Chapter 4
National Forest Inventory Data to Evaluate Climate-Smart Forestry

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Abstract National Forest Inventory (NFI) data are the main source of information on forest resources at country and subcountry levels. This chapter explores the strengths and limitations of NFI-derived indicators to assess forest development with respect to adaptation to and mitigation of climate change, that is, the criteria of Climate-Smart Forestry (CSF). We reflect on harmonizing NFI-based indicators across Europe, use literature to scrutinize available indicators to evaluate CSF, and apply them in 1) Switzerland, where CSF is evaluated for NFI records and simulation model projections with four management scenarios; 2) 43 selected European

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countries, for which the indicators for Sustainable Forest Management (SFM) are used. The indicators were aggregated to composite indices for adaptation and mitigation and to an overall CSF rating. The Swiss NFI records showed increased CSF ratings in mountainous regions, where growing stocks increased. Simulations under business-as-usual management led to a positive CSF rating, whereas scenarios of increased harvesting decreased either only adaptation or both mitigation and adaptation. European-level results showed increases in CSF ratings for most countries. Negative adaptation ratings were mostly due to forest damages. We discuss the limitations of the indicator approach, consider the broader context of international greenhouse gas reporting, and conclude with policy recommendations.

4.1 Introduction

Climate-Smart Forestry (CSF) has been suggested as forest management concept with the goal to combine 1) the adaptation of forests to climate change, 2) the mitigation of climate change through the sequestration of atmospheric carbon by trees, and 3) the maintenance of forest ecosystem service provision (Bowditch et al. 2020). Previous applications of the CSF concept mainly focused on mitigation potentials at the national to European scale using available literature (Nabuurs et al. 2017) or simulations of forest development under various management scenarios (Nabuurs et al. 2018; Jandl et al. 2018; Yousefpour et al. 2018). A stand-scale application of the CSF concept has been developed by participants of the COST Action CLIMO (see Chap. 3 of this book: del Río et al. 2021) using a comprehensive set of indicators to evaluate both the adaptation and mitigation potential of mixed spruce, fir, and beech forests in Europe (Pfatrisch 2019). However, a comprehensive

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assessment method that simultaneously accounts for the three CSF aspects of adaptation, mitigation, and sustainable provision of ecosystem goods and services (ES) at a national to European scale is still lacking.

Assessments of CSF at this national to continental scale is important for forest policy making (Verkerk et al. 2020). Forests play an important role in fulfilling the reduction goals of greenhouse gas emissions as per the Paris agreement (Seddon et al. 2019). Thus, national governments are encouraged to device forest policy recommendations to mitigate climate change (FAO 2018). This can be achieved with management that favors tree and forest growth such that more CO_2 is sequestered from the atmosphere than released from the forest through respiration, decay of deadwood, and the decay and burning of harvested wood products (Köhl et al. 2020). This may encompass the prolongation of cutting cycles to sequester carbon in the living biomass. This, in turn, may be in conflict with policies that aim at raising the capacity of forests to adapt to climate change by reducing rotation lengths and cutting cycles. Shorter management intervals may be applied as part of conversion strategies to promote more drought- and disturbance-resistant tree species and a higher species diversity in currently species-poor forests. However, forest management to increase forest growth through stand density reduction (thinning) may also be in concert with the goal of carbon sequestration (Lindner et al. 2010; Diaconu et al. 2017; Jandl et al. 2019). Reducing timber harvesting may conflict with policies to sequester carbon in wood products and to substitute fossil fuel–intensive energy and building material (Sathre and O'Connor 2010). Management for adaptation may conflict with nature conservation goals, such as the retention of old-growth forest structures. Mitigation through carbon assimilation in standing tree biomass may collide with the need for ensuring advanced regeneration and stability in forests that protect against rockfall and avalanches in mountain areas (Brang et al. 2006). Hence, adaptation, mitigation, and the provision of ES need to be balanced in climate-smart management recommendations, also at a regional to national scale.

NFIs provide reliable and robust data and indicators on a regular basis that are representative at the national scale and cover time periods of several decades in many countries (Alberdi et al. 2016b). Thus, they allow the identification of forest development trajectories that resulted from climate-smart (active or passive) forest policy making. Most NFIs record information at the plot level, such as silvicultural treatments, and others at the tree level, such as tree species, stem diameter, tree height, or health status (Tomppo et al. 2010). By identifying the drivers of past forest development and CSF indicators, we may be able to derive climate-smart policy recommendations that simultaneously promote adaptation, mitigation, and ES provision.

The Pan-European criteria and indicators for Sustainable Forest Management (SFM) were established as a basic tool for defining, promoting, and monitoring SFM across Europe, with the last updated set being endorsed by the seventh Ministerial Conference in Madrid in 2015 (Forest Europe 2015a). These 34 quantitative and 11 qualitative indicators are organized in 6 criteria, are broadly accepted, and are publicly available at the national level through the reports on the State of

Europe's Forest (SoEF, Forest Europe 2015b, https://foresteurope.org/state-europes-forests-2015-report/, Accessed 8 December 2020). They cover a broad range of aspects on the state of forests (e.g., growing stock, age class distribution, and forest type) and their functions in terms of timber and the production of nonwood goods, biodiversity conservation, protection of ecosystem functions, and socioeconomy. The broad thematic coverage of the SFM indicators may allow their application as national-scale proxies for the contribution of forests to climate change mitigation and their capacity to adapt to climate change.

The goal of this chapter is to explore the possibilities and potential limitations of NFI-based indicators to quantify the mitigation and the adaptive capacity of European forests. To this end, we use the available literature to scrutinize NFI-based indicators, including the ones of Forest Europe for SFM, for their suitability as proxies for mitigation and adaptive capacity (Sect. 4.2 of this chapter). We highlight the advances in the harmonization of the indicators based on the NFIs from different countries, with different recording methods, and the necessary considerations with respect to comparing indicator development across countries (Sect. 4.3). To test this approach, we evaluate forest development with respect to mitigation and adaptive capacity in two cases: 1) for the five biogeographic NFI production regions of Switzerland and 2) for selected European countries. In Sect. 4.4, we describe the calculation of indicators and how estimates for adaptive capacity and mitigation were derived. Sections 4.5 and 4.6 contain the results for Switzerland and the selected European countries, respectively. We critically evaluate the approach and identify areas for improvement in Sect. 4.7 and, thus, interpret the results with respect to the broader context of international greenhouse gas reporting and global climate dynamics (Sect. 4.8). We conclude with management and policy recommendations in Sect. 4.9.

4.2 Indicators to Quantify Adaptation and Mitigation, a Review

Adaptation and mitigation are considered the most important management measures to counteract climate change and its negative impacts on forests (Spittlehouse 2005; Nabuurs et al. 2018) and society. Despite the increased awareness among forest decision makers and managers to promote adaptation and mitigation strategies, there are still large uncertainties on how to evaluate the effects of their implementation. Differences in socialeconomic and environmental conditions, challenges in data collection, and the analysis of climate change impacts in general are mentioned by many authors as the main causes of these uncertainties (Seidl and Lexer 2013; Forsius et al. 2016; Viccaro et al. 2019). Participatory approaches involving diverse expert and stakeholder groups were often suggested as a viable tool to overcome the uncertainties in measuring the effects of management to adapt forest ecosystems to climate change (Nelson et al. 2016). It is a very common approach to select and rank SFM alternatives (Santopuoli et al. 2012; Paletto et al. 2014;

Pastorella et al. 2016b) through the collection and evaluation of stakeholder opinions. Nevertheless, evaluations based on participatory approaches could be subjective, depending on the stakeholder experiences and priorities.

For this reason, the development of an objective method to use SFM indicators for assessing adaptation, mitigation, and CSF is strongly required. Criteria and indicators (C&I) for SFM represent the most important tools to assess the sustainability of forest management at the pan-European scale (Santopuoli et al. 2016; Baycheva-Merger and Wolfslehner 2016). However, it is crucial to select a subset of indicators from the whole C&I set that is a suitable measure for adaptation to and mitigation of climate change. Here, we conducted a literature review to highlight those indicators from the pan-European C&I set that have been frequently considered suitable to assess adaptation and mitigation management measures in forest ecosystems.

The search was conducted in February 2020 using the Scopus® database (https://scopus.com) through two queries, one for adaptation and one for mitigation using the following Boolean search terms:

- (TITLE-ABS-KEY (climate AND adaptation) AND TITLE-ABS-KEY (sustainable AND forest AND management) AND TITLE-ABS-KEY (indicator))
- (TITLE-ABS-KEY (climate AND mitigation) AND TITLE-ABS-KEY (sustainable AND forest AND management) AND TITLE-ABS-KEY (indicator))

We did not use constraints about the year of publication, but we excluded non-English as well as not relevant articles, that is, publications not strictly focused on the use of SFM indicators. For this reason, all papers were accurately screened, duplicates removed, and SFM indicators used to assess adaptation and mitigation, respectively, were identified and recorded.

