Chapter 3
Assessment of Indicators for Climate Smart Management in Mountain Forests

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Abstract This chapter addresses the concepts and methods to assess quantitative indicators of Climate-Smart Forestry (CSF) at stand and management unit levels. First, the basic concepts for developing a framework for assessing CSF were reviewed. The suitable properties of indicators and methods for normalization, weighting, and aggregation were summarized. The proposed conceptual approach considers the CSF assessment as an adaptive learning process, which integrates scientific knowledge and participatory approaches. Then, climate smart indicators

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were applied on long-term experimental plots to assess CSF of spruce-fir-beech mixed mountain forest. Redundancy and trade-offs between indicators, as well as their sensitivity to management regimes, were analyzed with the aim of improving the practicability of indicators. At the management unit level, the roles of indicators in the different phases of forest management planning were reviewed. A set of 56 indicators were used to assess their importance for management planning in four European countries. The results indicated that the most relevant indicators differed from the set of Pan-European indicators of sustainable forest management. Finally, we discussed results obtained and future challenges, including the following: (i) how to strengthen indicator selections and CSF assessment at stand level, (ii) the potential integration of CSF indicators into silvicultural guidelines, and (iii) the main challenges for integrating indicators into climate-smart forest planning.

3.1 Introduction

In many countries worldwide, a transition from the paradigm of sustainable management focused on wood production (von Carlowitz 1713) toward multi-criteria forest ecosystem management is observed (Lindner 2000; Bolte et al. 2009; Messier et al. 2013, 2015; Bončina et al. 2019). The main causes for this paradigmatic shift (Yaffee 1999) are related to the enhanced need for various ecosystem services

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beyond forest products, such as recreation, protection of biodiversity (De Groot et al. 2002), but also the finding that diverse forests may have higher stability and recover capability in view of environmental threats (Knoke et al. 2008; Biber et al. 2015). The tools for monitoring, assessing, and managing forest ecosystems originally developed from sustainable wood production forestry (Hundeshagen 1826, 1828, Speidel 1972, pp. 162–164). In view of the paradigm shift, they need to be adapted to the extended scope and multiple criteria of forest ecosystem analyses and forest management (Pretzsch et al. 2008; Schwaiger et al. 2019; Hilmers et al. 2020). Examples for such an extension are criteria and related indicators for addressing biodiversity (Schulze et al. 2004; Geburek et al. 2010; Heym et al. 2021) or nutrients balance (Stupak et al. 2011), needed for sustainability.

Sustainability indicators quantify the state and the development of specific aspects of forest ecosystems and management in order to describe, assess, and manage forests regarding ecological, economical, and socioeconomical criteria (Azar et al. 1996; Pretzsch and Puumalainen 2002). Climate smartness has been introduced as a new concept for sustainable forest management (SFM) in view of climate change (Bowditch et al. 2020). According to Bowditch et al. (2020), Climate-Smart Forestry (CSF) is defined as "sustainable adaptive forest management and governance to protect and enhance the potential of forests to adapt to, and mitigate climate changes. The aim is to sustain ecosystem integrity and functions and to assure the continuous delivery of ecosystem goods and services (ESs), while minimizing the impact of climate-induced changes on mountain forests on well-being and nature's contribution to people".

This can be perceived as a new dimension of forest management, protection, health, and stability in terms of the current European perspective of sustainability (MCPFE 1993; Mayer 2000), which strengthens the delivery of ESs. In order to make it operational for monitoring and management purposes, climate smartness may be characterized by criteria and quantitative indicators (Pretzsch 2009, pp. 536–537).

The aim of this chapter is to evaluate criteria and indicators for CSF assessment at stand and management unit level. In detail, we (i) review existing approaches for CSF assessment, (ii) develop a list of indicators for climate smartness quantification at stand level, (iii) exemplarily apply a set of climate smartness indicators at stand level to mixed mountain forests, (iv) review concepts to integrate criteria and indicators of CSF in forest management planning; and (v) discuss the developed approaches and concepts in order to evaluate and demonstrate their potential impact on adaptive forest ecosystem management in terms of Lindner (2000) and Bolte et al. (2009). Notice that Chapter 4 of this book (Temperli et al. 2021) further derives the idea of smartness criteria and indicators at the spatial units beyond the stand and forest management unit level, i.e., at the regional or national scales.

3.2 Concepts for Assessing Climate-Smart Forestry at Stand and Forest Management Unit Level

The assessment of CSF can be done at different spatial scales, from stand or management unit levels, both directly linked to forest practice, to large scales such as regional, national, or global, which are more relevant for forest policy issues. Criteria and indicators (C&I) selected by Bowditch et al. (2020) in the framework of (CSF) definition were based on the Pan-European C&I for sustainable forest management (SFM), which are suitable to address adaptation to and mitigation of climate change (see also Chap. 2 of this book; Weatheral et al. 2021). Some few more indicators were added to the existing concept. The assessment of C&I of SFM and CSF have been widely developed at large scales, such as national scale (Wijewardana 2008; Pülzl et al. 2012; Santopuoli et al. 2020). However, the selection of indicators and their assessment, including their standardization and weighting for aggregation to a smartness composite indicator, should be adapted at the scale they are going to be used. Here, we focus on stand and forest management unit levels.

3.2.1 Indicator Selection

When selecting C&I, there are several recommended characteristics to be considered (e.g., Vacik and Wolfslehner 2004; Hagan and Whitman 2006; Reed et al. 2006), which might be more or less relevant depending on the goals and the scale of application. Among them, the following properties can be highlighted for CSF assessment at stand and forest management unit level:

- *Relevance* – the indicator is closely related with the criteria, with sound scientific information that support this relation (e.g., carbon stocks in aboveground biomass).
- *Sensitivity* – the indicator provides a measure so that changes in the indicator directly reflect observed changes in the climate smartness criteria. They can be linear (positive or negative) or nonlinear. As the aim is to characterize climate smartness of forest management, it is important that the indicator is sensitive to different management options.
- *Practicality* – the indicator is easily estimated from the available information or can simply integrate existing information, i.e., at stand level from forest inventories, remote sensing images, or visual assessments without need for additional analyses.
- *Understandability and utility* – the indicator is clearly understandable and interpretable by different users and can be easily applied in forest practice.

Other characteristics, like the indicator providing a direct measure instead of using a surrogate function (“validity” in Vacik and Wolfslehner 2004), may be less relevant at stand or landscape level. For some functions covered by the concept of CSF, it is not always possible to provide direct indicators at stand level as it would

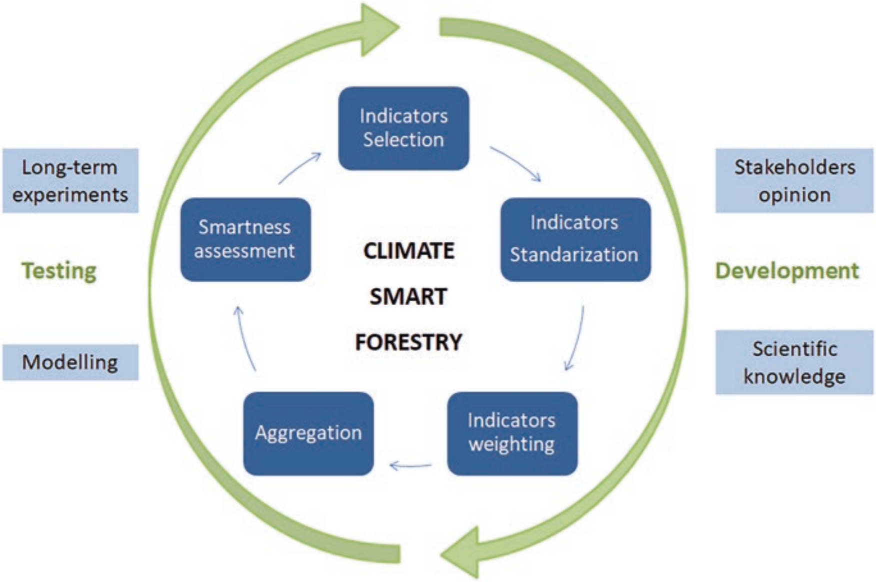


Fig. 3.1 Adaptive learning process for developing the framework to assess CSF at stand and management unit levels

require additional measurements, analysis, or even destructive sampling, which could reduce their practicality and utility. For instance, for assessing biodiversity, the number of large trees or microhabitats is often used as surrogate of flora and fauna diversity (Winter and Möller 2008; Alberdi et al. 2013).

In some cases, there is a trade-off between practicality and scientific rigorousness of indicators. Generally, indicators developed based on local context (bottom-up approach) prioritize the practicality, while indicators derived from expert and scientific knowledge (top-down approach) are generally more rigorous (Reed et al. 2006). However, the practicality, understandability, and utility are indeed key characteristics for the implementation of C&I for CSF assessment. Therefore, indicators based on top-down approach should be tested and evaluated in a local context. This means that adaptive learning processes for indicator development and assessment are recommended ways to improve the robustness and utility of methods (Reed et al. 2006) (Fig. 3.1).

3.2.2 *Indicator Normalization*

To compare the values of different indicators and to aggregate them into a composite indicator that summarizes the complement of several criteria, in our case for the CSF at stand and management unit (landscape) level, it is necessary to normalize or standardize the different indicators as they may be defined in different bit comparable units.

According to Pollesch and Dale (2016), three aspects can be considered when normalizing indicators: (i) the indicator bearing, i.e., whether an increase in the indicator means an approach to the "ideal" (i.e., optimal, theoretical) value or more distance; (ii) whether the normalization is internal or not, i.e., based on the data set; and (iii) the normalization scheme or method used. Different methods of normalization have been presented for standardizing indicators (e.g., Pollesch and Dale 2016); here, we summarized them in three groups:

(a) Ratio and z-score normalization methods. Ratio normalizations use the minimum, the maximum, or both values from the data set, whereas the z-score normalization is based on the mean and standard deviation of the data set. In this group, the normalization is therefore internal.
(b) Target normalization schemes or goal standardization, which use a baseline and/or target values for transformation (different functions can be used). The advantage of the target normalization schemes is that they can be used with various data sets.
(c) Benchmarking normalization function or value function approach, which assigns a normalized value to each indicator value based on existing knowledge (scientific knowledge, expert knowledge, questionnaires, etc.). It can be done by the direct rating, difference standard sequence technique, or mid-value method. As with the target normalization schemes, this method is not internal.

The method used for standardization is relevant as it can strongly influence the results and final climate smartness assessment (Talukder et al. 2017). When developing a framework for CSF assessment at the stand and forest management unit level, several normalization methods can be jointly applied for indicators, depending on data sources, knowledge, and indicator nature. However, aiming to develop a CSF assessment process that can be broadly applied internal methods should be avoided.

3.2.3 Weighting and Aggregating

Once indicators are assessed, a common option is to aggregate them into a composite indicator, which reflects the status of the object under evaluation. In some cases, different sub-indicators are also aggregated in a composite indicator linked to criteria. However, such aggregation is not always well accepted as the final value can involve loss of meaning and other disadvantages (OECD 2008, pp. 14). One common option is to avoid aggregation by the use of graphical summary of indicators, e.g., wheel or amoeba diagrams (Reed et al. 2006).

The way to weight the different indicators is probably the most challenging task when using composite indicators. Different weighting and aggregation methods to develop composite indicators were recently reviewed by Greco et al. (2019). Here, we briefly summarized the most relevant aspects and methods for developing C&I of CSF at stand and forest management unit level.

The simplest option is *not weighting*, i.e., giving the same value to each indicator/sub-indicator and then average or sum them. In this case, it can be particularly important to aggregate first the sub-indicators of a given indicator (same dimension) in a unique value or even all the indicators linked to a given criterion. This means that the final weight of some sub-indicators will vary. This method is often applied due to its objectivity and simplicity in spite of neglecting different relevance of indicators and correlations among them.

One option to weight indicators is to focus on data sources and nature of indicators, assigning higher weight to indicators based on more trustworthy and sound data (Freudenberg 2003). In the case of CSF, it is reasonable to consider to what extent an indicator is linked to adaptation and mitigation issues, giving more weight to indicators which are directly and accurately related to them, e.g., carbon stocks related to mitigation. However, the best approaches to avoid biases related to indicators' nature and data availability are those based on participatory processes. There are different participatory approaches such as the *budget allocation process*, in which participants have to distribute "n" points among indicators; the *analytic hierarchy process* based on pairwise comparisons of importance expressed on an ordinal scale; and *conjoint analysis* based on participant's preferences. The participatory approaches are difficult to implement when the aim of the C&I assessment is not clearly communicated or when there are too many indicators (Greco et al. 2019). Regarding C&I of CSF, it may be challenging for the participants to balance the different components of the CSF definition, i.e., sustainability, adaptation, mitigation, and ecosystem service provision (Bowditch et al. 2020).

Other options consider the relationship among indicators/sub-indicators in the weighting process or *data-driven weights*. These methods are based on different statistical methods, such as correlation analysis, multiple linear regression, principal component analysis (PCA), or data envelopment analysis (DEA). For example, the factor loadings of the first component of the PCA can be used as weights of the single indicators.

Regarding the aggregation, which is the final step in developing a composite indicator, different classification approaches are introduced in literature. Following the review by Greco et al. (2019), they can be divided in compensatory and non-compensatory aggregation, besides other mixed strategies. In *compensatory* approaches, for instance, using averages (arithmetic, geometric, etc.), a low value of one indicator can be compensated by a high value of another indicator. This approach bears the risk of hiding existing trade-offs between indicators resulting in undesirable incoherencies with the applied weighting. Using geometric averages instead of arithmetic averages can reduce the compensability among indicators (OECD 2008). *Non-compensatory* methods based on multi-criteria decision analysis avoid compensations among indicators and inconsistencies with the weighting process and thus involve a more complex analysis. Consequently, the method has not received a wide application to natural resource management outside of theoretical studies. While the compensatory technique provides a sound measure of overall performance of a given system (e.g., forest system), the non-compensatory technique alerts decision makers to presence of particularly poor performance with respect to individual criteria (cf. Jeffreys 2004).

3.2.4 Framework for CSF Assessment at Stand and Management Unit Level

To build up a framework for assessing CSF involves all steps, described above, from selection to aggregation of indicators into a composite CSF indicator (Fig. 3.1). In each step, different options with varying degrees of complexity can be selected, which can result in different weaknesses and strengths of the process and finally in different smartness assessments. Thus, any developed framework should be tested several times and iteratively refined until reaching a consolidated version, i.e., the development should be an adaptive learning process.

Science-based indicators and normalization and aggregation methods frequently derive in complex approaches, which later can be hardly applied in forest practice (top-down approaches). Contrary, other approaches focus on end-users' perceptions and local context to guarantee further application (bottom-up) but which can fail in assessment accuracy. Following Reed et al. (2006), an iterative learning process, which integrates top-down and bottom-up approaches, may result in a scientifically rigorous and feasible final framework.

Focusing on CSF assessment at stand and management unit level, any approach may unquestionably consider the integration of forest managers through participatory methods to warranty applicability. The extensive scientific knowledge on forest dynamics and management can assure the reliability of the process. On the other hand, information provided by long-term experiments in mountain forests (Pretzsch et al. 2019, 2021) as well as the more sophisticated and accurate forest models and decision support systems (Mäkelä et al. 2012) can help to test and improve the developed framework (Fig. 3.1). In the following paragraphs, we draft an approach for developing a framework to assess CSF at stand and management unit levels.

