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Application of climate-smart forestry – Forest manager response to the relevance of European definition and indicators

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A R T I C L E I N F O

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A B S T R A C T

Climate change impacts are an increasing threat to forests and current approaches to management. In 2020, Climate-smart Forestry (CSF) definition and set of indicators was published. This study further developed this work by testing the definition and indicators through a forest manager survey across fifteen member European countries. The survey covered topic areas of demographics, climate change impacts, definition and indicators assessment, as well as knowledge and communication. Overall, forest managers considered the threat of climate change to their forests as high or critical and 62% found the CSF definition clear and concise; however, the minority suggested greater simplification or nuance. Indicators were viewed as comprehensive but too numerous to integrate into management activities. Two highest ranking indicators were 'Trees species composition', and 'Erosion protection and maintenance of soil condition'. Many managers were aware of suitable alternative species, but also stressed that greater resources should focus on exploring adaptable provenances. Demonstration sites and interactive guides were ranked highest for communication and dissemination; however, online multimedia tools and workshops were also ranked highly. Local perspectives on providing more relevant CSF ranged from silviculture systems, finance and funding, education and training, and social awareness, to tree species mixes and development of protective functions. In summary, forest managers were generally open to CSF, but required greater guidance and proof of application.

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1. Introduction

In the current environment of increased climate change impacts (United Nations, 2015; IPCC, 2019) multiple sectors such as construction, transport and agriculture are seeking to respond to the threats that climate change presents. Climate-smart Forestry (CSF) is one such iteration, stemming from the Climate-smart Agriculture (CSA) approach that helps people who manage agricultural systems to effectively respond to climate change (FAO, 2010). CSF currently shares similar objectives of adaptation and mitigation of Greenhouse Gases (GHGs) through carbon sequestration, substitution of fossil fuels and effective species mixtures that optimise growth, diversify timber products and increase biodiversity and resilience (Nabuurs et al., 2017; Yousefpour et al., 2018; Jandl et al., 2018). Tree species mixtures would mitigate against the vulnerabilities of large single species forests to disturbances that widely impact the sector and communities. Forests have four major roles in climate change, contributing to one-sixth of the global carbon emissions through harvesting activities overuse and degradation, as well as mitigation through sensitive Sustainable Forest Management, substitution of fossil fuels through production of woodfuel and their potential to absorb about one-tenth of carbon emissions over the next 50 years through storage in biomass, soils and products (FAO, 2020).

Attention around CSF has grown in recent years, however work has mainly focussed upon the role of carbon sequestration and storage, and wider GHGs emissions reduction strategies (Nabuurs et al., 2017; Yousefpour et al., 2018; Mostegl et al., 2019). To date, there has been little work on social-ecological elements of CSF that engages forest managers, which highlights the disconnect between policy, science and practice interface (Fischer et al., 2015; Cockburn et al., 2016; Pascual et al., 2017). This is mirrored at times by the knowledge and readiness of state forests (otherwise known as public forests) compared to private forests, especially small-scale owners (Mostegl et al., 2019).

Hanewinkel et al. (2013) explore the economic impact of climate driven changes in temperature and precipitation in 2100, which could have severe implications for the European forest economy. The authors predicted a loss of 14% to 60% of economically valuable species potentially equating to a loss of hundreds of billion euros due to the shift in environmental conditions. Furthermore, increased vulnerability to diseases and disturbances on forest ecosystems are predicted due to climate change which will impact forest productivity and supply chains. These are most likely to impact coniferous forests in Europe more than other types, therefore forest ecosystems and society need to be prepared to manage an adapt to greater disturbances in future forests (Seidl et al., 2017).

Forest managers are key to implementation of forestry and forest-related goals, whether planting targets, emissions reduction, timber production or maintenance of crucial ecosystem services (de Groot et al., 2010; Hansen et al., 2010; Chapin et al., 2011; Dandy, 2016). Information and guidance on achieving these goals often needs to be disseminated and communicated from policy-level to practitioners on the ground who will facilitate the integration of these new approaches into management activities, actions and plans (Buttoud et al., 2011; Cockburn et al., 2016; Pascual et al., 2017). Despite the growing area and continual refinement of SFM, many managers are finding themselves ill-equipped to adapt their management to the uncertainty of climate change (Sousa-Silva et al., 2018). Adaptation to climate change is a complex task and lack of action has been widely reported with a call to increase manager awareness along with better knowledge transfer to bridge the gap between knowledge and action (IPPC, 2014; Sousa-Silva et al., 2018). The recent bark beetle (*Ips typographus*) outbreak in 2019 is evidence that climate change impacts large ecosystems and insect communities that managers are unable to anticipate or adapt to over short periods of time (Pureswaran et al., 2018). Outbreaks have continued in subsequent years over Europe mainly due to wind disturbance and previous years of drought, however continued outbreaks are expected in the future due to the continuing impact of climate change (Hlásny et al., 2021a, Hlásny, Zimová and Bentz, 2021b). The increasing impact and role of wind disturbances in recent years (Forzieri et al., 2020) needs to be considered within adaptive management approaches to climate threats and the future management of forest environments and services (Seidl and Rammer, 2017; Monge and McDonald, 2020).

1.1. Aims of the study

Between 2017 and 2021, an international group of forest research professionals in the EU COST Action on Climate-smart Forests in Mountain Regions (CLIMO) developed a CSF concept, definition and set of indicators through consensus building workshops to guide policy-makers and managers in the future practice of CSF (Bowditch et al., 2020). This concept (Box 1), supported in adaptation, mitigation and social dimensions, is focussed on SFM and governance improving adaptation and mitigation to climate change through maintenance of ecosystem functions and services, minimising impacts of climate-induced changes on mountain socio-ecological systems. This definition is to be the first iteration that will be continually developed through further research and engagement. The set of indicators were developed from Pan-European Sustainable Forest Management Criteria and Indicators (Forest Europe, 2015) and the Common International Classification of Ecosystem Services- (CICES) (Haines-Young and Potschin, 2012) along with additional indicators added by the CLIMO team (e.g. management system and vertical and horizontal distribution of crowns), which can be viewed in supplemental information section. The indicators were ranked by the CLIMO project members to assess the strength of their connection with adaptation or mitigation and were then subjected to a network analysis to identify core and peripheral indicators (Bowditch et al., 2020). Additional higher level themes were identified to describe the set of indicators selected in those processes:

1 CSF is not limited to regulating ecosystem services
2 Strengthening adaptation and mitigation measures to support forest management strategies
3 Forest health and vitality are crucial for protecting and maintaining a wide-range of forest functions
4 Maintaining forest biodiversity is key to counteracting climate change impacts
5 CSF has to maintain and enhance the provision of ecosystem services
6 Integration social dimensions is key for implementing climate-smart forestry

Although the CLIMO project is now complete, work on CSF continues with greater engagement and co-development with managers and policy-makers required to ensure its effectiveness on the ground with practitioners and impact on a wider socio-economic scale (Verkerk et al., 2020; Santopuoli et al., 2020). In order to test the CSF definition and indicators, a survey was designed and disseminated across the COST Action member countries with the aim of capturing forest managers' perceptions of CSF and examining the accessibility, utility and potential application of the concept and indicators to improve the effectiveness of CSF in practice. The survey also captured forest managers' opinions of tailoring CSF to regional conditions around Europe.

This paper presents the results of the CSF definition and indicators survey to develop a potential roadmap for refining and shaping CSF to bridge the gap between concept and adoption through practice. A cornerstone of this survey was to engage forest managers in the next stage of developing a relevant definition and indicators that can be linked to a set of tools to support management plans and monitoring activity.

