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ARTICLE

Pan-European sustainable forest management indicators for assessing Climate-Smart Forestry in Europe[1]

G. Santopuoli, C. Temperli, I. Alberdi, I. Barbeito, M. Bosela, A. Bottero, M. Klopčič, J. Lesinski, P. Panzacchi, and R. Tognetti

Abstract: The increasing demand for innovative forest management strategies to adapt to and mitigate climate change and benefit forest production, the so-called Climate-Smart Forestry, calls for a tool to monitor and evaluate their implementation and their effects on forest development over time. The pan-European set of criteria and indicators for sustainable forest management is considered one of the most important tools for assessing many aspects of forest management and sustainability. This study offers an analytical approach to selecting a subset of indicators to support the implementation of Climate-Smart Forestry. Based on a literature review and the analytical hierarchical approach, 10 indicators were selected to assess, in particular, mitigation and adaptation. These indicators were used to assess the state of the Climate-Smart Forestry trend in Europe from 1990 to 2015 using data from the reports on the State of Europe's Forests. Forest damage, tree species composition, and carbon stock were the most important indicators. Though the trend was overall positive with regard to adaptation and mitigation, its evaluation was partly hindered by the lack of data. We advocate for increased efforts to harmonize international reporting and for further integrating the goals of Climate-Smart Forestry into national- and European-level forest policy making.

Key words: silviculture, adaptation, mitigation, forest inventory, forest damage.

Résumé : La demande croissante pour des stratégies innovantes en aménagement forestier, dans le but d'atténuer les effets du changement climatique et de s'y adapter tout en ayant un effet positif sur la production des forêts, ce qu'on appelle la foresterie intelligente face au climat, exige un outil pour le suivi et l'évaluation de la mise en œuvre de ces stratégies et de leur effet sur le développement de la foresterie dans le temps. L'ensemble paneuropéen de critères et d'indicateurs pour un aménagement forestier durable est considéré comme un des outils parmi les plus importants pour évaluer plusieurs aspects de l'aménagement forestier et sa durabilité. Cette étude offre une approche analytique pour choisir un sous-ensemble d'indicateurs destinés à supporter la mise en œuvre de la foresterie intelligente face au climat. Sur la base d'une revue de littérature et d'une approche analytique hiérarchique, 10 indicateurs ont été sélectionnés pour évaluer plus particulièrement les mesures d'atténuation et d'adaptation. Ces indicateurs ont été utilisés pour évaluer l'état de la tendance européenne en matière de foresterie intelligente face au climat de 1990 à 2015 à l'aide de données provenant de rapports sur l'état des forêts européennes. Le dommage causé aux forêts, la composition en espèces arborescentes et le stock de carbone étaient les indicateurs les plus importants. Bien que la tendance ait été dans l'ensemble positive en ce qui concerne l'adaptation et l'atténuation, son évaluation a été en partie entravée par le manque de données. Nous recommandons d'augmenter les efforts visant à harmoniser sur une base internationale la présentation des rapports et d'intégrer davantage les objectifs de la foresterie intelligente face au climat dans l'élaboration des politiques forestières à l'échelle nationale et européenne. [Traduit par la Rédaction]

Mots-clés : sylviculture, adaptation, atténuation, inventaire forestier, dommage causé aux forêts.

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G. Santopuoli and R. Tognetti. Dipartimento Agricoltura, Ambiente e Alimenti, Università degli Studi del Molise, Via Francesco De Sanctis, 86100 Campobasso, Italy; Centro di Ricerca per le Aree Interne e gli Appennini (ArIA), Università degli Studi del Molise, via Francesco De Sanctis 86100 Campobasso, Italy.
C. Temperli. Swiss Federal Institute for Forest, Snow and Landscape Research WSL. Zürcherstrasse 111 CH-8903 Birmensdorf, Switzerland.
I. Alberdi. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria, Ctra. A Coruña, 7.5 Km, 28040, Madrid, Spain.
I. Barbeito. Southern Swedish Forest Research Center, Swedish University of Agricultural Sciences Sundsvägen 3, Box 49, 230 53 Alnarp; Université de Lorraine, AgroParisTech, INRA, UMR Silva, Nancy, France.
M. Bosela. Faculty of Forestry, Technical University in Zvolen, Slovakia.
A. Bottero. Swiss Federal Institute for Forest, Snow and Landscape Research WSL. Zürcherstrasse 111 CH-8903 Birmensdorf, Switzerland; SwissForestLab, CH-8903 Birmensdorf, Switzerland.
M. Klopčič. Biotechnical Faculty, Department of Forestry and Renewable Forest Resources, Jamnikarjeva ulica 101, SI-1000 Ljubljana, Slovenia.
J. Lesinski. Department of Forest Biodiversity. University of Agriculture. Al. 29-Listopada 46. 31-425 Krakow, Poland.
P. Panzacchi. Facoltà di Scienze e Tecnologie, Libera Università di Bolzano, Piazza Università 1, 39100, Bolzano/Bozen, Italy; Centro di Ricerca per le Aree Interne e gli Appennini (ArIA), Università degli Studi del Molise, via Francesco De Sanctis 86100 Campobasso, Italy.

Corresponding author: Giovanni Santopuoli (email: giovanni.santopuoli@unimol.it).

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1. Introduction

Over the years, the anthropogenic impacts on natural resources due to the increased societal demand for ecosystem services have challenged the sustainable management of forests. Climate change has further increased the pressure on forests, threatening their stability, biodiversity, and productivity, thereby limiting the provision of forest ecosystem services. This fostered the development of the concepts of Climate-Smart Forestry (CSF) (Jandl et al. 2018; Kauppi et al. 2018; Nabuurs et al. 2018; Yousefpour et al. 2018; Bowditch et al. 2020; Verkerk et al. 2020), which focused mostly on the improvement of production, adaptation, and mitigation and the maintenance of biodiversity and delivering of ecosystem services. For these reasons, forest policy decision makers and managers are called to define and implement proactive forest management strategies to promote resistance and resilience to climate change, as well as to develop policies to use forests, forestry, and the wood industry for carbon sequestration and substitution (Klenk et al. 2015).

