Funded by
the European Union's
Horizon Europe
Programme

informa

SCIENCE-BASED INTEGRATED
FOREST MANAGEMENT
FOR CLIMATE MITIGATION

D3.1 Barriers and opportunities

Planned delivery date (as in DoA): 31.12.2022

Due date of deliverable: 02.02.2023

Work Package: 3

Work Package leader: USV Laura Bouriaud

Deliverable leader: USV Laura Bouriaud

Version: 1.0

HORIZON-CL6-2021-CLIMATE-01/ HORIZON-CL6-2021-CLIMATE-01-09

Project Acronym: INFORMA

Science-based INtegrated FORest Mitigation mAnagement made operational for Europe

Duration of the project: July 2022 – June 2026

Version history

Version	Date	Author /Reviewers	Partner	Description
0.1	4.01.2023	Laura Bouriaud, Ramona Scriban, Cosmin Cosofret, Gabriel Duduman, Olivier Bouriaud Julia Grimaud, Océane Le Pierres	USV I4CE	Review of environmental, technical and institutional barriers and opportunities of forest- based mitigation and adaptation strategies as identified in past projects and relevant scientific papers.
0.2	23.01.2023	Reviewer: Ciprian Palaghianu	USV	Review of draft deliverable 1.0
1.0	16.02.2023	José-Vicente Oliver Celia Yagüe Hurtado	UPV	Final control Final version for submission

Disclaimer

Funding Acknowledgement

This project has received funding from the European Union’s Horizon Europe research and innovation programme under Grant Agreement no. 101060309.

Table of contents

1 Executive Summary

Understanding the nature of barriers to adaptation is important to find out how to deal with them (Biesbroek *et al*., 2015). The **Task 3.1: Framing patterns of forest-based mitigation and adaptation** (Months: 1-6; Lead: USV; Participants: I4CE) addresses this objective through a literature review and a subsequent analysis of the existing macro-economic data. The results (materialised in D3.1) will provide input to WP1 (Information and Knowledge Transfer) and WP4 (Development and Impact of Sustainable Forest Management Alternatives) concerning the barriers and opportunities of regional mitigation and adaptation strategies and also the factors that may help or hamper the strategies of carbon stocking in long-life projects. Our reviewing methodology was based on both, a bibliographic study on specialized scientific-technical literature at global level (162 papers reviewed) dealing with forest-based mitigation and adaptation and a synthesis work on core literature that addresses the issue of barriers and opportunities for implementing such mitigation and adaptation strategies.

Nowadays, various approaches of the issue of barriers to adaptation exist. Moser and Ekstrom (2010) analysed the barriers for adaptation to climate change along the different stages of decision-making process. Besides, at each decision-making level, the individual level, organizational level and enabling environment level may lead to identify various barriers, not all of them being specific to climate-change policies. The literature review sort out different types of barriers:

(1) Implementation gaps;

(2) Social acceptability and preferences;

(3) Addressing uncertainities and lack of information;

(4) Conflicts in the forest utilisation and land-use system and trade-offs; and

(5) Financing.

However, the literature review shows that there are enabling measures tested or suggested as to cope with these barriers:

(1) Measures to increase the social and policy up-take of the technical solutions, the acceptance of new strategies and planned advisory services; and

(2) Measures to facilitate institutional innovation and integrative policies.

Regardless of the measures proposed, there are implicit trade-offs if considering multiple ecosystem services or multiple competing demand offorest products and services.

On the other hand, opportunities to change forest management strategies depend on the different levels of decision and on the power-relationship present at every level of decision-making. The current state of forests (legacies, planning system, age, restoration measures' needs, prevention of major disturbances, etc.) and ongoing forest-related policy processes represent opportunities for both adaptation and mitigation. There are plenty of opportunities for long-life high-value wood products as well as non-timer forest products (NTFP) driven by policies and by markets.

While pre-existing conditions and arrangements determine barriers and opportunities, multilevel governance is a wisdom of opportunity within the institutional stability proper to the European forest sector, if the scale of time can be adapted to embrace short-time vision policy-driven and long-time needed investment in enabling adaptation infrastructure. A particular difficult barrier remains the data uncertainty: different assumptions and modelling frameworks can give very different conclusions regarding the effectiveness of forest-based climate mitigation or climate adaptation techniques.