The definition although aiming to be comprehensive may from some perspectives omit important information on key economic or societal issues related to forests. Co-production of knowledge with managers and wider stakeholders provides a foundation for effective adaptation that can encourage and implement new or modified practices and planning,

Climate-smart forestry in mountain regions is sustainable adaptive forest management and governance to protect and enhance the potential of forests to adapt to, and mitigate climate change. The aim is to sustain ecosystem integrity and functions and to ensure the continuous delivery of ecosystem goods and services from mountain-specific contexts, while minimising the impact of climate-induced changes on mountain forests on well-being and nature's contribution to people.

Adaptation measures forests that maintain or improve their ability to grow under current and projected climatic conditions and increase their resistance and resilience. The adaptive capacity to changes in climate and to the timing and size of climate-induced disturbances (e.g., fire, extreme storm events, pests and diseases) can be enhanced by promoting genetic, compositional, structural, and functional diversity at both stand and landscape scales. This includes facilitating natural regeneration and planting of native as well as non-native tree species, genetic variants and individuals that are considered to be adapted to future conditions. Increased connectivity assists the migration of forest species.

Mitigation of climate change by forests is a combination of carbon sequestration by trees, carbon storage by forest ecosystems, especially soils, and forest derived products, such as structural timber, and by carbon substitution - directly by replacing fossil fuels with bioenergy and indirectly through use of wood to substitute for higher carbon footprint materials.

The ***social dimension*** of forestry holds many aspects, from the involvement of stakeholders from local communities, and their conflicts over land use or for the access to skills and technology, to global forest governance challenges. Climate change may jeopardize forest ecosystem functioning and brings social and economic consequences for people, which may modify priorities of ecosystem services at various scales. Assessment for ecosystem services could be a tool making this process more efficient with respect to indicators relevant for governance regime and actors involved.

In summary, **climate-smart forestry in mountain regions** should enable both forests and society to transform, adapt to and mitigate climate-induced changes.

Box 1. Climate-smart Forestry definition produced by CLIMO project using adaptation, mitigation and social dimensions as the three pillars (Bowditch et al., 2020).

therefore early engagement and collaboration is more likely to produce socially and professionally accepted indicators (Meadow et al., 2015; Halofsky et al., 2018).

2. Materials and methods

Forest managers from both state and private sector were the major target of the survey, however additional manager types that represented significant holdings within each country were included (Community ownership, Non-Governmental Organisations, National Park, Protected Area, Church and Family). Due to the broad geographical spread of the participant countries, an online survey format was selected for effective accessibility and reach.

2.1. Survey implementation

The survey was hosted on the online platform "Online surveys" (Jisc, 2020) and was disseminated using a hyperlink sent to forest managers by a representative from each participating country. A team of forest professionals (three researchers and one manager from four different European countries: UK, Italy, Germany and Poland) who were directly involved in developing the CSF concept, definition and indicators designed, tested and finalised the survey. Each researcher represented a different working group under the project, however involvement of more forest managers at this stage would have enhanced the research design.

The survey remained open for approximately four months between 20th November 2019 and 31st March 2020 to give country representatives sufficient time to access networks and capture response level required (full list of questions can be viewed in supplementary material).

2.1.1. Questionnaire framework

A framework of questions based upon the accessibility, relevance and utility of the CSF definition and indicators was prepared by the team and finalised through three rounds of interrogation and testing to produce the most concise and relevant set of questions. Each round was shared with the group via email, with suggested questions and ways of presentation that would be comprehensible for the wide range of managers. Comments and suggested changes would be returned to the lead author to synthesise and modify into the next version. After the third round, a final version was agreed upon by the team and transferred to the 'Online surveys' platform in draft survey form. A hyperlink was then generated for testing by the team members reviewing for smoothness of operation, mistakes and glitches with final tests piloting the survey in full and checking the subsequent outputs. The final survey prepared and launched including a total of twenty questions within four topic areas:

1 **Demographics** – aimed to contextualise the respondents background and describe forest ownership including age-group, forest ownership, size and main objectives. These were broken down into various options with space for the respondent to elaborate.
2 **Climate change impacts** – aimed to investigate the threat level that climate change impacts would have from a manager's perspective on the forest under their management (answers were classified as: very low, low, medium, high, and critical).
3 **Definition and indicators assessment** – aimed to investigate the usefulness of CSF definition for managers, as well as ranking the eight most important ecosystem services and CSF indicators ranking them from 1-5 (1=very important to 5=not important). The survey also broadly investigated potential future tree species for each country. More precisely, respondents were asked to identify the most promising species, in their opinion, to adapt to climate change impacts. List of species provided by country were collated and ranked by the frequency of selection, the five highest ranked species are presented from each country, unless there were less than five species identified. However, these are not correlated to specific regions, conditions or habitats.
4 **Knowledge and communication** – identify preferred methods of communication and dissemination for CSF material for professional development and reference. This included a range of options for example, books, online platforms, social media, demonstration sites etc. Respondents could choose multiple options which were aggregated to identify the most popular methods.

Moreover, due to the wide geographic coverage of the survey spanning the entire continental latitude of Europe (Iceland to Turkey) and the relatively broad CSF definition, respondents were asked to identify important management considerations for their local forest area. This was an open question, so managers could impart any relevant information pertaining to potential management challenges in responding to climate change.

2.1.2. *Survey dissemination*

National representatives in each of the twenty-eight member countries of the CLIMO project were contacted and asked to disseminate the survey to forest managers in their country and in some cases translate both the survey (into native language) and responses (back to English). Out of the twenty-eight project countries contacted, twenty responded positively to disseminating the survey with fifteen countries returning the minimum of four responses. Unfortunately, the representative distributing the survey for the Germanic speaking countries (Germany, Austria and Switzerland) was unable to participate due to unforeseen circumstances, which omitted these countries from the study.

The twenty countries that agreed to participate distributed the survey to forest managers in both the public and private sectors within their professional networks, the most common route was to advertise in the countries forestry professionals representative body, if these did not exist then the research would use their own professional network. The aim was to receive a minimum of four responses from each country with a spread from both private and public managers, unless the country had a different mix of forest manager typologies, such as dominance of family forests (Ma et al., 2012; Wästerlund et al., 2017; Kang et al., 2019).

2.3. *Data collection and analysis*

At the end of March 2020, the survey was closed, and the results were downloaded into excel file format and merge with the other language versions of the surveys (Polish, Portuguese and Czech). The other countries translated the survey and translated the responses before inputting them into the English language version of the survey. These were organised by question, the quantitative survey results were collated and separated out into individual excel tabs to analyse, interpret and produce representational charts of the collective results. Qualitative results were uploaded to NVivo version 12 and coded to produce common themes and identify the most relevant answers for across the survey. As many questions offered both quantitative value and the opportunity to comment further the quotes from managers have been grouped with their corresponding question in the results section to highlight further depth and discussion of the question.

CSF indicators responses were cumulatively aggregated for each indicator and then weighted against the entire sample of indicator votes to produce a ranking identifying the most important and those seen as least important indicators. This was done separately for both the Sustainable Forest Management and Ecosystem Services indicators, as well as filtering through state, private and National Park groups. Additional indicators were coded in NVivo 12 to identify overarching themes and were then assessed for the number of mentions by the respondents against the total number of respondents. Future species was measured by the number of mentions each species received within each country future species. Both communication preferences and importance of local perspectives open questions were analysed through thematic analysis to draw out the major themes for forest managers across the respondents.

3. Results

Fifteen countries returned survey results (Table 1), with a total of 76 individual responses.