A total of 50 papers were extracted from the Scopus® database, 20 for adaptation, and 30 for mitigation. During the screening phase, we discarded 32 papers that were considered not relevant. We counted the occurrence of SFM indicators in the remaining 18 articles, 6 for adaptation, and 12 for mitigation, respectively. All papers, but one in 1997, were published in the period 2011–2017.

Scrutinizing the 18 articles revealed that 22 out of 34 indicators were suitable to assess adaptation and mitigation (Fig. 4.1). In particular, 13 out of 22 were useful to assess both adaptation and mitigation, while 4 indicators were mentioned only for adaptation (i.e., 4.2, 6.3, 6.4, 6.11) and 5 only for mitigation (i.e., 1.1, 3.3, 4.3, 6.5, 6.9).

Overall, authors highlighted 17 indicators as suitable to assess adaptation, among which *tree species composition*, *roundwood*, *forest damage,* and *deadwood* were the most frequent. In particular, authors stressed that biodiversity conservation strongly supports adaptive management strategies (Klenk et al. 2015). According to many authors, all the 17 indicators could provide support for forest decision and policy makers (Hlásny et al. 2014). These indicators may raise awareness among forest managers and practitioners about climate change impacts and promote the implementation of adaptive management at local level (Seidl and Lexer 2013). Moreover, they provide support to researchers for developing new and more appropriate scenarios for the sustained provision of ecosystem services (Klenk et al. 2015; Hlásny et al. 2017).

Energy from wood resources and *carbon stock* were the most frequent among the 18 indicators mentioned to assess the mitigation of forest management measures. Particular attention is given to the forest carbon stock, highlighting that forest management can increase the carbon storage in forests (Colombo et al. 2012). In addition, forest management plays a crucial role in producing high-quality timber products, allowing to store carbon for years to decades, while promoting ecological sustainability through the production of wood energy (Paletto et al. 2017; Buonocore et al. 2019).

In conclusion, the literature review highlighted that *carbon stock* is in absolute terms the most mentioned SFM indicator, followed by *tree species composition* and *roundwood quantity*. Slightly less mentioned were *forest damage*, *growing stock,* and *deadwood*, while *energy from wood* was only mentioned for mitigation issues.

4.3 National Forest Inventories: Harmonization of Mitigation and Adaptation Indicators

NFIs are one of the main data sources for national-, continental-, and global-scale assessments of forest resources and their sustainability (McRoberts et al. 2012). Due to increasing information needs, the scope of NFIs has been broadening to include new variables (Tomppo et al. 2010; Vidal et al. 2016). However, the estimates produced by different countries frequently lack international comparability due to differences in applied definitions, sampling designs, and measurement protocols (Lawrence et al. 2010; Alberdi et al. 2016a). The European National Forest Inventory Network (ENFIN) carried out numerous research projects to develop tools for comparable results at the international level (Vidal et al. 2016). Comparability of European NFIs can be achieved by defining “reference definitions” and by establishing “bridging functions” as tools to calculate harmonized estimations from national inventories (Ståhl et al. 2012; Alberdi et al. 2016a). Thus, many indicators were subject to harmonization at the European scale, such as forest area (Vidal et al. 2008; Gabler et al. 2012), growing stock (Vidal et al. 2008; Tomter et al. 2012; Gschwantner et al. 2019), and others, like stem quality and increment, that were investigated to identify harmonization opportunities (Bosela et al. 2016).

From the ten most frequent indicators for adaptation and mitigation in Fig. 4.1, five are typically provided by the NFIs: carbon stock, tree species composition, forest damage, growing stock, and deadwood volume. A Europe-wide, harmonized database of tree species distribution was elaborated using NFI data (~375,000 sample plots) and additional information to create “The European Atlas of Tree Species: modelling, data and information on tree species” (de Rigo et al. 2016). However, it is important to mention that the effect of monitored area and plot design on the probability of discovery needs further research.

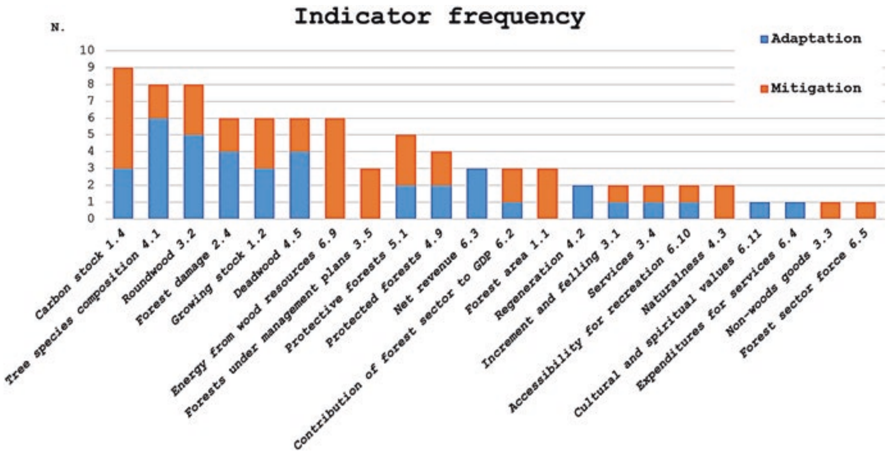

Fig. 4.1 Indicator frequency for adaptation (17 blue bars) and mitigation (18 orange bars) according to the overall frequency

Growing stock is one of the most analyzed variables for harmonization. Vidal et al. (2008) published a reference definition, establishing its components and thresholds. Differences in field measurements at the sample tree-level (e.g., minimum diameter at breast height) and tree compartments included in volume models (stump, stem top, or branches) cause the main differences. Tomter et al. (2012) presented case studies for six European countries and more recently, Gschwantner et al. (2019) published harmonized growing stock estimates at the European scale.

Deadwood volume is another key variable in terms of harmonization. Woodall et al. (2009), Chirici et al. (2011), and Rondeux et al. (2012) established a reference definition and performed case studies. However, further analysis on the performance of bridging functions and estimation methods is desirable.

The total carbon stock is composed of carbon in a) all living above-ground biomass, including stem, stump, branches, bark, seeds, and foliage; b) all biomass of living roots; c) all nonliving woody biomass not contained in the litter, either standing, lying on the ground, or in the soil; d) all nonliving biomass with a diameter less than the minimum diameter for deadwood; and e) organic carbon in mineral and organic soils. From these components, only the carbon of living above-ground biomass can be considered as harmonized (Avitabile and Camia 2018). To complement the picture on the potential of forests to sequester carbon, the assessment of wood quality and assortment structure is essential (Bosela et al. 2016). This allows to prioritize between climate policies for in situ carbon storage, for biomass harvests to generate energy and for harvesting quality construction timber (Obersteiner et al. 2010; Böttcher et al. 2012). Harmonization of the assessment of wood quality and timber assortments among NFIs of European countries is necessary for NFI data to be used for such prioritization at the European scale.

Finally, the indicator of forest areas with damages has not yet been harmonized across NFIs. Kovac et al. (2020) recognize it as a key indicator for the assessment of the conservation status. However, there are open questions, such as the severity of damages considered or the required proportion of damaged trees, to classify a plot as undamaged or damaged.

4.4 Methods To Assess Forest Development Using NFI-Data and CSF Indicators

4.4.1 Case Study 1: Switzerland

The goal of the analysis described here was the calculation of aggregated indices for the mitigation and the adaptive capacity of the five Swiss NFI production regions (Fig. 4.2). Forests in Switzerland are dominated by beech (*Fagus sylvatica* L.) at low elevations (<600 m a.s.l.), with the proportion of fir (*Abies alba* Mill.) and spruce (*Picea abies* L.) increasing toward the tree line, where stone pine (*Pinus cembra* L.), larch (*Larix decidua* Mill.), Scots pine (*Pinus sylvestris* L.), and mountain pine (*Pinus mugo* Turra.) dominate (Cioldi et al. 2010). Past management favored conifers predominantly in the Jura, the Plateau, and in the Prealps, but more recent changes in management have reduced the area covered by pure conifer forests by 8% since 1985 (Brändli and Röösli 2015).