In general, adaptation to climate change deals with the reduction of the adverse impacts of climate change on forest ecosystems, through the adjustment of forestry practices, to optimize the provision of forest goods and services (Seidl and Lexer 2013). In particular, adaptation measures aim to decrease the occurrence and impacts of forest damages triggered by climate change while exploiting the beneficial opportunities to promote the environmental, economic, and social sustainability (Jandl et al. 2013).

Developing adaptive management measures is challenging due to the rapid changes in climate and land use and the wide range of forest types and the traditional management objectives that characterize the European forestry sector. For this reason, appropriate indicators for monitoring and supporting CSF are necessary to counteract and promptly respond to ongoing environmental changes.

It is recognized worldwide that forests and forest management play a crucial role in mitigating climate change (Makundi 1997; Grace et al. 2014; Nabuurs et al. 2017). This important awareness among forest policy and decision makers and more generally among stakeholders of the forestry sector has promoted a wide range of forest management strategies, which in the last three decades have resulted mainly in an increment of European forest area and ageing of forests (Forest Europe 2015). These dynamics of forest ecosystems were further exacerbated, particularly in southern Europe, by the depopulation of rural environments and abandonment of forestry practices (Burrascano et al. 2016), namely in mountain areas. Nevertheless, the increased growing stock alone is not enough to ensure the effective contribution of forests to the mitigation of climate change, and active forest management is required to valorize the role of forests and to improve the effectiveness of mitigation strategies. For example, the integration of mitigation actions with policy and programs that promote wood production is strongly recommended (Makundi 1997; Colombo et al. 2012; Jasinevičius et al. 2017; Bowditch et al. 2020) to sequester carbon in long-lived wood products. Balancing the provision of regulating, cultural, and economic forest ecosystem services is ever more becoming a demanding task.

Forestry plays an important role in fulfilling the goals of reducing greenhouse gas emissions, and national governments are encouraged to deliver forest policy recommendations for climate change mitigation (FAO 2018). This can be achieved with appropriate silvicultural interventions to facilitate, for example, tree and forest growth such that more CO_2 is sequestered from the atmosphere than released from the forest through respiration, decay of deadwood, and production of wood for energy (Colombo et al. 2012; Jandl et al. 2013; Köhl et al. 2020). This typically encompasses abandoning timber harvesting, which may be in conflict with policies that aim to raise the capacity of forests to adapt to climate change by reducing rotation lengths and harvesting cycles, promoting more drought- and disturbance-resistant tree species, and generally fostering tree species diversity (Lindner et al. 2010; Diaconu et al. 2017; Jandl et al. 2019). Reducing timber harvesting may also conflict with policies aimed to sequester carbon in wood products and substitute fossil fuel in intensive energy building material (Colombo et al. 2012; Jasinevičius et al. 2017).

Management for adaptation may conflict with nature conservation goals such as retention of old-growth forest structures, and mitigation goals may collide with the need for ensuring advanced regeneration and stability in forests that protect against rockfall and avalanches in mountainous areas (Brang et al. 2006). Hence, mitigation, adaptation, and the provision of ecosystem goods and services need to be balanced in CSF recommendations at local to national scales (Bowditch et al. 2020).

In the last years, the concept of CSF becomes a promising solution to integrate both adaptive and mitigative management strategies (Bowditch et al. 2020; Tognetti 2017). Previous applications of the CSF concept focused mainly on mitigation potentials at national to European levels (Nabuurs et al. 2018) or simulations of forest development under various management scenarios (Jandl et al. 2018; Yousefpour et al. 2018), though there are likely many other benefits beyond the reduction of greenhouse gas emissions if planned and implemented carefully (Nabuurs et al. 2018; Verkerk et al. 2020). In this context, forest growth models and climate change scenarios have been used to assess future and long-term forest dynamics (Bontemps and Bouriaud 2014; Pretzsch et al. 2014; Yang et al. 2015).

Though the CSF concept is increasingly used among forest and forestry actors in Europe, a comprehensive assessment method that simultaneously accounts for the two CSF aspects of adaptation and mitigation at national to European scales is still lacking. Developing both adaptive and mitigative management strategies requires accurate and updated information about forest resources. In Europe, National Forest Inventories represent the most important source of data about forest ecosystems (Winter et al. 2008), while the pan-European set of criteria and indicators (C&I) for sustainable forest management (SFM) is considered the most important tool for monitoring, assessing, and reporting on forest management in Europe (Santopuoli et al. 2016*a*; Wolfslehner and Baycheva-Merger 2016). Facilitating the assessment of CSF is necessary to provide quick responses about forest management and practices helpful in minimizing climate change impacts. To accomplish this target, the development of a methodology to use SFM indicators for assessing adaptation, mitigation, and CSF is required. Though Bowditch et al. (2020) provided a first step to selecting CSF indicators, to date, no set of indicators has been suggested to comprehensively monitor and assess CSF, even though several sets of C&I for SFM were developed worldwide (Castañeda 2000).

The aim of this study is twofold: (*i*) to develop a viable method for assessing CSF using data collected through the pan-European set of C&I for SFM, and (*ii*) to assess the CSF trend over time across Europe. For the purposes of this study, we address the following research questions. Are SFM indicators suitable to assess CSF? How is the CSF trend over time in Europe?

2. Methods

The methodological approach implemented in this study comprises (*i*) a literature review and (*ii*) an evaluation of the CSF trend over time. The literature review focused on collecting papers that deal with the adaptation and mitigation potential of forest management directed to select SFM indicators useful for assessing CSF. To evaluate forest development with regards to CSF indicators at the European level, two substeps were required. The first step aimed to assign a weight for each pan-European SFM indicator selected through the literature review using an analytical hierarchical process (Saaty 1990, subsection 2.2). The second step aimed to assess and display the trend over time of aggregated indicators, describing the capacity of forests to both adapt to climate change and mitigate climate change across European countries (subsection 2.3).

2.1. Indicator selection through a literature review

For this study, we selected, through a literature review, a subset of indicators from the current pan-European C&I set as reported by Forest Europe (Forest Europe 2015). In particular, we used the literature review to identify the most recurrent indicators, from the whole quantitative C&I set, that are suitable measures for adaptation to and mitigation of climate change in forest ecosystems.

