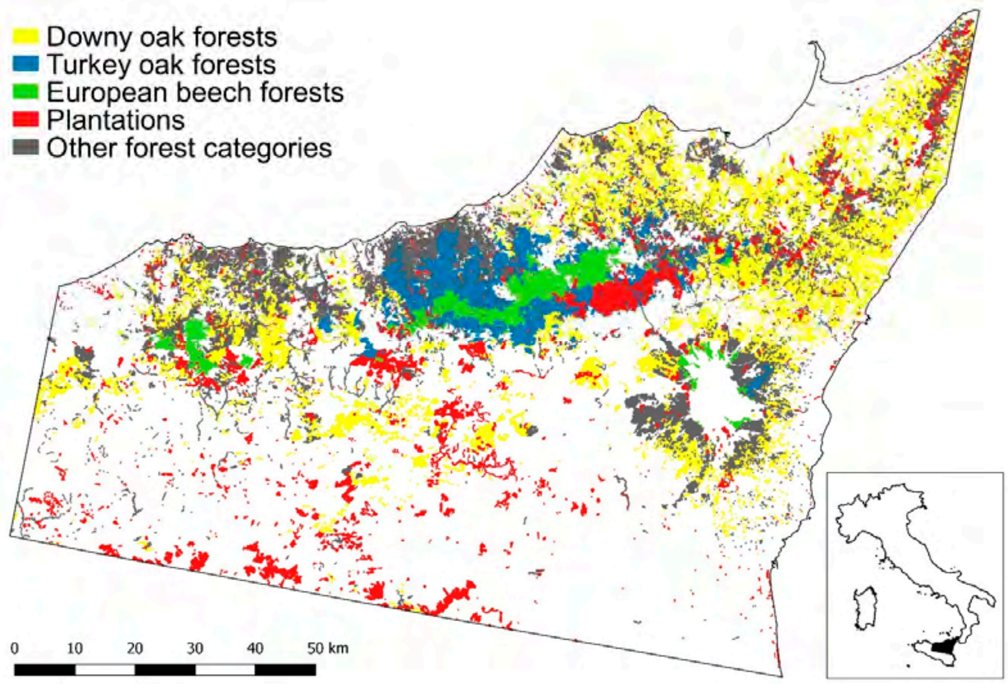

Figure 1. Map of Italy (bottom right) and study area highlighted in black. The close-up of the study area shows the forest cover differentiated according to the most common forest categories (labelled in the legend).

Table 1. The main quantitative variables available for each forest management unit.

Forest Variable	**Measurement Unit**	**Average Value (±SD)**
Altitude	m a.s.l.	788 (±403)
Slope	%	34 (±17)
Age	years	18 (±12)
Standing volume	$m^3 \cdot ha^{-1}$	87.6 (±51.5)
Above-ground biomass	$Mg \cdot ha^{-1}$	73.7 (±41.9)

2.2. The MIMOSE Approach

MIMOSE is a spatially-explicit approach that is useful to assess, in both biophysical and economic terms, different FES and their related trade-offs (i.e., timber harvesting versus carbon sequestration) under various management strategies [24]. In the present work, we implemented this approach following three steps, as proposed by Olander et al. [35]: (i) alternative forest management strategies (i.e., business-as-usual, BaU; nature conservation, NC; and wood production, WP) were applied at the FMU level in the study area; (ii) the InVEST model was applied to assess and map timber production and carbon sequestration over a 20-year time period (from 2015 to 2035) under different management strategies; and (iii) a large-scale forest management plan was hypothesized to maximize the total ecosystem services value at the regional scale.

2.2.1. Forest Management Strategies

We considered three alternative forest management strategies, hereafter named BaU, NC, and WP. BaU (business-as-usual) represents the current forest management approach required by local forest regulations. NC and WC were designed to represent management strategies directed more towards nature conservation or wood production, respectively, compared to BaU. We assumed that all forests were managed as even-aged systems in BaU and WP, and that high forests were managed with the aim of transitioning towards uneven-aged systems in NC. For each forest management strategy, the following three management systems were considered: coppice (including simple coppice forests and coppice forests with standards) [36], coppice in conversion to high forest [37], and high forest. Clearcutting was used as a silvicultural practice for coppices in BaU, NC, and WP, and for high forests (conifer species) in BaU and WP. The shelterwood practice [38] was used for both high forests (broadleaved species) and coppices in conversion to high forests in BaU and WP. The selection cut system was used in NC for both high forests and coppices in conversion to high forests (additional information regarding, e.g., rotation age and the limitations set in the diverse forest management strategies depending on terrain slope, presence of protected areas, and maximum size of clearcutting areas can be found in Bottalico et al. [24]). Table 2 reports harvesting intensity, expressed as the percentage of total growing stock adopted for BaU, NC, and WP, which was set based on the national literature [39–41] and in cooperation with local forest managers. Forest residues were estimated taking into account that approximately 77% of wood volume (m^3) is available for wood supply and the remaining as residuals [42]. The share of removed residues was set at 75% and 90% of the total residues for BaU and WP, respectively. For NC, the share of removed residues varied from 0% to 75% depending on terrain slope [43]. The forest management strategies were implemented at the FMU scale over a 20-year period (2015–2035) using the area control method and the current annual increment of wood volume ($m^3 \cdot ha^{-1} \cdot year^{-1}$) for the different forest categories [44]. Thinning operations were performed twice during the simulation period, once every 10 years, depending on the forest management strategy employed.