Aggregated indices for adaptive capacity and mitigation were used to evaluate forest management or policies in regions, at the country level and under specific

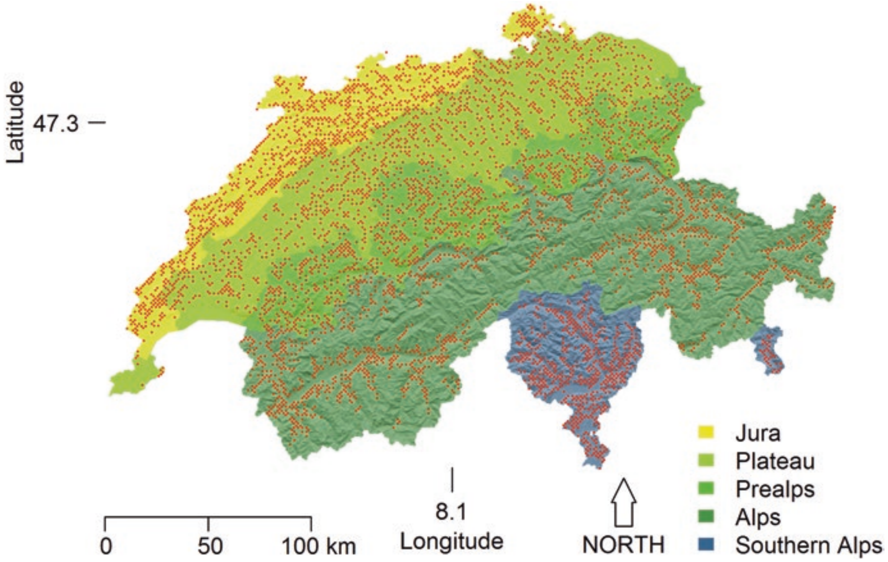

Fig. 4.2 Location of NFI sample plots (red dots) in Switzerland. The color shading shows the borders of the five NFI production regions of Switzerland

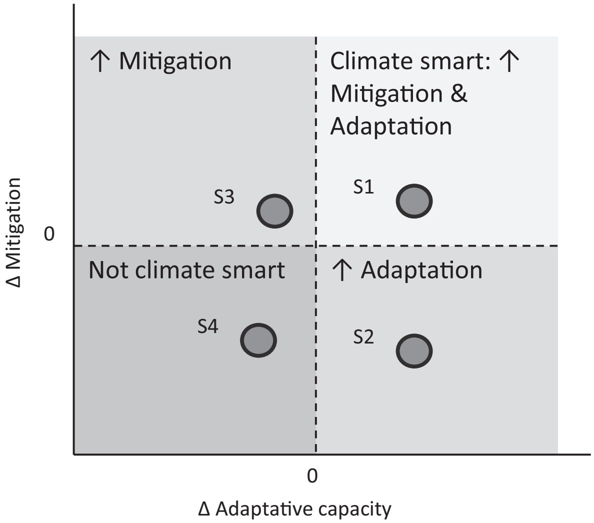

Fig. 4.3 Conceptual diagram showing how forest development or forestry that leads to positive changes (Δ) in adaptive capacity (adaptation) and mitigation is considered climate smart (i.e., scenario S1)

scenarios (S1–S4; Fig. 4.3). Positive changes in adaptive capacity and mitigation were considered as climate smart (S1). Adaptive capacity at the cost of mitigation (S2) vice versa (S3) and negative changes in both adaptive capacity and mitigation (S4) were not considered as climate smart. The following steps were necessary to arrive at the aggregate indicators for adaptive capacity (adaptation) and mitigation:

1. Selection of indicators: We used a set of indicators that was available from the Swiss NFI to quantify the provision of a range of ecosystem services (Blattert et al. 2017; Temperli et al. 2020) and that corresponded well to a subset of the Forest Europe SFM indicators (Table 4.1).
2. Indicator calculation and aggregation: Growing stock, density of large trees, diversity of tree diameters at breast height (DBH), tree species diversity, and deadwood volume were calculated at the level of sample plots and then averaged to the 5 NFI production regions. Sustainability was assessed as the difference between harvested wood and increment at the level of production regions. Avalanche and rockfall protection (API and RPI, respectively) were assessed with indicators combining stand- and site-related factors to estimate a ratio of the current stand parameters and those needed for optimal protection (Berger and Dorren 2007; Cordonnier et al. 2013). The proportions of sample plots with API and RPI >0.95 were used as estimates for avalanche and rockfall protection at the regional and national levels. The indicators were categorized to represent the provision of ecosystem services: the maintenance of resources, the production of timber, the provision of biodiversity, and the provision of protection against rockfall and avalanches. See Table 4.1 for the categorization and note that the indicators only partially correspond to the Forest Europe C&I for SFM.

Calculation of change in mitigation and adaptive capacity: The regional-/national-level indicator values were scaled between the minimum and maximum values

Table 4.1 Correspondence between indicators available from the Swiss NFI and the Forest Europe SFM indicators, together with the proposed categorization for ecosystem service representation and the weights representing their suitability as proxies for adaptation and mitigation

Available indicator from Swiss NFI	Indicator description	Corresponding SFM Indicator	Ecosystem service	Adaptation (weight)	Mitigation (weight)
Growing stock	Volume (m^3 ha^{-1}) of stem wood >12 cm DBH within bark (incl. stump and top)	1.2 growing stock	Resources	0	1
Density of large trees	Number of trees per ha >80 cm DBH	1.3 age structure and/or diameter distribution	Biodiversity	1	0
DBH diversity	Shannon diversity of basal area in 4 cm DBH classes (note: highly correlated with growing stock at regional scale)	1.3 age structure and/or diameter distribution	Biodiversity	1	0
Sustainability	Difference between harvested wood and increment (m^3 ha^{-1} $yr.^{-1}$)	3.1 increment and felling	Production	1	0
Tree species diversity	Shannon diversity based on basal area share of species	4.1 diversity of tree species	Biodiversity	1	0
Deadwood	Volume (m^3 ha^{-1}) of standing and lying deadwood (fine and coarse)	4.5 deadwood	Biodiversity	0.5	0.5
Avalanche protection	Proportion of sample plots within the SilvaProtect avalanche protection perimeter with avalanche protection index >0.95	5.1 protective forests – soil, water, and other ecosystem functions – infrastructure and managed natural resources	Protection	0.5	0.5
Rockfall protection	Proportion of sample plots within the SilvaProtect rockfall protection perimeter with rock fall protection index >0.95	5.1 protective forests – soil, water, and other ecosystem functions – infrastructure and managed natural resources	Protection	0.5	0.5

observed in different regions and time steps. Each indicator change was then calculated as the difference between the scaled regional indicator values at the beginning and at the end of the observed time period. The changes were then averaged across the indicators with weights that describe the indicators' contribution to mitigation and/or adaptation (Table 4.1). The different values of weights impact the contribution of each indicator to mitigation and adaptation as follows: with a value of 0, the indicator has no contribution to mitigation or adaptation; with a value of 1, the indicator contributes entirely to mitigation or adaptation; with a weight of 0.5, the indicator contributes equally to mitigation and adaptation. These weights were derived during several CLIMO workshops by a varied group of forestry and forest ecology experts.

We calculated changes in mitigation or adaptation *retrospectively* for the 5318 NFI sample plots that were visited during NFI2 (1993–95), NFI3 (2004–06), and NFI4 (2009–17) (Abegg et al. 2014; Traub et al. 2017) and *prospectively* using simulation results of the NFI-based scenario model MASSIMO for years 2016–2106 under 4 contrasting management scenarios (Stadelmann et al. 2019). These scenarios were developed during a previous project to assess potential timber yields in Swiss forests. They included 1) a business-as-usual (BAU) scenario that assumed a continued increase in growing stock in poorly accessible mountain forests and a decrease in growing stock in the Plateau region. 2) Under a so-called constant stock scenario, harvest is increased or decreased to maintain a constant growing stock as observed in NFI4 in all production regions. 3) The conifer scenario promoted conifers (mainly Norway spruce) in the regeneration to meet future increases in the demand for construction wood and assumed a reduction of growing stock to 300 m3 ha − 1 until 2046 and then an increase to 300–330 m3 ha − 1, depending on the region. 4) Under the energy scenario, timber production was maximized to meet the increasing demands for energy wood and wood-based chemicals. Target diameters were assumed to be of little importance under this scenario, such that growing stock was reduced until 2046 to 200–300 m^3 ha^{-1}, depending on the region, and thereafter growing stock was held constant (for details, see Stadelmann et al. 2016).

4.4.2 Case Study 2: Selected EU Countries

The proposed methodological approach to evaluate forest development with regard to Climate-Smart Forestry indicators at the European level included two main steps. 1) Assign a weight for each pan-European SFM indicator based on a literature review. 2) Display the trend over time of aggregated indicators describing how forestry may mitigate climate change and how the capacity of forests to adapt to climate change develops across European countries.

Step 1): Following the literature review, a subset of indicators was selected (see Sect. 4.2) from the current pan-European set of C&I (Table 4.1). The subset included the indicators that were mentioned at least 3 times (6 was the maximum value obtained from the literature review). The weights were assigned through a pairwise comparison as per the Analytic Hierarchy Process (AHP, Saaty 1980). The AHP is frequently used in environmental and forest sectors as a decision support tool (Kuusipalo and Kangas 1994; Ananda and Herath 2003; Wolfslehner et al. 2005; Santopuoli et al. 2016).