The literature review was carried out in February 2020 using the Scopus® database. We used two queries, one for adaptation and one for mitigation:

- (TITLE-ABS-KEY (climat* AND adapt*) AND TITLE-ABS-KEY (sustainable AND forest AND management) AND TITLE-ABS-KEY (indicator)); and
- (TITLE-ABS-KEY (climat* AND mitigat*) AND TITLE-ABS-KEY (sustainable AND forest AND management) AND TITLE-ABS-KEY (indicator)).

We did not use constraints on the year of publication but did exclude non-English and non-relevant articles, i.e., articles that were not strictly focused on the use of SFM indicators. For this reason, all papers were accurately screened to remove duplicates and extract the SFM indicators used to assess adaptation and mitigation, respectively. Ecological, social, and economic aspects of the SFM were considered equally important, and indicators were selected if explicitly mentioned in the articles or if there was some clear linkage to them. For example, indicator 4.1 "tree species composition" was mentioned as a solution to promote adaptation through forest management strategies by many authors (Jandl et al. 2013; Hlásny et al. 2014; Klenk et al. 2015). On the other hand, forest "carbon stock" and "energy from wood resources" were cited several times as indicators to assess many aspects of mitigation strategies such as ecological sustainability (Colombo et al. 2012), forest harvesting and bioeconomy (Jasinevičius et al. 2017; Paletto et al. 2017), and wood energy (Forsius et al. 2016; Buonocore et al. 2019; Szulecka 2019).

Following the literature review, a subset of indicators was selected from the current pan-European C&I set. The following criteria were used for selecting indicators: (*i*) the indicators should reflect as many aspects of adaptation and mitigation issues as possible; and (*ii*) the number of indicators should not exceed nine, as this was required for the method (see section 2.2) to weight each indicators among the others (Saaty and Ozdemir 2003). We prioritized those indicators that were mentioned most frequently in the reviewed literature. In particular, we assessed the frequency of each indicator, and thereafter, selected those indicators that were in the third quartile in terms of times mentioned. This resulted in a selection of eight adaptation-related indicators that were mentioned at least three times and four mitigation-related indicators that were mentioned at least five times.

2.2. Analytical hierarchical process to weight SFM indicators

The analytical hierarchical process (AHP) can be used to assign indicator weights through a pairwise comparison and is frequently used in environmental and forest sectors as a decision support tool (Kuusipalo and Kangas 1994; Ananda and Herath 2003; Wolfslehner et al. 2005; Santopuoli et al. 2016*b*).

To implement the pairwise comparison, firstly, the relative priority of indicators was calculated as follows:

$$\mathrm{RP} = \left(\frac{\mathrm{Cit_{np}}}{\mathrm{Cit_{pmax}}}\right)\left(\frac{1}{\mathrm{Cit}_1} + \frac{1}{\mathrm{Cit}_2} + \ldots + \frac{1}{\mathrm{Cit}_n}\right)$$

where RP is the relative priority; $\mathrm{Cit_{np}}$ is the number of publications that mention the focal indicator; $\mathrm{Cit_{pmax}}$ is the maximum number of times that one of the indicators was mentioned, i.e., seven for "tree species composition" and 12 for "carbon stock" for adaptation and mitigation, respectively; Cit_1 is the total number of indicators mentioned by the same author at the first time; Cit_2 is the total number of indicators mentioned by the same author at the second time; and Cit_n is the total number of indicators mentioned by the same author at the *n*th time. For example, indicator 1.2 "growing stock" was mentioned in three papers ($\mathrm{Cit_{np}} = 3$) among those used for the adaptation review. The total number of indicators mentioned by the first paper was seven ($\mathrm{Cit}_1 = 7$), while the second and third papers mentioned a total of six ($\mathrm{Cit}_2 = 6$) and five ($\mathrm{Cit}_3 = 5$) indicators, respectively. Considering the $\mathrm{Cit_{pmax}}$ of seven, the RP for "growing stock" was 0.218.

Subsequently, the RPs were used to create the reciprocal matrix (Saaty 1980; Kangas et al. 1993; Mendoza and Prabhu 2000) for adaptation and mitigation separately to obtain the eigenvector for each indicator. The pairwise comparison was carried out considering the differences between RPs and obtaining a consistency ratio lower than 10% (Ananda and Herath 2003), which was 0.07 for both matrices.

The overall priority was calculated for each indicator considering the ratio of the number of articles, 11 and 19 for adaptation and mitigation, respectively, and the total number of the articles (30) multiplied by the eigenvectors (i.e., overall priority = $0.37 \times \mathrm{Eigen_A} + 0.63 \times \mathrm{Eigen_M}$).

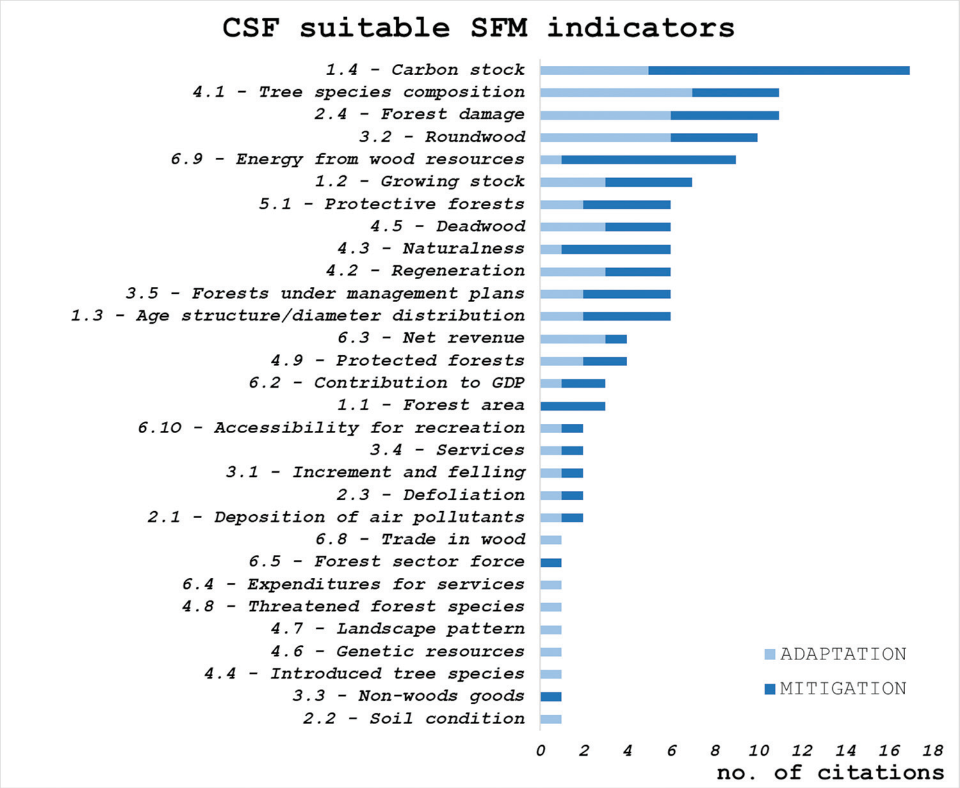
2.3. Calculation of adaptation and mitigation indicators

