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WHICH SILVICULTURAL MEASURES ARE RECOMMENDED TO ADAPT FORESTS TO CLIMATE CHANGE? A LITERATURE REVIEW

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Abstract: *Climate change is a challenge for forest managers and owners. The trees regenerated in forest stands today will have to cope with changing conditions during their lifetime. Adaptive forest management includes a large variety of silvicultural measures: changes in species composition by converting monocultures to mixed forests, changes in forest structure, intensified thinning, or the reduction of rotation time. The aim of this review is to highlight the silvicultural measures and practices that have been recommended for adaptation to climate change, and to apply Bolte's classification of adaptation strategies in order to identify which type of strategy is recommended in the literature. The literature review shows that active adaptation strategy tends to dominate as compared with passive adaptation or forest conservation measures. On the other hand, active adaptation with intensified thinning, shorter rotation periods, and change in the forest structure presents the risk of being rejected by a part of society for which climate change adaption should be a natural process. In addition, the current policy framework may limit the freedom of active adaptation measures.*

Keywords: *climate change, silvicultural measures, adaptation strategies*

1. Introduction

1.1. Climate Change

Forests are affected fundamentally by climate change as a combination of warming, alteration of precipitation regime, an unpredictable pattern of extreme events, and a changing disturbance regime [54].

For forestry, climate change is a challenge due to the direct impacts on forest ecosystems and the lag effect of management decisions on forests [127]. The expected effects on forests ranging from a different distribution of tree species [44], effects on forest productivity [97], to increased risk of storms [62] and fires [22], increased frequencies of insects, pests [99], and drought [1].

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Climate change at large scales may have a strong influence on forest species composition, forest communities, and the dynamics and structure of a forest [44], [69], [97], [115] because forest response to the climate is influenced by topography, spatial distribution, and site-specific growth conditions, the last two being the result of past forest management [33], [114].

A large number of studies show that climate change is altering flowering, fruiting (phenological processes) [6], [92], seed establishment and germination, the early growth and physiological processes, respiration [23, 71], the suitable habitat for individual species, community composition, and species distributions [24], [94].

On the other hand, climate change may have positive effects on forest productivity in some parts of Europe [30, 78], influencing forest growth in areas where the limiting factors are low temperatures and short growing seasons (higher altitudes and latitudes, oceanic NW parts of Europe) [3], [8]. For example, Norway spruce forests from Sweden and Finland [60] will probably increase their productivity [7], if they are not affected by insect attacks [14] or windthrows. The increased concentration of atmospheric CO_2 has a fertilizing effect that may boost tree productivity, tree growth, and water stress tolerance. The effect on drought tolerance differs, being dependent on many other factors (e.g. altitude, site, tree dimensions etc.) [37], [47], [121].

The interspecific tree competition is expected to be altered by increasing temperatures [79]. The recent drought induced dieback in Central Europe forests [1], [74] acknowledged that drought is the most significant threat to forests [14], [69].

Drought and climate warming may also make the growing conditions suboptimal for some tree species like Norway spruce, affecting mortality, growth, and tree species composition in forests [1], [4], [44, [69], [117]. In Southern Finland, the reduced soil water availability combined with severe climate warming is expected to lead to a decrease in the growth and increment of Norway spruce [21], [58], [100], [117]. In Spain, Scots pine forests declined in areas close to their dry distribution limit [98] and in Flanders, during the late 20th century, the growth of common beech (*Fagus sylvatica*) declined [61] and the tree mortality increased [1], [10].

The high occurrence of environmental changes raised concerns because the adaptation of trees is not fast enough [27]. During their evolutionary history, tree species have been exposed to long-term environmental changes and have shown the capability to respond and adapt to these changes [43]. However, the pace of climate-induced changes would require active human intervention for adaptation, because the trees regenerated in forest stands today will have to cope with changing environmental conditions during their lifetime [65]. There is a need of changing the forest management to help forests adapt to the climate change, particularly in those highly sensitive forests which are most exposed to stresses like heavy grazing or extreme events (storms, fires) [16].