To implement the pairwise comparison, first, the relative priority of the indicators (RP) was assessed as follows:

$$RP = \left(\frac{Cit_{np}}{Cit_{pmax}}\right)\left(\frac{1}{Cit_1} + \frac{1}{Cit_2} + \cdots + \frac{1}{Cit_n}\right)$$

where

RP is the relative priority
Cit_{np} is the number of publications that mention the focal indicator
Cit_{pmax} is the maximum number of times that one of the 12 indicators was mentioned (i.e., 6 for *tree species composition* and 6 for *carbon stock* for adaptation and mitigation, respectively),
Cit_1 is the total number of indicators mentioned by the same author for the first time
Cit_2 is the total number of indicators mentioned by the same author for the second time
Cit_n is the total number of indicators mentioned by the same author for the n time

For example, the indicator 1.4 *carbon stock* was mentioned in three papers ($Cit_{np} = 3$) among those used for the adaptation review. The total number of indicators mentioned by the first paper was seven ($Cit_1 = 7$), while the second and third papers mentioned a total of six ($Cit_2 = 6$) and four ($Cit_3 = 4$) indicators, respectively. Considering the Cit_{pmax} of six, the RP for carbon stock was 0.280.

Subsequently, the RPs were used to create the reciprocal matrix (Saaty 1980; Kangas et al. 1993; Mendoza and Prabhu 2000) for adaptation and mitigation separately to obtain the Eigenvector for each indicator. The overall priority was calculated for each indicator, considering the ratio of the number of articles, 6 and 12 for adaptation and mitigation respectively, and the total number of the articles (18) multiplied by the Eigenvectors (i.e., overall priority = $0.33 * Eigen_{\mathbf{Adaptation}} + 0.67 * Eigen_{\mathbf{Mitigation}}$). The indicators *energy from wood resources*, *carbon stock,* and *tree species composition* yielded the highest overall priority (ranks 1–3), while *forest area*, *net revenue,* and *deadwood* the lowest (ranks 10–12), reflecting their frequency of association with adaptation and mitigation in the literature (Table 4.2).

Step 2): The calculation of the aggregate indices for adaptation and mitigation was based on the data reported in the State of Europe's Forests (SoEF) database. First of all, all available data were downloaded for each indicator for the years 1990, 2000, 2005, 2010, and 2015. Subsequently, four pairwise comparisons (i.e., 2000 vs. 1990; 2005 vs. 2000; 2010 vs. 2005; 2015 vs. 2010) were made for each indicator, assessing the relative trend (i.e., percentage of changes) at country level.

Table 4.2 Indicator weights for the subset of indicators used in the evaluation of adaptation and mitigation across Europe. The reported values represent the Eigenvectors obtained through the pairwise comparison (Saaty 1980) for adaptation ($\text{Eigen}_{\text{Adaptation}}$) and mitigation ($\text{Eigen}_{\text{Mitigation}}$) and the overall priority. The rank reflects the overall priority values

Indicator	Indicator name	$\text{Eigen}_{\text{Adaptation}}$	$\text{Eigen}_{\text{Mitigation}}$	Overall priority	Rank
1.1	Forest area	–	0.049	0.033	10
1.2	Growing stock	0.040	0.034	0.036	7
1.4	Carbon stock	0.059	0.240	0.180	2
2.4	Forest damage	0.097	–	0.032	11
3.2	Roundwood	0.202	0.025	0.084	4
3.5	Forests under management plans		0.069	0.046	6
4.1	Tree species composition	0.463	–	0.154	3
4.2	Regeneration		0.050	0.033	8
4.5	Deadwood	0.040	–	0.013	12
5.1	Protective forests		0.120	0.080	5
6.3	Net revenue	0.099	–	0.033	9
6.9	Energy from wood resources	–	0.414	0.276	1

Three out of 46 pan-European countries (Holy See, Monaco and Russian Federation) have been excluded, because no data were available for some of the indicators and years.

To arrive at a measure for adaptation capacity and mitigation, the relative changes observed for each indicator were multiplied with the overall priority value (Table 4.2) for adaptation and mitigation separately. The obtained values were then summed for each country and for each observed period and displayed in a scatter plot, within which adaptation was on the x-axes and mitigation on the y-axes. A European-level estimate was calculated as the average value for adaptation and mitigation.

4.5 Results of the Swiss Case Study

The time period between NFI2 and NFI4 was characterized by increasing growing stock throughout Switzerland, except for the Plateau region, where it decreased (Fig. 4.4). This is also reflected by the sustainability indicator that decreased the most in the Plateau, with the dip in 2006 (NFI3) being due to the storm Lothar in 1999. Deadwood and number of stems >80 cm DBH increased, whereas species diversity remained mostly unchanged. DBH diversity decreased in the Plateau and the Prealps, while it increased in the other regions. Protection against avalanches and rockfall generally increased in the Alps and the Southern Alps.

The aggregated indicators for change in adaptation and mitigation (Fig. 4.5) reflected the increasing growing stock in the Alps and the Southern Alps, where adaptation and mitigation increased in total and for most criteria. In contrast, the reduction in the production-related indicator (sustainability) in the Jura, the Plateau, and the Prealps resulted in an overall negative CSF evaluation, which was accentuated in the Plateau by the decrease in growing stock.

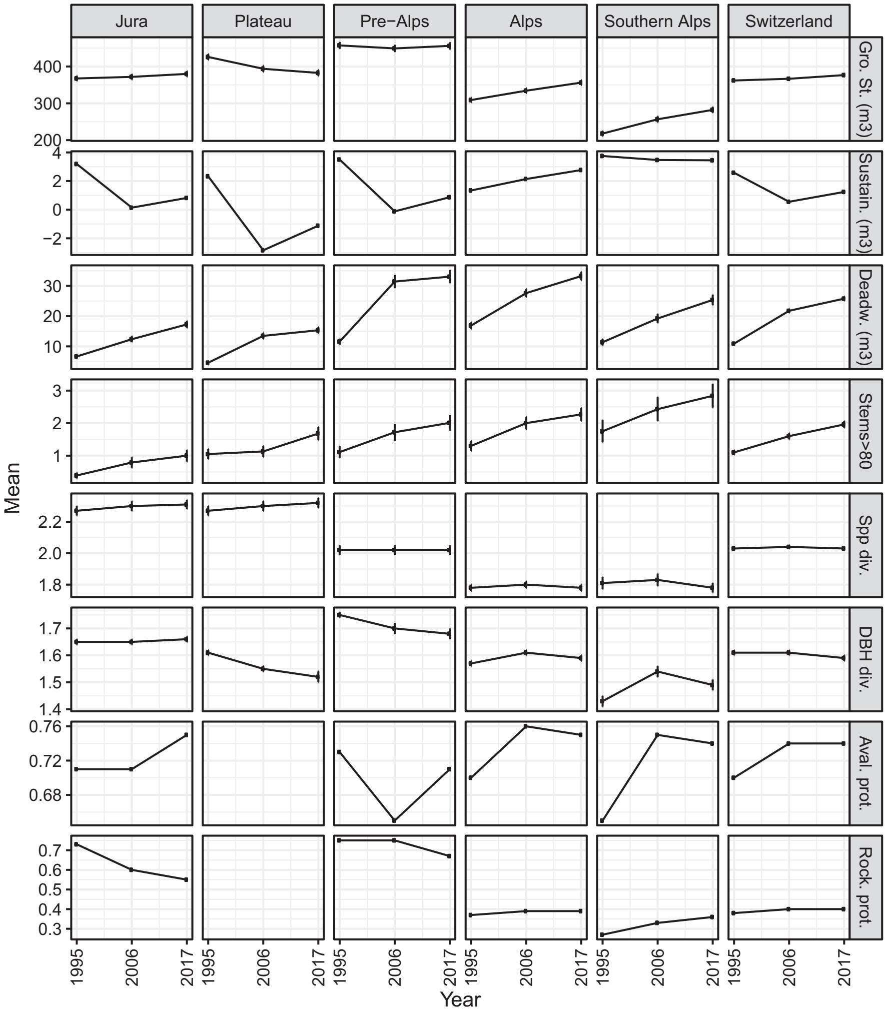

Fig. 4.4 Indicator development in the 5 NFI production regions and for the whole of Switzerland (columns) from NFI2 (1993–1995) to NFI3 (2004–2006) to NFI4 (2009–2017). Error bars show standard errors of the mean across sample plots. Note that avalanche and rockfall protection was only calculated for sample plots within the protection forest perimeter, which does not overlap with the Plateau region

The development of indicators under the four management scenarios in Switzerland reflected the scenario specifications (Fig. 4.6). Growing stock along with deadwood and the number of stems with DBH >80 cm continued to increase under the BAU scenario in most parts of Switzerland, except for the Plateau (not shown). The increased harvesting under the conifer and the energy scenarios until 2046 resulted in the sustainability indicator to drop sharply at the beginning of the simulations and to recover after 2046, when harvesting was reduced again.