As evident from Table 1, responses range from 4 to 7 within each country with state forest managers being the dominant respondents in seven countries, co-dominant in four countries, private in three countries and National Park in one country.

The majority (45.5%) of respondents were involved in managing state or public forests, followed by private forest (25.5%) and then National Parks (13.6%). Community forest managers represented 10% of the respondents. Church, Non-Governmental Organisation and family management (small-scale private forests) (1.8% each) were the smallest management types represented.

The majority of managers (60.3%) viewed the impacts of climate change as 'critical' or 'high'. State managers represented 79% of the critical concern, and 56% of the high concern, whereas the other categories showed an even spread of manager types. However, this is to be expected as state managers were the dominant respondents and were the majority that identified that climate change was a critical threat to forests. Those managers that viewed the threat level as 'low' or 'very low' were located in the north of Europe or were managers of smaller forest areas.

3.1. *CSF Definition accessibility*

Many respondents (61%) found the CSF definition easy to understand, while 39% said it was not easy to understand, indicating approximately one in three forest managers required the definition to be modified to make it more comprehensible and easier to understand. Approximately 38% of the managers found the definition either 'very useful' or 'useful', whereas 28% of managers found the definition either 'marginally useful' or 'not useful'. 34% of managers found the definition 'moderately useful'.

Utility of indicators

3.2.1. *Sustainable forest management indicators*

The SFM indicator identified as most important was '*Tree species composition*' followed by '*Natural regeneration*', '*Protective forest – soil,*

Table 1
– Number of respondents per Country.

Country	Manager type	Dominant type	Responses	Percentage
Bosnia and Herzegovina	State, Private (individual and company), family	State	7	9.2
Bulgaria	State	State	4	5.3
Czech Republic	State, Private (individual and company), Community, Church	State	7	9.2
England	State, Private	Equal divide	4	5.3
Hungary	State, Private	Equal divide	4	5.3
Iceland	State, National Park	State	5	6.6
Ireland	State	State	4	5.3
Italy	State. Private (Company and individual)	Equal divide	4	5.3
Poland	State, Private (individual), National Park	State	7	9.2
Portugal	Private (individual and company), NGO	Private (individual)	5	6.6
Scotland	Private (company and individual)	Private (individual)	7	9.2
Slovakia	National Park, State, Private (company)	National Park	5	6.6
Spain	State, Private (individual)	Equal divide	4	5.3
Sweden	Private (company), Community, State	Private	5	6.6
Turkey	State	State	4	5.3
Total			**76**	100

water and other ecosystem services', '*forest structure and/or diameter distribution', 'forest damage' and 'Management plans'* (top five) (Fig. 1). '*Soil condition*', '*Forest area*' and '*Naturalness*' were ranked 6th to 8th by forest managers. While '*Slenderness coefficient*' and '*Roundwood*' were ranked as the least important indicators. Interestingly, indicators around production and commercial areas of forestry, '*Trade in wood*' and '*wood consumption*' and '*energy from wood resources*' ranked low (Fig. 1).

There was some difference in the top five identified indicators that were separated out to reflect the state, private and National Park groups with '*Management systems*' unique to state managers whereas '*Age structure/diameter*', '*forest damage*' and '*soil condition*' as unique (Fig. 2). Both the state and National Parks identified '*Accessibility for recreation*' and '*Regeneration*' as key indicators and National Parks alone identified '*Naturalness*' as important. '*Slenderness coefficient*' and '*Vertical*

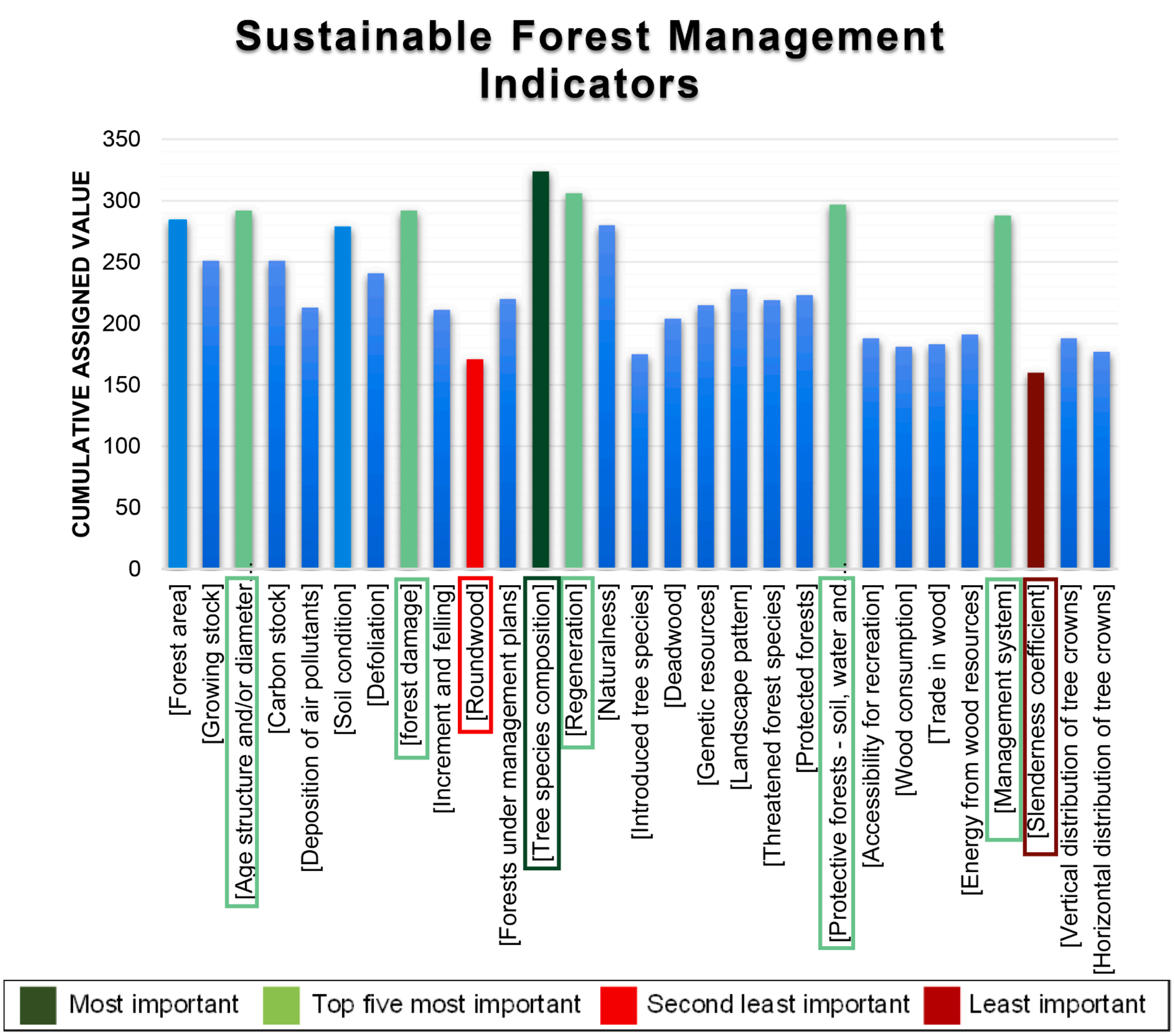

Fig. 1. CSF Sustainable forest management (SFM) indicators cumulative weighted ranking.