Table 2. Harvesting intensity (percentage of total growing stock) for the forest management strategies. BaU, business-as-usual; NC, nature conservation; WP, wood production.

Management Strategy	BaU	NC	WP
Simple coppice	100%	-	100%
Coppice with standards	60%–70%, depending on forest categories	40%–65%, depending on forest categories	70%–80%, depending on forest categories
Coppice in conversion to high forest	Thinning: 50% for the first, then 20% Seed cut: 30% Removal cuts: 30%	Thinning: 50% for the first, then 15% Selection cut: 10%–30% based on the concept of the minimum growing stock [41]	Thinning: 50% for the first, then 25% Seed cut: 30% Removal cuts: 30%
High forest	Thinning: 20% Broadleaved species- Seed cut: 30% Removal cuts: 30% Conifer species- Clear cut: 100% (max 3 ha)	Thinning: 15% Selection cut: 10%–30% based on the concept of the minimum growing stock [41]	Thinning: 25% Broadleaved species- Seed cut: 30% Removal cuts: 30% Conifer species- Clear cut: 100%

2.2.2. Ecosystem Services Assessment

The InVEST model [45] was used to assess and map the effects of the three forest management strategies on two FES, namely carbon storage and sequestration, and wood production. These effects were evaluated in both biophysical and economic terms. The amount of wood harvested from 2015 to 2035 was simulated using the InVEST Managed Timber Production model. This tool allowed considering different harvest intensities and frequencies, according to the three alternative management strategies. The InVEST Managed Timber Production model was applied at the FMU level, assuming that the total amount of timber harvested is used as firewood [46]. The economic outputs of the model are provided as net present value (NPV). NPV represents the net economic value at the starting point (2015 in our case) of timber production, according to all forestry interventions, as planned for the entire simulation period (i.e., 20 years). NPV (€$\cdot ha^{-1}$) was calculated for each FMU as a function of the amount of timber harvested, as well as its price (divided into hardwood and softwood) and harvesting costs. These values were then discounted in 2015 by adopting a discount rate of 3% [24]. The InVEST Carbon Storage and Sequestration model was implemented to assess forest carbon sequestration from 2015 to 2035 at the FMU level. In biophysical terms, carbon storage in 2035 was estimated by subtracting the simulated wood removals (i.e., harvested biomass) and adding the current annual increment of wood volume during the 20-year simulation period, as also suggested by the Italian national forest inventory [44] for forest growth simulation. The amount of carbon was not only estimated for the above-ground living biomass compartment, but also for other carbon pools: below-ground biomass, dead organic matter, including dead wood and litter, and soil organic matter (see also the IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry—GPG-LULUCF) [47]. Carbon sequestration was finally estimated by subtracting carbon storage in 2035 from carbon storage in 2015. The biophysical value was then converted into economic terms using the social cost of carbon (SCC) [48], considering a single SCC value of 109 $€\cdot\text{Mg}^{-1}$ and 7% as the discount rate (see Bottalico et al. [24] for further details). It is important to highlight that because SCC represents the total value of the incremental damage due to a small increase in carbon dioxide emissions [49], it can be considered more as a social than a pure market value and is, therefore, suitable to evaluate the social impacts of certain climate change policies and strategies [48]. NPVs and SCCs related to FMUs were finally aggregated for the whole study area to evaluate the total net present value (TNPV) and total social cost of carbon (TSCC), respectively.