The calculation of the aggregate indicators for adaptation and mitigation was based on the data reported in the State of Europe's Forests (SoEF) database (https://foresteurope.org/state-europes-forests-2015-report/#1476295991324-493cec85-134b, accessed 11 March 2020). First, all available data were downloaded for the years 1990, 2000, 2005, 2010, and 2015 for each indicator. Data on other wooded lands were then excluded from the analysis, because we focused only on forests. We assessed the trend in indicator development for four time periods (2000–1990; 2005–2000; 2010–2005; and 2015–2010) by calculating the percentage changes in the values of each of the 10 indicators at the country level.

The direction of change in the value of indicators was considered differently, depending on the SFM indicator in calculations of aggregated indicators for adaptation and mitigation. For most indicators, a positive development was assumed to positively affect adaptation ("growing stock", "carbon stock", "roundwood", "deadwood, "net revenue") and mitigation ("carbon stock", "energy from wood resources"); however, an increment in "forest damage" between two consecutive years was considered to negatively affect both adaptation and mitigation. Changes in "regeneration", calculated as the ratio between the afforested (by planting and seeding) forest area and the naturally regenerated or coppiced forest area, were considered to positively affect adaptation. A positive change in "naturalness", which was assessed as an increase in the percentage of forest plantation cover with respect to the total forest cover, was considered to negatively impact mitigation. "Tree species composition" was calculated as the ratio of mixed forest to pure forest, and its change was interpreted to positively affect adaptation.

The relative change of each indicator was multiplied by the overall priority value for adaptation and mitigation separately. The obtained weighted indicator values were then summed for each country and for each period and displayed in a scatterplot, with adaptation as the *x* axes and mitigation as the *y* axes.

Fig. 1. Sustainable forest management (SFM) indictors used to assess adaptation and mitigation in the reviewed literature. [Colour online.]



Three of 46 pan-European countries (Holy See, Monaco, and the Russian Federation) were excluded because data were not available for all indicators and for all the years. Finally, results were displayed for the 27 countries of the European Union, Switzerland, and the United Kingdom (UK), and a European-level estimate was calculated as the average of the country-level adaptation and mitigation estimates.

3. Results

3.1. SFM indicators frequently used to assess adaptation and mitigation

A total of 73 scientific papers were extracted from the Scopus® database, 36 for adaptation and 37 for mitigation. During the screening phase, 43 papers were considered non-relevant articles. The final list of papers used for identifying SFM indicators suitable for CSF assessment consisted of 30 articles, 11 for adaptation and 19 for mitigation. All the articles were published in the period 2011–2020, except one published in 1997.

Scrutinizing the 30 articles revealed that 30 out of 34 quantitative indicators were suitable to assess adaptation and mitigation (Fig. 1). Twenty out of 30 indicators were useful to assess both adaptation and mitigation, while seven indicators were mentioned only for adaptation (i.e., 2.2 "soil condition", 4.4 "introduced tree species", 4.6 "genetic resources", 4.7 "landscape pattern", 4.8 "threatened forest species", 6.4 "expenditure for services", 6.8 "trade in wood") and three were mentioned only for mitigation (i.e., 1.1 "forest area", 3.3 "non-woods goods", 6.5 "forest sector force"). The most frequent SFM indicators mentioned for assessing adaptation were 4.1 "tree species composition", 3.2 "roundwood", 2.4 "forest damage", 1.4 "carbon stock", and 1.2 "growing stock". For the assessment of climate change mitigation, 1.4 "carbon stock", 6.9 "energy from wood resources", 2.4 "forest damage", and 4.3 "naturalness" were the most suitable indicators. The indicators 6.1 "forest holding", 6.6 "occupational safety and health", 6.7 "wood consumption", and 6.11 "cultural and spiritual values" were never mentioned.

The overall most frequent indicators, considering both adaptation and mitigation, were 1.2 "growing stock", 1.4 "carbon stock", 2.4 "forest damage", 3.2 "roundwood", 4.1 "tree species composition", 4.2 "regeneration", 4.3 "naturalness", 4.5 "deadwood", 6.3 "net revenue", and 6.9 "energy from wood resources". They represent the subset of indicators selected from the literature review and used for assessing the CSF trend over time, in Europe, in this study (Table 1).

The AHP highlighted that "tree species composition" and "forest damage" were the indicators with the highest priority values, with 0.399 and 0.238, respectively, for adaptation (Table 1). "Carbon stock" and "energy from wood resources" were the most important indicators for climate change mitigation, showing priority values of 0.660 and 0.211, respectively. "Carbon stock", "tree species composition", and "forest damage" yielded the highest overall priority (ranks 1–3), while "growing stock", "deadwood", and "net revenue" yielded the lowest (ranks 8–10). This reflects the frequency of these indicators to be mentioned in connection with adaptation and mitigation in the literature.

3.2. CSF trend from 1990 to 2015

The trend in the period 1990–2000 was positive, particularly for mitigation, for which most of countries, except the Netherlands and Slovenia, showed positive values (Fig. 2). In contrast, the negative trend of countries such as the Netherlands and Slovenia registered for adaptation was most probably driven by the increased forest damages between 1990 and 2000 (see National Report available on https://foresteurope.org/state-europes-forests-2015-report/#1476295965372-d3bb1dd0-e9a0, accessed 11 March 2020).