Adaptation to climate change is now perceived as a prime challenge for modern society [31], [52]. The climate change progress represents a new source of change and uncertainty which needs attention in adaptive forest management [125].

Climate change adaptation involves monitoring and anticipating changes, avoiding negative consequences, and taking advantage of the potential benefits of those changes [103]. The aim of the adaptation strategies is to reduce the vulnerability to the increasing threats of natural disasters or extreme events, to support and assist the stress resistance of forest ecosystems, to increase the resilience capacity, and to respond to the progressive changes or climate extremes [14].

The adaptation of managed forests to the changing environmental conditions must be achieved by modifying the traditional forest management strategies [67].

Reducing stand susceptibility to disturbances, lowering disturbance impacts, and improving forest resilience are urgent requirements for adaptive management. Adaptive management approaches are recommended at local and regional scale with the aim to reduce uncertainty and risk.

In forest management, adaptation actions can be grouped into general land management options, site-specific silvicultural practices, planning options, building social and community skills and policy [14].

1.2. Silvicultural Measures and Practices

In recent years, the interaction between management actions and the climate change impacts on forests has been the focus of a growing body of empirical studies as well as advanced simulations [97], [104], [114], [118].

In particular, management approaches intend to foster adaptation through maintaining complex forest composition and structure [26], [28].

Forest management means a whole range of decisions that should be considered: choice of species, provenances, regeneration approach, thinning and tending practices, harvest age or size, drainage, protection measures, afforestation, deforestation, etc. [125]. These measures are not new, having been used in forestry long before climate change issues [110]. Firstly, forest management directly influences the state of the forest, but it may also modify other existing relations: susceptibility to windthrows, consequences of drought, and the economic impact of a given ecological response (cutting losses, enhancing benefits) [125].

Adaptive forest management includes a large variety of silvicultural measures: changes in species composition by converting monocultures to mixed forests, changes in forest structure (conversion from even-aged to uneven-aged or coppice to high forest), intensified thinning or the reduction of rotation length [127].

The rotation length reduction decreases the exposure time of timber crops to risk [101, 102], limits the top height reached, reducing the risk of windthrows [101] and generally reduces uncertainty, allowing better adapted species to be replanted. Changing the species composition can avoid the risks associated with certain species, e.g. windthrows and bark beetles in Norway spruce [109] or drought-intolerant species. Trying to use more species than recommended is also a risk, called in the literature insurance hypothesis [36].

Forest thinning needs to be more aggressive than traditionally practiced, in order to stimulate the growth of large residual trees, improve drought resistance, and provide greater resilience to future climate-related stress [59].

A range of studies demonstrated that repeated thinning during a forest rotation increases carbon storage rather than directly clear-cutting short rotation stands with no thinning [45]. Also, the carbon stock differs according to the thinning method (e.g. thinning from above versus from below) [26, 90]. For successfully coping with forest vulnerability to climate change, Austrian Federal Forests has promoted mixed stands of species well adapted to the changing environmental conditions, silvicultural techniques fostering complexity and a more intensive management [108].

The uncertainty is still large regarding several climate change aspects [68]; changing climate conditions are generally foreseen to alter European forests significantly, most severely in Southern regions [44]. The regional policy frameworks, with different degrees of freedom in choosing the forest management options [81], limit the range of possible adaptive management activities, yet it is important to have flexibility in the adaptation to different objectives and perceived future risks [46].

This study aims to review the literature addressing the issue of forest adaptation to climate change, with particular focus on the recommended silvicultural measures and practices, and to provide an overview of the potential options to increase forest adaptation to climate change for forest owners and managers. We applied Bolte's classification of adaptation strategies to identify the types of strategies recommended in the literature and to what extent these strategies are linked to a certain climate change threat or a certain forest management tradition.