2.2.3. Spatially-Explicit Analysis

The total ecosystem services value (TESV) is calculated as the sum of TNPV and TSCC, and represents the capacity of a given area to provide multiple services [50]. TESV can be equal to zero if no added benefits to society are provided through a specific activity, or negative if the costs of the activity are higher than the incomes (i.e., SCC is higher than NPV), or positive in the opposite case. Unlike Bottalico et al. [24], the primary aim of our study was not to investigate the relationships between the two FES, but to develop a forest management plan that maximizes TESV at the regional scale. Although a relatively higher TESV could be achieved through one of the three proposed management strategies (BaU, NC, and WP), perhaps the best result might be reached by mixing and merging them within the same forest management plan, according to the specific FMU characteristics (forest type, age, slope, etc.). To test this hypothesis and create the so-called optimized forest management plan (OFMP), we performed an FMU-based analysis to select that management strategy that maximizes TESV within each FMU. Accordingly, each FMU was assigned to a specific management strategy and then aggregated into a forest compartment (CMP), which is homogenous from the management perspective. Three CMPs were created and named according to the original forest management strategy (BaU, NC and WP). These three CMPs were finally merged into a single OFMP. The implications in terms of TESV, and the relationships between the two FES considered, were then analyzed, particularly accounting for their effects on private and social benefits and, consequently, on related sustainability.

3. Results and Discussion

3.1. Forest Ecosystem Services

In the case of timber production, TNPV was 140.6 M €, 70.4 M €, and 236 M €, equivalent to 8.8 M m^3, 4.7 million m^3, and 12.9 million m^3 of wood harvestable under the BaU, NC, and WP management strategies, respectively. On average, NPV was 707.6 $€\cdot\text{ha}^{-1}$, 354.4 $€\cdot\text{ha}^{-1}$, and 1187.3 $€\cdot\text{ha}^{-1}$, equivalent to 44.2 $\text{m}^3\cdot\text{ha}^{-1}$, 23.7 $\text{m}^3\cdot\text{ha}^{-1}$, and 64.7 $\text{m}^3\cdot\text{ha}^{-1}$ for the three management strategies, respectively. For carbon sequestration, TSCC was 83.8 M €, 306.1 M €, and -167.2 M €, corresponding to a total carbon removal of approximately 1.4 million Mg, 5 million Mg, and -2.7 million Mg for the BaU, NC, and WP management strategies, respectively. Carbon sequestration values were negative when the amount of carbon removed was greater than the current increment during the simulation period. This led to negative values of SCC, as it represents the costs of damage related to carbon emissions (carbon sources). On average, SCC was 421.6 €·ha^{-1}, 1539.9 €·ha^{-1}, and −841.4 €·ha^{-1}, and carbon stock increased by 6.8 Mg·ha^{-1}, 24.9 Mg·ha^{-1}, and decreased by −13.6 Mg·ha^{-1} for the same management strategies, respectively. TESV was 224.4 M €, 376.5 M €, and 68.8 M € for the three management strategies, respectively. In particular, the average TESV was 1129.2 €·ha^{-1}, 1894.3 €·ha^{-1}, and 345.9 €·ha^{-1} for the BaU, NC, and WP management strategies, respectively. Figure 2 provides a detailed illustration of TNPV, TSCC, and TESV in a specific location of the study area.

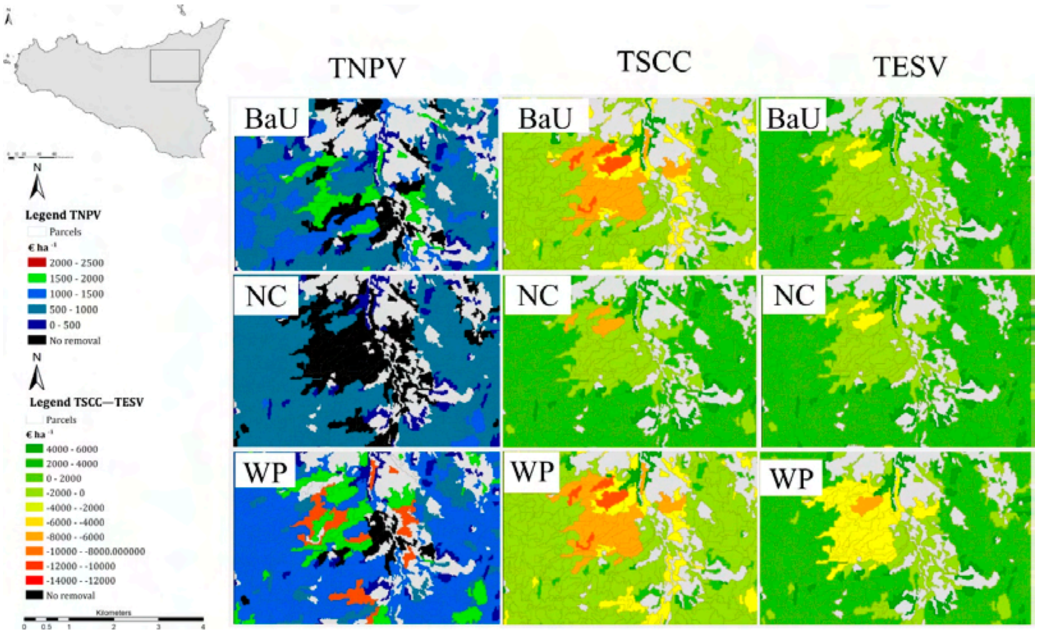

Figure 2. Maps showing the spatial distribution of total net present value (TNPV; €·ha^{-1}), total social cost of carbon (TSCC; €·ha^{-1}), and total ecosystem services value (TESV; €·ha^{-1}) for the simulated forest management strategies (BaU, business-as-usual; NC, nature conservation; and WP, wood production) in the area surrounding the volcano Etna.