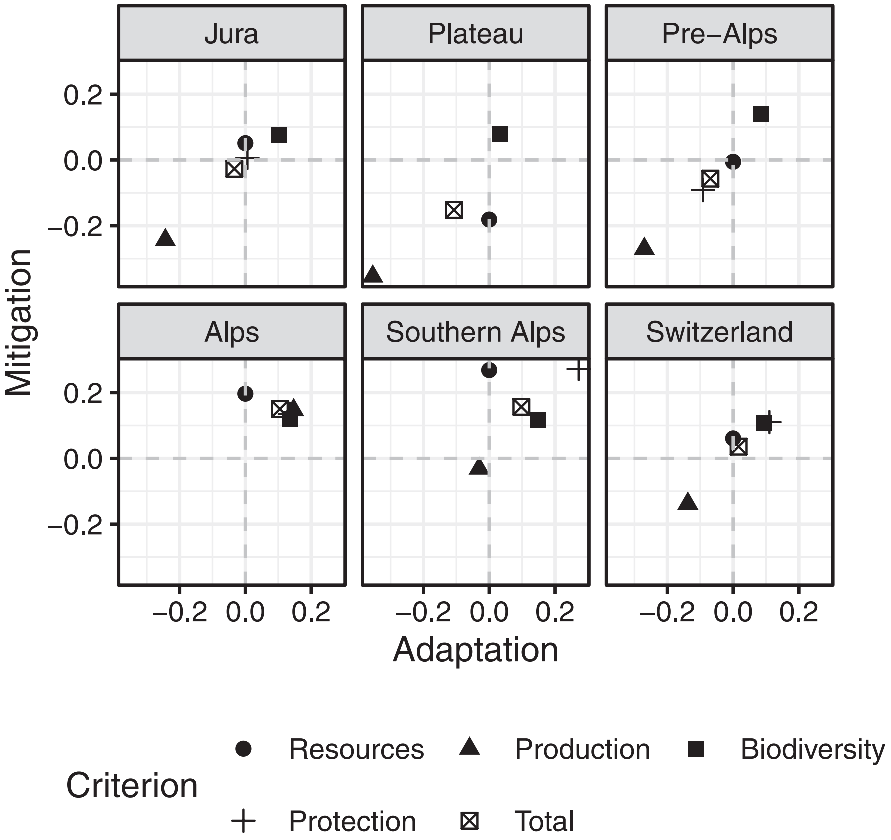

Fig. 4.5 Change in adaptation and mitigation by NFI production regions of Switzerland and the whole country, SFM criteria, and average of all indicators (Total). Note that the scale is relative to the range of regional indicator values. Positive changes in adaptation and mitigation (top-right quadrant) are considered as "climate-smart"

DBH diversity decreased under all scenarios, but predominantly under the conifer and energy scenarios, in which increased timber harvesting resulted in more homogeneous forest structures. Species diversity dropped similarly under all scenarios, probably due to a modelling artifact: the number of species in the regeneration data (<12 cm DBH) was lower than in the record of trees (>12 cm DBH) used to initialize simulations. Avalanche protection decreased and rockfall protection increased due to a simulated increase in average DBH, to which avalanche protection is negatively and rockfall protection positively related (Cordonnier et al. 2013).

BAU management was the most climate-smart option, considering the whole of Switzerland after 90 years (2106) of simulated forest development (Fig. 4.7). BAU benefited all SFM criteria and thus led to a positive change in both adaptation and mitigation. Increased harvesting under the three other scenarios reduced the

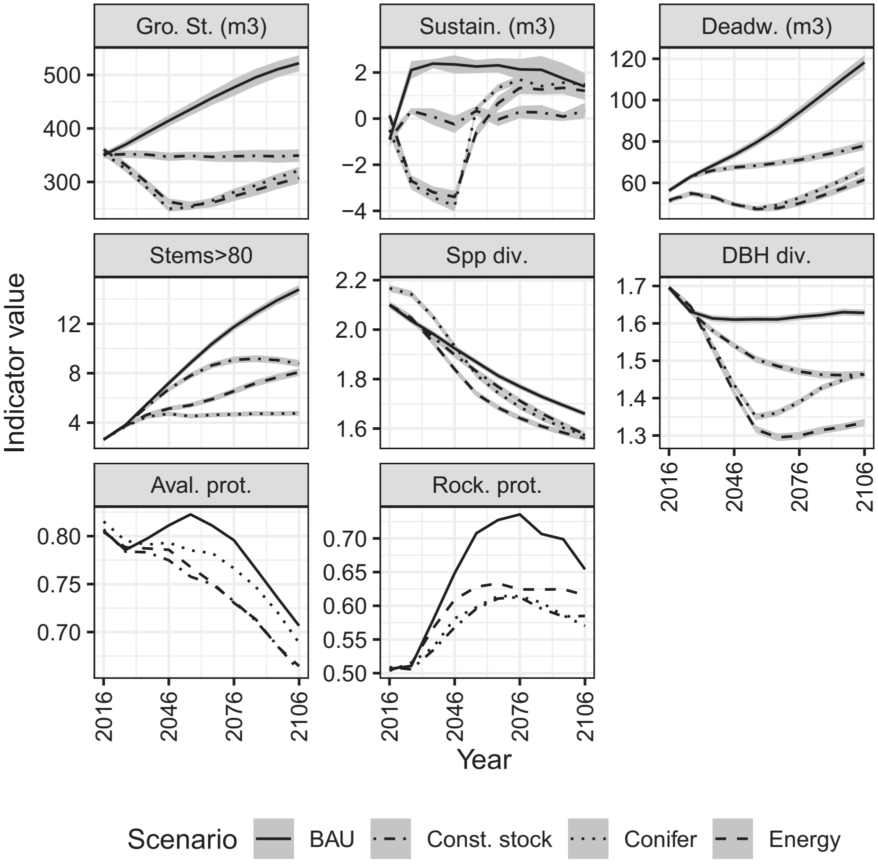

Fig. 4.6 Indicator development for Switzerland under four forest management scenarios. Shaded bands show standard errors of the mean across sample plots and 20 replications of model simulations

resources, biodiversity, and protection criteria and thus decreased only adaptation (constant stock) or both adaptation and mitigation (Conifer and Energy). The sustainability indicator recovered by 2106, such that the production criterion benefitted both adaptation and mitigation under all scenarios.

4.6 Results of the European Case Study

Overall, a positive trend was observed in the period 1990 and 2000 for mitigation (Fig. 4.8). Changes in the adaptive capacity of forests were mixed, showing a slightly positive trend with more countries on the right side of the graph than on the left side. Only few countries show a clear positive trend for both adaptation and mitigation. For example, Belarus (BY), for which an increase in the proportion of

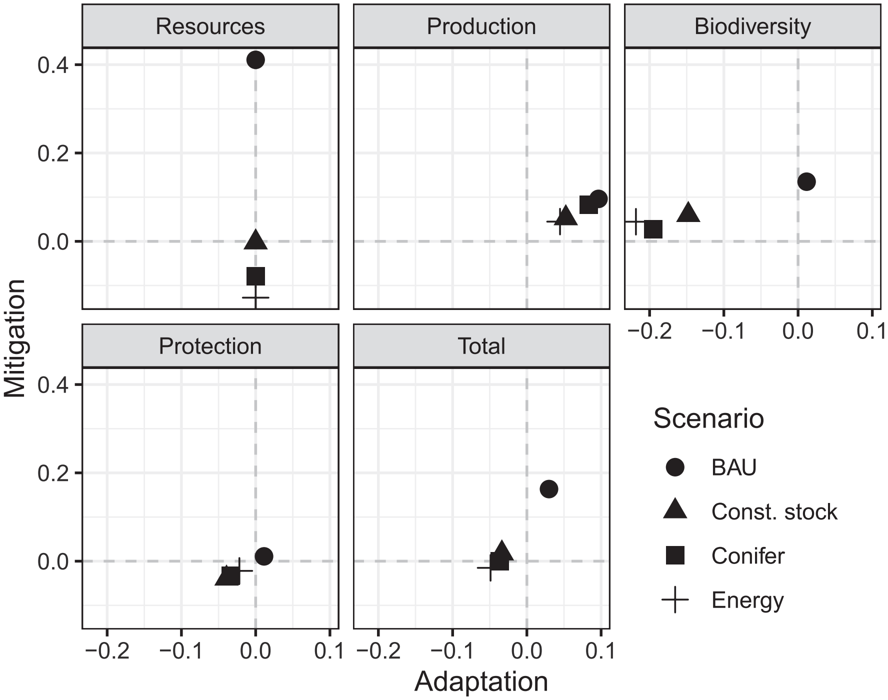

Fig. 4.7 Change in adaptation capacity and mitigation for the whole of Switzerland and for years 2016–2106 by simulated management scenario, SFM criteria, and averaged overall indicators (Total)

forests covered by a management plan was observed in 2000, and Iceland (IS), where an increased afforestation rate was observed. Moreover, IS experienced increases in both growing stock and area of mixed forest, which are the most important indicators for adaptation.