The implications for WP1 and WP4 are:

1) it is needed to deal with uncertainty and to be able to communicate with stakeholders in the EU forest sector about this;

2) it is required to consider local expertise, perceptions, trade-offs and controversies to increase research results uptaking in forest practice;

3) it is needed to be aware about forest legacies when select the appropriate climate change adaptation and mitigation strategies.

2 Introduction

One of the WP3 objectives is to provide a meta-analysis of environmental, socioeconomic, technical, political, and legal/administrative barriers and opportunities of forest-based mitigation and adaptation strategies at regional scale, as identified in past projects, available macro-economic data and sociological analysis.

The **Task 3.1: Framing patterns of forest-based mitigation and adaptation** (Months: 1-6; Lead: USV; Participants: I4CE) addressed this objective through a literature review and an analysis of the existing macro-economic data, e.g., forest productivity, forest investments and/or forest inventory data. The results (meterialised in D3.1) provide input to WP1 and WP4 concerning barriers and opportunities of mitigation and adaptation strategies at regional scale, and the factors that may help or hamper the strategies of carbon stocking in long-life projects.

Our reviewing methodology was based on a literature study dealing with forest-based mitigation and adaptation and on a synthesis work on core bibliography that address the issue of barriers and opportunities for implementing such mitigation and adaptation strategies.

3 Methodology

The different methods for reviewing literature and identifying relevant projects is described in the following subsections.

3.1 Theoretical model of adaptation to climate change

Defining the barriers is very challenging when it comes about climate change adaptation.

Moser and Ekstrom (2010) define them as obstacles, Eisenack et al. (2014) as challenges, obstacles and constraints, Jones and Boyd (2011) as cognitive, normative and institutional perspectives. Although the barriers of adaptation are of different nature (environmental, economic, legal, institutional), the literature analysed them most often from an integrative perspective. For example, barriers of different nature are integrated in the Process Model of private proactive adaptation to climate change (MPPACC) via a mediator variable – the governance process and the individuals' perception on their capacity and ability to adapt (Moser and Ekstrom 2010) (Figure 1). One other integrative models are the Socio-ecological system (Ostrom *et al*. 2009) (Figure 2) that put into the center of the adaptation the interractions between the ressource utilization and the users claims over resource units; or Ostrom's (1994) Institutional Analysis and development framework (applied by Bouriaud *et al*. 2015) (Figure 3) that center the adaptation inside the so-called action-arena that could be assimilated in most fo the European countries as being the forest amangement planning process.

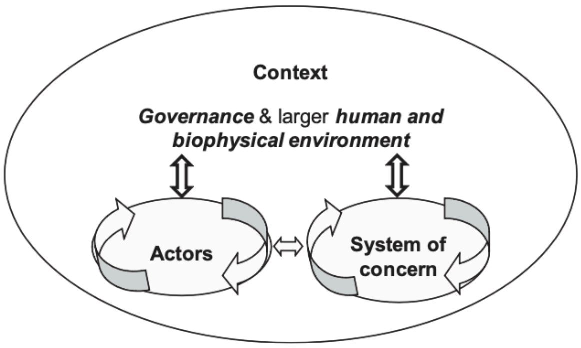

Figure 1. A framework to diagnose barriers to a system of concern (Moser and Ekstrom, 2010).

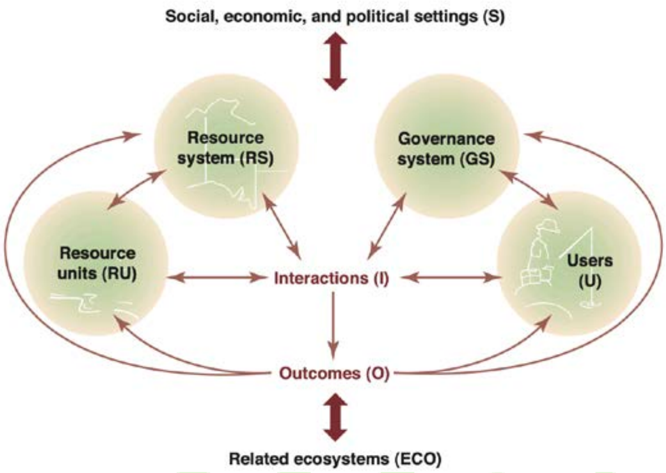

Figure 2. The socio-ecological system. Source: Ostrom *et al*. (2009).