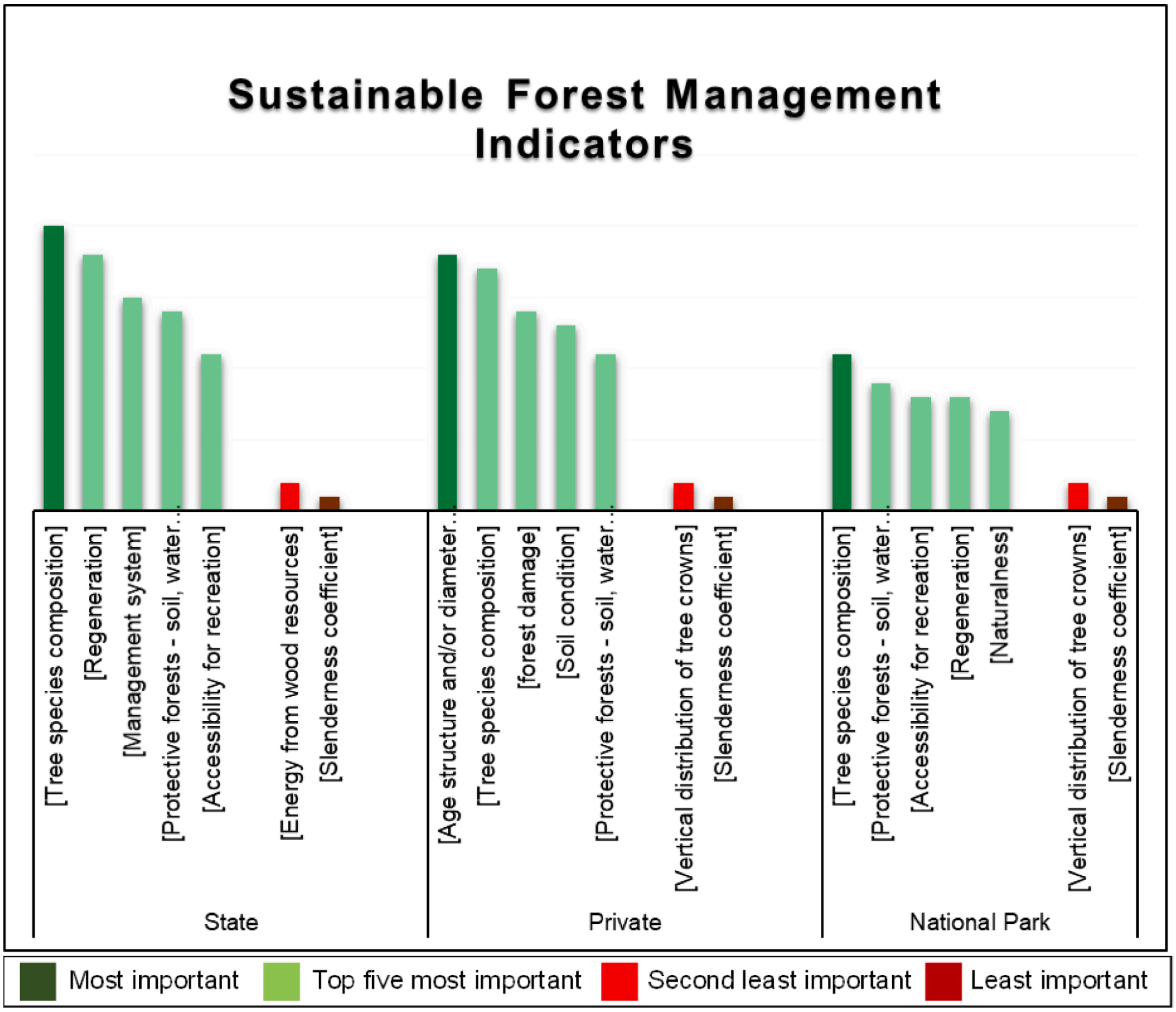

Fig. 2. Sustainable Forest Management Indicators most important and least important for state, private and National Park managers.

distribution of tree crowns' were the least important indicators with only state managers differing with '*Energy from wood resources*' differing.

3.2.2. Ecosystem services indicators

Indicators selected as relevant to CSF (Fig. 3) were mainly within regulating ecosystem services, namely '*Erosion prevention and maintenance of soil health*', which was ranked as the top indicator, followed by (ranked 2nd to 5th) '*Purification of water and air*', '*Carbon sequestration and storage*', but also '*Maintenance of genetic diversity'* and '*Production of atmospheric oxygen*'. '*Moderation of natural disturbances (e.g. flood alleviation'' and 'Soil formation and retention*') were ranked 6th to 8th. The indicator ranked lowest was '*Pharmaceuticals and bio-chemicals'* followed by '*Food*'. Indicators of cultural ecosystem services such as '*Spiritual sense of place*' and '*Aesthetic appreciation and inspiration for culture'* were also ranked very low.

'*Erosion prevention and maintenance of soil health'* indicator was most important for state and private managers and third most important for National Parks (Fig. 4). '*Moderation of natural disturbances*' was nearly rated just as highly across the tree groups. '*Habitat for species*' was identified as important for both state and National Park managers. '*Carbon sequestration and storage*' were third and fourth most important for private and National Park managers. However, each group identified a unique indicator state: '*Maintenance of genetic diversity*', private: '*Timber, fuel and fibre*', National Park: Recreation, mental and physical health, which was closely followed by Tourism (which was sixth most important). All groups identified '*Pharmaceuticals and bio-chemicals*' and '*Food'* as the lowest ranked and second lowest ranked indicator.

3.2.3. Additional indicators

The majority of managers did not add any additional comments or suggest other indicators, agreeing that "*it is a relevant and comprehensive although long list of indicators*". Some felt "*there was too many to integrate into management*" and "*a shortened list that focusses on measurable and mitigating outcomes would benefit planning*". In general, all managers that responded to this question suggested that more guidance would be needed to implement monitoring of these areas (Table 2).

3.3. Adapting to future species

Despite the wide range of suggestions 64% of respondents also highlighted that the current native species in their country had enough resilience to cope with potential threats of climate change (Fig. 5). Approximately 41% of respondents said that they would seek alternative provenances for native species; these respondents were from northern European countries, which possessed less species diversity and relied on native species with extensive natural ranges.

Pseudotsuga menziesii (Douglas fir) was the most cited (82%) species in the central and northern European countries (Fig. 5).

Utilising species that are drought tolerant and thrive under more extreme temperatures was viewed by approximately 72% of mangers as a priority. *Quercus rubra* (Red oak) and *Castanea sativa* (Sweet chestnut) were both identified as significant future species in western Europe.