3.3 Assessment of CSF in Mountain Forest Stands: Exemplified by Norway Spruce-Silver Fir-European Beech Mixed Stands

3.3.1 Development of C&I Framework for Assessing Indicators of CSF at Stand Level

A forest stand is the smallest unit where forest management activities are decided on and implemented. Type and intensity of the management activities (e.g., thinning type, regeneration) depend on the management objectives and the current status of forest stands. Objectives may be manifold like timber production and/or forest for recreation or protection. Here, we describe an approach for assessing CSF at stand level when climate smartness (e.g., adaptation, mitigation) is intended to act as a general management strategy. The method presented can be generally used for assessing CSM at stand level. Through subsequent evaluations, the effect of management on the development of climate smartness can be monitored.

The approach was developed by using data from 12 long-term plots in the Bavarian Alps for assessing CSF in mixed stands of Norway spruce (*Picea abies* L- Karst), silver fir (*Abies alba* Mill.), and European beech (*Fagus sylvatica* L.) in mountain areas. Later, it was adapted to mixed mountain forests in other regions using six long-term plots in Bosnia and Herzegovina and two plots in Slovenia, as well tested in long-term experimental plots. However, the developed framework can be readjusted to other forest types, management systems, and regions by adapting the normalization of indicators/sub-indicators to specific characteristics of the respective region.

3.3.1.1 Selection of Indicators

We selected a subset of climate smartness indicators (Bowditch et al. 2020) that relate to stand-level characteristics (Table 3.1). A standardized protocol for data recording and assessment was set up (Pfatrisch 2019). This includes the definition of up to five quantitatively measurable or ratable characteristics of the indicator (sub-indicators) (Table 3.1). In our study, detailed yield data from long-term experimental plots were used, but the protocol is also applicable using yield data from common forest inventories and some additional information, which can be easily compiled in the field.

The values of the stand-specific indicator/sub-indicators were derived from existing measurements and from estimations in situ following standardized procedures (e.g., Level I protocol for 2.3 defoliation (Forest Europe 2015)). Some indicator values were assessed on species level (e.g., 4.3 naturalness) and then aggregated at stand level. Others are only evaluated on stand level (e.g., 1.2 growing stock).

3.3.1.2 Normalization

The indicator values need to be normalized to compare different sub-indicators and to aggregate them. The basic principle of the assessment was to reference the plot-specific values of the sub-indicators' characteristics in relation to reference values derived from existing information and knowledge. For most of the sub-indicators, target normalization schemes (goal standardization) were employed, using the target values either as a maximum or minimum threshold or as a mean reference value. For the other indicators/sub-indicators, the direct-rating approach (benchmarking normalization function approach) was used.

The transforming functions used in the target normalization schemes were linear, following three main patterns depending on the indicator bearing and reference values. When the benchmarking value represents the maximum value desired an increasing function was used, having the optimum at the maximum value of 1 (Fig. 3.2a), e.g., the maximum aboveground carbon stock expected for N.

Table 3.1 Selected climate-smart indicators and corresponding characteristics of assessment (sub-indicators), required plot data

Nr	Indicator	Sub-indicators	Abbrev.	Required plot data
1.2	Growing stock	Growing stock	G_1.2	Growing stock in m^3/ha
1.3	Diameter distribution	Diameter/age distribution	Dd_1.3	Diameter distribution in defined classes
1.4	Carbon stock	Carbon Stock	C_1.4.1	Carbon stock in C t/ha
		Development of Carbon Stock	C_1.4.2	10-year change of carbon stock C t/ha
		Substitution	C_1.4.3	Total quantity of carbon substitution in the last 10 years by products from fellings
2.3	Defoliation	Defoliation	Def_2.3	Estimated needle/leaf loss of five dominant trees per species
2.4	Forest damage	Risk probability	Dam_2.4.1	Estimated risk probability of different forest damages
		Impact of damage	Dam_2.4.2	Estimated impact of forest damages
2.5	Stability	Slenderness coefficient	Stb_2.5.1	Slenderness coefficient
		Tree height	Stb_2.5.2	Tree height in m
		Stock density	Stb_2.5.3	Stock density (yield table related)
3.1	Increment and fellings	Increment	IF_3.1.1	Annual increment in m^3/ha
		Fellings	IF_3.1.2	Average annual fellings in m^3/ha
		Effect on growing stock	IF_3.1.3	Annual relative rate toward target growing stock
4.1	Tree sp. suitability	Tree species suitability	Sp_4.1	Site suitability of occurring tree species weighted by species-specific basal area proportion
4.2	Regeneration	Regenerated area	Reg_4.2.1	Area proportion of regeneration in %
		Height of regeneration	Reg_4.2.2	Area related height of the regeneration in cm
		Density of regeneration	Reg_4.2.3	Plant density of regeneration in plants/ha
		Regeneration potential	Reg_4.2.4	Number of tree species in regeneration and main stand
		Browsing	Reg_4.2.5	Estimated damage by browsing
4.3	Naturalness	Naturalness (stand establishment)	Nat_4.3.1	Type of stand historic regeneration and species choice
		Naturalness (sp. composition)	Nat_4.3.2	Tree species basal area in % and dominance % rate in the regeneration
		Soil scarification	Nat_4.3.3	Impact factor for and scarification of soil
4.4	Introduced tree sp.	Introduced tree species	Int_4.4	Tree species stem number in %

(continued)

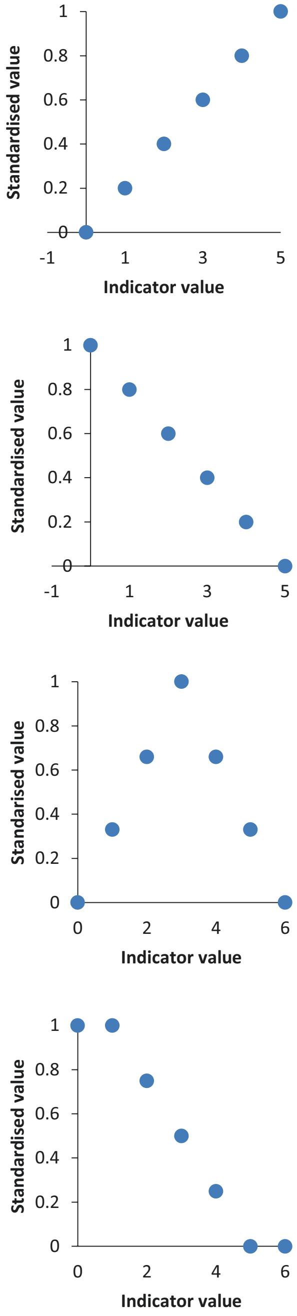
Table 3.1 (continued)

Nr	Indicator	Sub-indicators	Abbrev.	Required plot data
4.5	Deadwood	Quantity of deadwood (total)	Dead_4.5.1	Estimated deadwood quantity
		Standing deadwood volume	Dead_4.5.2	Estimated volume of standing deadwood
		Decomposition rate	Dead_4.5.3	Percentage of quantity in different decomposition classes
		Light exposure	Dead_4.5.4	Estimated percentage in three exposure steps
4.6	Genetic resources	Phenotypic similarity	Gen_4.6.1	Similarity level by species and species proportion in stem number
		Gen conservation	Gen_4.6.2	Method of stand regeneration
4.8	Threatened forest sp.	Threatened forest species	Thr_4.8	Number of stems in %
4.91/2	Distribution of tree crowns	Crown layers (vertical)	Ver_4.9.1	Crown layers
		Canopy level (horizontal)	Hor_4.9.2	Canopy level/crown closure
6.10	Accessibility	Distance to road	Acc_6.10.1	Shortest distance to next forest road
		Road density	Acc_6.10.2	Road density within the surrounding 100 ha

spruce-silver fir-E. beech mixture in Bavaria is 360 C t·ha^{-1}. This value was derived from unmanaged long-term yield trials located in the Bavarian Alps. When the optimum represents a minimum value, a decreasing function was applied (Fig. 3.2b), e.g., difference between the "ideal" size distribution and observed distribution, for which no difference is the best value (1). In other cases, the reference value represents a maximum within a range, with an increasing function below this reference and a decreasing function above this (Fig. 3.2c), e.g., optimum growing stock for rich sites is 350 m^{3}ha^{-1} (Bayerische Staatsforsten 2018). Independently of the pattern, when the reference value benchmarks a regional mean value, it is correlated to the smartness value of 0.5, e.g., for volume increment, the average value in Bavaria is used as reference for mean smartness 0.5. When necessary, the functions were truncated in order to assign a 0 or a 1 beyond established limits (Fig 3.2d). For instance, for the coefficient of slenderness as stability indicator, below 40 always means the highest smartness (1) and above 120 always the lowest (0), assigning a mean smartness (0.5) to a coefficient of slenderness of 80 (Pretzsch 2009). In some cases, only a one-sided truncation was applied.

Due to practicality, some indicators were estimated by direct rating. This method was applied when required measurements for indicator estimation would involve long time-consuming and expensive work or when the indicator expresses a qualitative aspect that can be assessed by discrete classes. For example, the sub-indicator browsing damage was assessed in the field classifying the damage in four classes

Fig. 3.2 Transforming function types for indicators normalization



from high (0) when most of the trees were affected by wild game to low (1) in case of absence or only single, scattered damages in the stand.

The data base for the determination of the necessary reference values were obtained from various sources (e.g., forest inventories, soil/hazard maps, silvicultural guidelines, literature). These reference values can be index values, specific limits, or region-specific values. For the indicators/sub-indicators that were standardized using a region-specific value, this value was adapted when the approach was extended to mixed mountain forests in Bosnia and Herzegovina and in Slovenia. It is important to consider the regional character of references to be able to classify the plot-specific climate smartness at regional level. This enables a comparison of assessments of climate smartness values of different stands at different study sites and also over time.

3.3.1.3 Description of Indicators

The indicator "growing stock" (G 1.2) was evaluated by the measured merchantable wood of the respective plot or forest stand. For the evaluation, the current growing stock was set in relation to the stock targeted for the area. In the case study, for the Bavarian Alps, this was 350 m^3 and 300 m^3 ha^{-1}, respectively, on productive and less productive sites according to the management goal of the Bavarian State Forest Enterprise (Bayerische Staatsforsten 2018) for continuous cover forest management. The transforming process followed the function in Figure 3.2c.

The current diameter distribution (Dd_1.3) was compared to the ideal diameter distribution for mixed mountain forests indicating a stable structural diversity (Bayerische Staatsforsten 2018) (50% in class 7–20 cm; 25% in 21–40 cm; 12,5% in 41–60 cm; 6,25% in 61–80 cm; 3,13% in >80 cm). Transforming was done using a declining function (Fig. 3.2b).

The indicator "1.4 carbon stock" was composed of three sub-indicators. Firstly, carbon stock itself (C_1.4.1) was calculated by applying species-specific biomass expansion factors to the growing stock of merchantable wood (Forrester et al. 2017). The reference value was 360 t ha^{-1}, reflecting a mean maximum value within fully stocked mountain mixed forest in Bavaria. Transforming used an increasing function. Secondly, the development of the carbon stock within the last 10 years period was referenced against the initial carbon stock. The application of an increasing transformation function led to higher smartness values with higher rates of recent carbon sequestration. In case of substitution (C_1.4.3), savings in terms of carbon release through substituting materials and fossil fuel were considered. The amount of harvested timber within the last 10 years period was converted into substituted carbon amounts by applying specific factors for roundwood and fuelwood reported by Hofer et al. (2007). As reference for a mean, a 10-year substitution effect of 16.09 t ha^{-1} C was used. This value was derived from an analysis of Klein and Schulz (2012), who investigated the substitution effect based on timber harvest information from 2003 to 2008 in Bavaria. The transformation process followed a right-side truncated increasing function.

Direct rating was applied to defoliation (Def_2.3), which was assessed by classifying the percentage of needle or leaf loss of five dominant tree per species. The classification referred to the graduation according to Forest Europe (2015). Estimations were first species-specific. In the second phase, the species-specific values were weighted by the percentage of basal area of the species and aggregated to a mean plot value.

"Forest damage" (2.4) combined the risk probability (Dam_2.4.1) of each possible risk (e.g., windthrow, bark beetle, snow breakage) and its impact (Dam_2.4.2) on plot level. Possible risks were derived from hazard maps or the previous occurrence of damages. The appraisal was based on expert knowledge and used classes from very high (smartness value = 0) to very low (smartness value 1). The impact was evaluated considering the impact on vitality, stability, and quality, which could have different weighting if necessary. Finally, a mean value for smartness was attained by averaging the damage-specific values. The third sub-indicator evaluated the number of possible damages (Dam_2.4.3).

The slenderness coefficient (Stb_2.5.1), tree height (Stb_2.5.2), and stocking density (Stb_2.5.3) were assessed within the indicator stability (2.5). Concerning the slenderness coefficient, species-specific values were weighted by their basal area proportion and then transformed by a two-sided truncated function. In literature, the value 80 for slenderness coefficient is reported as benchmark (Pretzsch 2009) with lower values indicating higher stability and higher values indicating less stability. Tree height was assumed to indicate higher stability with values below 20 m (mean value of the indicator scale) and less stability with higher values, respectively (Rottmann 1986). Transforming thus followed a decreasing function (Fig. 3.2b). Lastly, stocking density was classified into three classes (smartness values 0, 0.5, 1) by indexing the stocking density against yield table values. Classes considered higher stability at very low and very high stocking densities (Rottmann 1986).

"Increment and felling" (3.1) consisted of the three sub-indicators increment (IF_3.1.1), fellings (IF_3.1.2) and the mutual effect of both toward the target growing stock (IF_3.1.3). In case of increment and felling, the respective current values were benchmarked to 9.3 m^3 ha^{-1} $year^{-1}$, representing a mean value in mountain mixed forests (Hilmers et al. 2019a). The transforming process used an increasing function (Fig. 3.2a). The effect toward the target growing stock was assessed by calculating the annual relative trend rate of stock change. Positive values indicated an approaching trend and negative values, a diverging trend. The rates were classified into five levels of smartness.

Occurring tree species were appointed to one of three classes of site suitability (unsuitable, suitable, and optimal) in sub-indicator Sp_4.1. The suitability was assessed using information about growing conditions and literature (e.g., Otto 2000; Schütt et al. 2002). The species-specific value was weighted by its basal area proportion.

"Regeneration (4.2)" was divided into five sub-indicators. As regeneration, all plants below 7 cm diameter at breast height were considered. Firstly, the regenerated area (Reg_4.2.1) concerned the proportion of regenerated area of the entire plot. Transformation followed an increasing function using 100% as maximum. Secondly, the mean height of the regeneration (Reg_4.2.2) was related to the maximum browsing height, indicating a trusted regeneration. Values were converted by an increasing function; values above the threshold were capped. Thirdly, the observed density of regeneration (Reg_4.2.3) was related to general species-specific plant densities of artificially regenerated stands. Values above twice the number of the reference were truncated during a linear increasing transformation. Regeneration potential (Reg_4.2.4) evaluated the number of tree species found in regeneration against the number of species in the main stand. Again, the linear transformation function was cut at numbers of species in the generation, doubling the number of species in the main stand. Lastly, the damage by browsing (Reg_4.2.5) was categorized into four classes adapted from StMELF (2017) with higher smartness at less browsing damage.

The naturalness of stand establishment (Nat_4.3.1) grouped the evaluated stand into classes, which were defined by the proportion of natural and artificial regeneration and the closeness of involved species to the potentially natural vegetation (adopted from MacDicken 2015). Groups ranged from natural regeneration with naturally occurring tree species to artificial planting of non-autochthonous species. The naturalness of species composition (Nat_4.3.2) (Riedel et al. 2017) considered the current composition within two layers of a stand, i.e., the understory/regeneration (height < 4 m) and main stand (height > 4 m). The layer which was in future silvicultural focus received a double counting. The composition within the layers was grouped into classes defined by the proportion of species belonging to natural vegetation. Within sub-indicator Nat_4.3.3 (soil scarification), the affectation of the stand by different agents (cattle trampling, tracks, waste deposition, fertilization, forest roads) (Beer 2003) was reducing the maximum achievable smartness value. To each factor, a specific negative value was assigned and multiplied by a three-level intensity factor (three levels).