2. Methodology

To access and collect the papers relevant for this review, a systematic search involved a keyword driven approach. We used a combination of the following terms: "climate change" AND ["forest management" OR "forest measures"] and "adaptation" to search article titles and abstracts. Two search engines were used: "Web of Science" and ”Google Scholar" and our search yielded a gross list of 162 articles. These publications were screened and 98 articles did not in fact describe silvicultural measures or practices for adaptation. We created a literature database with remaining papers, which provides information about author, title, year, journal, region, and silvicultural measures for adaptation.

Bolte et al. [13, 14] identified different adaptation strategies:

1. Active adaptation, using silvicultural methods (e.g. tending, thinning) to change stand structure and composition for a forest better adapted to climatic change impacts;
2. Passive adaptation, using spontaneous adaptation processes such as natural succession and species migration. The input efforts are minimized and there are reduced possibilities to control forest composition, stand structure and forest functioning;
3. Forest structure conservation, with the aim to maintain a constant forest structure even against the increased successional pressure due to environmental changes.

Based on Bolte and his collaborator's [13, 14] classification of adaptation strategies, we grouped the silvicultural measures identified as follow:

1. Active adaptation: increase thinning frequency - ITN, increase thinning intensity - ITI, reduced rotation length - RRL, mixed tree species composition

- MTSC, introduction of more adapted species - MAS, change in stand structure (uneven-aged stand) - UEA;
2. Passive adaptation: conversion to natural vegetation - CNV, increase rotation length - IRL, low intensity - LI, shelterwood / natural regeneration - SNR;
3. Forest structure conservation: no management - NOM, increasing afforestation - IAFF (Annex 1).

We analysed the relations between the different variables identified in the scientific papers, with the aim to identify the factors that discriminate to a great extent the set of measures proposed by the retained articles [12]. For this purpose, we used multiple correspondence analysis (MCA). The method is suitable for describing, analyzing, and visualizing qualitative information contained in a table of categorical variables [12].

Data analysis was performed with R and multivariate processing was performed with the library FactoMineR [49].

3. Results and Discussion

3.1. The Scientific Literature Analysed

Our analysis included 64 articles published in 30 different journals (Annex 2). If in the early 2000s there were just a few occasional publications, the number of publications increased between 2000-2012 with a drop in 2013-2014, followed by a high increase in 2015-2017 and a decline after 2017 (Figure 1). The majority of studies focused on temperate oceanic, temperate continental, and boreal regions (Figure 2). The "general" category represents review articles or articles analyzing all bioclimatic regions.