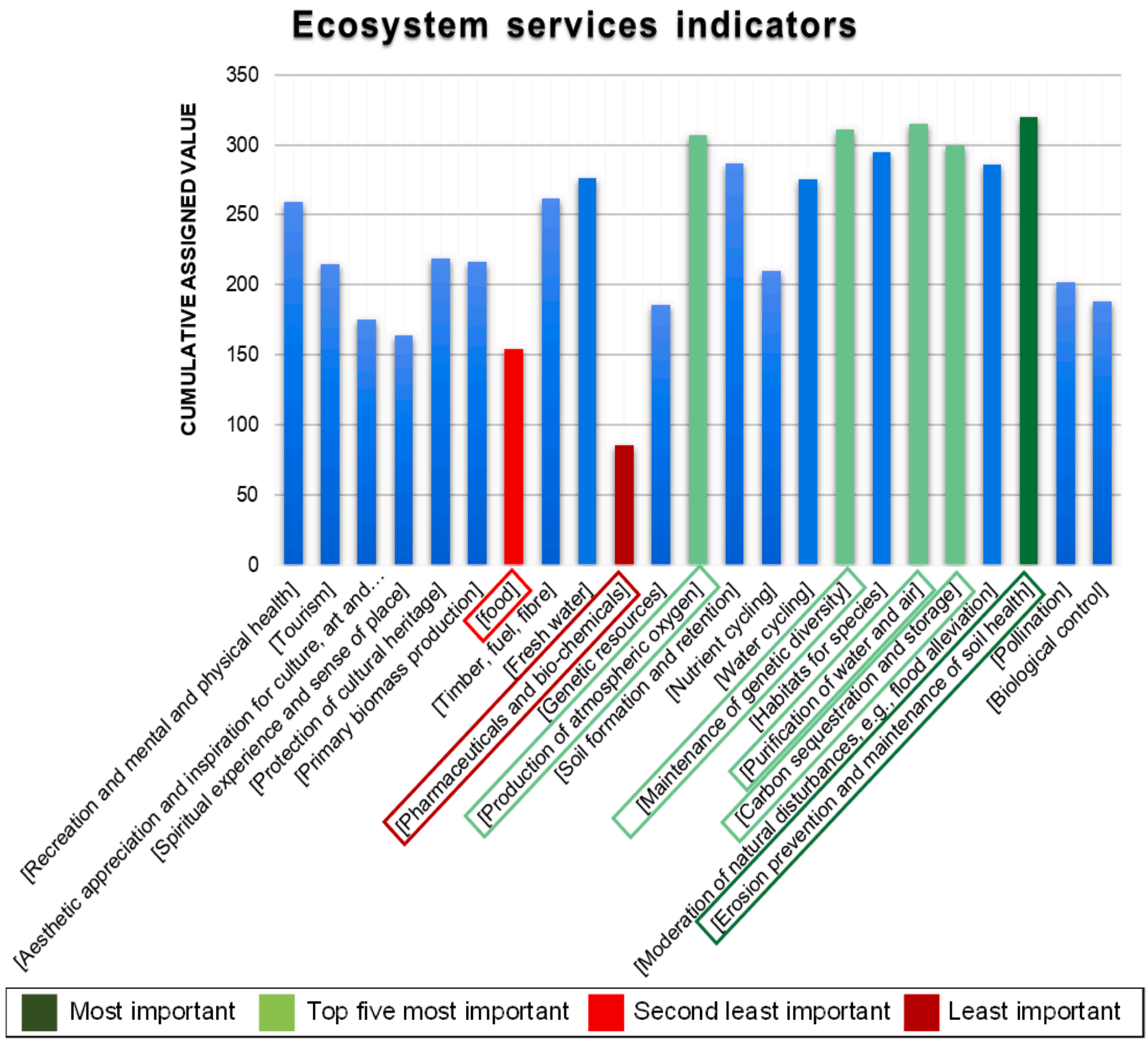

Fig. 3. CSF Ecosystem Services indicators cumulative weighted ranking.

Other genera mentioned were *Fagus, Betula, Acer, Abies, Alnus* and *Quercus. Larix decidua* (European larch) was indicated by 68% of the managers. Outlying species include *Paulownia tormentosa* (Princess tree - Bosnia Herzegovina), *Corylus colurna* (Turkish Hazel - Hungary), *Acacia* spp. (Spain and Portugal), *Sequoia* (Redwood - Scotland), *Robinia pseudoacacia* (Black locust - Poland). In Spain, *Pinus halepensis* and *Pinus uncinata*; whereas its neighbour Portugal identified a more broadleaf centric diverse mix of species including *Betula celtiberica, Fraxinus angustifolia* but also conifers like *Pinus pinea*. Scotland identified the only hybrid species *Picea x lutzi* (*Picea stitchensis x Picea glauca*). Additionally, Scotland identified solely conifer species including *Thuja plicata* and *Tsuga heterophylla. Sorbus torminalis,* a valuable hardwood timber with a wide climatic range, was ranked first by Italian forest managers and was identified by other countries, but did not make the top five list.

3.4. Communication preferences of CSF to managers

In terms of communication, most managers (22%) would view ‘Demonstration sites’ employing CSF actively as most beneficial. However, more interactive material such as ‘Instructional guide with diagrams and infographics’ (19%) and ‘Online multimedia tool’ (18%) were a popular option with managers: “*most people are more inclined to use online resources, as this is the growing culture*”. These, along with ‘Workshops’ (17%), show a preference for interactive ways of communication and learning. ‘Books’ (13%) and ‘Videos’ (9%) were the least preferred options.

3.5. Local perspectives

The majority of emergent themes, though identified from a local management perspective, could be applicable to a wide range of forest ecosystems (Table 3, Fig. 6).

4. Discussion – CSF for managers

The discussion is split into three sections to discuss the main themes and issues that were highlighted by the results of the survey relating to forest managers’ understanding and ability to respond to climate change impacts in their own forest areas.

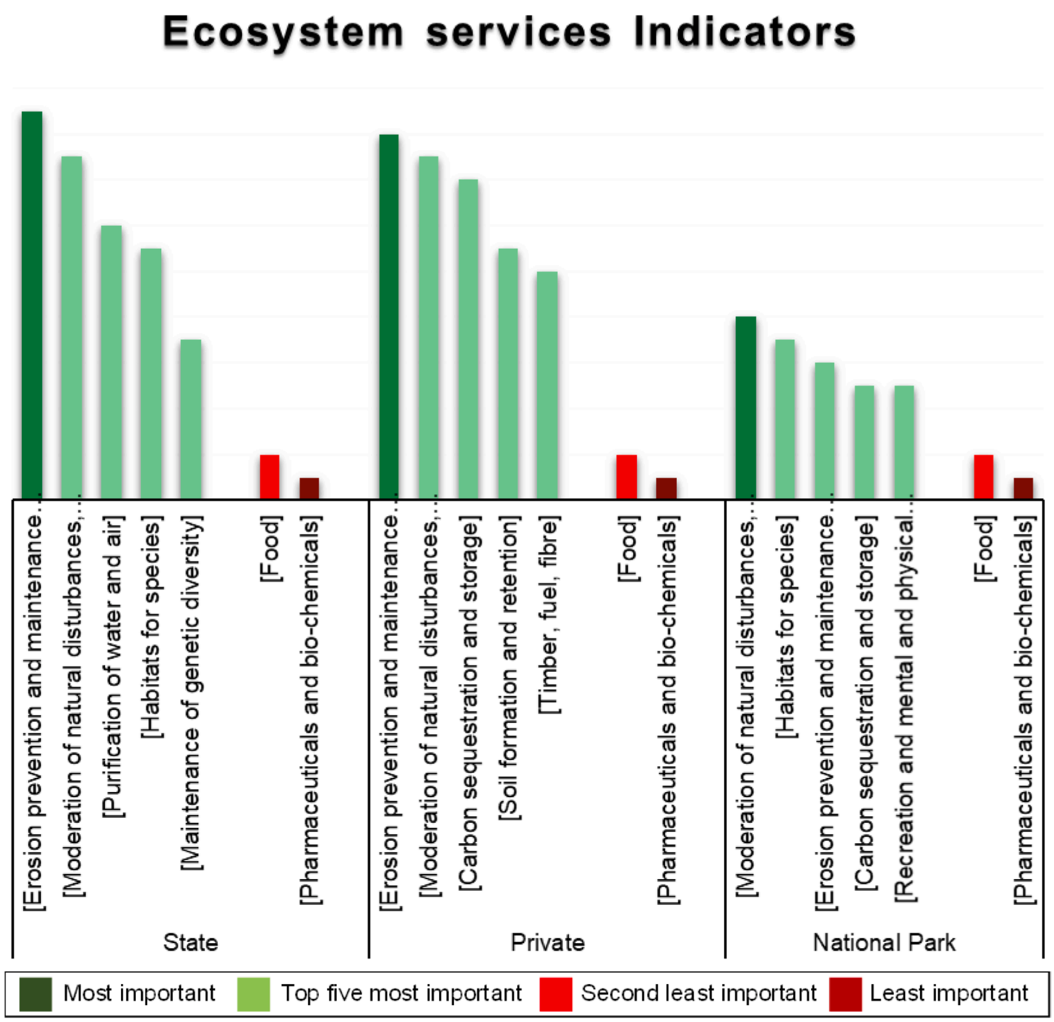

Fig. 4. Ecosystem Services Indicators most important and least important for state, private and National Park managers.