The indicator “Introduced tree species” (Int_4.4) classified occurring tree species into five categories of invasiveness according to Spellmann et al. (2015), ranging from species of natural vegetation to invasive species causing harm to natural vegetation and humans. Each tree species was weighted by its stem number proportion giving the same weight independently from tree size.

Smartness related to deadwood (4.5) considered the amount and structural characteristics of deadwood for biodiversity reasons. Four sub-indicators were addressed. The first total amount of deadwood (Dead_4.5.1) considered standing and lying deadwood. The amount was classified into five groups, whereas group borders were drawn using reported functional group-specific minimum amounts (Bauer et al. 2005; Moning et al. 2009). Solely standing deadwood was evaluated by the second sub-indicator (Dead_4.5.2). Here, a threshold of 15 m^3 ha^{-1} was used indicating a prerequisite for the occurrence of the three-toed woodpecker species (*Picoides* sp.) (Bütler et al. 2004). An increasing function was applied for smartness-value transformation. The proportion of decomposition degrees was addressed with sub-indicator Dead_4.5.3. Higher smartness values were achieved when all decomposition degree classes according to Lachat et al. (2014) were evenly distributed. Thus, transformation followed a decreasing function (Fig. 3.2b). As different light exposure situations of deadwood were relevant in terms of habitat provision, the distribution of deadwood amounts was classified into three light exposure classes (Dead_4.5.4) by assessing the crown closure degree above deadwood. The measured values were transformed as in the previous sub-indicator, whereas the optimal distribution was not equal between classes.

“Genetic resources” (4.6) were indirectly assessed through five classes of phenotypic similarity (Gen_4.6.1) of each tree species (Priehäusser 1958). Species-specific values were weighted by the species proportions of the total stem number. Genetic conservation (Gen_4.6.2) as second sub-indicator was evaluated by assigning the plot to one of five classes. Classes considered both, the genetic resources of the main stand and the management approach of regeneration (Kätzel and Becker 2014; Konnert et al. 2015).

The indicator “Threatened forest species” (4.8) recognized the occurrence of locally endangered red list species within the plot using the IUCN database. Classification followed the definition by Forest Europe (2015) of increasing imminence. The occurrence of a species belonging to the class of most endangered species determined the smartness value.

The “Distribution of tree crowns” was evaluated by determining visually or quantitatively the vertical layering (Ver_4.9.1) and the proportion of horizontal crown coverage (Hor_4.9.2) (Pretzsch 2009). Vertical layering was assessed using three scales (mono-layered, double-layered, multilayered). In case of crown coverage, a full coverage of the plot area was assumed as possible maximum value.

Accessibility (6.10) was of interest for forest economical and recreational purposes. Here, assessment was guided by economic criteria. In the first step, the minimum distance of the plot to a forest road (distance to road, Acc_6.10.1) was quantified and classified considering the distance dependent applicable most efficient transportation system. Secondly, the general road density (Acc_6.10.2) in terms of running meters per ha was estimated using a circular sample centered within the plot. A reference of 25 running meters per hectare was used as reference. The transforming process used an optimum within a range algorithm (Fig. 3.2c).

3.3.2 Indicator Assessment in Spruce-Fir-Beech Mixed Forest Stands

The selected indicators were assessed in 20 long-term experimental plots of spruce-fir-beech mixed mountain forests. We selected this forest type as a model example as it represents the most frequent and relevant mountain forest in Central and Eastern Europe (Hilmers et al. 2019a). The long-term experimental plots represent managed and unmanaged stands of these mixed mountain forests. In Table 3.2, the main characteristics of the studied long-term plots are presented. However, in most of the plots, there were no felling during the last 10 years (period used for estimation of time-dependent indicators).

Figure 3.3 shows the mean and standard deviation of the 36 sub-indicators and indicators from the values estimated on the 20 plots. On average, the greatest values (smartest) were found for sub-indicators related to the criteria “Biological

Table 3.2 Long-term experimental plots in mixed mountain forests used to assess CSF indicators. Main stand variables in the last survey are included. N, tree number per ha; BA, stand basal area; V, volume; PAIV, periodical mean annual stem volume increment

Plot	Country	Altitude m.a.s.l.	N Trees·ha^{-1}	BA m^2·ha^{-1}	V m^3·ha^{-1}	PAIV m^3·ha^{-1}·year^{-1}
1	Germany	1271	257	37.7	518.9	6.1
2	Germany	1463	362	43.7	570.8	4.7
3	Germany	1235	319	56.4	896.1	9.5
4	Germany	1091	241	23.8	334.7	4.6
5	Germany	1091	493	36.4	455.7	3.9
6	Germany	1281	378	42.8	598.5	7.7
7	Germany	1281	433	80.7	1284.9	14.5
8	Germany	1294	590	41.0	475.9	13.3
9	Germany	860	854	45.0	546.1	7.8
10	Germany	934	1259	20.3	211.1	7.3
11	Germany	934	696	22.7	326.3	7.7
12	Germany	884	659	53.8	833.4	11.4
13	Bosnia & Herzegovina	1110	701	38.1	390.1	10.2
14	Bosnia & Herzegovina	1280	538	40.3	425.9	10.5
15	Bosnia & Herzegovina	1320	468	39.6	521.3	11.6
16	Bosnia & Herzegovina	1400	297	33.9	477.7	7.0
17	Bosnia & Herzegovina	1220	377	44.2	538.1	9.7
18	Bosnia & Herzegovina	1320	431	38.5	454.9	8.0
19	Slovenia	1421	500	60.8	925.2	13.3
20	Slovenia	1375	650	52.5	738.2	13.7

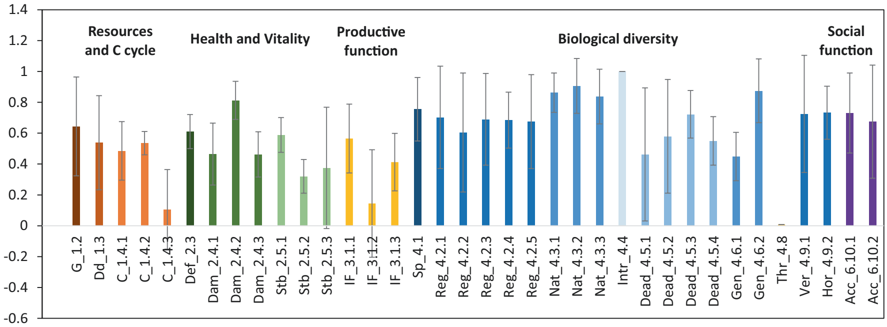


Fig. 3.3 Mean and standard deviation of the 36 sub-indicators and indicators representing five different criteria estimated in the 20 experimental plots in mixed mountain forests

diversity." The lowest values were obtained for sub-indicators related to "productive functions" (C_1.4.3 and IF_3.1.2), due to the absence of felling during the studied period in most of the plots. For most of the indicators/sub-indicators, the variability among studied long-term experimental plots was rather high. Two exceptions were the indicators for introduced (Intr_4.4) and threatened species (Thr_4.8), which showed no variation at all. All plots reveal the best rating regarding introduced species and the lowest rating regarding threatened species. This indicates that for the considered spruce-fir-beech mixed forests, these indicators were not very relevant. However, we kept them in the list of indicators, as in other stands or other types of forests they may have higher relevance. In this way, they may provide useful information for comparison with other less natural forests. The accessibility sub-indicators (Acc_6.1.1 and Acc_6.1.2) were estimated only in 13 experimental plots.

For a more understandable assessment of CSF at stand level, the different sub-indicators of a given indicator were aggregated. As the first option, equal weighting was evaluated. But taking the nature and difficulty of accurate estimation of some sub-indicators into account (Sect. 3.3.1.3), it was decided to apply a different weighting of indicators (C_1.4, Stb_2.5, IF_3.1, Reg_4.2, Nat_4.3, Dead_4.5). This weighting was based on the information content and accuracy of sub-indicators and on positive and negative correlations among sub-indicators of a given indicator (Sect. 3.4.3). Such correlations revealed some redundancy and trade-offs between different aspects of climate smartness. Nevertheless, the two weighting options resulted in similar indicator values (results not shown).

Figure 3.4 depicts that for most of the 16 indicators, the mean value of the 20 experimental plots reached or exceeded the value of 0.5 (average or greater smartness). The highest values were again observed for indicators related to biological diversity, especially those referring to species composition (Sp_4.1, Nat_4.3, Intr_44), except for threatened species (Thr_4.8). The mean value of the indicator related to carbon stocks (C_1.4) was below 0.5. This indicated that in most of the plots, the mitigation capacity was not as high as possible in this type of forest. Furthermore, these low values can be explained by the high reference value used for carbon stocks and by the low amount of carbon in products (substitution) due to the lack of felling, which also resulted in a low value of indicator IF_3.1. Another indicator with a mean below 0.5 was stability (Stb_2.5), due to the high stand density and mean height (Fig. 3.3), which creates high risk of windthrow and snow breakage.

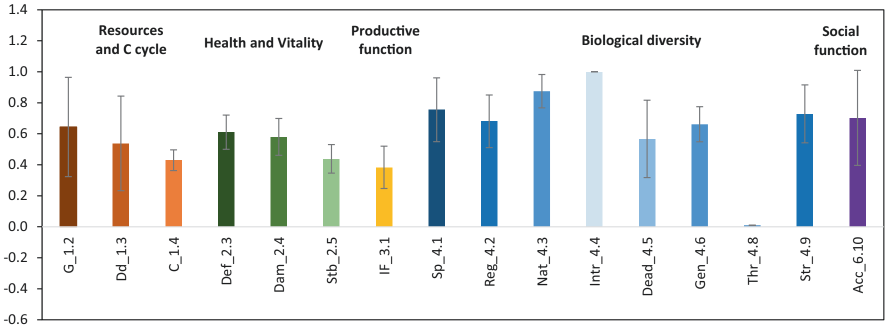


Fig. 3.4 Mean and standard deviation of the 16 weighted and aggregated indicators estimated for the 20 experimental plots in mixed mountain forests

3.3.3 Redundancy and Trade-offs Among Indicators

The values obtained for most of the indicators on the experimental plots were used to analyze whether there is some redundancy among indicators as well for detecting the presence of trade-offs between different aspects of climate smartness. For this analysis, the sub-indicators Intr_4.4 and Thr_4.8 were removed from the analysis as they showed a constant value in all the plots. The same was applied to Acc_6.10.1 and Acc_6.10.2 sub-indicators because they were not available for seven plots.

First, a correlation analysis was done among sub-indicators belonging to indicators with several sub-indicators (Fig. 3.5). The Spearman's rank order correlation was applied as some sub-indicators did not follow a normal distribution. As the abovementioned, the sub-indicators of some indicators showed significant positive correlations, which suggest that some of them could be left out, reducing the efforts of field work. For example, this occurred for the first three sub-indicators of the deadwood indicator. As the sub-indicator decomposition rate (Dead_4.5.3) was

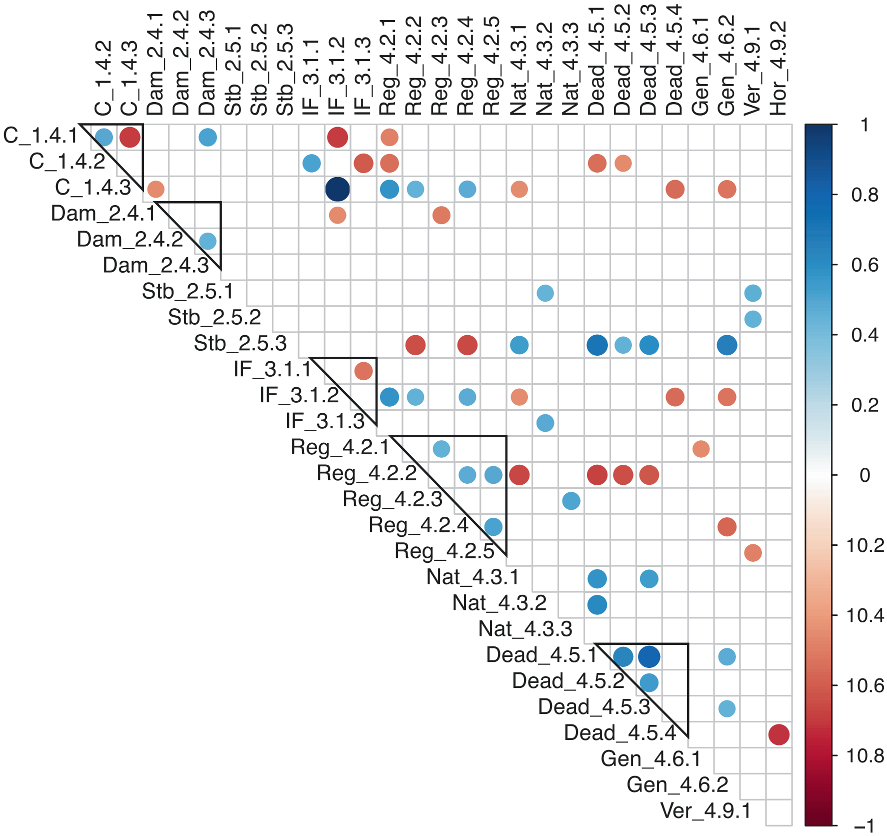


Fig. 3.5 Matrix of correlation among sub-indicators obtained from the 20 experimental plots in mixed mountain forests. Only significant Spearman correlations are shown ($p < 0.05$). Black triangles comprehend the correlations among sub-indicators of a given indicator

highly correlated to deadwood amount (Dead_4.5.1), the former, which is more difficult to be precisely assessed in the field, could be omitted. If an ever-greater simplification is needed, only the sub-indicator standing deadwood volume (Dead_4.5.2) could be maintained, which is easily derivable from a standard forest stand inventory. Similarly, for regeneration either the sub-indicator height of regeneration (Reg_4.2.2) or browsing (Reg_4.2.5) could be omitted. In other cases, the correlations between sub-indicators of a given indicator were negative. This indicated the presence of some trade-offs and the importance of considering all of them, as it happened for carbon sub-indicators (C_1.4.1 and C_1.4.2). It is important to note that there are also some significant positive correlations between sub-indicators of different indicators, as it occurred for C_1.4.3 and IF_3.1.2. Although it might suggest some redundancy, they should be maintained as they are expressing different aspects of their respective indicators, which can be compensated by other sub-indicators resulting in lack of correlation between indicators (as occurred between C_1.4 and IF_3.1, Fig. 3.6). Notice that any conclusions regarding information content or redundancy of the indicators cannot be transferred to other forest types without further analyses.