The negative trend observed for adaptation depends mostly on the increase in forest damages between 1990 and 2000, especially for countries such as Serbia (RS) and Liechtenstein (LI), which showed the lowest negative values. The main causes for the high damages in Serbia were insects and diseases and in LI, it was wildlife browsing. Negative results were observed also for the Netherlands (NL) due to the increased forest damage caused by fire. The average trend over all countries (EU, which includes also countries outside the European union) was negative with respect to changes in adaptation (−0.11) due to the strongly negative values in RS, LI, and NL. Without the negative outliers, the average values of EU are positive with 0.03 for adaptation and 0.08 for mitigation.

In the period 2000–2005, results showed a positive trend in mitigation, with many countries moving to the right side of the scatter plot, and few countries that showed a negative mitigation trend (Fig. 4.9). Concerning adaptation, the negative trend mainly depended on the increase in forest damages. Nevertheless, this increase was strongly affected by methodological reasons rather than by an actual increase in

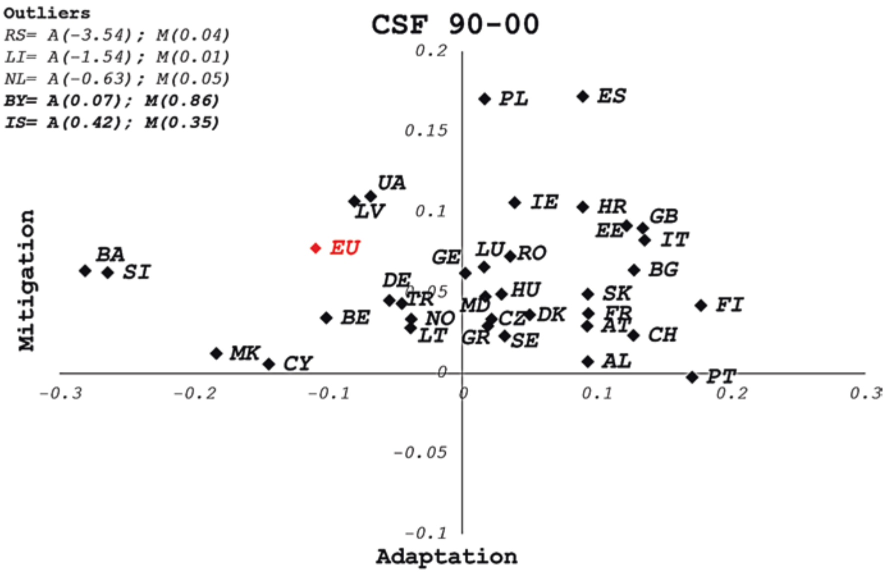

Fig. 4.8 Change in adaptation and mitigation for the period 1990–2000. Positive changes in both adaptation and mitigation (top-right quadrant) are considered as climate smart. The countries reported as outliers are those with extreme values. The red diamond, reported as EU, is the average value over all countries

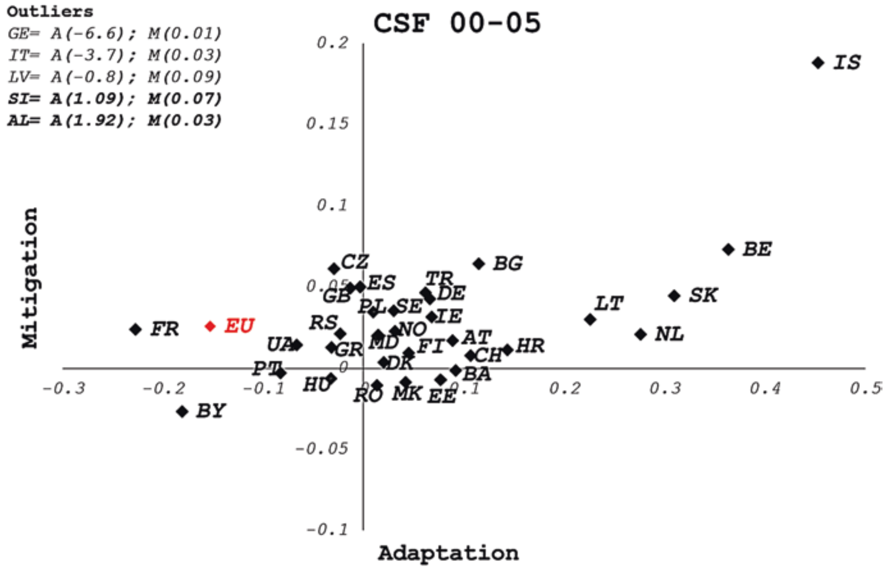

Fig. 4.9 Change in adaptation and mitigation for the period 2000–2005. See caption of Fig. 4.8 for details

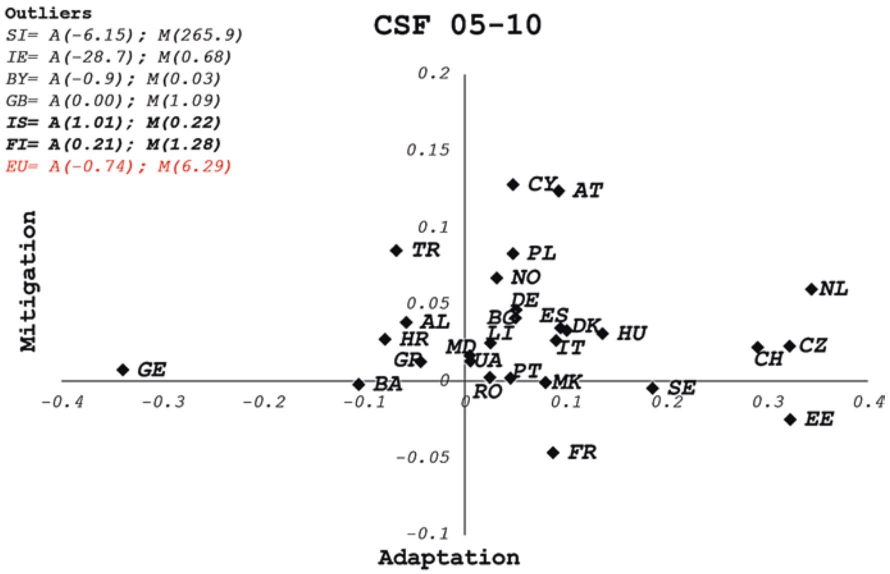

Fig. 4.10 Change in adaptation and mitigation for the period 2005–2010. See caption of Fig. 4.8 for details

forest damages. For example, in Georgia (GE), since 2005, the national report has also included abiotic and biotic causes for assessing forest damages in addition to forest fire. Similarly, in Italy (IT), other causes are reported only for the year 2005, which strongly affected the trend. Differences in data collection and reporting affected the evaluation at both, country and European levels.

Even though most countries showed very small changes, positive trends were observed. For example, the increased area of mixed forests and the increased net revenue are the main indicators that highlight the positive adaptation trend for Slovenia (SI). In Albania (AL), such an indicator is the deadwood amount, which increased strongly in the 2000–2005 period, while increases of timber production and growing stock were observed in IS.

In the period 2005–2010, most countries showed a positive trend for both mitigation and adaptation (Fig. 4.10), with few cases for which a negative trend was rather strong, particularly for adaptation. The main causes can be found in the reduced cover of mixed forests with respect to pure forests in SI and BY. In 2005, there were 1,182,000 ha of mixed forests (2 or more tree species) in SI and 61,000 ha of pure forests. In 2010, mixed forests covered 1,065,500 ha, while pure forests suddenly covered 181,500 ha. We are unable to explain this large increase in pure forest cover, which resulted in the ratio of mixed to pure forest to drop from 19.37 to 5.87 between 2005 and 2010, thus contributing to the low adaptation value. The cause for the low adaptation values in Ireland (IE) was an increase in forest damages between 2005 and 2010. Positive trends mainly reflected increases in net revenue and timber production as for IS. Concerning mitigation, wood for energy was the most important indicator and increased in Finland (FI) and SI, where also an increase of protection role by forest was registered.