Table 2
Additional indicators suggested by forest managers using keywords identified from qualitative analysis.

Additional indicators	Description	keywords
Financial planning and markets	Help managers track financial return, profitability, and plan activities with market analysis	Economic, finance, markets
Forest products carbon lifecycle	Tracking the carbon price of producing, transporting and lifecycle of carbon	Carbon, tracking, product
Community connection and engagement with forests resource	Evaluating the connection, services and benefits the local communities derive from forests, and subsequent understanding of forest management	Awareness, community, connection
Effectiveness of mitigation measures	Enabling managers to monitor and assess effectiveness of mitigation measures put in place over time	Mitigation, monitor, success
Forest health and restoration	Assessing holistic forest health plan and framework to monitor progress of vulnerable species and diseases	Mortality, vulnerable species, recovery
Supporting climate offsetting	Demonstrating a clear impact from fossil fuel substitution related to management of the forest	Substitution, monitor, fuel

4.1. *Accessibility of forest climate policy and practice*

A continual disparity persists between stand level management, and high level policy and economic aims of forest management; therefore finding effective channels of communication that facilitates complementary adaptation pathways would be beneficial for forest management across the sector (Hengst-Ehrhart, 2019). As evidenced by the survey results the connection between public interest and the realities of practice needs to be strengthened, so that the public understand the ways in which forest management aids the fight against climate change, supports economies and provides important services (see sections 3.4 and 3.5). Even more urgent is the need to create pathways for learning and understanding to make new approaches and policy and practice accessible to managers, as in general there is a certain level of frustration with the inability to respond accordingly to threats such as climate change and disturbances (Pinkard et al., 2015; Hengst-Ehrhart, 2019). However, adaptation measures are difficult to implement on a wide-scale, with varying constraints of national systems and patterns of ownership (Andersson et al., 2017). Therefore, embedding adaptation and resilience in support systems, planning, industry codes of practice, as well as certification schemes will be an important step to implement future monitoring and climate-smartness of forests (Keskitalo, 2013).

There is also concern that while large state and private forests are being targeted and advised for climate change adaptation, smaller-scale forest owners or those that manage smaller areas have not received as much attention and is unclear whether they perceive climate change impacting their land which negates the need to adopt adaptation

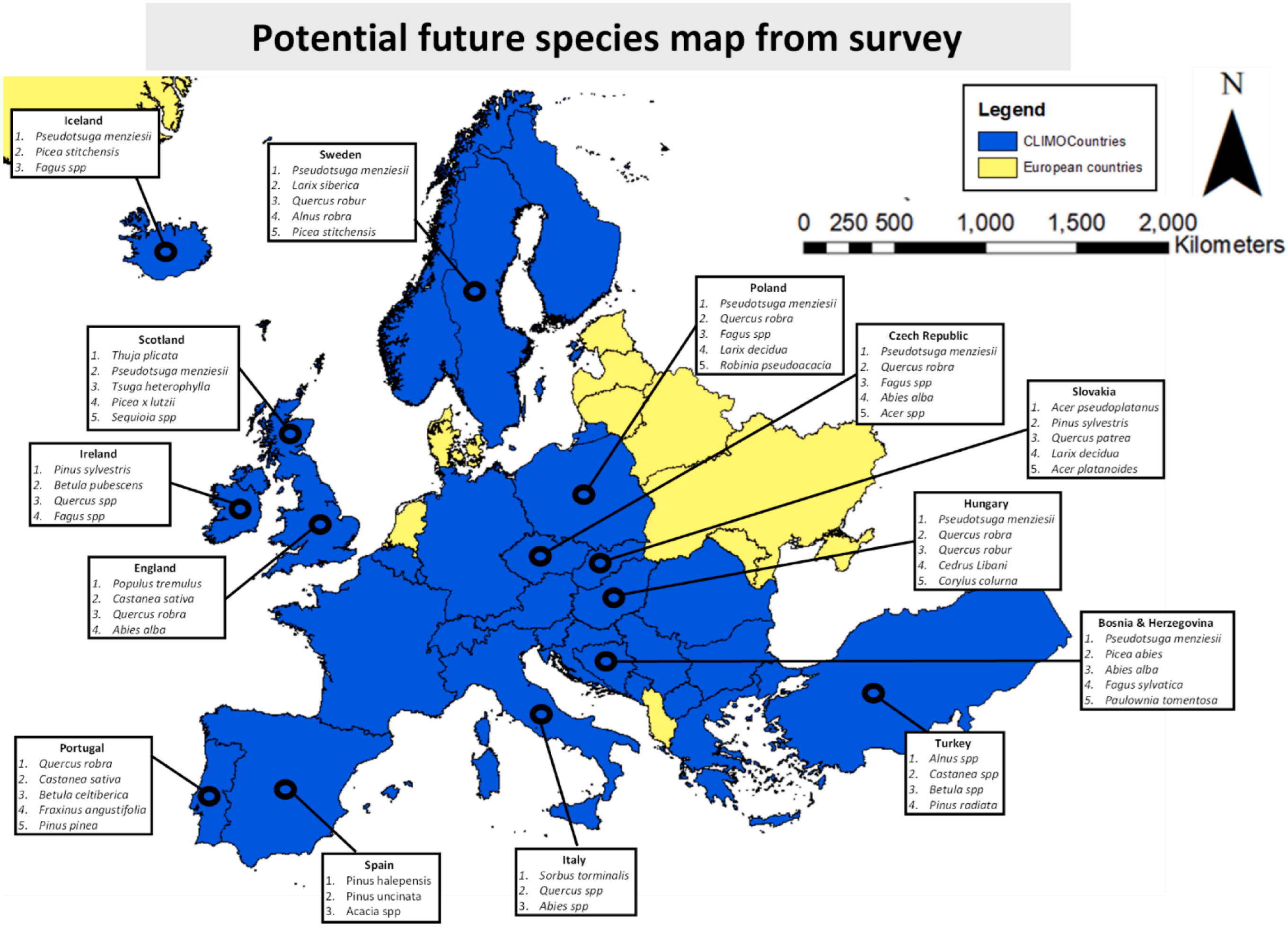

Fig. 5. Future use of species geographically referenced according to forest managers from each country.

measures, and places diverse forests at risk (Mostegl et al., 2019). Tailored management approaches specifically designed for small-scale forest owners are emphasised as promising strategies to generate knowledge and encourage action, as these managers will typically be less driven by state incentives and will depend upon small innovations to benefit and enhance the resilience of their forests (Mostegl et al., 2019; Bowditch et al., 2020).

Greater engagement, transparency and education of the public that generates social awareness and knowledge of forestry's role in providing public goods and services requires participation and engagement from managers to provide an accessible conduit between applied knowledge and wider stakeholders. Such provision would highlight a pivotal position in the green economy that would enhance support for forestry activities (Marchetti et al., 2014; Nijnik et al., 2016). In order to facilitate an effective interface between these three groups, communication and trust are key (Biggs et al., 2010). Non-jargon language and accessibility of forestry and ecosystem knowledge should be universally available within multiple-media platforms with the aim to create a deeper understanding of core forestry activities and methods through transparent decision-making (Meadow et al., 2015). Immersive real-time landscape education through long-term plots and demonstration sites could play a vital role in testing and refining the indicators through training activities that could provide managers with confidence in the CSF approach (Cosyns et al., 2018; Santopuoli et al., 2019), especially through peer-to-peer which are valuable resources for knowledge exchange but often underused (Eiseman et al., 2022).