When integrating the sub-indicators into indicators (Table 3.1), the positive correlations among indicators of a given criteria (1–4) were not significant (Fig. 3.6). Exceptions from this were the correlations between growing stock (G_1.2) and diameter distribution (Dd_1.3) and between naturalness (Nat_4.3) and deadwood (Dead_4.5). Moreover, for indicators related to biodiversity, there were negative correlations (trade-offs) between tree species composition (Sp_4.1) and deadwood (Dead_4.5) and between regeneration (Reg_4.2) and genetic resources (Gen_4.6). Among indicators from different criteria, there were some positive and negative significant correlations, which may indicate some redundancy and trade-offs among indicators for measured plots. For instance, stability (Stb_2.5) was positively correlated to stand structure (Str_4.9), which could suggest that the indicator of structure added in the context of climate smart definition (Bowditch et al. 2020) could be eventually left out. Accordingly, there were some evident trade-offs as those between naturalness (Nat_4.3) and deadwood (Dead_4.5) with growing stocks (G_1.2) and diameter distribution indicator (Dd_1.3). There were further trade-offs between deadwood with carbon stocks (C_1.4), defoliation (Def_2.3), and species composition (Sp_4.1), which possibly indicate that deadwood presence is to some extent related with the degree of stand decay in the stands investigated here.

An analysis of principal components (PCA) was performed to further explore the redundancy among indicators and to explain the variability of the assessed indicators in mixed mountain forest stands. This statistical technique can also be used to reduce the number of indicators to be used in the assessment, simplifying the subsequent application of the developed C&I framework. The first two principal components explained 54% of the total variance. The first factor accounted for 30% of the total variance, the indicators of the criterion 1 (G_1.2, Dd_1.3, C_1.4), defoliation (Def_2.3), and tree species composition (Sp_4.1), being the indicators with

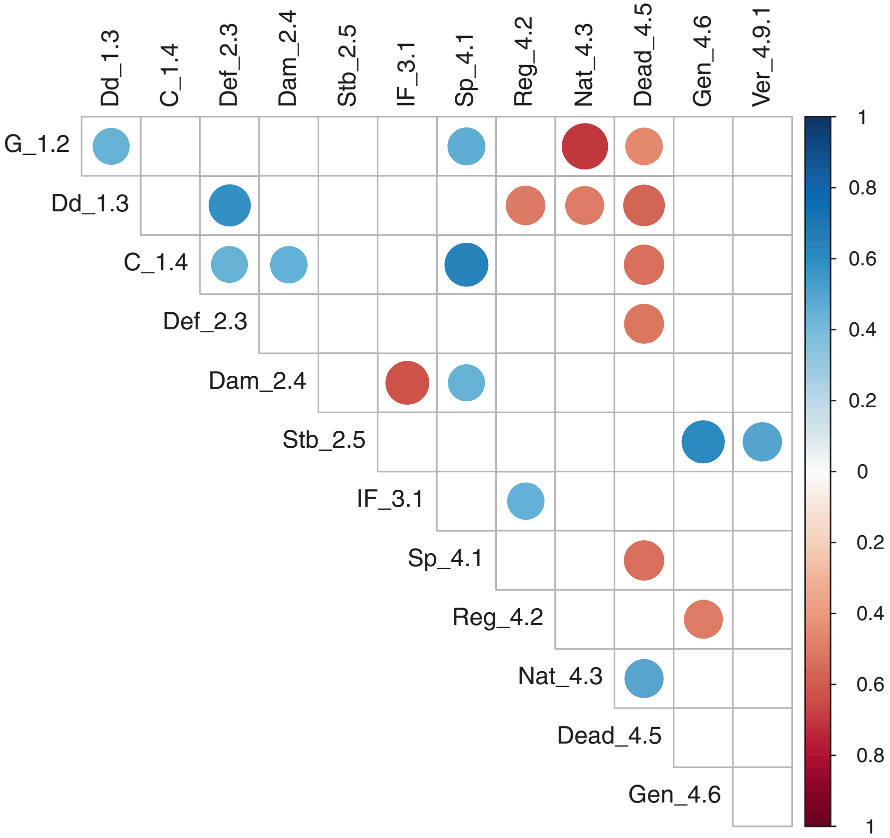


Fig. 3.6 Matrix of correlation among indicators obtained from the 20 experimental plots in mixed mountain forests. Only significant Spearman correlations are shown ($p < 0.05$); the larger the dot, the greater the correlation

higher positive loadings in these axes (Fig. 3.7), while deadwood (Dead_4.5) and naturalness (Nat_4.3) showed high negative loadings, which agrees with previous identified trade-offs. The second component explained 24% of the variability, with high positive loadings for stability (Stb_2.5) and genetic resources (Gen_4.6) and negative for increment and felling (IF_3.1) and regeneration (Reg_4.2).

In the biplot (Fig. 3.7), three groups of plots can be identified: the first group with high positive values in the first component (plots 13,14,15,16, 17, 18, 19, 20); the second group linked to the high values of indicators increment and felling and regeneration (plots 4, 10, 11), which are those plots with felling during the last 10 years; and the more dispersed third group with negative scores in the first component and positive in the second (plots 1, 2, 3, 5, 6, 7, 9, 12).

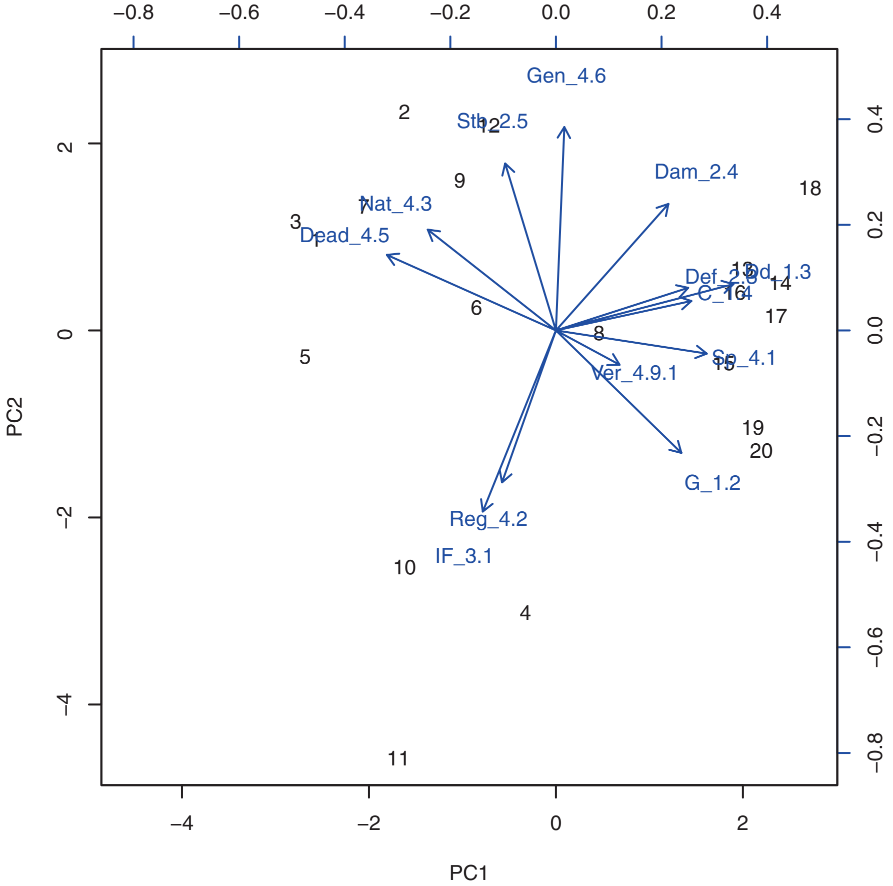


Fig. 3.7 Principal component analysis biplot showing the variation in plots (black numbers) and their relationships to indicators (blue arrows)

3.3.4 Assessing CSF in Spruce-Fir-Beech Mixed Stands

The aggregation of indicator values to a final score of climate smartness can simply be achieved by directly averaging the values. This method, although being objective, might not be the most appropriate, considering the number and information content of the indicators (see Sect. 3.2.3). Here, three methods of weighting were applied to obtain a composite indicator by averaging weighted indicators (compensatory aggregation method) in the 20 studied plots (Fig. 3.8).

(i) *Equal weighting or non-weighting*. All the indicators receive the same importance in the composite climate smartness indicator.

(ii) *Weighting by suitability for adaptation and mitigation monitoring*. In this option, if a given indicator is suitable for monitoring both aspects, adaptation and mitigation simultaneously, its weight is double than if it is suitable for

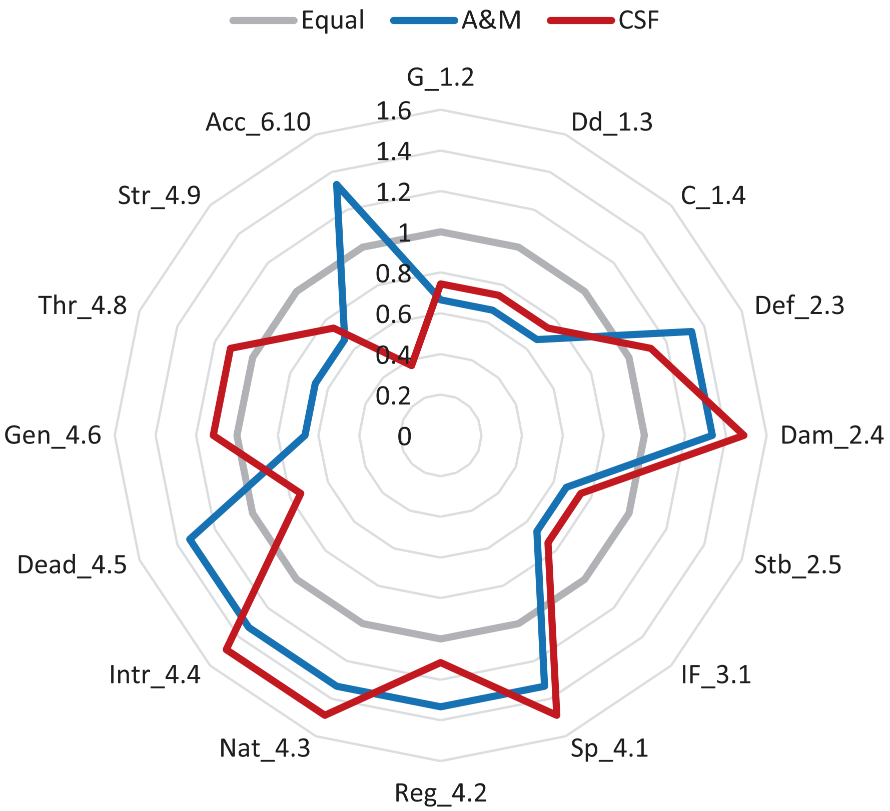


Fig. 3.8 Different weightings of the CSF indicators. Equal, same weight in all the indicators; A&M, weighting by capability to monitor suitability for adaptation and mitigation; CSF, weighting by the centrality for CSF (Bowditch et al. 2020)

monitoring only one of them. The suitability of the different indicators for assessing adaptation and mitigation forest management was based on the classification developed by Bowditch et al. (2020), who used an iterative participatory process involving various experts in forest-related fields from the Cost Action CLIMO.

(iii) *Weighting by the centrality for Climate-Smart Forestry*. In Bowditch et al. (2020), the most relevant indicators for assessing CSF were identified by a network analysis, which considered both the suitability of indicators to monitor adaptation and mitigation and the forest ecosystem services they address. They established four groups of indicators considering their degree of centrality, which were used for weighting purposes. The highest weight was assigned to the indicators belonging to the first core group (e.g., forest damage Dam_2.4) and the lowest weight to the second peripheral group (e.g., accessibility Acc_6.1) (Fig. 3.8).

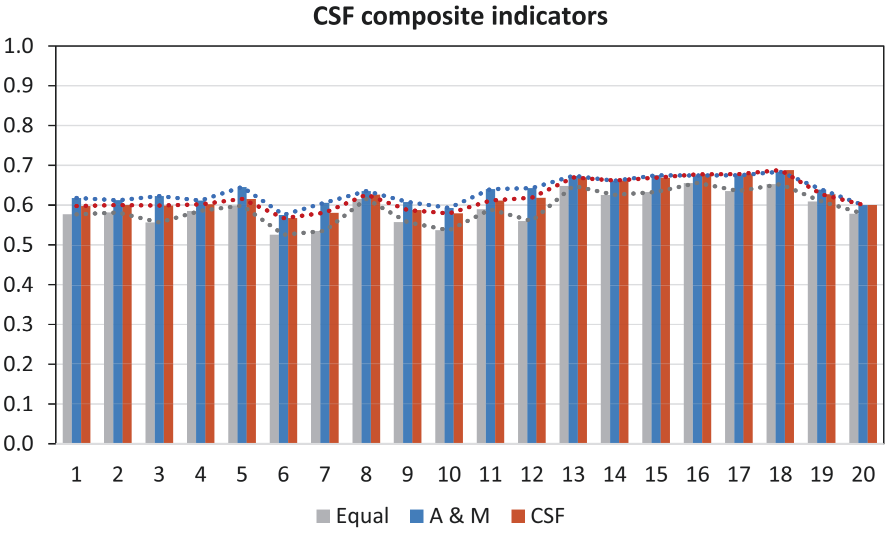


Fig. 3.9 Final climate smartness values of the 20 experimental plots according to the three weighting types. Equal, same weight in all the indicators; A&M, weighting by suitability for adaptation and mitigation monitoring; CSF, weighting by the centrality for CSF (Bowditch et al. 2020)

Figure 3.9 presents the resulting plot-specific CSF values according to the three different types of weighting for the 20 plots. Notice that the results do not include the indicator accessibility (Acc_6.1) as this indicator was not always available. The differences among the three weightings were small, with mean values of 0.59 (±0.04) for equal weighting, 0.63 (±0.03) for weighting by suitability for adaptation and mitigation monitoring, and 0.62 (±0.04) for weighting by centrality for CSF. The largest differences within weighting types were found for plots 3, 7, and 12, whereas in each case the highest values occur when using the second weighting.

In all cases, the CSF composite value is greater than 0.5 (Fig. 3.9), which represents the mean climate smartness following the used indicator normalization and weighting procedure. Concerning the CSF weighting type, the plot 18 showed the highest value (0.69) and plot 6 the lowest value (0.57). It can be observed that the highest values were reported for the Bosnian plots (plots 13–18), which are those with greater values in the indicators related to the first principal component (Dd_1.3, C_1.4, Def_2.3, Sp_4.1) (Fig. 3.7).

3.3.5 *Sensitivity of CSF Indicators*

To test the sensitivity of the indicators concerning different species composition, environmental changes, and management, data from additional long-term experimental plots in mountain forests in Bavaria were used (Table 3.3). Four plots representing different species composition were selected from the experimental site

Table 3.3 Geographical information and site characteristics of the 10 experimental plots. E, elevation (m a.s.l.); T, mean annual temperature (°C); P, annual precipitation (mm)

Experiment	N°. plots	Composition	Treatment	Period	No. of surveys	Longitude	Latitude	E	T	P
ZWI 111	4	E. beech; N. spruce; N. spruce-E. beech	Light-heavy thin. f. above, mixture portion	1954–2015	10	13°18′22″	49°3′57″	745	5	1270
FRY 129	6	N. spruce-E. beech-S. fir	Selection forestry; level of standing stock and threshold diameter	1980–2018	7	13°35′184″	48°51′19″	720	6.5	1200

ZWI -111 (Hilmers et al. 2019b), including one monospecific spruce plot, two monospecific beech plots (two thinning options), and one mixed spruce-beech plot. The experimental site FRY-129 (Pretzsch 2019) (6 plots) was chosen to compare the effect of different levels of growing stock (management) in uneven-aged spruce-fir-beech mixed stands. A more detailed information about the main stand characteristics of the long-term experimental plots can be found in Appendix 3.1.

For the chosen long-term experimental plots, the sub-indicators corresponding to indicators growing stock, diameter distribution, carbon stock, stability, increment and felling, and structure were estimated from inventory data during the monitoring period (Table 3.3). The sub-indicators were aggregated into the six indicators using the same weighting as in Sect. 3.3.2 in order to be comparable with the previous CSF assessment.