Figure 3 depicts the trends of TNPV, TSCC, and TESV, as well as the harvesting intensity, according to the three forest management strategies. In general, TESV increased by approximately 67.8% when passing from the baseline (BaU) to the more conservative forest management strategy (NC), and decreased by approximately 69.4% when transitioning towards a more productive strategy (WP). TESV was indeed influenced by the combined effects of the forest management system adopted, the harvesting intensity and frequency, and the characteristics of forest stands, such as the average stand age, which is 18 years (in the investigated stands). The adoption of different management strategies was, in fact, demonstrated to directly influence FES trade-offs [51]. Considering that coppice stands with an average age of, for example, 15–20 years [52] have almost reached the end of the rotation period, depending on forest category, certain simulated silvicultural practices (e.g., final coppicing in standard forests vs. no intervention in coppice forests) may create a borderline between an increased TESV when adopting a more conservative approach (NC) and a reduced TESV when implementing a more productive strategy (WP).

In the case of Turkey oak forests, which cover more than 12% of the total forest area, prolonging the rotation period and converting the coppice stands into high forests (increasing the relative area four times the size) contributed to increase TESV (+18.6 M €) when passing from the BaU to NC management strategy. On the other hand, implementing a standard management of the coppice forests for the same forest category (i.e., coppice forests with standards release) induced a decreased TESV

(−19.8 M €) when passing from the BaU to WP management strategy. Indeed, prolonging the rotation length, as in the case of the NC strategy, was found to lower the incomes from wood production (cf. [53]). Moreover, in the total forest area, the reduction of the coppice forest area subjected to the final cut, with standard release (−40.4%), resulted in an increased TESV (+15.9 M €) when passing from the BaU to NC management strategy. On the contrary, increasing the area of coppice forests with standard release (+8.1%) for the same forest category resulted in a dramatic reduction of TESV (−56.2 M €) when passing from the BaU to WP management strategy. This discrepancy is due to the allocation of a large portion of the downy oak forest area (~40%) converted from coppice to high forest, and left to natural evolution, in the case of the NC management strategy for the time period under study. In this way, future carbon accumulation is facilitated (cf. [54]). Concerning the European beech forests (9% of the total forest area), the simulated forest interventions resulted in a decreased TESV (−25.7 M €) when passing from the BaU to WP management strategy. This may be due to the fact that the increase in TNPV still remained lower in comparison with the decrease in TSCC when passing from the BaU to WP management strategy, though most of the European beech coppice forests with standard release are actively managed (i.e., harvested). Accordingly, the period chosen for the simulations (i.e., 20 years) seems to be short to effectively understand the future development of forest stands and, in turn, assess the implications of some silvicultural interventions on TESV, such as natural evolution, conversion of coppice forests to high forests, and so forth.

These results are similar to those obtained in Bottalico et al. [24] for the Molise region (South-central Italy). The average TESV ha^{-1} was higher in the Molise region for the NC management strategy than in the Sicilian case study (+314 €·ha^{-1}), while it was lower for the WP strategy (−136 €·ha^{-1}). This was mainly due to the presence of younger stands and the adoption of less intensive forestry interventions when comparing the Sicily and Molise region studies. In the case of the NC management strategy, the harvesting rates during the simulation period were lower for the Sicilian forests compared with those of the Molise region (55% vs. 62%). Conversely, in the case of the WP management strategy, the harvesting rates were higher for Sicilian forests when compared with those for the Molise (88% vs. 83%). This may be due to the fact that the European beech forests in the Sicilian case study are mostly located at higher elevations and within protected areas and, thus, less intensive forestry interventions for these stands were implemented during the simulation in the case of the NC management strategy.