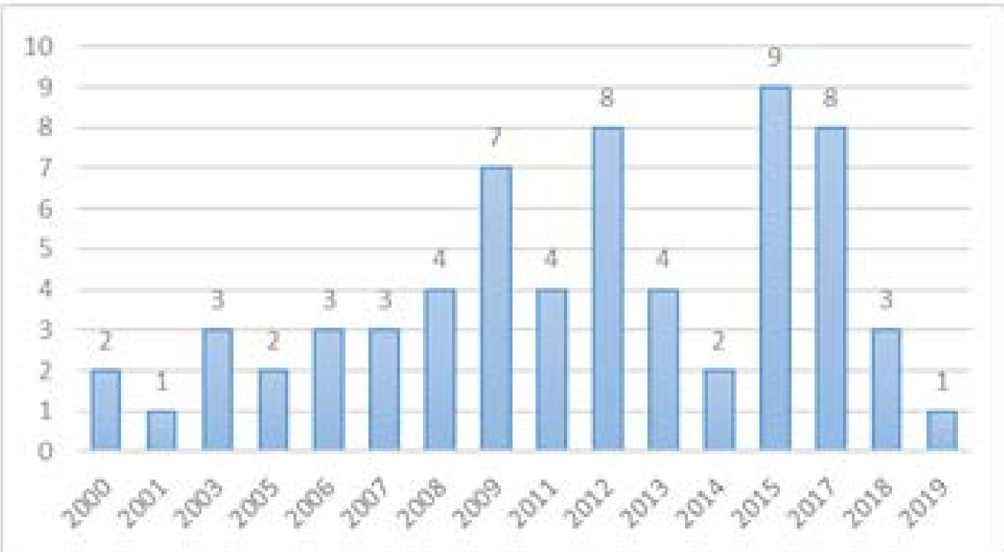

Fig. 1. *Publications dealing with forest climate change adaptation measures*

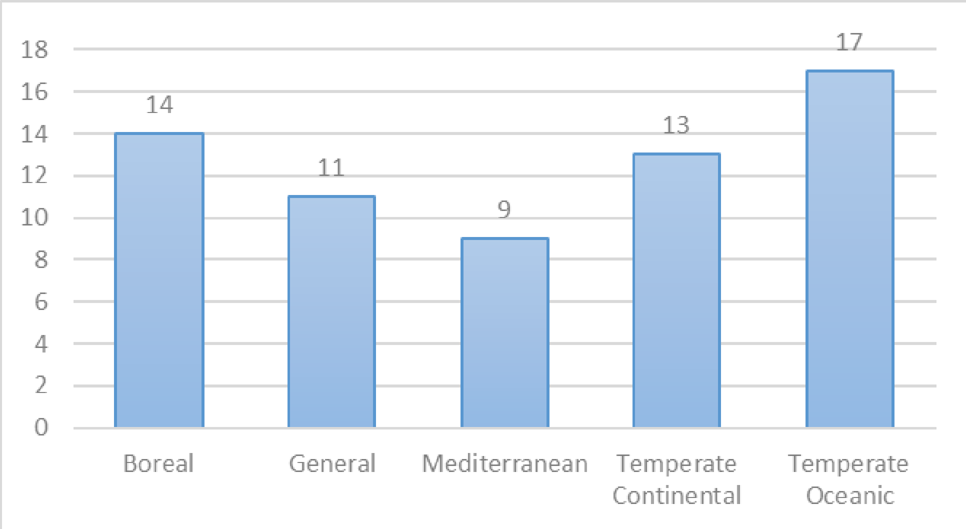

Fig. 2. *The number of publications per bioclimatic region*

For the articles reviewed, we identified 12 options of adaptive silvicultural practices and measures (Figure 3). The two most frequent practices were "mixed tree species composition – MTSC" and "increase thinning intensity – ITI" recommended in 36 articles, followed by "reduce rotation length – RRL" (30 articles) and "introduction of more adapted species – MAS" (29 articles). The silvicultural measure "low intensity – LI" and "increase afforestation – IAFF" were recommended in only three articles.