The effect of the species composition on selected indicators was in general larger than the effect of different growing stocks, reflected by higher variance between types (Fig. 3.10 left and right plots). By trend, in uneven-aged spruce-fir-beech mixed forests, the indicators showed higher values. The indicator growing stock (G_1.2) was very variable among and within plots, showing a decreasing trend with time in experimental plots with high standing volume (less removed volume) (Appendix 3.1). However, the spruce-fir-beech plots with lower growing stock and one beech plot, which maintained a lower growing stock, presented higher smartness values (Fig. 3.10b). This indicates that the selected reference value and normalization function penalize stands with high growing stocks.

The diameter distribution (Dd_1.3) and structure (Str_4.9) indicators were mainly influenced by species composition and age structure (Fig. 3.10c, d, k, and l), being greater for uneven-aged spruce-fir-beech mixed stands; medium for beech, probably to its strong shade tolerance; and lower for spruce-beech and spruce plots. It is noteworthy that in spruce-fir-beech mixed plots, there was a decreasing trend in Dd_1.3, but it was not observed for Str_4.9.

The indicators carbon stocks (C_1.4) and stability (Stb_2.5) did not vary largely among the different plots, being rather stable over time (Fig. 3.10e–h). The smartness value of the stability indicator was greater in spruce-fir-beech plots than in the other plots but in all cases lower than the medium smartness (0.5). For carbon, it ranged between 0.4 and 0.6. This agrees with the values shown in Figure 3.4 and suggests a low sensitivity of these two indicators for this type of mountain forest. The respective values might be readjusted in future applications by revising the reference values or/and changing the transforming functions.

The indicators increment and felling (IF_3.1) were sensitive to felling but not to species composition (Fig. 3.10i, j). However, the volatile changes observed suggest that the period of 10 years used for its evaluation influences the sensitivity. Using longer reference periods could result in more stable lines, which would reflect better long-term trends, which is more relevant for CSF. Accordingly, upscaling to the management unit would allow a better assessment of this indicator.

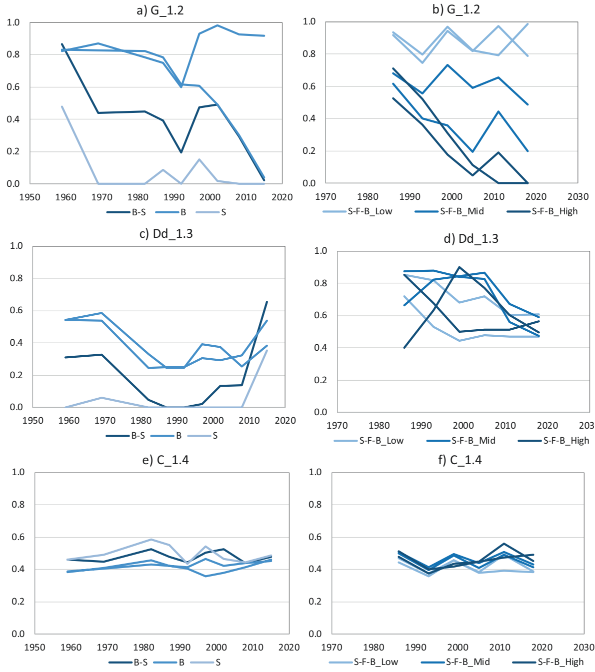


Fig. 3.10 Development of indicators for different stand compositions (B, beech; F, fir; S, spruce; mixed: BS and SFB) and growing stocks (low, middle, and high). (**a–b**), Growing stock G_1.2; (**c–d**), diameter distribution Dd_1.3; (**e–g**), carbon stock C_1.4; (**g–h**), stability Stb_2.5; (**i–j**), increment and fellings IF_3.1; (**k–l**), distribution of tree crowns Str_4.9

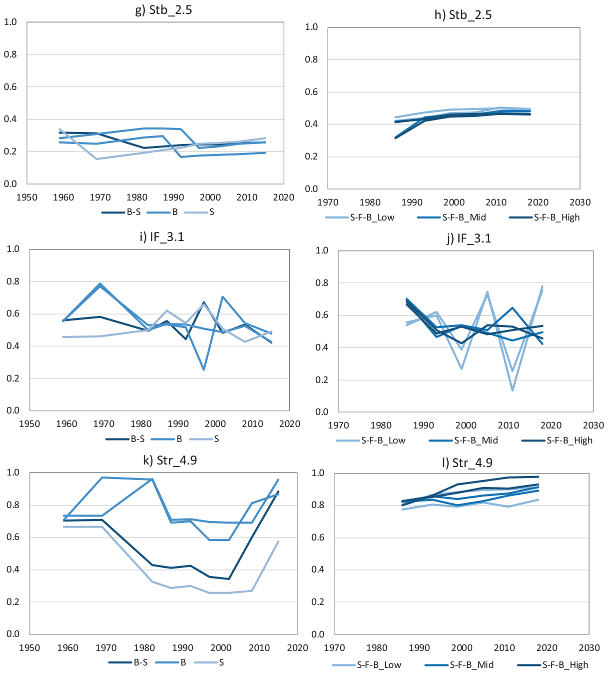


Fig. 3.10 (continued)

3.4 Importance of C&I of CSF in Forest Management Planning

3.4.1 Forest Planning and Climate-Smart Forestry

This section is focused on the importance of C&I of CSF in forest planning. The target scale is forest management unit level (FMU), since in many countries FMU is the most common spatial scale (combining stand and landscape) of forest planning (Cullotta et al. 2015). While in the past, the primary goal of traditional forest management planning was to ensure timber sustainability (Pommerening and Murphy 2004), nowadays forest planning can be understood as a tool to provide the desired ecosystem services for society and forest owners in a sustainable manner under socio-environmental changes. Due to climate change and increasing frequency of disturbances such as windthrows, ice storms, and insect attacks (Hanewinkel et al. 2012; Seidl et al. 2014; Nagel et al. 2017), forest planning needs to be adequately adapted to a changeable environment. This implies the continuous, repeated, and extensive monitoring to better understand the influence of climate change on forest dynamics, along with adapting forest management to the expected changes through managing uncertainties and risks. Beside adaptation, mitigation strategies are gaining more relevance in forest planning, since they may contribute greatly to enhancing forest carbon stores (Hof et al. 2017).

Indicators of sustainable forest management (SFM) (Bachmann 2002) have been traditionally applied in forest planning (Bončina 2001). Mostly, they are related to the status of forest stands (e.g., growing stock, stand volume increment, tree species composition), forest management activities (e.g., annual cut, proportion of natural regeneration in total regeneration), and impact of environmental change (e.g., sanitary felling). Climate change adaptation and mitigation strategies can be viewed as a risk component of SFM (Spittlehouse and Stewart 2003). Therefore, this calls to additional C&I. Indicators of CSF may have a substantial role in forest planning to better monitor and address the needs for adaptation and mitigation in forest management.

3.4.2 Involvement of CSF Indicators in the Forest Planning Process

To understand the importance of indicators for climate smart forest management planning, the whole planning process can be divided into five phases which are interconnected:

1. *Inventory, analyses, and evaluation*: to begin with the process of management planning, the current state of the respective FMU needs to be sampled and analyzed. The essential aspects of CSF can be recorded using the classical or further improved forest inventories (e.g., broadening their scope to include variables related to forest carbon pools and carbon sequestration, forest health, or biodiversity (Corona et al. 2011)). Thus, many above indicators at stand level (e.g., growing stock (1.2), regeneration (4.2), carbon stock (1.4), and stability (2.5)) (Table 3.1) are relevant for the assessment of CSF at FMU. For instance, some of them may indicate forests' response to climate change (e.g., damage level of forest stands, growth of stands and trees, regeneration pattern) or show response of forests to recent management activities carried out for adaptation of forests to climate change (e.g., tree species composition, diameter structure of forest stands). When dealing with those indicators, two aspects should be considered. Firstly, indicators are more powerful for the assessment of CSF if their current value is compared to their values from previous inventories. This enables insight into changes of structure and processes in forest stands. Secondly, the same indicators are useful for assessing various CSF aspects, e.g., impact of climate change on forest stands and effectiveness of forest management activities for adaptation.
2. *Defining (management) objectives*: management objectives should reflect demands of forest owners and society. Management objectives are operationalized through operational objectives. Thus, the desired structure and composition of forest stands are defined by silvicultural objectives. For CSF, it is important to search for forest stand composition and structure which will be adapted to

changeable climatic conditions and thus contribute to reducing the risks in forest management (see also Chap. 8 of this book; Pach et al. 2021). Silvicultural objectives are usually determined separately for the different forest site types; they are defined with selected stand parameters, which can be treated as indicators of CSF. Among them, tree species composition, stand structure, and target diameter of tree species are the most relevant.

3. *Modeling and elaborating scenarios:* based on the analysis and defined management goals, projections of potential forest development paths are undertaken which can be model aided. Usually, a number of different forest management are explored in a scenario analysis, and the best option under the given constraints and management objectives is identified (cf. Pommerening and Grabarnik 2019). Models of forest stand development are important for many purposes: i) adaptation of forests and forest management to climate change, ii) selection of optimal management strategies, and iii) reduction of risks and uncertainties in forest management. When modeling stand development, the same indicators might be applied as in planning phase 1. Scenarios are often focused on demographic changes of forest stands (important CSF indicators: diameter structure, age structure, stand density, etc.) under different management strategies (CSF indicators: cut intensity, silvicultural system) (e.g., Rosset et al. 2014).
4. *Defining management activities:* then, results of sampling and scenario analyses feed into the management plan as a set of silvicultural prescriptions to the given stand. The main part of management activities is focused on silvicultural activities (important CSF indicators: structure of planned harvesting, felling intensity, thinning concept, regeneration system etc.) and protection measures. All measures influence the structure and processes in forest stands, and therefore, their impacts reflect in changed values of CSF indicators related to the status of forest stands, which can be observed in the next forest inventory. Management decisions were made for other fields of forest management beside silviculture (e.g., forest road construction, forest protection, recreation). Better accessibility to forest areas and suitable harvesting technologies contribute to effective forest management when huge forest damages occur; therefore, they can serve as important CSF indicators as well.
5. *Monitoring of forests and forest management:* implemented management activities are usually registered, this being important for understanding how forest stands react to specific management activities under changeable environment. New experiences can be applied into future decision-making about forest management activities. Besides forest management, some other impacts on forest stands can occur. Among them, severe disturbances noticeably change the structure and composition of forest stands. Therefore, registration of sanitary felling is a part of forest management monitoring; the amount and structure of sanitary felling can serve as an important CSF indicator. Monitoring of sanitary felling (e.g., Klopcic et al. 2009) in a longer time period is substantial for understanding the susceptibility of forest stands to various agents of natural disturbances and for adapting forest management to reduce risks.

3.4.3 Estimation of Importance of CSF Indicators in Forest Planning at the Forest Management Unit Level

A list of possible CSF indicators available in forest planning was created, and the importance of indicators for assessing CSF at the level of forest management unit in four countries was estimated by Likert scale (1, not important for CSF at all; 2, not important; 3, neutral; 4, important; 5, extremely important). Assessment of indicators was based on the definitions of CSF (Bowditch et al. 2020) and on the possibilities to operationalize them in the forest management unit plan.

The scheme of European criteria of SFM was followed, but a much larger set of possible indicators was included into the analyses. It included most of the above-mentioned indicators for CSF assessment at stand level (Table 3.1) but without disaggregating them into sub-indicators. In total, a set of 56 parameters was estimated (Appendix 3.2). The importance of indicators was estimated in regard to their role in the planning process for:

- Understanding the influence of climate change on forests structure and stand dynamics in a FMU
- Analyzing the status of forests in a FMU in regard to the impact of climate change
- Modeling the development of forest stands in regard to the changed climatic conditions
- Evaluating the effectiveness of implemented silvicultural activities
- Determining the objectives and measures which will contribute to the adaptation and mitigation of forests and forest management in a FMU
- Monitoring the development of forest stands in regard to the implemented management activities and climate change

Ranking of indicators' importance for climate smart forest planning by representatives from four countries (Bosnia and Herzegovina, Poland, Slovenia, and Spain) shows that quite a number of indicators, which are not part of the European system of C&I of sustainable forest management, are very important in forest planning at the FMU level (Table 3.4). Tree species composition of natural regeneration was uniformly estimated as the most important indicator for CSF planning. It indicates capacity for adaptation of forest stands to climate change as well as the effectiveness of past forest management. Some indicators in the list are crucial for assessing the impact of extreme events on trees and forest stands as well as the susceptibility of stands to natural disturbances (e.g., forest damage, vitality status, amount, and structure of sanitary felling). Climate change may strongly influence the tree growth pattern; therefore, quite expectedly some indicators may be connected to tree and stand growth. Forest plans define the management activities for the next period. Consequently, it was to be expected that some management indicators were ranked as very important, e.g., planned and implemented silvicultural works, management system applied, and felling. Silviculture and cutting are the main tools for creating structure and composition which is adapted to climate change. This is why indicators describing forest stand structure and composition were assessed as highly

Table 3.4 Mean value of the importance of parameters for the CSF assessment of CSF in forest planning at the FMU level (only indicators with average value > = 4 is presented; indicators were assessed with ranks from 1 to 5) (CV – coefficient of variation in percentage)

Indicators	Mean value of importance	CV (%)
Tree species composition of natural regeneration	5.00	0.0
Forest damage	4.83	2.3
Regeneration (type of regeneration)	4.75	5.3
Vitality status of tree species/forest stands	4.67	4.8
Silvicultural works (planned and implemented)	4.67	4.8
Management system applied	4.58	5.5
Growth of trees and stands (e.g., diameter growth…)	4.58	5.5
Register of harvested trees in past planning period (tree species, dimension)	4.33	15.4
Tree species composition of single forest stands	4.33	5.1
Growth intensity of forest stands (volume increment/stand volume)	4.33	5.1
Increment and felling	4.25	5.9
Density of forest stands (basal area, tree number, SDI)	4.17	2.7
Protective forests – soil, water, and other ecosystem functions	4.17	18.7
Diversity of tree species	4.17	18.7
Damages of trees (stands) per agent (wind, snow…)	4.08	0.7
Growing stock	4.00	16.7
Amount and structure of sanitary felling according to the main agents	4.00	16.7

important (e.g., growing stock, tree species composition, stand density). In most European countries, forest planning supports multi-objective forest management oriented to providing various services. One indicator directly related to ecosystem services was included into the set of important indicators at the FMU level. Some of the indicators from the list (e.g., register of harvested trees) indicate that monitoring is an important part of CSF and planning.

3.5 Challenges and Perspectives

3.5.1 Refining the Selection of Indicators/Sub-indicators at Stand Level

The selection of indicators is an important step in the development of any assessment framework. Indicators can provide a reliable overview of the forest situation, allowing a comprehensible and transparent assessment of forest management (Blattert et al. 2017). Although Pan-European indicators for SFM were designed for application at the national scale, in this study they were adapted for their application at stand level. Suitable, quantifiable, or ratable sub-indicators were defined and forest-type and region-specific reference values and transforming functions assigned. However, the presented approach may not give the full picture of CSF as not all aspects have been addressed.