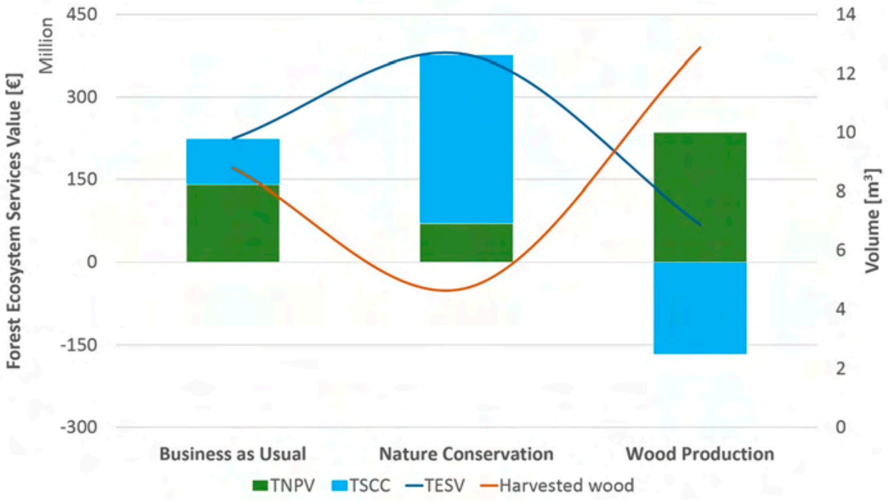

Figure 3. Bar chart representing the total net present value (TNPV; €), green bars, and the total social cost of carbon (TSCC; €), light blue bars, for each management strategy (*x*-axis); and the trends of both the total ecosystem services value (TESV; €), on the curved dark blue line, and the harvested wood (m^3), on the curved red line, when passing from one strategy to another.

The results mainly show that overall timber provision and carbon sequestration are conflicting services. Biomass removal yields high timber revenues (TNPV) and low carbon stock (TSCC), at least in the short-term. This indicates that simulations should be extended for more than 20 years to further understand the development of forest stands over time. Forestry interventions must be implemented by considering their effects on the biophysical properties of the forest stands and the objectives to be reached [55]. In this way, a deeper understanding of the spatial patterns and implications of forest management intensity and frequency on FES and their trade-offs are extremely important [56]. For example, increasing harvesting intensity may lead to a strong reduction of the total biomass and, subsequently, of carbon stock over the short run, particularly in younger and more intensively managed forest stands (see also [57]). Especially in forest landscapes in the Mediterranean region, which are often abandoned or degraded [58], forest management and planning must balance incomes with increased ecosystem resilience and stability [59]. This is the case for the Mediterranean and mountainous coniferous plantations in the investigated area, where TESV increased by approximately 32 M €, especially due to the adoption of thinning practices in previously unmanaged forest stands when passing from the BaU to NC management strategy. The implementation of active forest management may also reduce the negative impacts of external disturbances (e.g., wildfires) on FES provision and ensure the stability of forest stands for long periods [60].

3.2. Balancing Forest Ecosystem Services for Sustainable Planning Purposes

The most effective forest management strategy was selected and adopted to maximize TESV within each FMU (see the Materials and Methods section); the resulting OFMP map is depicted in Figure 4 and the relative TESVs are shown in Figure 5. The OFMP was largely dominated by FMUs, which were managed using a more conservative approach (NC management strategy; 83% of the forest area), while the more productive plan was limited to a few highly-productive FMUs (WP management strategy; 5% of the forest area). The remaining 12% of the forest area was managed by applying the current forest management strategy (BaU). In this case, no changes in the FMUs' TESV were observed when passing from the BaU to the more conservative or productive strategies. These FMUs are, indeed, those where interventions were neither considered nor planned for the future because of existing legal (i.e., protected areas) and morphological (i.e., high steepness) constraints. Moreover, these FMUs are characterized by cork oak and other broadleaved mixed forests comprising almost 80% of the forest CMP area, and refer to young stands in early secondary evolution stages that are neglected due to low market potentialities and average stand age, respectively. Conversely, the WP compartment is largely dominated by Mediterranean and mountainous pine forests (52% of the forest CMP), and is characterized by high growing stock volumes and limited harvesting restrictions. Finally, the NC compartment is dominated by mixed deciduous oak forests (holm oak and Turkey oak), which represent almost 60% of its forest area.

The TESV of the OFMP is 380 M € and proportionally distributed among the three forest CMPs based on their coverage (Figure 6). Almost 79% of the TESV is related to carbon sequestration (TSCC), while only 21% is related to timber harvesting (TNPV). Timber harvesting is mainly concentrated in the WP compartment, where the average harvesting rate is 16% of the total compartment's growing stock and decreased to approximately 8% in the NC compartment. Nevertheless, only a limited part of the regional TNPV (almost 19%) was derived from the WP compartment, while the remaining portion is related to the NC compartment owing to its larger area. It is important to highlight that even if covering only 5% of the whole forest area, the WP compartment contributes almost 20% to the TNPV (Figure 6), thus, substantially increasing private benefits for local populations, whereas the BaU compartment yields no contribution in terms of TNPV. According to the OFMP, the net carbon stored in the study area is 4.9 million Mg, corresponding to a TSCC of 301.6 M €. In this case, the contribution of the BaU compartment in terms of TSCC is more than proportional to its size (16%), while the WP compartment's contribution was drastically reduced (1%). This is quite obvious considering that no harvesting activity (i.e., carbon removal) was considered in the BaU compartment compared with the WP compartment.