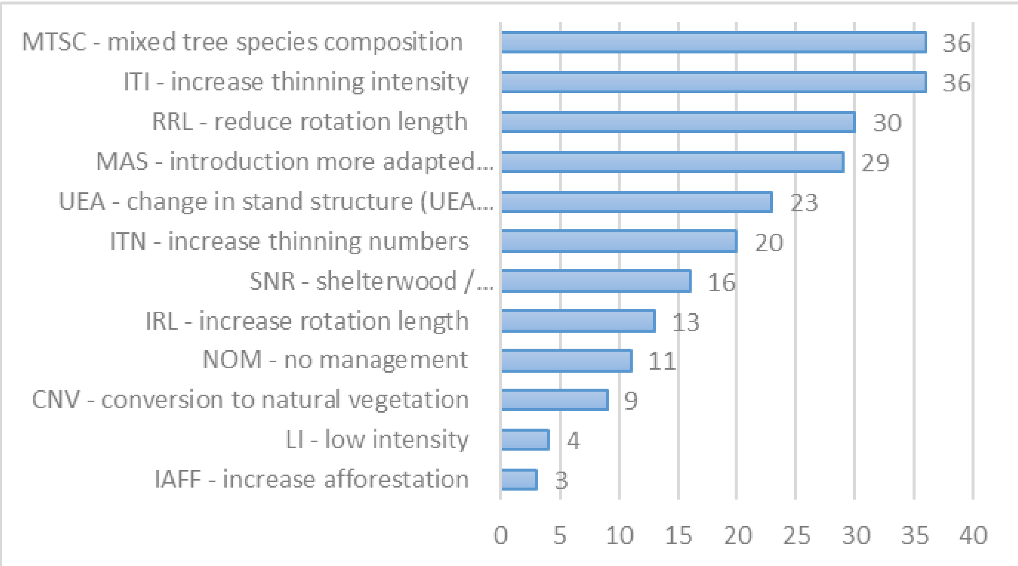

Fig. 3. *Recommended silvicultural practices in the analysed articles*

3.2. Correlations between Silvicultural Measures and Practices and Types of Forests or the Climate Change Challenge

The first two dimensions of the MCA explain together 37.4% of the variance (Figure 4). Dimension 1 is defined by the silvicultural measures UEA – change in stand structure (uneven-aged stand), IRL – increase rotation length, MTSC – mixed tree species composition, and ITI – increase thinning intensity. The second dimension is determined by ITN – increase thinning frequency, LI – low intensity, and IAFF – increase afforestation. The first dimension (green circle) expressed an active adaptation strategy, focusing on uneven aged forests, with a good mixture of species, well thinned and with high rotation length.

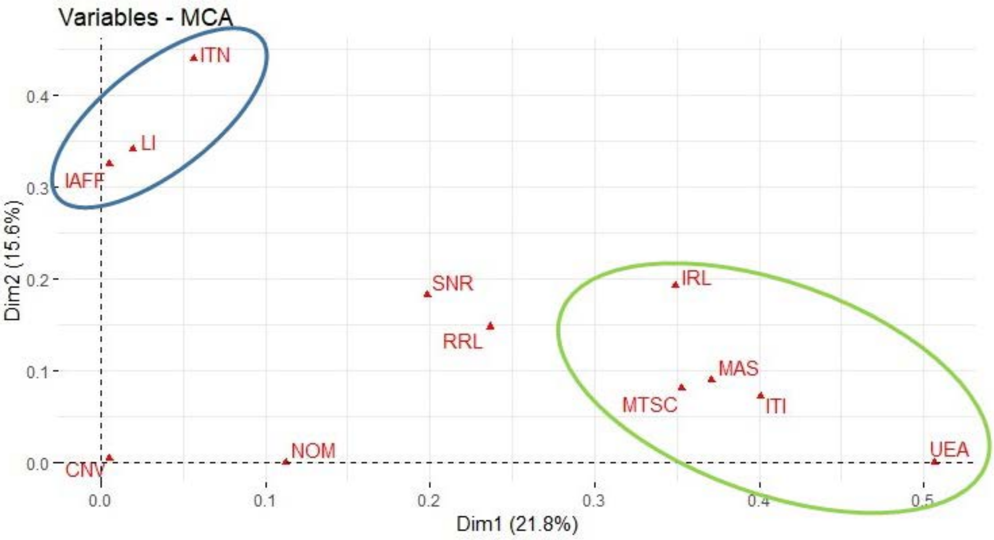

Fig. 4. *Multiple Correspondence Analysis of silvicultural practices and measures. Abbreviations description: ITN - increase thinning numbers, ITI - increase thinning intensity, RRL - reduce rotation length, MTSC - mixed tree species composition, MAS - introduction of more adapted species, UEA - change in stand structure (uneven-aged stand), CNV - conversion to natural, IRL - increase rotation length, LI - low intensity, SNR - shelterwood/natural regeneration, NOM - no management, IAFF - increase afforestation*

If most of the silvicultural measures which correlated with the first dimension can be included in "active adaptation strategy", those which are correlated with the second dimension are not included in one single adaptation strategy. ITN is included in active adaptation, LI in passive adaptation, and IAFF in forest structure conservation. However, the second dimension expresses a trend to propose more frequent interventions, but of lower intensity as a means of forest adaptation to climate change (blue circle).