For example, protective functions, like protection against avalanches and rockfalls, as well as protection of soil not included, yet play an important role in mountain areas. Although these agents are known to highly depend on physiographic and site factors (e.g., slope, soil type, roughness of the forest floor), stand-level indicators related to the structure and composition of forest stands may also provide important information about the protective role of a stand (Blattert et al. 2017). These variables include the mean stand density, the basal area (or the average diameter at breast height), and the percentage of evergreen/deciduous species for rockfall protection (see *Rockfall Protection Index* in Cordonnier et al. 2013); the mean tree height, the canopy cover during the winter, and the stand density or basal area for protection against snow avalanches (see *Avalanche Protection Index* in Cordonnier et al. 2013); and the forest canopy cover (%) for landslide and erosion protection. Some of these parameters were here used in other indicators but not explicitly to assess the protective function.

Soils in native forest seldom experience significant disturbances which are more common for soils in other land-use systems; thus, the importance of soil characteristics is often underestimated in forest management practices and planning. However, climate change, atmospheric deposition, and/or deforestation can cause dramatic changes in the quality of forest soils, by altering the soil organic matter (Raison and Khanna 2011; Prietzel et al. 2020), and changes in hydrological processes which can enhance surface runoff and soil erosion, increase the recharge of groundwater, and cause the reduction of organic carbon, nitrogen, phosphorous, and exchangeable potassium, calcium, and magnesium (Pennock and van Kessel 1997). Furthermore, bedrock has a significant role in vegetation growth by regulating physical and chemical properties in soils (Hahm et al. 2014); it can also change the response of vegetation to climate factors (Jiang et al. 2020). Thus, some indicators related to soil properties could help to estimate the future forest growth and vitality and the need for adaptation under conditions of climate and/or land-use change. The most important soil characteristics for predictions of changes that can occur in forests due to land-use and/or climate change are texture, content of organic carbon, and available ions.

Mountain forests are also known to hold important biodiversity values, since they provide habitats for many animals and plant species of high community interest. Stand-level indicators related with the capacity of forests to sustain biodiversity are varied (Gao et al. 2015) and include the following: (*i*) the diversity of species of both the tree and the understory strata, which can be calculated using Shannon's index with basal area or plant cover as a measure of species relative abundances, respectively (Neumann and Starlinger 2001); (*ii*) the tree size diversity (i.e., structural diversity) (Staudhammer and LeMay 2001); (*iii*) the presence of large standing and lying deadwood (m^3/ha) and its decay class (fresh vs decay) (Lassauce et al. 2011); (*iv*) the abundance of large living trees ($\text{trees}\cdot\text{ha}^{-1}$) (Vuidot et al. 2011); and (*v*) the presence and number of microhabitats in the trees such as cavities, bark pockets, cracks, sap runs, or trunk rots (Bütler et al. 2013). The first three types of indicators are included in the presented approach to assess CSF, but indicators for the last two groups might be added. In the last decade, some efforts have been made to compile biodiversity indicators into a single index (Geburek et al. 2010; Gonin et al. 2017) with the aim of providing forest managers with a simple tool of both: to evaluate the potential of a given forest stand to support diverse species and to identify the factors that can be improved through the implementation of forest management and planning strategies. Since sustaining biodiversity helps to maintain robust ecosystems, CSF calls for a detailed inclusion of biodiversity indicators.

As an integral part of the biological diversity, genetic variation safeguards adaptability of forest species and their populations to environmental changes and impacts by pests, diseases, and by climate change (El-Lakany et al. 2001). Accordingly, high adaptability based on biological variation definitely starts at the genetic level. Assessing and monitoring genetic resources in forests should be one of the main prerequisites for CSF. The impacts of silvicultural methods and the management practices on the genetic resources have only recently received increasing interest. DNA markers allow the initiation of different genetic surveys with the aim to estimate the quality of forest genetic resources. However, there is still low practical experience of these activities and have rarely been applied on a larger scale. Multiple genetic parameters like diversity indices of population (heterozygosity, allele frequencies, inbreeding coefficients) will enable to early detect potentially harmful changes of forest adaptability, before these appear at higher biodiversity levels, e.g., species or ecosystem (Fussi et al. 2016). To explore the evolutionary adaptability of populations in a specific environment and to get insights into the selection drivers, breeding programs or directed selections for climate-smart forests are needed. In the LIFEGENMON (http://www.lifegenmon.si/) project ending in 2020, a research group proposed to define respective optimal indicators and verifiers and to edit guidelines for a forest genetic monitoring system for selected tree species in different European countries and regions. This can serve as an early warning system to aid the assessment of a species response to environmental change at a long-term temporal scale and also be used for CSF assessment.

Providing space for recreation and human well-being is nowadays an important forest ecosystem service in mountain and other forests but especially in the urban and near urban forest areas (Pröbstl et al. 2009). Due to climate change and increased people's awareness about the importance of outdoor activity, the increased demands for especially warm-weather recreation activities (i.e., hiking, backpacking, picnicking, camping) may appear (Hand and Lawson 2018), triggering higher pressure on (mountain) forests in the future. Thus, regulating recreation is an important issue of forest management planning (Wilkes-Allemann et al. 2015), to address the trade-offs between recreation demand, timber production (Ahtikoski et al. 2011), and the provision of habitats for endangered plant and animal species (Rösner et al. 2014). Accessibility to (mountain) forests was recognized as a relevant indicator of recreational forest ecosystem service when evaluating CSF (see Table 3.1). Köchli and Brang (2005) used accessibility together with patch diversity, stand structure, and developmental stage of a stand to develop a recreation index. In addition, Edwards et al. (2012) evaluated recreation through visual attractiveness of forest stands by assessing 12 indicators of forest stand structure, such as tree sizes, spacing, visual penetration through the stand, deadwood, etc. Several indicators exposed in Köchli and Brang (2005) and Edwards et al. (2012) or their proxies are already on the current list of indicators to assess CSF, while others could possibly be added. Even if many indicators can be included into CSF assessment, one has to take the proportionality of data collection effort and the added informational value into account.

3.5.2 *Strengthening CSF Assessment at Stand Level*

Beyond the selection of proper and relevant indicators, they as well as the composite indicators need to be validated and readjusted to improve CSF assessment. This validation should be done at the different steps, from selection, normalization, and weighting to the aggregation (Singh et al. 2012). The developed framework for assessing CSF considers from the beginning the need for continuous updating by defining the framework as an adaptive learning process (Fig. 3.1). This chapter shows the first attempt to fulfill the different phases of the developed framework, but further efforts are needed until a satisfactory CSF assessment is reached. Linking the development of indicators framework to data collection efforts allowed us to have the first evaluation and propose improvements for future attempts.

Defining the right thresholds and transforming functions is a complex task, which needs further testing and readjustments. In Sect. 3.3.1.3, the regional thresholds for the different indicators and sub-indicators were set up from expert knowledge and literature. The use of target normalization based on such reference values has been recommended against other normalization methods when the indicator assessment is context dependent (Pollesch and Dale 2016), as occurs with CSF assessment. Hence, the specific thresholds used for single indicators need a regional reference. The first test of CSF assessment presented in this chapter made this obvious. For instance, the high reference value used for carbon stocks (C_1.4.1) derived from Bavarian sites resulted in low values of smartness for this indicator despite the rather high growing stocks in many plots. Complex uneven-aged mountain forests managed by a selection or irregular shelterwood system are characterized by very stable but medium values of aboveground productivity over time, and thus of carbon stock. However, they might have very positive long-term effect on soil organic carbon storage (Seidl et al. 2008), that was not investigated in this study. Similarly, some of the simple transforming functions could be revised. For growing stock (G_1.2), one possible improvement could be to change the slope of the transforming function in the right branch (Fig. 3.2c), which then results in a lower decrease in smartness when the difference to the reference value is caused by higher values compared to lower values.

In case of trade-offs between indicators, weighting is increasingly important. The varying but specific social and manager's demands concerning expected ecosystem services can thus better be considered. For example, if we consider the observed oppositional trade-off between the indicators' "naturalness" (Nat_4.3), which here is strongly related to regeneration and "growing stock" (G_1.2), the increase of one entails a reduction of the other. Depending on their focus, the managers need to decide on weighting. With a defined weighting of related indicators, a target-oriented forest management can then be planned and implemented more precisely.

Our evaluation regarding the weighting methods, which tested three different weighting options, did not provide a clear basis for decision to select one (Fig. 3.9). However, weighting by the centrality for CSF may be recommended. Forest management in mountain areas has to consider the large body of ecosystem services (Blattert et al. 2017). Weighting by centrality allows addressing the importance of different ecosystem services and reducing the possible inherent bias of selected indicators. Nevertheless, it is important to remark that the kind of normalization used introduces implicit weighting of indicators (Booysen 2002), by including thresholds and transforming functions which consider smartness. This can be observed in Figure 3.10, where the stability indicator (Stb_2.5) showed low values, although they represent different species composition and management, which might result in lower values of the composite indicator.

In future steps, other methods for weighting and aggregating should be tested to guarantee the robustness of the composite indicators. Thus, non-compensatory aggregations could be compared to the used compensatory ones. Multi-criteria decision analysis (MCDA) can be used to deal with possible trade-offs among indicators or overrepresenting indicators (e.g., several indicators for a given criteria) (Wolfslehner and Vacik 2011). Finally, sensitivity analyses can be used to determine the indicators influence on the composite indicator value, giving a better understanding of the whole process (Greco et al. 2019).

3.5.3 Use of Indicators of Climate Smartness for Development of Silvicultural Prescriptions

In the past, the development of silvicultural prescriptions and guidelines focused mainly on wood production; in the last few decades, additional aspects such as carbon sequestration, biodiversity, or recreation were integrated (Hilmers et al. 2020). Indicators and criteria of climate smartness may become essential additional aspects of silvicultural prescription in regions with increasing risk of drought, snow breakage, or storm (Churchill et al. 2013). No matter whether silvicultural prescriptions are derived and formulated normatively and qualitatively or based on scenario analyses, both approaches should consider the mitigation and adaptation aspects of the derived and prescribed silvicultural guidelines for a given region and forest type (D'Amato et al. 2011).

Quantitatively based indicators and criteria of climate smartness have the advantage that they may be implemented in forest stand simulators in addition to other criteria of an extended concept of sustainability (Kneeshaw et al. 2000). Consideration of climate smartness aspects becomes of increasing importance, as in the last decades forest science and forestry were faced with environmental impacts on forest ecosystems such as acid rain, increasing atmospheric ozone concentration, and eutrophic deposition as well as climate change. There was hardly any previous experience from experiments or monitoring how forestry may mitigate or adapt to such environmental changes (see Chap. 10 of this book; Tognetti et al. 2021). Field experiments are costly and very long-lasting; they are important but not sufficient to quickly provide forest management with recommendations for decision-making under environmental stress. Under such conditions, simulation models and model scenarios are often the only alternative for getting decision support. And stand or tree simulators, equipped with indicators and criteria of climate smartness, may be just the appropriate tool for developing new well through-thought silvicultural guidelines by scenario analyses (see also Chap. 8 of this book; Pach et al. 2021). The resulting quantitative silvicultural prescriptions may subsequently promote the transition from the analysis to the design of complex mixed-species stands and their increased implementation and successful regulation.

3.5.4 Prospects for Adapting the Set of Indicators for Climate Smart Forest Planning

There are many challenges for forest planning to address climate smartness. Issues related to how to manage and limit uncertainties and risks in forest management are probably the main ones. Traditional forest planning based on stable conditions is certainly not appropriate any more. The concept of adaptive, climate smart forest management also involving new silviculture strategies seems to be a more promising alternative.

Forest planning is an important tool for CSF operationalization as a merged part of SFM (Nabuurs et al. 2017). As previously mentioned, the European set of C&I of SFM is predominantly aimed at forest policy at national spatial level. But similar to stand level, they can be used in planning processes as soon they are operationalized. Nonetheless, additional indicators at the FMU need to be considered for CSF. The important indicators for climate smart forest planning as defined in our study are related to describing (1) forest management, (2) forest stand reaction to implemented forest management activities, (3) impact of extreme events on forest stands, and (4) capacity of forest stands (and management) for adaptation and mitigation.

The selected indicators (Table 3.4) are important in the whole planning process. By introducing the system of forest inventory based on permanent sample plots, the quality of information was strongly improved (Tomppo et al. 2010), as it enables insight into changes of forest stands. However, the role of indicators is not limited to understanding forest stand development only, since they are important for management decisions, too. CSF, similarly as SFM, should be understood as an active approach. There are many general suggestions about the adaptation of forest management to climate change and its mitigation potential, e.g., those related to the rotation length, silvicultural systems, and thinning regime (e.g., Ruiz-Peinado et al. 2013; Brang et al. 2014; Bravo et al. 2016; Sohn et al. 2016; Socha et al. 2017). However, the general suggestions should be adapted to the natural, economic, and social settings in single FMUs. As a consequence, indicators describing active forest management at the FMU level and its impact on forest stands are crucial for operational CSF.

A set of indicators can be applied in multi-criteria decision analysis (MCDA) (e.g., Duncker et al. 2012; Blattert et al. 2017) to support decision-making as well in the estimation of management effectiveness for providing CSF. This seems to be a promising approach for CSF planning. A forest management unit can be an appropriate spatial framework for applying MCDA.

In the concept of adaptive forest management, improved management activities can be understood as a "new experiment." This is why monitoring of forest stand response on various activities is crucial. For both – management activities and response of forest stands to them – indicators are needed. By integrating CSF assessment at stand and management unit, some indicators at stand level (Table 3.1) may increase their significance when being upscaled for providing information of spatial variability at forest management unit (e.g., growing stock, size distribution in even-aged structures, increment, and felling).

Long-term experimental plots can strongly support the development of adaptive forest management. This chapter shows an example of how experimental plots (Sect. 3.3.5) can be used for extracting information of the impact of different silvicultural options for climate smartness, as well as for evaluating indicator assessment. New adaptive forest management strategies to achieve CSF need to be tested scientifically, so collaborative experimental networks which cover different conditions (site, owners, management objectives, etc.) are required (Holmes et al. 2014). The application of the developed framework to broader networks of experimental plots, such as those presented in Chapter 5 of this book (Pretzsch et al. 2021), would enable to improve the framework and reach a robust system for climate smartness assessment.