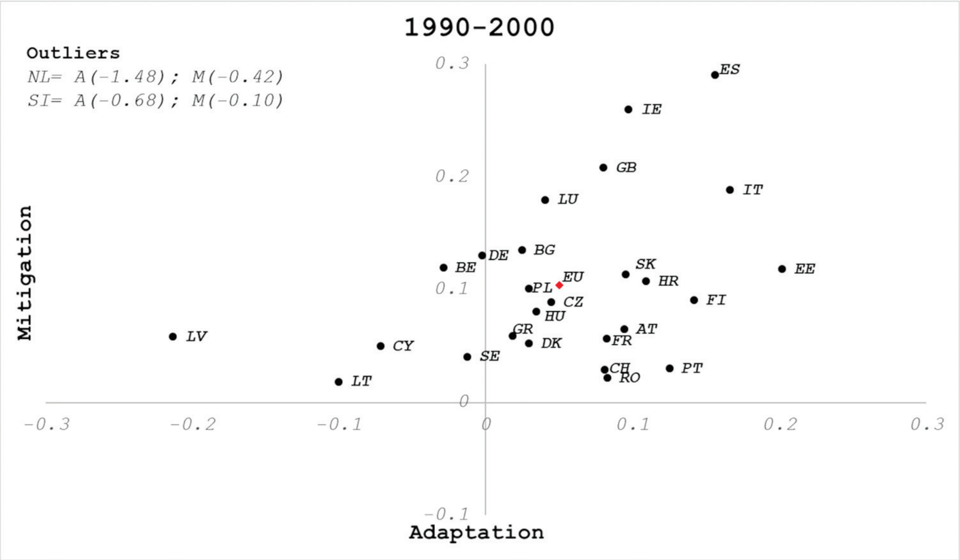
The decrease in forest damages between 1990 and 2000 in most countries was the most influencing aspect, resulting in positive values of adaptation and mitigation. In particular, the positive trend observed in Spain could be ascribed mainly to the increment of forest carbon stock and the reduction of forest damages. In addition, further positive values were also observed for "net

Table 1. Indicator weights for the subset of sustainable forest management (SFM) indicators used in the evaluation of adaptation and mitigation across Europe.

SFM indicator	Adaptation	Mitigation	Overall priority	Rank
1.2 — Growing stock	0.026		0.009	8
1.4 — Carbon stock	0.147	0.660	0.472	1
2.4 — Forest damage	0.238	0.079	0.137	3
3.2 — Roundwood	0.100		0.037	5
4.1 — Tree species composition	0.399		0.146	2
4.2 — Regeneration	0.039		0.014	7
4.3 — Naturalness		0.050	0.032	6
4.5 — Deadwood	0.026		0.009	9
6.3 — Net revenue	0.025		0.009	10
6.9 — Energy from wood resources		0.211	0.134	4

Note: The reported values represent the eigenvectors obtained through the pairwise comparison (Saaty 1980) for adaptation ($\text{Eigen}_{\text{Adaptation}}$) and mitigation ($\text{Eigen}_{\text{Mitigation}}$) and the overall priority. The rank reflects the overall priority values.

Fig. 2. Changes in adaptation and mitigation between 1990 and 2000. Note that a positive change in both adaptation and mitigation (top-right quadrant) is considered climate smart. The ISO 3166-1 alpha-2 are used for country abbreviations. [Colour online.]



revenue" and "growing stock". Positive values for Italy depended mainly on the reduction in burned forest area registered for 2000 compared with 1990, i.e., 82 000 and 48 000 ha, respectively.

The overall trend observed in the period 2000–2005 is positive, even if some countries showed negative values for both adaption and mitigation (Fig. 3). The negative trend was influenced mostly by countries such as Italy, Latvia, and Cyprus that reported very negative values, especially for the indicator "forest damage". Contrary to the previous period, the increase in forest damages between 2000 and 2005 was affected by the addition of types of forest damages considered in the national reports that were not considered in the previous years.

Positive trends were observed in many countries, as in the Netherlands, for which not only a reduction of "forest damage" was observed in 2005 with respect to 2000, but also increments of "net revenue", "tree species composition", and "deadwood", which strongly contributed to the positive trend in adaptation. This was particularly evident in Slovenia, where increased "forest damage" and the higher increments of both "tree species composition" and "net revenue" strongly contributed to the positive evaluation of adaptation.

Most of the countries showed positive values for both adaptation and mitigation in the period 2005–2010, and the average trend in Europe was also positive (Fig. 4). The introduction of forest damages by abiotic agents within the "forest damage" indicator caused a large part of the negative trend in both adaptation and mitigation in Ireland. Nevertheless, the higher value for mitigation resulted from the impacts of "energy from wood resources", which increased from 2005 to 2010. The European value was also particularly influenced by the data from Slovenia, where adaptation was strongly and negatively affected by the reduction in the tree species composition indicator (ratio of area of mixed forests to pure forest), while the increments of "net revenue" and "energy from wood resources" positively affected the evaluation of the mitigation trend. The increment of the production of "energy from wood resources" observed in Finland and the UK in the period 2005–2010 positively impacted the overall mitigation trend. On the other hand, the increment in "tree species composition" and the reduction of "forest damage" positively affected the adaptation trend, as observed in, for example, Belgium and the Netherlands.

A positive trend was observed in the period 2010–2015 for both adaptation and mitigation in all countries (Fig. 5). Nevertheless, results were strongly affected by the lack of data in 2015 for "forest damage", "regeneration", "tree species composition", "deadwood", and "net revenue". For this reason, countries such as Cyprus and the UK, which reported a positive trend in "energy from wood resources", showed increased values for mitigation. Little changes among countries were observed for adaptation,

Fig. 3. Changes in adaptation and mitigation between 2000 and 2005. [Colour online.]