The Multiple Correspondence Analysis results do not offer a clear differentiation of silvicultural measures according to bioclimatic region.

Increasing thinning frequency (ITN) was recommended in 20 articles, specifically in those which analyzed forests from boreal (8) and temperate continental regions (5), and in only 4 articles, regarding forests in Mediterranean regions. This measure seems not to be recommended in temperate oceanic regions. Instead, increase of thinning intensity was recommended in 36 articles, 18 articles analyzed temperate oceanic and temperate continental regions, and only 7 proposed this measure in boreal forests.

Reduction of rotation length does not represent a viable silvicultural practice for Mediterranean regions (recommended in only 2 articles), but it represents a potential solution for both boreal (8) and temperate regions (13). We expected that mixed tree species composition would dominate the recommended measures in temperate regions (16), but we also found in 9 cases recommendations of mixed tree species in boreal regions. Furthermore, the introduction of more adapted species was strongly recommended in articles which analyzed temperate regions (13) and boreal regions (8). Changing forest structure from even-aged to uneven-aged was recommended in 23 articles dealing with forests equally distributed across regions. Increasing rotation length was recommended in 13 articles which focused on opposite regions: boreal (4) and Mediterranean (4).

Shelterwood or natural regeneration measures (16 articles) were recommended only for temperate forests and in general, since boreal and Mediterranean regions are dominated by conifers. “No management” was recommended as a silvicultural measure for adaptation in 11 articles, most probably used as a reference for comparison with other options.

3.3. Categories of Silvicultural Practices and Measures Identified

3.3.1. Active adaptation

The species selection in the regeneration phase has a long-term impact, but the practices applied after the stand is established in order to promote target species composition, stand stability, quality, and a certain structure have effects in the short-term [65].

Changing the frequency or intensity of the thinning activities [65] should support mixed stands with more adapted tree species coping with climate change via diversification [112]. The aim is to increase the growth rates of the forest stands from the boreal zone [21], [40], and the high altitude forests and forest stands from drought prone sites [64], [112]. The mature and structurally uniform forests need measures to increase their structural diversity and reduce standing stocks through adapted thinning frequency and intensity [108].

Shortening the rotation length generates a large volume to be harvested and a faster species conversion speed [103]. However, shortening the rotations period by 10 years and more intense thinning proved to have only a moderate effect on species composition and total biomass [17], therefore the expected adaptation effect may not occur at all. An increased adaptive potential of tree species is believed to be higher in mixed stands [63]. These stands are considered to be superior to the pure stands in terms of productivity [89], ecosystem functioning, and resilience [63].

The conversion from even-aged Norway spruce stands to uneven-aged forests influences the competition and has strong consequences for forest biodiversity. The transformation to uneven-aged forests can lead to higher species diversity [5]. In the conversion process to uneven-aged, the resulted mosaic of uneven and even-aged structures has higher species diversity than each forest structure separately.

3.3.2. Passive adaptation

Increasing rotation length usually means a higher risk of windthrows and a high risk of quality losses [93].

The promotion of harvesting systems which support the natural regeneration of suitable species was recommended due to increased spatial heterogeneity and biodiversity at landscape level [112].

Natural regeneration offers a direct and immediate opportunity to manipulate species or stand composition. The adaptive response of forest regeneration is to increase genetic diversity by benefiting from successive fruiting years or through weeding and planting in natural regenerated stands [65].

Low-intensive silviculture compared to a clear cut system showed a gain in biodiversity at stand level. Older stands with big trees and great structural diversity also mean an increase in deadwood. A benefit from low intensive silviculture systems was the increased number of larger trees despite less valuable small-diameter wood [93]. However, the sawmill industry and the wood-based panel industry are not necessarily capable of processing larger diameters [101].

Assisted migration of more adapted species represents an important tool in reducing the vulnerability of forest ecosystems [29], [123] whereby species (often non-native) are intentionally transferred to regions outside their natural range. Many forest conversion activities in Europe in the past decades have already applied this approach [73]. In regions with significant land degradation, the transfer of suitable non-native species proved successful in establishing forest ecosystems [113]. Assisted migration also comprises the choice of appropriate provenances, tolerant to extreme weather events [20].