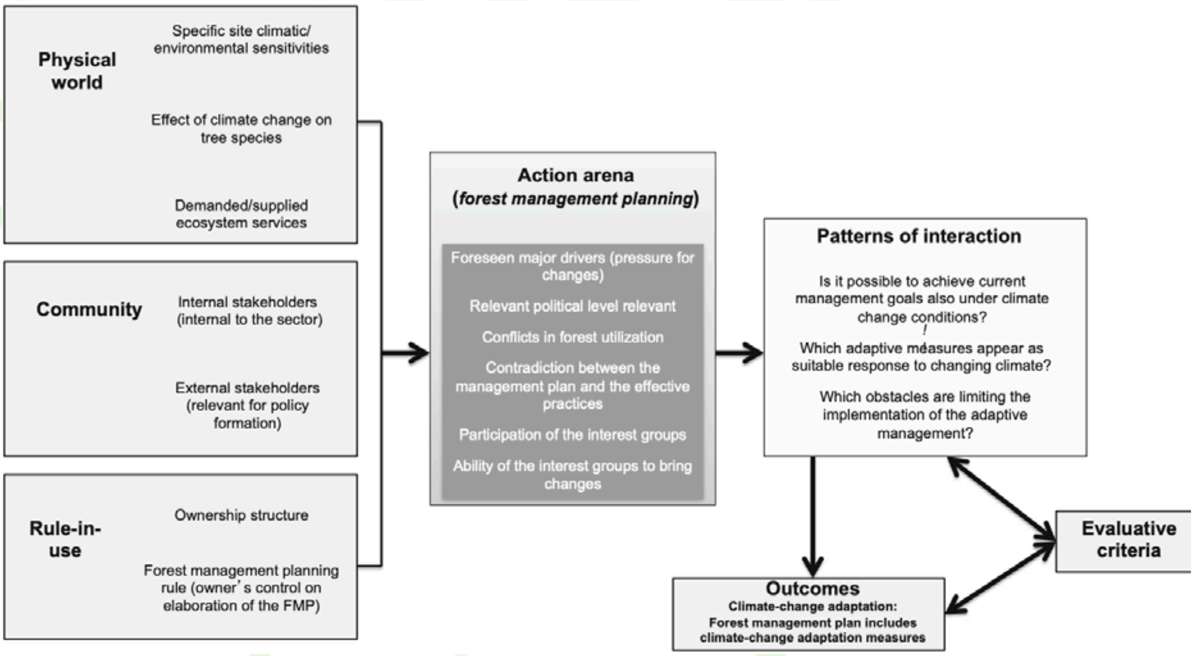

Figure 3. Institutional analysis and development framework applied to climate-change adaptation. Source: Bouriaud *et al*. (2015) adapted from Ostrom (1994).

Local (or national) perceptions of the climate chage and local (or national) forest management practices constitute social drivers that lead to policies and therefore to changes in the legislative framework. On the other hand, legislative changes lead to new economic or social behaviour. Therefore, the complex relationship between social, economic or legal drivers are better described in terms of governance of forest management adaptation to climate change.

According to the literature in the field of adaptation, barriers and opportunities for adaptation are present at three levels:

(1) individual level;

(2) organizational level, and

(3) enabling environment level.

They can occur during the entire climate policy cycle (Reyes 2017, Sietz *et al*. 2011).

Moreover, Biesbroek *et al*. (2011) identify seven categories of barriers, but they are not specific to climate change adaptation. These are:

(1) conflicting timescales;

(2) substantive, strategic and institutional uncertainty;

(3) institutional crowdedness and institutional void;

(4) institutional fragmentation;

(5) lack of awareness and communication;

(6) motives and willingness to act, and

(7) lack of resources.

Other studies categorize barriers as financial, technological, cognitive, cultural and institutional (Eakin and Luers 2006, Adger *et al*. 2009), or even more broadly as natural, human, and social (Jones and Boyd 2011).