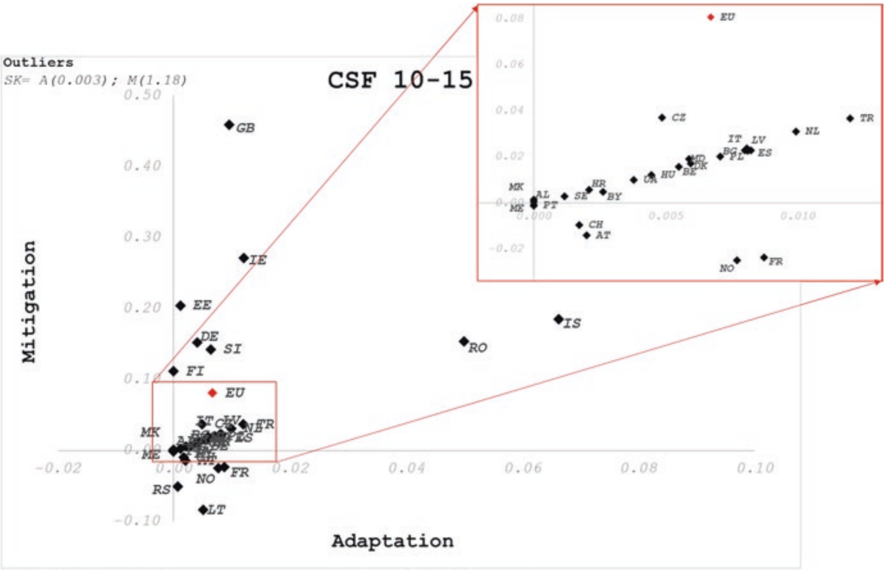

Fig. 4.11 Change in adaptation and mitigation for the period 2010–2015. See caption of Fig. 4.8 for details

For the period 2010 and 2015, results show a positive trend, with few countries showing a negative trend for mitigation (Fig. 4.11). Nevertheless, there is one critical point that hinders a correct evaluation, which is the lack of data for 2015 in most countries and for many indicators. Most of the indicators are provided by the NFIs, and the reporting frequency of the NFIs is often not the same as for the SoEF report (Marchetti et al. 2018). For this reason, not all indicators were available at the time of the SoEF publication.

The available indicators include *forest area*, *growing stock*, *carbon stock,* and *energy from wood*. Changes in these indicators show positive trends, especially for SK, which reported a considerable increase in wood for energy supply (+297%) between 2010 and 2015.

4.7 Critical Evaluation of Indicators and Potential for Improvement

This chapter described a subset of SFM indicators that can be used for assessing the potential for adaptation and mitigation. However, the catalog of variables monitored in NFIs, their field protocols, and definitions vary between countries (Tomppo et al. 2010). Therefore, some counties experienced difficulties to report data according to terms and definitions established by Forest Europe, for example, regarding forest available for wood supply (Alberdi et al. 2016b). These issues have at least partly led to gaps in the available Forest Europe SFM indicator data for some countries and years. To avoid the dependence on missing data, the method applied here returns the results based on the cumulative effect of available indicators multiplied by their relative value. This requires at least one indicator to be available for at least two subsequent inventory periods. The missing data were considered as null. Missing data can be compared with no change values between two subsequent inventory periods, because in both cases, the value of change is zero and thus does not add to the cumulative value. Even though a “missing data” entry is different from a “no-change” value, in practice, it results in no development in both cases. The lack of data can be considered one of the most hindering factors for developing and implementing CSF strategies (Santopuoli et al. 2020). Thus, monitoring, assessing, and accurate reporting are crucial for supporting CSF policy making, and researchers should facilitate methods for data collection and analysis.

To improve data availability, the timber assortment structure of the European forests as well as the use of harvested timber in the managed forests is crucial to gain a holistic picture on the potential of forests in carbon management (i.e., mitigation). Such information is particularly important to assess the carbon sequestration in wood products and the effect of wood products and wood-based energy to substitute fossil energy sources (Obersteiner et al. 2010; Braun et al. 2016; Köhl et al. 2020). However, only a few European countries assess wood quality and even less countries quantify timber assortments in their NFIs (Bosela et al. 2016). For example, in Switzerland (first case study in this chapter), the consideration of carbon sequestration in wood products and substitution of fossil fuel–intensive energy may have changed the CSF assessment for the Plateau region, where overharvesting (negative change in sustainability indicator) resulted in the negative overall CSF assessment due to decreasing growing stock (Blattert et al. 2020). Currently, many European NFIs are not yet capable of reporting on timber assortments in a harmonized way and further developments toward more integrated and harmonized NFI-based indicators on carbon sequestration and substitution are necessary at the European level.

Forests provide multiple ES to the society. However, the NFI-based indicators mainly cover provisioning and regulating services and indicators on sociocultural ES categories are lacking in many NFIs, but see, for example, NFIs of Denmark (DK) and United Kingdom (UK, Edwards et al. 2011). One of the most important ES from the last category is tourism and outdoor recreation in forests (Sievänen et al. 2013), with recreational tourism evolving from a niche market to a mainstream element of global tourism with annual growth rates of 10–30 percent (Bell et al. 2009; FAO 2010). In the last decades, several studies have provided insights on stand attributes that define forest recreational attractiveness (Giergiczny et al. 2014). Most of these studies found that visitors in Europe prefer mixed over monospecific forests (Gundersen and Frivold 2008; Paletto et al. 2013; Giergiczny et al. 2015; Grilli et al. 2016; Hegetschweiler et al. 2017; Pelyukh et al. 2019) and uneven-aged forests with at least a few large trees (Ribe 2009; Filyushkina et al. 2017). A high depth of view, that is, high visual penetration, was also preferred (Heyman 2012). The perception of deadwood varies and likely needs to be differentiated. Visitors prefer root plates and highly degraded deadwood pieces over fresh harvesting residues (Rathmann et al. 2020). The presence of deadwood is more appreciated when visitors are informed about the ecological function of deadwood (Pastorella et al. 2016a; Gundersen et al. 2017).

The marginal rate of substitution (MRS) reflects one's willingness to pay for visiting the forest concerned (Bańkowski 2019). The MRS index could be expressed by the distance that somebody is willing to travel in order to reach the desired forest. Higher values of the MRS index correspond to a higher recreational attractiveness of the forest. This index has been developed for all forests in Poland by Bańkowski (2019), who described forest recreational attractiveness using attributes, such as forest age, age diversification (even- or uneven-aged), forest type (monospecific and mixed: two-specific, multispecific), diversification of the tree-species composition, abundance of advance growth and/or undergrowth, height of the ground vegetation cover, silvicultural system applied, and touristic infrastructure and facilities. The mentioned indicators for these stand attributes determining visual attractiveness can be derived from data collected in most NFIs. They can thus be used to complement the indicators for adaptation and mitigation, allowing for balanced assessments that also consider sociocultural ecosystem services.

4.8 Inventory-Based Assessments of CSF in a Broader Context

The case studies presented in this chapter provide a basis for future assessment of climate smartness of European forests and its change over time. They present a possible way to use forestry statistics, either those reported in SoEF or other aggregated data provided by NFIs, to assess the adaptation and mitigation potential of European forests. Working with the data of a single country, such as Switzerland in our first case study, has the advantage of the data being consistent and harmonized. This allowed comparisons of indicator developments among regions and, together with the MASSIMO forest development model, potential forest management scenarios could be evaluated in terms of adaptation and mitigation. This evaluation of management scenarios showed that BAU management that continues harvests below the mean annual increment in Swiss mountain regions performed best in terms of adaptation and mitigation. Hence, this illustrates a potential trade-off between timber harvesting and CSF.

Based on the statistics reported in SoEF, the results of our second case study suggest that the forests in most European countries positively contribute to both adaptation and mitigation, with a few exceptions. However, there are changes in the potential over time, which might be partly attributed to a change in the accuracy of provided data over time, as well as due to a change in the methodological approach. For example, a country may have started to use NFI data to report to SoEF instead of less statistically sound data from other sources during the time period of 1990–2015. Another factor that strongly affects CSF indicator development across Europe is the occurrence of large-scale disturbances, including windstorms followed by bark beetle outbreaks (Seidl et al. 2017), which certainly was decisive for the CSF assessment of some countries. Finally, the selection of indicators, which was limited to those that are reported by the European countries to SoEF, may have affected the overall assessment of the adaptation and mitigation potential.