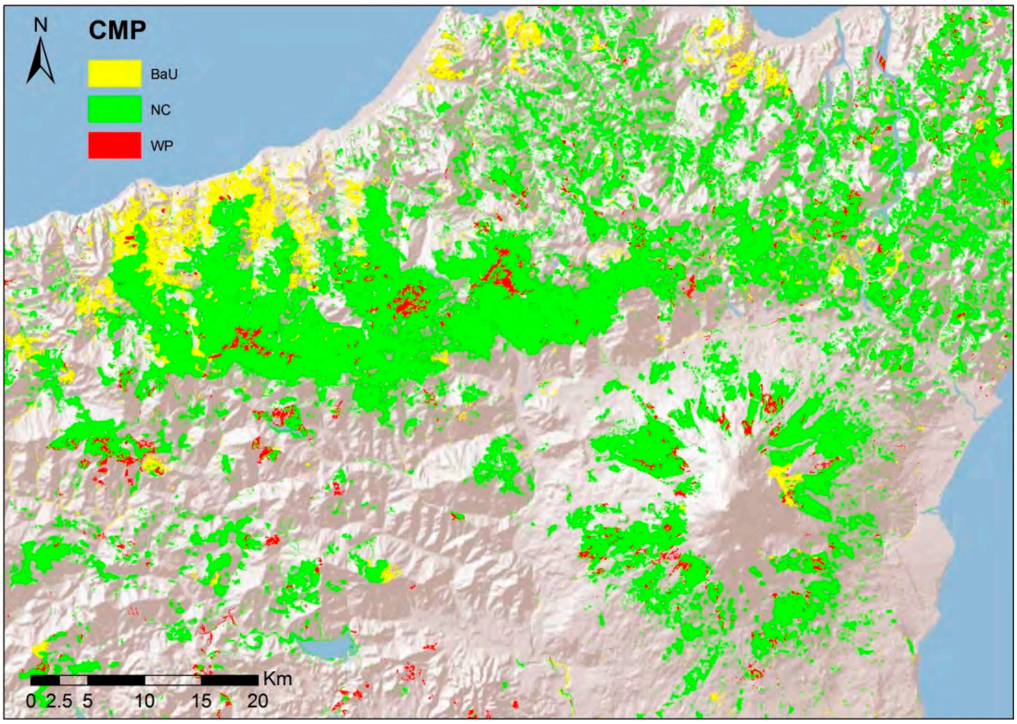

Figure 4. The optimized forest management plan map showing the spatial distribution of the three forest compartments (CMPs) adopted throughout the forest management unit. BaU, business-as-usual; NC, nature conservation; WP, wood production.