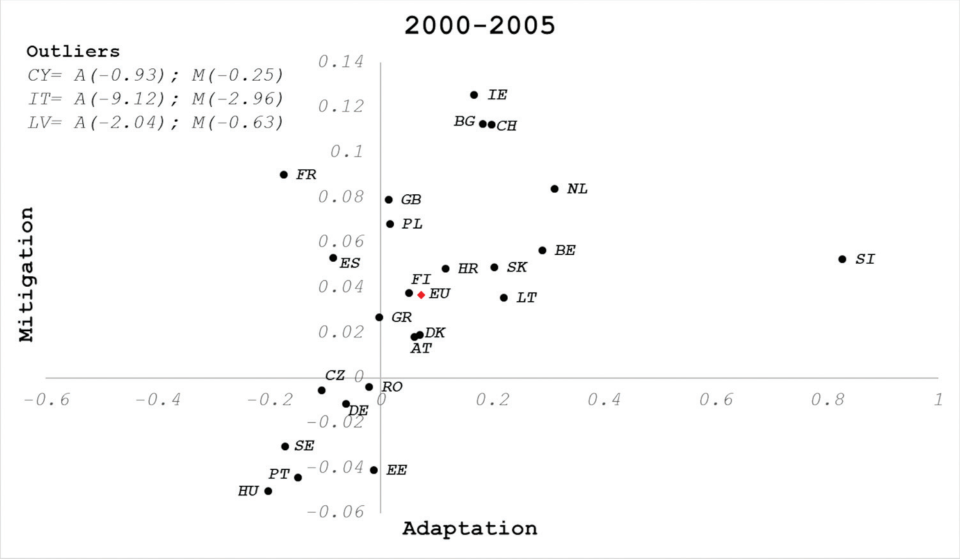
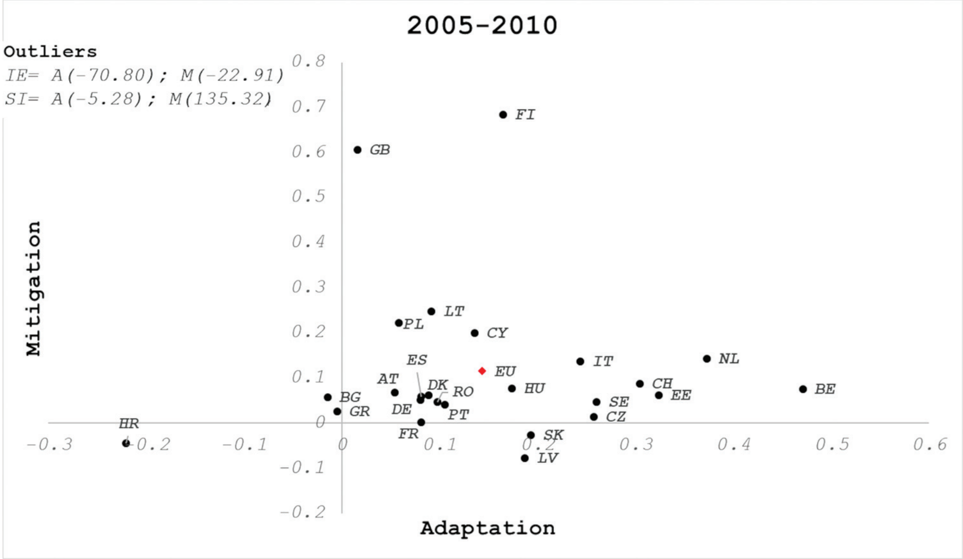


Fig. 4. Changes in adaptation and mitigation between 2005 and 2010. [Colour online.]



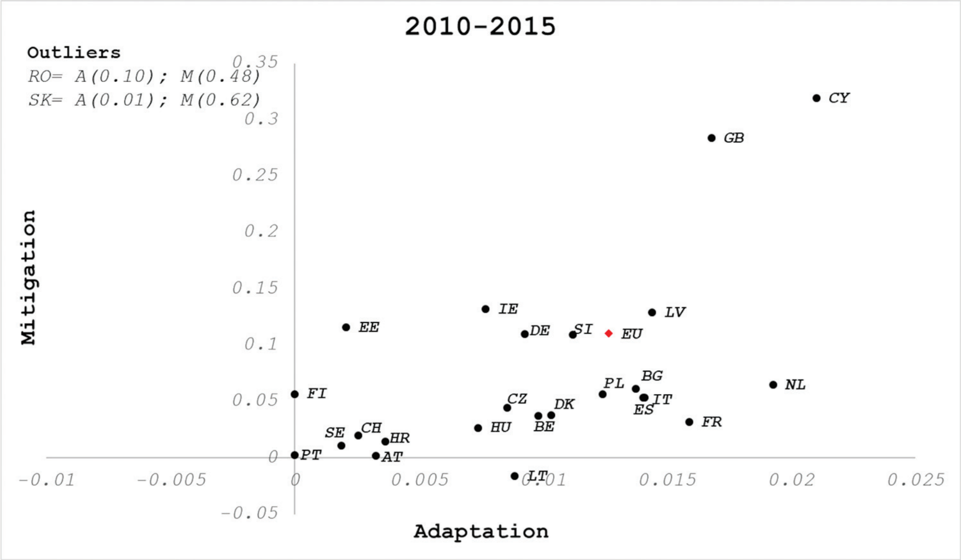
with Romania showing the highest value due to the increase in the "naturalness" indicator.

4. Discussion

4.1. Multifaceted shape of SFM indicators

In this study, selected SFM indicators were used to assess the trend over time of adaptation and mitigation, which are considered two important aspects of CSF according to many authors (Spittlehouse 2005; Nabuurs et al. 2018; Bowditch et al. 2020). Adaptation and mitigation, together with the social dimension, are crucial to counteracting climate change and its negative impacts on forests and society, as well as to ensuring the provisioning of forest ecosystem services (Bowditch et al. 2020; Verkerk et al. 2020). Despite the increased awareness among forest decision makers and managers to promote adaptation and mitigation management strategies, there are still large uncertainties concerning how to evaluate the effects of their implementation. Differences in socioeconomic and environmental conditions, challenges in data collection, and the analysis of climate change impacts in general are mentioned by many authors as causes of these uncertainties (Seidl and Lexer 2013; Forsius et al. 2016; Viccaro et al. 2019). The versatility of the SFM indicators allows them to be used for multiple aspects of forest management, e.g., to assess stakeholders' perceptions (Santopuoli et al. 2012; Paletto et al. 2014; Pastorella et al. 2016), facilitating the balancing of alternative management options in specific environmental and socioeconomic contexts. Recently, a study (Bowditch et al. 2020) based on the participatory approach revealed that SFM indicators can support CSF implementation; however, evaluations based on participatory approaches could be subjective, depending on the stakeholder's experiences and priorities, hindering a solid comparison over time because they change depending on the involved stakeholders. With this study, for the first time, we offer a fairly analytical method to assess CSF based on a literature review and an AHP. This approach allows for objective weighting of indicators, which are frequently used to assess adaptation and mitigation, supporting forest managers and decision makers. The economic and political implications of the SFM–CSF interface, although crucial to developing appropriate management strategies, are difficult to quantify and are thus not directly considered