3.3.3. Forest structure conservation

Although the “no management” option seems to benefit the biodiversity objectives [116] and carbon storage [106], this cannot be an economically viable adaptive management strategy for state and private forest owners [119]. Besides, some studies show that “no management” leads to only a minor increase in species diversity at lower elevation and no change at medium and higher elevation. This means that forests tend to keep their monospecific composition even if the forest damage increases [48]. The result of the no management measure is a high number of old trees, whose production rate may be less sensitive to climate change compared to young trees resulted after management intervention, which have higher growth rates [48].

In afforestation, there are a range of measures recommended to respond to the climate change challenge. For example, planting in drought prone areas can be adapted through a wider initial spacing of trees in combination with rigorous weed control to reduce water competition [112]. Shifting planting season from spring to autumn and adding site preparation could enhance the drought resistance of planted trees as a result of initial rooting.

Since 2017, we have observed a decreasing trend in articles about silvicultural measures for adapting forests to the climate probably due to the fact that silvicultural practices will not change in the near future [18]. One other explanation may be the fact that the marginal gain of forest adaptation to climate change is low compared to the challenges of implementing radical changes in the forest management strategies. On the other hand, the measures proposed should be interpreted in the context, e.g. increasing rotation length is an option when the forest is managed on 80 years' rotation basis, but it may be a risky decision when the forest is managed on 140 years' rotation basis.

Not only may the implementation be fastidious and lengthy in time, but some measures assume longer rotation and a change towards more drought resistant species that may finally lead to a decrease in timber production and future incomes from the forestry sector [65]. These may enhance social opposition, either from private forest owners that are directly affected by these measures or from environmental NGOs that would oppose increased human intervention in forests.

"No management" is not a recommended measure for adaptation because forest dieback and disturbances at large scales following "no management" would probably have a more drastic economic impact [65].

4. Conclusions

A lot of knowledge about forest adaptation and potential silvicultural measures has been identified in the literature, but practical implementation is still lagging behind. There are few case studies where silvicultural measures for adapting forests to climate change were applied in forest modelling.

For a successful adaptation of forest management to climate change we need a difficult-to-reach combination between the fundamental research on climate change and forest modelling with results available at local or regional level, local foresters' expertise on forest vulnerabilities and resilience, and an open regional political process for negotiating the measures to be implemented for forest climate change adaptation.

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SUPPLEMENTARY MATERIAL

Silvicultural measures and practices in bioclimatic regions Table 1

No. crt.	ITN	ITI	RRL	MTSC	MAS	UEA	LI	SNR	CNV	IRL	NOM	IAFF	Bioclimatic region	Author
1		1	1	1		1							General	[127]
2						1			1				Temperate Oceanic	[126]
3										1			Mediterranean	[34]
4	1						1			1			Mediterranean	[85]
5	1									1			Mediterranean	[39]
6		1	1	1									Temperate Continental	[72]
7				1						1			Boreal	[91]
8				1									Temperate Oceanic	[124]
9	1										1		Mediterranean	[42]
10		1	1						1				Temperate Oceanic	[93]
11													Temperate Oceanic	[104]
12	1	1	1										Temperate Continental	[17]
13				1									Temperate Continental	[35]
14	1									1	1		Boreal	[119]
15		1											Mediterranean	[87]
16			1										General	[103]
17			1		1								Boreal	[58]
18	1		1	1							1		Boreal	[50]
19				1	1								Temperate Oceanic	[67]
20	1	1		1							1		Temperate Continental	[105]
21		1			1						1		Temperate Oceanic	[46]
22			1						1	1	1		Temperate Oceanic	[15]
23	1									1	1		Boreal	[88]
24		1		1	1	1			1				Temperate Oceanic	[114]
25			1	1									General	[82]
26			1	1	1								Boreal	[86]