4.2. *Developing effective indicators*

Despite many respondents stating that the list was too long to incorporate into management and planning, the list of CSF indicators were mostly viewed as comprehensive by managers. Additional indicators were suggested by managers that would help guide planning and enhance management in response to the uncertainty of climate change (Whittet et al., 2016; Paul et al., 2019). This highlights the challenge managers face in balancing and delivering a wide range of objectives and services (Bizikova et al., 2012; Blanco et al., 2017). A streamlined way to frame CSF for managers and utilise the long list of relevant indicators would be to match them with the aims and goals of clients whether the general public, specific private owners or community owners. Therefore, creating an optimum set of relevant indicators that could be regionalised and customised for different management objectives/types (productive, protective, amenity, recreation), these developing subsets would be more effective to guide and assess the climate-smartness of their forest and could be continually redesigned and developed through shared community experience and knowledge (André et al., 2017a; Langston et al., 2019).

One determining factor for implementing CSF will be the quality of baseline data and the longevity of monitoring plans. Absence of these provisions could limit the use of indicators into future management and identified gaps could be addressed by establishing new monitoring protocols, especially for locally or culturally specific indicators. The managers tended to rank indicators that have easily applied metrics and baselines as the most relevant (soil, carbon, regeneration, species composition) whereas those more difficult to measure and define were

Table 3
Summarised local perspective of forest managers and example quote.

Local perspectives	Example quote
Enhanced institutional and sector communication	*"the forest ecosystem is not separate from the rest of the landscape and cannot be protected without a link to agriculture. In my opinion, every large farmer should be encouraged to leave biodiversity belts in the form of wider breaks and cultivate areas to prevent wildfire"*
Tree species mixes and use of alternative provenances	*"ensuring adequate genetic variability of forests; establishing species-differentiated crops and establishing crops with high genetic variability and thus high potential for adaptation to environmental changes"*
Financial structures and incentives	*"landowners lack incentives to take action, someone has to pay for CSF and the value added within management"*
Developing the protective functions of forests	*"soil formation and retention is the most important because the region has a continental climate, which is a key consideration when setting achievable and reasonable long-term aims"*
Silvicultural systems should be reassessed and diversified	*"forest and tree silviculture should be reassessed or explored in relation to new threats"*
Education and training needs to be integrated more widely for the forestry sector	*"education of both the public and new generations of land managers is key to adaptation, as mindsets and thinking need to change first"*
Social awareness of forests/forestry	*"Educating and campaigning for recognition of forests and forestry, so that the public understand the expertise, the science and progress that has taken place in recent years, and appreciating the crucial role it plays supporting communities"*
Inclusion of indigenous populations	*"as they often derive their livelihoods from natural resources and have managed the land longer than anyone"*

ranked much lower (sense of place, aesthetics and genetic resources). In many ways the indicators that encompass the core areas of forest managers jobs are logical key indicators and within their comfort zone but the expanding remit of forestry gives greater focus on those indicators that may seem out of place from a traditional forestry perspective (Smithwick et al., 2019).

Assessing proposed and additional key indicators may require modification to the managers' current activities and might require adopting new technologies in the field to aid transitional knowledge bases through analysis software and using new open-source tools to improve understanding of constraints and opportunities. This change in management activity may require support and training which would benefit from a trusted communications platform to capture and relay the data. For example, bringing some of the more theoretical or academic knowledge would enhance the application of CSF indicators. Such as bringing net carbon balance within the manager's reach to integrate into management plans through accessible regional/national average data for different types of forests whether new afforestation sites, mature commercial timber, conifer plantation, native broadleaf or agroforestry (Harmon and Campbell, 2017). These would take into account the geography of the area and shape the indicators accordingly to include climate, soils characteristics, altitude, species, management regimes (Vizzarri et al., 2015), identifying carbon deficits and surpluses in different forest types, identifying impacts of different management approaches which could inform decision-making and the potential trade-offs between carbon sequestration and the multiple objectives a manager is expected to deliver (Matthews et al., 2020).

Socio-economic trade-offs were identified as important additional indicators from managers to help calculate the carbon cost of their actions, taking into account the growing stock as well as the storage timeline as end products (Handavu et al., 2017; Popp et al., 2017). Market forces and the dynamics of the forest sector within specific regions will impact the carbon cost, therefore indicators that can track trends of these supply chains and demands of the forest from both a societal perspective and consumer need could support manager's journey monitoring socio-economic CSF (Riccioli et al., 2019). This could be further enhanced by contextualising CSF management through important key activities to support the local economy, land use traditions and the most energy efficient way of managing the land for greatest benefit to the area (Howard et al., 2013; Statuto et al., 2019). As Fischer (2018) outlined, many concepts and definitions rarely account for the multiple ways in which social and economic conditions interact with ecological processes; therefore CSF should endeavour to work on a cycle of adaptation to create a flexible range of indicators that meet diverse managers' needs (Prager et al., 2012; Seidl et al., 2016). Therefore,

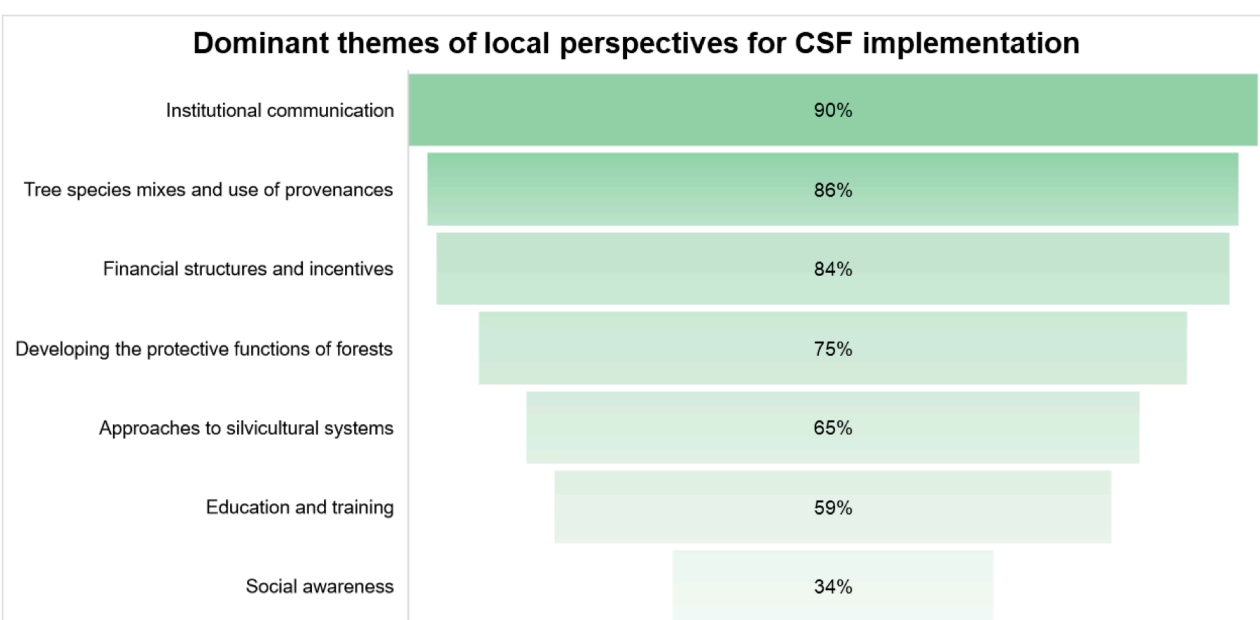

Fig. 6. Dominant themes to extend Climate-smart Forestry definition and indictors identified by forest managers.

incrementally building relevant knowledge and detail to support regionally, type and objective based indicators that can intuitively support a wide range of managers.