Fig. 5. Changes in adaptation and mitigation between 2010 and 2015. [Colour online.]



in this analytical approach. However, the C&I were developed through a voluntary, pan-European, high-level political process for intergovernmental dialogue and cooperation on forest policies in Europe and, thus, also comprise indirectly a political meaning.

4.2. Most important CSF indicators

Results reveal that 30 out of 34 indicators from the list of the pan-European set of C&I are useful to assess CSF. Nevertheless, the literature review highlights that only a subset of 10 indicators are frequently used to assess adaptation and mitigation management strategies of forest ecosystems. “Carbon stock” (mitigation), “tree species composition” (adaptation and mitigation), and “forest damage” (adaptation and mitigation) are, in absolute terms, the indicators that yielded the highest overall priority value. Results confirm what has arisen from a previous study (Bowditch et al. 2020) in which most of these indicators were considered core indicators for assessing CSF. Contrarily, the social aspect is poorly considered, even if recent evidence reports that it is one of the main pillars of the CSF concept (Bowditch et al. 2020), while ecological rather than economic aspects are frequently considered among scientific articles. Particularly, our results highlight that “forest damage” is the most impacting indicator determining the CSF evaluation in several cases. Variation in forest damages affects both adaptation and mitigation, resulting in extreme values of CSF evaluation, as in the Netherlands in the period 1990–2000 or in Italy in the period 2000–2005. Reducing forest damages, due to biotic and abiotic disturbances, is crucial to promoting resistance and resilience to climate change (Jandl et al. 2013; Hlásny et al. 2017; Viccaro et al. 2019), as well as to promoting CSF. Future climate change is likely to deteriorate forest health and cause increases in the occurrence of natural disasters (IPCC 2014). For this reason, continuous monitoring of damages in forest ecosystems is crucial to identifying the best adaptive management strategies to prevent and reduce the negative impacts caused by climate change on forest health. In some cases, however, the variation in such indicators was not caused by a real change of damages in forest ecosystems but by the source of information, as for the Netherlands using the average value of burned area (30 ha·year^{-1}) of the past 20 years, or by a change of the recorded data, as for Italy and Spain introducing the biotic damage for only one period (2005). Additionally, reference definitions of the different indicators (as area of damaged forest) may differ between countries, complicating the comparison. In the light of this, we strongly recommended fostering the facilitation and harmonization of data survey and collection.

The observed positive CSF trend highlights that, if well organized, implementation of adaptation measures can support many aspects of the forest sector and foster local economies. The outcome was a positive trend for CSF over time, particularly for countries in which “growing stock” and “net revenue” increased jointly, as in Spain in the period 1990–2000. Increasing the rotation period of forest harvesting activities allows an increase in both the growing stock and the quality of timber products due to the increment of tree sizes, promoting mitigation options (Jandl et al. 2018, 2019; Köhl et al. 2020). Alternatively, beyond the economic benefits (Colombo et al. 2012; Jasinevičius et al. 2017; Paletto et al. 2017), adaptive management strategies that involve increased timber harvesting may allow carbon storage in forest products for a long period, supporting climate change mitigation.

Our results reveal that indicator 6.3 “energy from wood resources” plays a very important role in the assessment of mitigation as observed for Finland, the UK, and Slovenia in the period 2005–2010 or for Cyprus and the UK in the period 2010–2015, within which an increment of this indicator positively affected the trend of CSF over time. For instance, Finland National Inventory Reports, belonging the United Nations Framework Convention on Climate Change (UNFCCC), reported an increase of wood fuels consumption by energy industries from 1990 to 2015 and an increase of growing stock, as well as of carbon stock, in both forests and harvested wood products. This study reveals that “energy from wood resources” yielded a high priority importance for both mitigation and CSF, as previously observed (Bowditch et al. 2020). Forest management strategies aimed to improve the efficiency of fuelwood promoting the use of wood for energy to replace fossil fuel based energy could reinforce the forest sector and at the same time promote climate change mitigation (Sacchelli et al. 2013; Lewandowski 2015; Szulecka 2019).

Biodiversity conservation strongly supports adaptive management strategies (Klenk et al. 2015; Isbell et al. 2015). In fact, this study shows that four out of nine indicators of criterion 4 “Forest Biological Diversity”, i.e., 4.1 “tree species composition”, 4.5 “deadwood”, 4.3 “naturalness”, and 4.2 “regeneration”, were included in the subset of indicators selected for assessing forest adaptation. Adaptive management strategies need to promote mixed forests with regular harvesting activities because the un-utilized forest resources are more vulnerable to natural disasters (Jasinevičius et al. 2017). Well-planned projects of afforestation and forest plantation, growing faster than natural regeneration, are helpful in implementing adaptive management strategies if they are carefully balanced with promoting forest resilience and biodiversity conservation goals. By contrast, the amount of deadwood within old-growth or less managed forests plays an important role for climate change mitigation, allowing long-term carbon storage.

The subset of selected indicators represents a valid tool to provide quick responses about the usefulness of adaptation and mitigation management strategies. As such, it will support researchers to develop new and more appropriate scenarios for the sustained provision of ecosystem services.