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Appendices

Appendix 3.1. Overview of Growth and Yield Characteristics of the 10 Long-Term Experimental Plots Used in the Evaluation of CSF Indicators Development (Sect. 3.3.5). B, E. beech; S, N. spruce; F, s. fir

Experiment	Plot	Composition	Survey period	No. of surveys	Value	Remaining stand							Removal stand			PAIV
						N	hdom	ddom	hq	dq	BA	V	N	BA	V	
			First-last			ha^{-1}	m	cm	m	cm	m^2ha^{-1}	m^3ha^{-1}	ha^{-1} $year^{-1}$	$m^2ha^{-1}y^{-1}$	$m^3ha^{-1}y^{-1}$	$m^3ha^{-1}y^{-1}$
ZWI 111	2	B	1954–2015	10	mean	507	31.7	42.3	27.8	31.3	25.1	380.7	13	0.6	9.3	9.9
					min - max	139–1076	24.6–36.5	31–49	20.1–34.3	17.3–42.9	18.8–31.6	274.6–497.9	0–38	0–2.7	0–42.8	8.5–11.3
ZWI 111	3	S-B	1954–2015	10	mean	459	34.3	47.1	32.1	39.1	35.7	560.2	10	0.6	9.3	13.8
					min - max	214–945	27–39.6	34.5–56.6	23.3–37.6	24–49.5	31.3–40.9	390.5–715.2	0–28	0–1.9	0–33.2	11.7–15.7
ZWI 111	4	B	1954–2015	10	mean	628	32.1	41.1	27.9	28.6	29.8	464.8	14	0.3	4.3	11.4
					min - max	292–1436	24.5–38.7	29.3–50.8	18.8–35.2	14.8–39.5	26.5–35.8	275–694.3	1–50	0–0.9	0.2–10.5	9.5–13.7
ZWI 111	5	S	1954–2015	10	mean	397	37.1	49	35	41.8	44.2	715.6	8	0.7	10.7	16.9
					min - max	206–806	26.9–42.1	33.5–61.4	23.6–40.9	25–54.8	39.4–52.6	462.6–872.7	0–24	0–1.8	0–30.3	11.2–24.3

			First-last			ha^{-1}	m	cm	m	cm	m^2ha^{-1}	m^3ha^{-1}	ha^{-1} $year^{-1}$	$m^2ha^{-1}y^{-1}$	$m^3ha^{-1}y^{-1}$	$m^3ha^{-1}y^{-1}$
FRY 129	11	B-S-F	1980–2018	7	mean	513	33.3	52.3	23.7	31.4	29.8	404	7	1	14.6	10.3
					min - max	364–704	30.5–34.7	45.6–56.9	18.7–29	22.7–41.6	23.3–37.5	293.1–507.1	0–14	0–2.2	0–33.8	7.4–13.4
FRY 129	12	B-S-F	1980–2018	7	mean	511	35.3	57.2	25.2	33.6	36.7	520.2	5	0.8	12	11.2
					min - max	344–932	34.4–36.1	53.8–59.9	20.3–29.1	25.3–40.5	32.6–41.4	468.4–574.9	1–13	0.1–1.8	1.3–28.5	8.3–13.7
FRY 129	21	B-S-F	1980–2018	7	mean	755	33.6	53.3	20.6	25.8	31.9	427.6	12	0.8	11.7	10
					min - max	444–948	32.3–34.5	50.3–57.6	18–23.9	21.4–31.7	28.2–35.1	378.7–489.6	0–23	0–1.7	0–27.6	8.6–12.1
FRY 129	22	B-S-F	1980–2018	7	mean	787	37.2	64.2	24.3	31.6	45.4	651.4	7	0.4	5.8	13.2
					min - max	356–1100	35.3–39.3	57.9–71	21.8–28.3	26.6–39.2	32.5–59.9	476.5–873.1	1–13	0–2.1	0–31.3	9.9–15.6
FRY 129	31	B-S-F	1980–2018	7	mean	415	37.1	65	27.4	38.9	38.8	601.1	5	0.8	11.8	12.3
					min - max	284–688	35.9–38.1	61–68.2	24.2–30.3	32.1–45.5	33.3–42.6	507.3–661.6	0–13	0–2.1	0–33.6	10.1–14.9
FRY 129	32	B-S-F	1980–2018	7	mean	457	37.8	66.2	27.9	39.1	42.9	660.8	5	0.6	8.8	10.5
					min - max	240–740	36.6–39.3	61.8–69.9	25.2–31.8	34.8–46	35.4–48.4	543.9–749.8	0–11	0–2.1	0–33.5	8.4–12.6

Appendix 3.2. List of Indicators Assessed for Their Importance for Climate-Smart Forestry Planning

Criteria	Indicators
Forest resources	Forest area
	Growing stock
	Age structure
	Diameter distribution
	Forest carbon
Forest health and vitality	Deposition and concentration of air pollutants
	Soil condition
	Defoliation
	Forest damage
	Forest land degradation
Productive functions	Increment and felling
	Roundwood
	Non-woods goods
	Services
Forest biological diversity	Diversity of tree species
	Regeneration
	Naturalness
	Introduced tree species
	Deadwood
	Genetic resources
	Forest fragmentation
	Threatened forest species
	Protected forests
	Common forest bird species
Protective function	Protective forests – soil, water, and other ecosystem functions
Socioeconomic functions	Forest holdings
	Contribution of forest sector to GDP
	Net revenue
	Investments in forests and forestry
	Expenditure for services
	Forest sector force
	Occupational safety and health
	Wood consumption
	Trade in wood
	Wood energy
	Accessibility for recreation
	Cultural in spiritual values

(continued)

Criteria	Indicators
Other	Management system applied
	Slenderness coefficient
	Vertical structure of forest stands
	Horizontal distributions of tree crowns
	Tree species composition of natural regeneration
	Recruitment of trees above threshold (usually dbh = 8 or dbh = 10 cm)
	Amount and structure of sanitary felling according to the main agents)
	Register of harvested trees in past planning period (tree species, dimension)
	Growth of trees and stands (e.g., diameter growth…)
	Vitality status of tree species /forest stands
	Horizontal structure of forest stands (patchiness)
	Density of forest stands (basal area, number, SDI)
	Tree species composition of single forest stands
	Silvicultural works (planed and implemented)
	Damages of trees (stands) per agents (wind, snow…)
	Mortality rate of trees
	Growth intensity of forest stands (volume increment/stand volume)
	Timber quality of trees
	Register of natural disturbances in a FMU (windthrow, draughts…)

References

Ahtikoski A, Tuulentie S, Hallikainen V, Nivala V, Vatanen E, Tyrväinen L, Salminen H (2011) Potential trade-offs between nature-based tourism and forestry, a case study in Northern Finland. Forests 2:894–912

Alberdi I, Cañellas I, Hernández L et al (2013) A new method for the identification of old-growth trees in National Forest Inventories: application to *Pinus halepensis* Mill. stands in Spain. Ann For Sci 70:277–285

Azar C, Holmberg J, Lindgren K (1996) Socio-ecological indicators for sustainability. Ecol Econ 18(2):89–112

Bachmann P (2002) Forestliche Planung I/III. Professsur Forsteinrichtung und Waldwachstum ETH Zürich

Bauer HG, Bezzel E, Fiedler W (2005) Kompendium der Vögel Mitteleuropas – alles über Biologie, Gefährdung und Schutz. Aula-Verlag Wiebelsheim

Bayerische Staatsforsten (2018) Waldbauhandbuch Bayerische Staatsforsten. Richtlinie für die Waldbewirtschaftung im Hochgebirge. Version 01.00 (03/2018), Regensburg, p 141

Beer P (2003) Vegetationskundliche Untersuchungen und Entwicklung eines Verfahrens zur Bewertung ausgewählter Laubwaldflächen im Schweizer Mittelland, Geographischen Institut der Universität Zürich, Diplomarbeit, Juni 2003

Biber P, Borges JG, Moshammer R, Barreiro S, Botequim B, Brodrechtova Y, Eriksson LO (2015) How sensitive are ecosystem services in European forest landscapes to silvicultural treatment? Forests 6(5):1666–1695

Blattert C, Lemm R, Thees O, Lexer MJ, Hanewinkel M (2017) Management of ecosystem services in mountain forests: review of indicators and value functions for model based multi-criteria decision analysis. Ecol Indic 79:391–409

Bolte A, Ammer C, Löf M, Madsen P, Nabuurs GJ, Schall P, Rock J (2009) Adaptive forest management in central Europe: climate change impacts, strategies and integrative concept. Scand J For Res 24(6):473–482

Bončina A (2001) Concept of sustainable forest management evaluation in forestry planning at the forest management unit level: some experiences, problems and suggestions from Slovenian Forestry. Criteria and indicators for sustainable forest management at forest management unit level (Franc A ed.). EFI Proc 38:247–260

Bončina A, Simončič T, Rosset C (2019) Assessment of the concept of forest functions in Central European forestry. Environ Sci Pol 99:123–135

Booysen F (2002) An overview and evaluation of composite indices of development. Soc Indic Res 59(2):115–151

Bowditch E, Santopuoli G, Binder F, del Río M, La Porta N, Kluvankova T, Lesinski L, Motta R, Pach M, Panzacchi P, Pretzsch H, Temperli C, Tonon G, Smith M, Velikova V, Weatherall A, Tognetti T (2020) What is climate-smart forestry? A definition from a multinational collaborative process focused on mountain regions of Europe. Ecosyst Serv 43:101113

Brang P, Spathelf P, Larsen B, Bauhus J, Bončina A, Chauvin C, Drössler L, García-Güemes C, Heiri C, Kerr G, Lexer MJ, Mason B, Mohren F, Mühlethaler U, Nocentini S, Svoboda (2014) Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. Forestry 87(4):492–503

Bravo F, del Río M, Bravo-Oviedo A, Ruiz-Peinado R, del Peso C, Montero G (2016) Forest management strategies and carbon sequestration. In: Bravo F, Lemay V, Jandl R (eds) Managing forest ecosystems: the challenge of climate change, 2nd edn. Springer, pp 251–275

Bütler R, Angelstam P, Ekelund P, Schlaepfer R (2004) Dead wood threshold values for the three-toed woodpecker presence in boreal and sub-alpine forest. Biol Conserv 119:305–318

Bütler R, Lachat T, Larrieu L, Paillet Y (2013) Habitat trees: key elements for forest biodiversity. In: Kraus D, Krumm F (eds) Integrative approaches as an opportunity for the conservation of forest biodiversity. European Forest Institute, pp 84–91

Churchill DJ, Larson AJ, Dahlgreen MC, Franklin JF, Hessburg PF, Lutz JA (2013) Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. For Ecol Manag 291:442–457

Cordonnier T, Berger F, Elkin C, Lämas T, Martinez M (2013) ARANGE deliverable D2.2 – models and linker functions (indicators) for ecosystem services

Corona P, Chirici G, McRoberts RE (2011) Contribution of large-scale forest inventories to biodiversity assessment and monitoring. For Ecol Manag 262:2061–2069

Cullotta S, Bončina A, Carvalho-Ribeiro SM, Chauvin C, Farcy C, Kurttila M, Maetzke FG (2015) Forest planning across Europe: the spatial scale, tools, and inter-sectoral integration in land-use planning. J Environ Plan Manag 58:1384–1411

D'Amato AW, Bradford JB, Fraver S, Palik BJ (2011) Forest management for mitigation and adaptation to climate change: insights from long-term silviculture experiments. For Ecol Manag 262(5):803–816

De Groot RS, Wilson MA, Boumans RM (2002) A typology for the classification, description and valuation of ecosystem functions, goods and services. Ecol Econ 41(3):393–408

Duncker PS, Raulund-Rasmussen K, Gundersen P, Katzensteiner K, De Jong J, Ravn HP, Smith M, Eckmüllner O, Spiecker H (2012) How forest management affects ecosystem services, including timber production and economic return: synergies and trade-offs. Ecol Soc 17(4):50

Edwards DM, Jay M, Jensen FS, Lucas B, Marzano M, Montagné C, Peace A, Weiss G (2012) Public preferences for structural attributes of forests: towards a pan-European perspective. For Policy Econ 19:12–19

El-Lakany H, Winkel K, Hawtin G (2001) Forest genetic resources, conservation and management. FAO, DFSC, IPGRI. 2: In managed natural forests and protected areas (in situ) Int Plant Genetic Resources Institute. Rome, Italy

Forest Europe (2015) Background information for the updated pan-european indicators for sustainable forest management. https://foresteurope.org/wp-content/uploads/2016/10/3AG_UPI_Updated_Backgr_Info.pdf, latest access 2020-12-15

Forrester DI, Tachauer IHH, Annighoefer P, Barbeito I, Pretzsch H, Ruiz-Peinado R, Stark H, Vacchiano G, Zlatanov T, Chakraborty T, Saha S, Sileshi GW (2017) Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. For Ecol Manag 396:160–175

Freudenberg M (2003) Composite indicators of country performance: a critical assessment. OECD science, Technology and industry working papers no. 2003/16. OECD Publishing, Paris

Fussi B, Westergren M, Aravanopoulos F, Baier R, Kavaliauskas D, Finzgar D, Alizoti P, Bozic G, Avramidou E, Konnert M, Kraigher H (2016) Forest genetic monitoring: an overview of concepts and definitions. Environ Monit Assess 188:493

Gao T, Nielsen AB, Hedblom M (2015) Reviewing the strength of evidence of biodiversity indicators for forest ecosystems in Europe. Ecol Indic 57:420–434

Geburek T, Milasowszky N, Frank G, Konrad H, Schadauer K (2010) The Austrian forest biodiversity index: all in one. Ecol Indic 10(3):753–761

Gonin P, Larrieu L, Deconchat M (2017) Index of Biodiversity Potential (IBP): how to extend it to mediterranean forests? Forêt Méditerranéenne 38(3):343–350

Greco S, Ishizaka A, Tasiou M et al (2019) On the methodological framework of composite indices: a review of the issues of weighting, aggregation, and robustness. Soc Indic Res 141:61–94

Hagan JM, Whitman AA (2006) Biodiversity indicators for sustainable forestry: simplifying complexity. J For 104(4):203–210

Hahm WJ, Riebe CS, Lukens CE, Araki S (2014) Bedrock composition regulates mountain ecosystems and landscape evolution. Proc Natl Acad Sci U S A 111:3338–3343

Hand MS, Lawson M (2018) Effects of climate change on recreation in the Northern Rockies Region. In: Halofsky JE, Peterson DL, Dante-Wood SK, Hoang L, Ho JJ, Joyce LA (eds) Climate change vulnerability and adaptation in the Northern Rocky Mountains [Part 2]. Gen. Tech. Rep. RMRS-GTR-374. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, pp 398–433

Hanewinkel M, Cullmann DA, Schelhaas MJ, Nabuurs GJ, Zimmermann NE (2012) Climate change may cause severe loss in the economic value of European forest land. Nat Clim Chang 3:203–207

Heym M, Uhl E, Moshammer R, Dieler J, Stimm K, Pretzsch H (2021) Utilising forest inventory data for biodiversity assessment. Ecol Indic 121:107196

Hilmers T, Avdagic A, Bartkowicz L, Bielak K, Binder F, Boncina A, Dobor L, Forrester DI, Habi ML, Ibrahimspahic A, Jaworski A, Klopcic M, Matocic B, Nagel TA, Petras R, del Río M, Stajic B, Uhl E, Zlatanov T, Tognetti R, Pretzsch H (2019a) The productivity of mixed mountain forests comprised of *Fagus sylvatica*, *Picea abies*, and *Abies alba* across Europe. Forestry 92(5):512–522

Hilmers T, Steinacker L, Pretzsch H (2019b) Zur Abhängigkeit der Zuwachsverteilung im Plenterwald von der Art und Größe der Bäume. DVFFA, Sektion Ertragskunde Zwiesel, Tagungsband: 1–11. ISSN 1432-2609

Hilmers T, Biber P, Knoke T, Pretzsch H (2020) Assessing transformation scenarios from pure Norway spruce to mixed uneven-aged forests in mountain areas. Eur J For Res 139:567–584

Hof AR, Dymond CC, Mladenoff DJ (2017) Climate change mitigation through adaptation: the effectiveness of forest diversification by novel tree planting regimes. Ecosphere 8(11):e01981

Hofer P, Taverna R, Werner F, Kaufmann E, Thürig E (2007) CO2-Effekte der Schweizer Forst- und Holzwirtschaft. Szenarien künftiger Beiträge zum Klimaschutz. Bundesamt für Umwelt (BAFU), Bern, Forschungsbericht

Holmes TP, McNulty S, Vose JM, Prestemon JP, Harbin L (2014) A conceptual framework for adaptive forest management under climate change. In: Vose JM, Klepzig KD (eds) Climate change adaption and mitigation management options. A guide for natural resource managers in southern forest ecosystems. CRC Press/Taylor and Francis, pp 45–60

Hundeshagen JC (1826) Die Forstabschätzung auf neuen wissenschaftlichen Grundlagen. Verlag Heinrich Laupp, Tübingen

Hundeshagen JC (1828) Encyclopädie der Forstwissenschaft, 2. Aufl. Verlag Heinrich Laupp, Tübingen