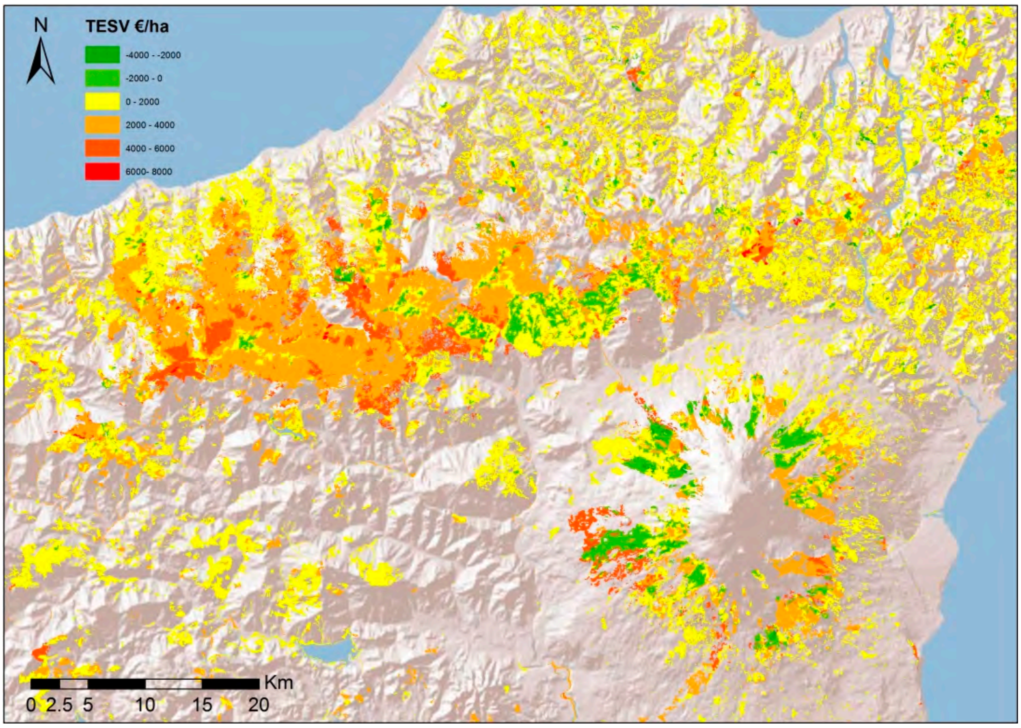

Figure 5. Map showing the spatial distribution of the total ecosystem services value (TESV; €·ha^{-1}) for the optimized forest management plan in the northeastern part of the study area.

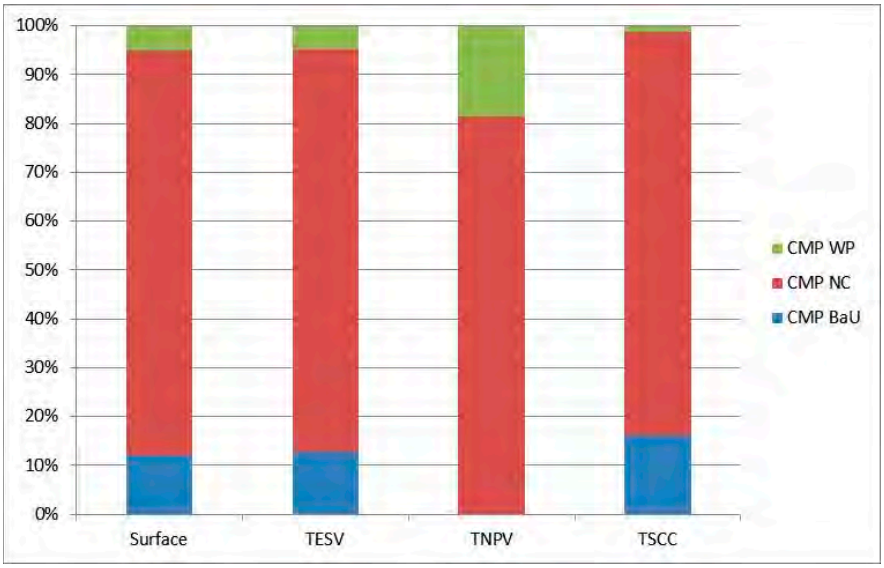

Figure 6. Relative contribution (%) of the three forest compartments (CMPs) in terms of surface, total ecosystem services value (TESV), total net present value (TNPV) and total social cost of carbon (TSCC). BaU, Business-as-Usual; NC, nature conservation; WP, wood production.

By comparing the OFMP with the three management strategies previously simulated, we observed that the former contributes to an increased TESV of about 4.2 M € compared to the NC management strategy (Figure 7). Considering both the BaU and WP management strategies, the net increase rose to 156.2 and 311.9 M €, respectively. Considering the wall-to-wall application of the NC management strategy, in the OFMP the TNPV increased by 8.6 M €, while the TSCC decreased only by 4.4 M €. Accordingly, the balance between TNPV and TSCC slightly increased in the OFMP compared to the NC management strategy (21% and 19%, respectively) (Figure 6). Even if the difference is very little, the increase in TNPV and, consequently, the increase in the TNPV/TSCC ratio, probably represents the most important achievement of the OFMP. In fact, in addition to the net increase of the regional TESV, the OFMP demonstrated to significantly increase the private benefits deriving from timber harvesting with low impacts on the social benefits, which decreased by lessening climate mitigation (i.e., TSCC). This contributes to balancing both private-economic and socio-environmental needs and, consequently, the sustainability goals in forest management planning. On the other hand, the substantial imbalance between TNPV and TSCC, corresponding to the wall-to-wall application of the BaU management strategy and even more to that of the WP strategy (63% and 343%, respectively), led to a significant decrease in regional TESVs. In these two cases, the significant private benefits have strong negative influences on the social benefits, thus leading to possible unsustainable and conflictual situations for the near future. Considering the NC management strategy, the relative increase of TNPV (11%) was higher than the relative increase of timber harvested (3%). This finding can be explained by considering that timber harvesting is more concentrated in suitable and profitable (maximized cost-benefit share) stands.