4.3. Species

Most forest managers recognised the logic and necessity of considering alternative species, mixes and provenances to future proof forest ecosystems and the wider forest industry. Transitioning to new species mixes and even provenances require investment, long-term monitoring and adaptation of the supply chain (Pinkard et al., 2015; Mina et al., 2017). Although current species may outperform alternatives, this may not be the case when considering climate change impacts and different objectives such as biodiversity or carbon (Meason and Mason, 2014). Climate scenarios and models provide evidence that delivering a wider range of services from forests (timber, carbon, biodiversity), has a significant probability of declining unless adaptive measures to climatic impacts are adopted such as species diversification and low-impact silviculture (Ray et al., 2015; Schelhaas et al., 2015; Jandl et al., 2018). Hof et al. (2017) highlight that negative impacts of climate change, especially precipitation levels may only be counteracted to a limited extent by species diversification. Therefore, using a range of genotypes (assisted gene flow) may further benefit adaptation to hotter and drier environmental change, but in these instances careful selection of climatically correct seed source is required to avoid undesirable outcomes from unsuitable provenances (Young et al., 2020). In light of this, common garden experiments could provide significant support to test growth of different provenances to support assisted migration and forest management and planning.

As many managers from the survey expressed frustration about the limitations imposed on them by the state system. Managers are not always supported to implement adaptation strategies, such as incentives to trial and test alternative species or provenances, as they do not align with public policy, which overlooks the aspirations and realities that face forest communities (Freer-Smith et al., 2019). Lawrence (2017) highlights that such practice is achieved through small innovations of interested land managers or owners that practice adaptive strategies without state support. Managers and/or their clients will often place their trust in tried and trusted species, ones that they know will perform and meet market demands, so a leap of faith, as well as an open mind to transitions of established management systems- needs to be developed (Abrams et al., 2021).

4.4. Adaptation and communication

A key enhancement area for progressing climate change strategies in forestry is the role of effective communication that could facilitate more effective adaptation measures and approaches to managers (Chan et al., 2012; Eddy et al., 2014; Townsend and Masters, 2015). Individuals, local cultures and social networks have a profound influence on the shape of forest management, meaning that the diversity of social landscape will determine whether CSF or any other concept is successfully adopted and integrated into forest culture (Aggestam et al., 2020). A key part of capacity building for forest communities is the co-development of innovative knowledge that will help grow more adaptive and resilient forests that can respond to multiple threats and demands (Nijnik et al., 2019). Lorente et al. (2018) recounts the co-construction of climate change adaptation indicators for Canadian foresters and highlight that ongoing communication with forest stakeholders is central to developing specific and relevant adaptation actions to meet the sector's needs and support on-the-ground implementation.

Sousa-Silva et al. (2018) highlight the crucial role of dissemination plays in equipping forest managers with the right knowledge and tools to incorporate adaptive practices and climate change responses into management. Demonstrated by crucial gaps in manager knowledge of mixed species forests, which included little knowledge of resistance and adaptability of mixtures to environmental change (Coll et al., 2018). This further emphasises the importance of designing research that will respond to practitioners' needs. Considering the wider issue of socio-economic ownership, small-scale private forest owners have been largely ignored and represent a significant area of forest land collectively (Wästerlund et al., 2017; Hiesl, 2018). Tailored approaches are required to communicate with small-scale private owners, as incentives rarely drive behaviour; therefore establishment of trust is central in helping them to actively manage forests in response to climate change (Mostegl et al., 2019). Enhanced climate change and adaptation communication for forests will not only depend on connecting with forest managers, but also others in the supply chain such as contractors and processors, as well as other land use managers (Blanco et al., 2017; Carter et al., 2018). Two powerful catalysts for encouraging action or implementing modified thinking and adaptation are 'experience and learning', as well as 'seeing is believing' (Weber, 2016; Hengst-Ehrhart, 2019) which is evidenced by demonstration being ranked as the preferred way to learn. However, this type of delivery is more challenging when disseminating and relating to large numbers of managers across diverse landscapes.

A central issue for some managers is finding an accessible pathway to information about climate change best practice and management measures that go beyond broad and vague advice of '*adapting*' and '*mitigating*'. Tools and trusted guidance on how to use tools appropriately, spatially and temporally could benefit management, however many climate adaptation tools are underused due to lack of relevance, specificity and urgency to implement change (Clar and Steurer, 2018; Mees et al., 2018). Access to user-friendly and open-source data is crucial for informing choices, whether in response to pest and diseases management, species and provenance selection, or water management. There are many databases and networks of useful information that managers could utilise, but they are often disparate and unknown to most but those contributing. Managers are more likely to respond and take advice from those they share common ground, respect or share a common experiential history, which makes support and knowledge sharing networks very important in disseminating knowledge, practice an learning tools (Krantz and Monroe, 2016; André et al., 2017b).

A CSF Hub would bring together a wide range of information and contextualise data through peer-to-peer advice, documented learning experiences of adaptation, potential funding opportunities, knowledge exchange discussion groups and collaborative work. Ideally, information hubs would be found at European, national and regional scales, being co-developed through bottom-up approaches by managers, citizen science, researchers and policy-makers contributing to the capacity and relevance of the material, as managers often are driven an understand their forests through local-based interests, knowledge and issues which shows preference and tendency for place-based decision-making (Uggla and Lidskog, 2016).

Detailed iterative input and assessment from managers is a key part of the process that can develop the definition and indicators from a logical list of forest issues into relevant and useful CSF guidance. Due to the small sample of mangers across the European countries this paper is in no way representative of forest manager views at a European scale, across diverse landscapes and conditions but endeavours to shed light on the potential gaps and critiques of the definition and indicators. Therefore, enabling the work to continue with greater engagement and feedback from key stakeholders and target audience.

5. Conclusion

This work highlights that there is increasing interest in the concept of CSF by the forest sector. However, there is still a lack of knowledge about the components of the CSF concept, particularly related to the transition from theory to meaningful practical management actions that ensure the continuous delivery of forest ecosystem services based on sustainable forestry. Climate change is seen as a high or critical threat by the majority of forest managers in Europe, despite the reduced concern from some private managers and smaller forest owners.

Though the CSF concept is rather clear, a simpler definition is required for a better implementation over a wider geographical area, particularly to improve awareness among small and private forest owners. Moreover, finding a way to shorten or tailor the list of indicators (as for example in (Santopuoli et al. 2020) is necessary to assess CSF for specific forest types or objectives. This will facilitate targeted CSF implementation and greater indicator usability that integrates with current management activities.

Developing tools and smart-techniques (ideally open access) for monitoring and assessing the state of forest resources and the sustainability of forest management is vital to promoting rapid implementation of CSF across European countries. Linking these with current knowledge and data in a user-friendly package could provide a greater depth to decision-making, if promoted by trusted sources and linked to some meaningful message for the managers.

Finally, training activities and communication programmes are recognised as key vehicles for increasing awareness and acceptance among forest managers. These will enhance managers' ability to adapt to and anticipate climate change impacts with greater ease and collectively develop and promote climate-smart forests.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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