Jeffreys I (2004) The use of compensatory and non-compensatory multi-criteria analysis for small-scale forestry. Small-Scale For 3:99–117

Jiang Z, Liu H, Wang H, Peng J, Meersmans J, Greem SM, Quine A, Wu X, Song Z (2020) Bedrock geochemistry influences vegetation growth by regulating the regolith water holding capacity. Nat Commun 11:2392

Kätzel R, Becker F (2014) Erhaltung und nachhaltige Nutzung forstlicher genressourcen. Eberswalder Forstliche Schriftenreihe 58

Klein D, Schulz C (2012) Die Kohlenstoffbilanz der Bayerische Forst und Holzwirtschaft / Bayerische Landesanstalt für Wald und Forstwirtschaft. – Abschlussbericht

Klopcic KM, Poljanec A, Gartner A, Boncina A (2009) Factors related to natural disturbances in mountain Norway spruce (*Picea abies*) forests in the Julian Alps. Ecoscience 16(1):48–57

Kneeshaw DD, Leduc A, Messier C, Drapeau P, Gauthier S, Par D, Carignan R, Doucet R, Bouthillier L (2000) Development of integrated ecological standards of sustainable forest management at an operational scale. For Chron 76(3):481–493

Knoke T, Ammer C, Stimm B, Mosandl R (2008) Admixing broadleaved to coniferous tree species: a review on yield, ecological stability and economics. Eur J For Res 127(2):89–101

Köchli DA, Brang P (2005) Simulating effects of forest management on selected public forest goods and services: a case study. For Ecol Manag 209:57–68

Konnert M, Müller D, Baier R, Huber G (2015) Konzept zum Erhalt und zur nachhaltigen Nutzung forstlicher Genressourcen in Bayern. Bayerische Amt für forstliche Saat und Pflanzenzucht

Lachat T, Brang P, Bolliger M, Bollmann K, Brändli U, Bütler R, Herrmann S, Schneider O, Wermelinger B (2014) Totholz im Wald - Entstehung, Bedeutung und Förderung. WSL-Merkblatt für die Praxis, Mai, Nr 52

Lassauce A, Paillet Y, Jactel H, Bouget C (2011) Deadwood as a surrogate for forest biodiversity: meta-analysis of correlations between deadwood volume and species richness of saproxylic organisms. Ecol Indic 11:1027–1039

Lindner M (2000) Developing adaptive forest management strategies to cope with climate change. Tree Physiol 20(5–6):299–307

MacDicken K (2015) FRA 2015 - terms and definitions. Forest Resources Assessment Working Paper 180

Mäkelä A, del Rio M, Hynynen J, Hawkins MJ, Reyer C, Soares P, van Oijen M, Tome M (2012) Using stand-scale forest models for estimating indicators of sustainable forest management. For Ecol Manag 285:164–178

Mayer P (2000) Hot spot: forest policy in Europe: achievements of the MCPFE and challenges ahead. Forest Policy Econ 1(2):177–185

MCPFE (1993) Resolution H1: general guidelines for the sustainable management of forests in Europe. Proceedings of 2nd Ministerial Conference on the Protection of Forests in Europe, Helsinki, Finland, p 5

Messier C, Puettmann KJ, Coates KD (eds) (2013) Managing forests as complex adaptive systems: building resilience to the challenge of global change. Routledge

Messier C, Puettmann K, Chazdon R, Andersson KP, Angers VA, Brotons L, Levin SA (2015) From management to stewardship: viewing forests as complex adaptive systems in an uncertain world. Conserv Lett 8(5):368–377

Moning C, Bussler H, Müller J (2009) Ökologische Schlüsselwerte in Bergmischwäldern als Grundlage für eine nachhaltige Forstwirtschaft. In: Wissenschaftliche Reihe, Nationalparkverwaltung Bayerischer Wald, Dezember 2009

Nabuurs G, Delacote P, Ellison D, Hetemäki L, Id ML (2017) By 2050 the mitigation effects of EU forests could nearly double through climate smart. Forests 8:484

Nagel TA, Mikac S, Dolinar M, Klopčič M, Keren S, Svoboda M, Diaci J, Bončina A, Paulic V (2017) The natural disturbance regime in forests of the Dinaric Mountains: a synthesis of evidence. For Ecol Manag 388:29–42

Neumann M, Starlinger F (2001) The significance of different indices for stand structure and diversity in forests. For Ecol Manag 145:91–106

OECD, European Commission, Joint Research Centre (2008) Handbook on constructing composite indicators: methodology and user guide. OECD Publishing

Otto HJ (2000) Standortsansprüche der wichtigsten Waldbaumarten, 8. Aufl. Auswertungs- und Informationsdienst für Ernährung, Landwirtschaft und Forsten e.V, Aschaffenburg

Pach M, Bielak K, Bončina A, Coll L, Höhn M, Kasanin-Grubin M, Lesiński J, Pretzsch H, Skrzyszewski J, Spathelf P, Tonon G, Weatherall A, Zlatanov T (2021) Climate-smart silviculture in mountain regions. In: Managing Forest Ecosystems, Vol. 40, Tognetti R, Smith M, Panzacchi P (Eds): Climate-Smart Forestry in Mountain Regions. Springer Nature, Switzerland, AG

Pennock DJ, van Kessel C (1997) Clear-cut forest harvest impacts on soil quality indicators in the mixedwood forest of Saskatchewan, Canada. Geoderma 75:13–32

Pfatrisch M (2019) Indicators to assess the climate smartness of mixed mountain forests containing Picea, Abies and Fagus. Masterthesis, Technische Universität München, DVFFA MWW-MA 2246, p 139

Pollesch NL, Dale VH (2016) Normalization in sustainability assessment: methods and implications. Ecol Econ 130:195–208

Pommerening A, Grabarnik P (2019) Individual-based methods in forest ecology and management. Springer, p 411

Pommerening A, Murphy ST (2004) A review of the history, definitions and methods of continuous cover forestry with special attention to afforestation and restocking. Forestry 77:27–44

Pretzsch H (2009) Forest dynamics, growth and yield. Springer, Berlin, p 664

Pretzsch H (2019) Transitioning monocultures to complex forest stands in Central Europe: principles and practice. Burleigh Dodds Science Publishing Limited. https://doi.org/10.19103/as.2019.0057.14

Pretzsch H, Puumalainen J (2002) Up- and downscaling: EU/ICP Level I and II. In: Puumalainen J, Kennedy P, Folving S (eds) Forest biodiversity - assessment approaches for Europe S.127: 50–61

Pretzsch H, Grote R, Reineking B, Rötzer T, Seifert S (2008) Models for forest ecosystem management: a European perspective. Ann Bot 101:1065–1087

Pretzsch H, Hilmers T, Uhl E, et al (2021) Efficacy of trans-geographic observational network design for revelation of growth pattern in mountain forests across Europe. In: Managing Forest Ecosystems, Vol. 40, Tognetti R, Smith M, Panzacchi P (Eds): Climate-Smart Forestry in Mountain Regions. Springer Nature, Switzerland, AG

Pretzsch H, del Río M, Biber P, Arcangeli C, Bielak K, Brang P, Dudzinska M, Forrester DI, Klädtke J, Kohnle U, Ledermann Th, Matthews R, Nagel J, Nagel R, Nilsson U, Ningre F, Nord-Larsen Th, Wernsdörfer H, Sycheva E (2019) Maintenance of long-term experiments for unique insights into forest growth dynamics and trends: review and perspectives. European Journal of Forest Research 138(1):165–185 https://doi.org/10.1007/s10342-018-1151-y

Priehäusser G (1958) Die Fichten-Variationen und -kombinationen des Bayerischen Waldes nach phänotypischen Merkmalen mit Bestimmungsschlüssel. In: Forstwiss Cbl, Nr. 77: 151–171

Prietzel J, Falk W, Reger B, Uhl E, Pretzsch H, Zimmermann L (2020) Half a century of Scots pine forest ecosystem monitoring reveals long-term effects of atmospheric deposition and climate change. Glob Chang Biol 26(10):5796–5815

Pröbstl U, Elands B, Wirth V (2009) Forest recreation and nature tourism in Europe: context, history and current situation. In: Bell S, Simpson M, Tyrväinen L, Sievänen T, Pröbstl U (eds) European forest recreation and tourism: a handbook. Taylor and Francis, pp 12–32

Pülzl H, Prokofieva I, Berg S, Rametsteiner E, Aggestam F, Wolfslehneret B (2012) Indicator development in sustainability impact assessment: balancing theory and practice. Eur J For Res 131:35–46

Raison RJ, Khanna PK (2011) Possible impacts of climate change on forest soil health. In: Singh B, Cowie A, Chan K (eds) Soil health and climate change. Soil biology, vol 29. Springer, Berlin/Heidelberg

Reed MS, Fraser EDG, Dougill EJ (2006) An adaptive learning process for developing and applying sustainability indicators with local communities. Ecol Econ 59(4):406–418

Riedel T, Henning P, Kroiher F, Polley H, Schmitz F, Schwitzgebel F (2017) Die Dritte Bundeswaldinventur – BWI 2012 – Inventur und Auswertungsergebnisse. Johann Heinrich von Thünen-Institut

Rösner S, Mussard-Forster E, Lorenc T, Müller J (2014) Recreation shapes a “landscape of fear” for a threatened forest bird species in Central Europe. Landsc Ecol 29(1):55–66

Rosset C, Schütz JP, Günter M, Gollut C (2014) WIS.2 – a sustainable forest management decision support system. Math Comput For Natl Res Sci 6(2):89–100

Rottmann M (1986) Wind- und Sturmschäden im Wald. J.D. Sauerländer’s Verlag

Ruiz-Peinado R, Bravo-Oviedo A, López-Senespleda E, Montero G, del Río M (2013) Do thinnings influence biomass and soil carbon stocks in Mediterranean maritime pinewoods? Eur J Forest Res 132:253–262

Santopuoli G, Temperli C, Alberdi I, Barbeito I, Bosela M, Bottero A, Klopčič M, Lesinski L, Panzacchi P, Tognetti R (2020) Pan-European sustainable forest management indicators for assessing Climate-Smart Forestry in Europe. Can J For Res 0(0):1–10. https://doi.org/10.1139/cjfr-2020-0166

Schulze CH, Waltert M, Kessler PJA, Pitopang R, Veddeler D, Mühlenberg M, Gradstein SR, Leuschner C, Steffan-Dewenter I, Tscharntke T (2004) Biodiversity indicator groups of tropical land-use systems: comparing plants, birds, and insects. Ecol Appl 14(5):1321–1333

Schütt P, Schuck HJ, Stimm B, Aas G, Baasch R, Blaschke H, Dobner M, Krug E, Maier J, Schill H, Schütt P, Schuck HJ, Stimm B (eds) (2002) Lexikon der Baum- und Straucharten. Nikol Verlagsgesellschaft mbh & Co.KG, Hamburg

Schwaiger F, Poschenrieder W, Biber P, Pretzsch H (2019) Ecosystem service trade-offs for adaptive forest management. Ecosyst Serv 39:100993

Seidl R, Rammer W, Lasch P, Badeck FW, Lexer MJ (2008) Does conversion of even-aged, secondary coniferous forests affect carbon sequestration? A simulation study under changing environmental conditions. Silva Fenn 42:369–386

Seidl R, Schelhaas M-J, Rammer W, Verkerk PJ (2014) Increasing forest disturbances in Europe and their impact on carbon storageç. Nat Clim Chang 4(9):806–810

Singh RK, Murty HR, Gupta SK, Dikshit AK (2012) An overview of sustainability assessment methodologies. Ecol Indic 15(1):281–299

Socha J, Bruchwald A, Neroj B (2017) Aktualna i potencjalna produkcyjność siedlisk leśnych Polski dla głównych gatunków lasotwórczych. Kraków

Sohn JA, Saha S, Bauhus J (2016) Potential of forest thinning to mitigate drought stress: a meta-analysis. For Ecol Manag 380:261–273

Speidel G (1972) Planung im Forstbetrieb. Verlag Paul Parey, Hamburg, Berlin, 267 pp

Spellmann H, Vor T, Bolte A, Ammer C (2015) Potenziale und Risiken eingeführter Baumarten - Baumartenportraits mit naturschutzfachlicher Bewertung. Universitätsverlag Göttingen

Spittlehouse DL, Stewart RB (2003) Adaptation to climate change in forest management. BC J Ecosyst Manage: 4/1: art1

Staudhammer CL, LeMay VM (2001) Introduction and evaluation of possible indices of stand structural diversity. Can J For Res 31:1105–1115

StMELF (2017) Anweisung - für die Erstellung der Forstlichen Gutachten zur Situation der Waldverjüngung 2018 / Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten (StMELF). Ludwigstraße 2, 80539 München – Anleitung

Stupak I, Lattimore B, Titus BD, Smith CT (2011) Criteria and indicators for sustainable forest fuel production and harvesting: a review of current standards for sustainable forest management. Biomass Bioenergy 35(8):3287–3308

Talukder B, Hipel KW, vanLoon GW (2017) Developing composite indicators for agricultural sustainability assessment: effect of normalization and aggregation techniques. Resources 6:66

Temperli C, Santopuoli G, Bottero A, et al (2021) National Forest Inventory data to evaluate Climate-Smart Forestry. In: Managing Forest Ecosystems, Vol. 40, Tognetti R, Smith M, Panzacchi P (Eds): Climate-Smart Forestry in Mountain Regions. Springer Nature, Switzerland, AG

Tognetti R, Valentini R, Belelli Marchesini L, Gianelle D, Panzacchi P, Marshall JD (2021) Continuous monitoring of tree responses to climate change for smart forestry – a cybernetic web of trees. In: Managing Forest Ecosystems, Vol. 40, Tognetti R, Smith M, Panzacchi P (Eds): Climate-Smart Forestry in Mountain Regions. Springer Nature, Switzerland, AG

Tomppo E, Gschwantner T, Lawrence M, McRoberts RE (2010) National forest inventories. Pathways for common reporting. Springer, New York

Vacik H, Wolfslehner B (2004) Entwicklung eines Indikatorenkatalogs zur Evaluierung einer nachhaltigen Waldbewirtschaftung auf betrieblicher Ebene. Schweizerische Zeitschrift fur Forstwesen 155(11):476–486

von Carlowitz HC (1713) Sylvicultura Oekonomica oder Haußwirthliche Nachricht und Naturmäßige Anweisung zur wilden Baum-Zucht. JF Braun, Leipzig

Vuidot A, Paillet Y, Archaux F, Gosselin F (2011) Influence of tree characteristics and forest management on tree microhabitats. Biol Conserv 144(1):441–450

Weatherall A, Nabuurs G-J, Velikova V, et al (2021) Defining Climate-Smart Forestry. In: Managing Forest Ecosystems, Vol. 40, Tognetti R, Smith M, Panzacchi P (Eds): Climate-Smart Forestry in Mountain Regions. Springer Nature, Switzerland, AG

Wijewardana D (2008) Criteria and indicators for sustainable forest management: the road travelled and the way ahead. Ecol Indic 8(2):115–122

Wilkes-Allemann J, Pütz M, Hirschi C (2015) Governance of forest recreation in urban areas: analysing the role of stakeholders and institutions using the institutional analysis and development framework. Environ Policy Gov 25(2):139–156

Winter S, Möller GC (2008) Microhabitats in lowland beech forests as monitoring tool for nature conservation. For Ecol Manag 255:1251–1261

Wolfslehner B, Vacik H (2011) Mapping indicator models: from intuitive problem structuring to quantified decision-making in sustainable forest management. Ecol Indic 11(2):274–283

Yaffee SL (1999) Three faces of ecosystem management. Conserv Biol 13:713–725

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