Considering the main outcomes, this study contributes to supporting sustainable forest management planning. FES mapping and trade-off assessments are extremely useful to identify priority areas for implementing specific planning strategies and distributing forestry interventions across the landscape, according to forest stand characteristics and economic revenues. In this way, our approach may help to bridge the gap between decision-making processes and local social and economic needs [61]; it may also contribute to the current state of forest stands in order to better adapt them to external disturbances or extreme events [62]. From the landscape to the regional scale, the OFMP may facilitate the implementation of forest planning guidelines of other plans at a higher hierarchical level (e.g., regional forest plan of the region of Sicily [63]) or of FES-related strategies, which are already available at the national, European (EU Forestry Strategy; COM(2013)

659 final), and global scales [64]. Lastly, the OFMP may also promote sustainability in the forestry sector (bioeconomy purposes; [10]). Our OFMP findings (increased TESV in the NC compartment) are consistent with the main guidelines from the "Forest landscape management plan of the North-western area of the Etna mountain" [65], which specifically focus on: (i) improving the conservation of forest habitats through the diversification of forest stand structures, enhancement of landscape heterogeneity, and release of deadwood and habitat trees; (ii) adopting forestry interventions that facilitate the conversion from coppice to high forest in European beech forests; and (iii) intervening with thinning in young coniferous forest stands to facilitate renaturalization with site-native species.

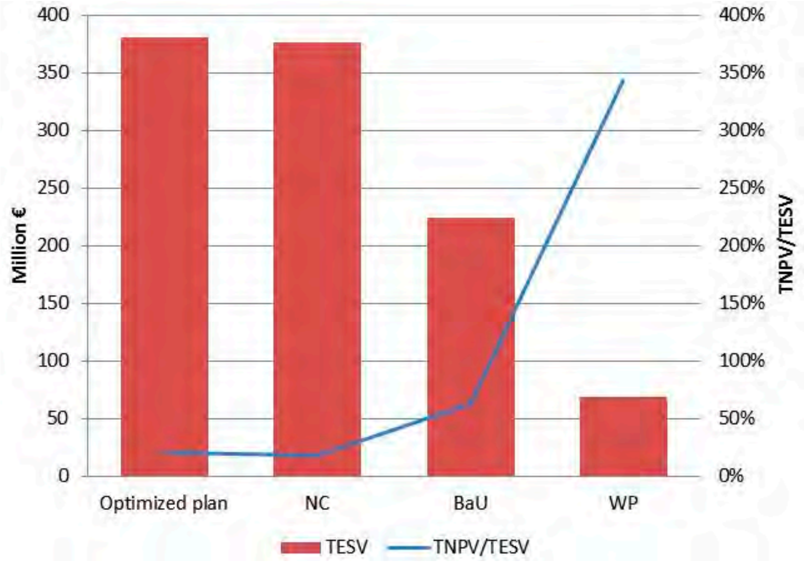

Figure 7. Total ecosystem services value (TESV; €) of the four alternative forest plans with the total net present value (TNPV)/TESV rate (%).

According to the main insights gained from our approach, sustainability in forest management planning may be enhanced by: (i) improving the implementation of optimization plans through, for example, effective investments in the forestry sector (rural development program [66]); (ii) adopting the payments for environmental services (PES) concept, which may facilitate compensation mechanisms and contribute to local development [67]; (iii) promoting both segregation and integration approaches in forest planning [68] to offset FES that need to be prioritized (e.g., biodiversity, carbon), or that are in competition with FES (e.g., timber); (iv) facilitating inter-sectoral coordination among different planning tools (forestry and protected areas management, or urban plans) [69]; and (v) strengthening public participation in forest planning [70] and exchanges with the research sector to promote a deeper understanding of the implications of future-oriented forest planning strategies on forest ecosystem functionality.

4. Conclusions

This study demonstrates that MIMOSE (multi-scale mapping of ecosystem services) is a suitable approach for assessing the influence of alternative management strategies on the provision of forest ecosystem services, as well as for understanding forest ecosystem dynamics and allocation, thus contributing to the effective implementation of sustainable forest planning from the landscape to the regional scale. Moreover, the integration of spatially-explicit data (biophysical characteristics) with an expert-based approach (management strategies) is highly relevant for supporting forest management planning in the following ways: (i) current and future-oriented information on forest stand development are simulated; (ii) the spatial distribution (location) of forest ecosystem services is provided; and (iii) the effects of forest management alternatives on forest resources are assessed over time and space. In addition, MIMOSE may be used to support the preparation of specific guidelines to balance ecosystem functionality and local socio-economic needs (through an optimized forest management plan). Hence, the MIMOSE approach may be replicated in other contexts with relatively low costs, since it is an effective tool for supporting decisions aimed at implementing more sustainable strategies in the forestry sector. This is crucial to promote and implement sustainable development goals, especially in the Mediterranean region (e.g., www.planbleu.org).

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