4.3. Data collection and availability

This study confirms that SFM indicators are a powerful tool for monitoring and assessing multifaceted aspects of forest management. It needs to be highlighted, however, that although numerous efforts were made to harmonize estimates from forest inventories (Winter et al. 2008; Tomppo et al. 2010; Vidal et al. 2016), comparisons among countries and between years are still challenging due to gaps in data availability. Even though, in 2015, data for many indicators were missing, the study revealed that the overall trend between years 1990 and 2015 was positive. Many aspects affect the availability of data over time. The costs for data survey and collection, particularly for forest ecosystems, is one of the most important aspects that hinder data availability. Furthermore, the timeline and the survey protocols represent challenging features that require additional efforts to allow the comparison over time, as well as the comparison among different geographical areas, as regions or countries. This makes a more complete (full) use of SFM indicators in practical applications difficult (Santopuoli et al. 2016*a*).

Advances in remote sensing techniques provided a powerful support to facilitate monitoring and mapping of forest resources at large scales (Chirici et al. 2012; Maselli et al. 2014; Frate et al. 2016; Antonucci et al. 2017; Santi et al. 2017). Nevertheless, the collection of data for specific indicators, e.g., “energy from wood resources”, “net revenue”, and “age structure/diameter distribution”, require field surveys, which are expensive and time consuming. The reports provided by National Forest Inventories represent the most important source of data about forest resources. Most of the SFM indicators depends on National Forest Inventory protocols; however, forest inventory protocols differ among countries and the output obtained requires further elaborations to perform comparisons (Winter et al. 2008). Yet, the forest inventory timeline is different, often longer than the reporting period of the SoEF. Consequently, countries report the same values for two consecutive SoEF reports, hindering trend evaluation for some indicators. This aspect is somewhat overcome in this study because the CSF trend evaluation is based on more than one indicator.

4.4. Management and policy implications

The widespread array of ecosystem services that forests provide to society call for multi-objective forest management. This is exacerbated by climate change that threats the health and vitality of forest ecosystems, as well as the delivery of forest goods and services, and requires appropriate adaptive and mitigative management strategies (Nabuurs et al. 2018; Yousefpour et al. 2018; Jandl et al. 2019; Bowditch et al. 2020; Verkerk et al. 2020). Balancing adaptation and mitigation strategies in forest management is challenging. Adaptation aims to reduce the adverse effects of climate change (Jandl et al. 2013) acting on the forest stand characteristics, while mitigation management strategies focus mainly on increasing the capacity of forests to store carbon in living and dead trees, litter, and soil, as well as in harvested timber products (Colombo et al. 2012; Jasinevičius et al. 2017); however, to improve the effectiveness of both adaptation and mitigation management strategies, ensuring forest health and vitality is mandatory. It should be noted that un-utilized forest resources are more vulnerable to natural disasters and, in the event of a disturbance, may emit more carbon than if harvested (Jandl et al. 2019). Moreover, healthy forests promote high-quality timber products, which is important to revitalizing the forestry sector, particularly in the inner and mountain areas. In particular, activities focused on the development of the bioeconomy will represent an optimal compromise between adaptive and mitigative management aims.

The overall ageing of European forests is ongoing, particularly in the southern countries (i.e., those most vulnerable to climate change), due to the lower value of harvesting rate (Forest Europe 2015), the depopulation of inner areas, and the abandonment of rural activities (Marchetti et al. 2018). Adaptive management strategies are urgently required to improve the resilience of forest ecosystems, to enhance forest health, and to promote forest productivity, particularly in more vulnerable regions. Rethinking of the forest sector framework will be necessary to adopt adaptive forest management, supporting the sustainability of forest management and the application of CSF strategies.

Forest management decisions regarding climate change adaptation need to explicitly address the reduction of the vulnerability of forests, which is particularly high in forests subjected to low-intensity silvicultural interventions or unmanaged for several years. Contextualizing silvicultural practices and management aims with landscape and local feasibility is necessary to improve the efficiency in delivering forest ecosystem services (Vizzarri et al. 2014). For example, mitigation practices such as reducing forest degradation, optimizing carbon stock, and improving the substitution effects are required to foster multiple co-benefits to the society (Smith et al. 2020). Particularly important for managed forests is the substitution effect played by harvested timber products (Pilli et al. 2015; Erb et al. 2018). Durable timber products will warrant carbon storage for a long period, with the requirement to replace products over time promoting circular bioeconomy. Assessing the trade-offs between storing carbon stock and ensuring timber for raw materials and energy purposes (Erb et al. 2018), as well as among other forest ecosystem services, is mandatory to optimize SFM and, at the same time, promote CSF. Maintaining and enhancing forest health and vitality allow the promotion of CSF implementation and, on the other hand, the improvement of the forestry chain, with profitable revenue for forest owners.

5. Conclusion

C&I is confirmed to be a powerful tool to support SFM, not only for reporting, but also for assessing different aspects of SFM, in particular, CSF. In the literature reviewed in this study, 10 indicators from the original set of 34 quantitative SFM indicators were shown to be the most frequent indicators used to assess CSF. Among them, “forest damage” is the most impacting indicator, showing the greatest variation, while “carbon stock”, “tree species composition”, and “energy from wood resources” are the most important in terms of citations in the literature. The overall trend of CSF in Europe is positive and slightly better for mitigation rather than for adaptation. Nevertheless, the lack of data impacts the trend evaluation and represents one of the most hindering challenges to performing such evaluations over time. Improvements in the harmonization of National Forest Inventories information are still required for obtaining better evaluation.

Beyond applying the sustainability concept, we strongly recommend that forest management adopt adaptive and mitigative strategies, as well as socioeconomic dimension, to face climate change, in short, the CSF approach. In particular, as highlighted in the international agreements such as the Land Use, Land Use Change, and Forestry (LULUCF) regulation, management strategies have to reduce emissions and maintain and enhance sinks and carbon stocks, also through long life cycle harvest timber products. These strategies should aim to maintain forest health and vitality and increase forest resistance and resilience. In addition, anticipating the adverse effects through the adoption of appropriate actions, as well as to take advantage of opportunities that may arise, it is strongly recommended that the damages caused by climate change be prevented or minimized. For instance, the increasing number of power stations using biomass in the UK is a successful example of mitigation strategy. However, mitigation measures may have to be adopted differently for high conservation value forests, where the carbon stored in the soil and deadwood is often higher than the amount stored in the living trees.

The proposed subset of indicators could represent the minimum set for developing a practical toolbox to foster CSF implementation and to monitor and re-evaluate national- to European-level forest policy making.

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