No. crt.	ITN	ITI	RRL	MTSC	MAS	UEA	LI	SNR	CNV	IRL	NOM	IAFF	Bioclimatic region	Author
27	1	1	1		1			1					General	[57]
28				1									General	[11]
29	1	1		1						1			Boreal	[51]
30											1		Temperate Continental	[48]
31							1	1					Temperate Oceanic	[25]
32		1	1		1			1			1		Temperate Oceanic	[38]
33	1									1		1	General	[55]
34		1		1	1	1							Temperate Oceanic	[70]
35	1	1	1	1	1	1							Boreal	[84]
36		1		1		1		1					General	[19]
37		1	1	1	1			1					Temperate Continental	[13]
38	1		1		1				1	1			Temperate Continental	[109]
39		1	1	1	1	1							Temperate Oceanic	[122]
40	1	1	1	1	1	1		1					Boreal	[83]
41			1	1	1	1							Boreal	[84]
42	1	1		1	1								Boreal	[9]
43		1		1	1								Temperate Oceanic	[2]
44		1	1	1		1			1				Temperate Continental	[112]
45		1				1				1			Temperate Oceanic	[32]
46		1	1	1	1	1						1	Temperate Oceanic	[75]
47		1											Boreal	[21]
48		1	1		1						1		Boreal	[40]
49		1	1	1	1	1		1	1		1		Mediterranean	[109]
50		1			1	1							Mediterranean	[80]
51	1	1	1	1	1	1		1					Temperate Continental	[77]
52				1	1	1			1				General	[111]
53				1		1							General	[76]
54		1		1				1					Temperate Oceanic	[66]
55		1	1	1		1		1					General	[56]

No. crt.	ITN	ITI	RRL	MTSC	MAS	UEA	LI	SNR	CNV	IRL	NOM	IAFF	Bioclimatic region	Author
56		1		1				1					Temperate Continental	[53]
57			1	1		1		1					Temperate Continental	[107]
58	1	1	1		1			1	1				Temperate Continental	[96]
59				1	1	1							Temperate Oceanic	[73]
60		1	1		1	1		1					Temperate Continental	[108]
61	1	1	1	1	1	1	1						Boreal	[41]
62	1	1	1		1		1	1		1		1	Mediterranean	[95]
63	1	1	1	1	1	1		1		1			General	[65]
64		1		1	1	1							Mediterranean	[120]
Total	20	36	30	36	29	23	4	16	9	13	11	3		

**ITN - increase thinning numbers, ITI - increase thinning intensity, RRL - reduce rotation length, MTSC - mixed tree species composition, MAS - introduction of more adapted species, UEA - change in stand structure (uneven-aged stand), CNV - conversion to natural, IRL - increase rotation length, LI - low intensity, SNR - shelterwood/natural regeneration, NOM - no management, IAFF - increase afforestation.*

Number of articles published in journals Table 2

Journal/Book	Number of publications
Regional Environmental Change	9
Forest Ecology and Management	5
Forest Policy and Economics	5
Forestry	4
Journal of Environmental Management	3
Ecological Applications	3
Annals of Forest Science	3
Climatic Change	3
Ecology and Society	3
Forests	2
Forestry Chronicle	2
Canadian Journal of Forest Research	2
Biological Sciences	1
Journal of Forestry	1
Environmental Reviews	1
Conservation Biology	1
Mitigation and Adaptation Strategies for Global Change	1
Unasylva	1
European Journal of Forest Research	1
Western Forester	1
Journal of Forest Science	1
Tree physiology	1
Management of European forests under changing climatic conditions	1
Ecosystem services	1
New Forests	1
Environmental Management	1
Sustainable Forest Management in a Changing World	1
Global Change Biology	1
Journal of Applied Ecology	1
Buying Time: A User's Manual for Building Resistance and Resilience to Climate Change in Natural Systems.	1
Adapting to climate change in European forests–results of the MOTIVE project	1
Forest Science	1