In the following, we discuss the broader context, in which large-scale assessments of CSF need to be interpreted. As a recent study by Naudts et al. (2016) suggested, wood harvesting and change in species composition in European forests had led to a carbon debt of 3.1 petagrams. Although there has been considerable afforestation since 1750, many originally broadleaved forests were replaced with coniferous species. From a more recent perspective, there has been considerable land cover changes in Europe since the 1990s (Huang et al. 2020). Abandonment of agricultural land and transition to forest was suggested to have a widespread cooling effect in western and central Europe, whereas in eastern Europe, this same land use transition had a warming effect. The opposite climate system response between the western and eastern parts of Europe is explained by the stronger contribution of a reduced surface albedo after reforestation in eastern Europe and a lower evaporative cooling of soils on eastern Europe (Huang et al. 2020). In general, afforestation and reforestation are considered to be the main processes driving forest-related carbon sequestration. Increasing the productivity of forests and thus increasing growing stock may also contribute strongly to carbon sequestration and thus climate change mitigation (Pretzsch et al. 2014). However, this entails a presumably higher disturbance risk (McDowell et al. 2020) and recently, there have been signs that the carbon sink in European forests saturated (Nabuurs et al. 2013). Hence, focusing on adaptation rather than mitigation may be of higher priority, where growing stocks are already high.

There is a strong debate whether a no-management approach is better for carbon sequestration than its managed counterparts (Van Deusen 2010; Griscom et al. 2017; Luyssaert et al. 2018; Baldocchi and Penuelas 2019; Grassi et al. 2019). Luyssaeret et al. (2018) found that if the current forest cover in Europe is sustained, the additional climate benefits from forest management are only modest and relevant at local level, but not at the global level. The authors of the study further suggest that Europe should not rely on forest management to mitigate climate change and should support the recommendation of focusing on forest adaptation. However, Grassi et al. (2019) put this into perspective by highlighting that our knowledge on management effects on CO_2 sequestration is still poor and that premature recommendations should be avoided. Further, Baldocchi and Peñuelas (2019) suggested that the rates and amount of net carbon uptake are low compared to the CO_2 released by fossil fuels combustion. They also point out that management of forests focused on carbon sequestration can cause unintended consequences and should be considered with caution. In response to that, Griscom et al. (2019) argued that ecosystem-based options have so far been underinvestigated and that there are some positive examples of policies that successfully integrated both fossil fuel emission reduction and natural climate solutions. Yousefpour et al.

(2018) suggested that an economically efficient CSF policy would prioritize carbon sequestration (with no-management option being dominant) in northern, eastern, and central European countries, where lower wood prices, high labor, and harvesting costs or a mixture thereof prevail. In contrast, forests in the west should be harvested to provide wood for the substitution of fossil fuels and carbon-intensive materials.

The fifth report by IPCC (IPCC 2014) suggested that forest management strategies should 1) lead to a sustained yield of timber, fiber, and energy, 2) maintain or even increase carbon stock in forests (including in the soil), and 3) preserve forest biodiversity. As pointed out by Hisano et al. (2018), biodiversity may aid in mitigating climate change impacts on biodiversity itself, because more diverse forests can be more resilient and thus can potentially better adapt to a changing climate. More diverse ecosystems can likely better maintain ecosystem functioning through enhanced facilitation effects (Hisano et al. 2018; Jactel et al. 2018; Ammer 2019). However, a recent study by Sabatini et al. (2019) showed a highly variable relationship between species richness and carbon stock at the stand scale in European temperate forests. They further suggested that maximizing cobenefits between carbon and biodiversity may require stand scale approaches to reach positive effects at the landscape scale.

These studies show that there are still important knowledge gaps on the effectiveness of adaptation and mitigations management and their consequences for ecosystem service provision. Forest inventory–based monitoring and scenario assessments, such as those that have been exemplified in this chapter, have a strong potential to fill some of these knowledge gaps. In particular, biodiversity-related indicators on regeneration and naturalness may gain importance. However, this requires further harmonization across countries and continents. Furthermore, ground-based assessments should be complemented with other data sources (e.g., remote sensing and eddy covariance flux towers) and projections from dynamic ecosystem models to capture factors, such as albedo, biodiversity-productivity relationships, disturbance vulnerability, and economic realities.

4.9 Conclusions and Outlook

To assess the vulnerability of forests to both gradual and sudden switches in environmental conditions, and to evaluate the adaptive capacity of forests and forestry to climate change, integration of multiscale forest ecological studies with repeated NFIs is required. NFIs are relevant as they are the primary data source for reporting on forest resilience and vulnerability to European institutions. To sustain forest-adaptive strategies and provide climate-smart indicators (Bowditch et al. 2020), integration of NFIs, experimental forest management plots, and other networks, such as ICP forest (e.g., Trotsiuk et al. 2020), are especially important due to the time elapsed between management actions and stand responses. Combination with airborne forest observation may provide additional information on stand structure, such that reliable biomass estimation and biodiversity monitoring at the stand-to-landscape scales are possible (see Chap. 11 of this book: Torresan et al. 2021).

Climate-smart approaches in forestry are dynamically connected with the sustainable delivery of forest products and ecosystem services (Nabuurs et al. 2015, 2017; Yousefpour et al. 2018). Mitigation measures undertaken in forests (reducing emissions from deforestation and forest degradation and enhancing forest carbon sinks and product substitution) will be effective in the long term (Kauppi et al. 2018); therefore, a European forest–related policy should be dynamically extended as well (Verkerk et al. 2020), to address climate targets in the forestry sector (Nabuurs et al. 2018). Adaptation measures in forests will be required to secure the continued delivery of forest ecosystem services. NFIs are, therefore, key tools for implementing, monitoring, evaluating, and revising CSF management practices at the landscape level, as well as policies at the country and European level.

In this context, spatial forestry planning may opt for a concentration of high-yield wood extraction in productive forest areas, and an expansion of forest land spared for other services and conservation (sensu Ceddia et al. 2014). A simultaneous implementation of intensification and conservation, however, needs to be accompanied by strategies that carefully regulate land use. This can be supported by flexible incentives and support policies at the regional scale and by strengthening co-management regimes in local communities. Straightforward identification of adaptation and mitigation options, land suitability ratings, and cost-benefit analysis that all can be supported with NFI data are necessary for risk assessments.

A mosaic of forest landscapes with mixed management strategies, combining productive forest units (e.g., short-rotation coppices) with high-nature-value forest areas (e.g., old-growth forests), can be envisaged for some areas in Europe (e.g., Schall et al. 2020), while in others, production and conservation goals can be integrated at relatively small forest areas (Kraus and Krumm 2013). Forest inventory data can assist in delineating these areas. The spatial and temporal distribution of wood harvesting should consider the patterns of environmental disturbances and extreme events that historically occurred within a specific region. Smartness indicators can be used to determine land-use intensity, underlying utilization benefits versus conservation options (e.g., separation of nature and silviculture vs. integration of ecosystem services and natural capital; abrupt changes in management zones vs. spatial continuity of mixed systems; intensification for equilibrium vs. maintenance of resilience). Harmonized statistics and agreed indicators are also necessary for applying decision-making processes and reporting climate-related measures linked with EU directives and regulations.

The scope of NFIs has broadened to satisfy increasing information requirements (Tomppo et al. 2010; Alberdi et al. 2017), collecting among other things (e.g., biodiversity, disturbance impacts, or nonwood forest products), information on carbon stocks, emissions and removals, and on anthropogenic forest-related emissions and land use activities (Tomppo et al. 2010). While there is a potential for forest mitigation in Europe by increasing carbon sequestration and through substitution effects (Grassi et al. 2019), their effect on the climate system is limited due to beginning of carbon sink saturation (Nabuurs et al. 2013) and shifts towards more frequent disturbances and younger forests (McDowell et al. 2020). Silvicultural treatments to adapt forest composition and structure to expected new climatic conditions and disturbance regimes should be prioritized over mitigation measures, especially for highly stocked forests with low carbon sink capacity and where vulnerabilities to disturbances are high (Luyssaert et al. 2018). Forest inventory data may assist in identifying and reconciling potential trade-offs among adaptation, mitigation, and management objectives to provide ecosystem services (Gutsch et al. 2018; Temperli et al. 2020).

Although production, adaptation, and mitigation practices tend to be approached separately due to a variety of technical, political, and socioeconomic constraints, the forest infrastructure may allow more holistic management, if designed, inventoried, and managed appropriately. The necessity to monitor both forest productivity, forest health and other ecosystem services, such as increasingly demanded recreational and tourism related services, suggests that future forest inventories should focus on testing and implementing indicators related to agreed criteria for Climate-Smart Forestry, balancing the different components. Information provided by NFIs will be critical for developing indicators to identify trade-offs between policies that may increase the vulnerability to disturbances (e.g., carbon sequestration in old-growth forests), strategies to increase forest resilience, timber production, recreation, biodiversity conservation, and other ecosystem services. In this context, NFI data are critical for monitoring the impacts of climate change and the effectiveness of Climate-Smart Forestry measures. Even though NFIs have originally been designed at the national or subnational levels, the emerging synergies of Climate-Smart Forestry at the European scale call for the synchronization of forest inventories and reporting schemes. Coordinated multipurpose forest inventories are needed for monitoring valuable multifunctional forest ecosystems.

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