Furthermore, another method (Moser and Ekstrom, 2010) consists in classifying the barriers in adaptation planning in six categories:

(1) leadership,

(2) resources,

(3) communication,

(4) information,

(5) values and

(6) beliefs.

Most of the studies are focused on a systematic review method (Biesbroek *et al*. 2013, Wang *et al*. 2019), a mixed-method approach (Reyes 2017), in which barriers are seen as static impediments and adopt a system-thinking approach, and participatory nature, in which was incorporated the meaning of experiential knowledge (Sanga *et al*. 2021, Jansson 2022). Moreover, Mukherjee (2018) and Ofoegbu *et al*. (2019) applied a policy arrangement approach with four dimensions: resources/power, discourses that are occured, game rules with formal and informal regulations, and involved actors. Wang *et al*. (2019) assessed the barriers' conditions from social and environmental perspectives and with its recommendation in urban areas. Climate change adaptation is among fields where a collaborative governance

(Kalesnikaite, 2019) has been supported for and reflected on many institutional barriers (Weber and Khademian 2008, Kalesnikaite 2019, Teermer *et al*. 2013). Moreover, the climate change is a cross-cutting issue being situated upon multilevel governance system, in which all four levels local, regional, national and global play an important role in governing climate change adaptation (Juhola and Westerhoff 2011, Ishtiaque *et al* 2021, Birchall *et al*. 2021, Dannevig and Aall 2015, Oulahen *et al*. 2018, Amaru and Chhetri 2013, Hague *et al*. 2018). Stern (2007) emphasizes that are few measures to prevent GHG emissions, but even so some barriers of behavior are present, such as awareness about the problem, finance, decisions methods, and attitudes problem among organizations.

Finally, Moser and Ekstrom (2010) evaluated the barriers for adaptation to climate change along the different stages of the decision-making process, e.g. understanding (detect a problem, get information, re-define the problem), planning (develop, assess and select options) and managing (implement, monitor and evaluate the implementation of the option) adaptation measures. The institutional adaptation is, however, context-dependent and therefore its analysis should consider both policy implementation and organizational transition (Primmer *et al*., 2011). In this context a comprehensive model of the decision-making process is the institutional analysis and development (IAD) framework (Ostrom 1990, Ostrom *et al*. 1994). However, even this comprehensive analytical framework is not self-explicit for the way the individuals and the organization will choose to adapt or not to adapt. Therefore, the IAD framework has to be combined with a cognitive model to place the motivation to act. The strengths of belief in climate change have an essential role in shaping adapting behaviour, as argued by Grothman and Patt (2005) who provide a scheme for understanding individual attitudes towards adaptation. The scheme can be applied also at the level of the organisation, eg. forest administrations or forest management structures.

3.2 Identifying the adaptation/mitigation measures and their barriers in the relevant literature

Following the steps proposed by Biesbroek *et al*. (2015), we performed a search in Google Scholar and the Web of Science's database using the key word '*forest mitigation and adaptation*' with different variants (*forest-based adaptation*, *forest-based mitigation*, *forest management adaptation to climate change*, *forest management contribution to mitigation of climate change effects*, *climate-smart forestry*, and *climate-adapted forestry*). The first query for the last 10 years provided us with 1,936 articles that we have further selected to comply with identifying the reference to barriers, opportunities or challenges. Thus, a final number of 162 papers were selected for review, which have been introduced in a database structured as following:

1. Article ID: (year, authorship, Title)
2. Key words
3. Abstract
4. Type of article: Review/ modelling / case-study/ other
5. Geographic region: Global, Europe-wide, boreal, continental, mediteraneean, atlantic, alpine, other
6. Proposed or analysed adaptation measure: is the study proposing measures and of which type (silvicultural, planning, policy, etc.) for adaption and mitigation?
7. Identified barriers: is the study considering the barriers and opportunities of adaptation and mitigation? It can be barriers/ obstacle/ bothlenecks/ risks of adaptation or mitigation, are they identified in the article, are they analysed?
8. Which are the projects financing the published research - project ID and name.

Among the 162 papers that were selected for reviewing, case-study based research is dominating with 84 publications, being followed by 37 based in modelling results and 41 reviews. Furthermore, only 94 of them are mentioning barriers and/or opportunities. The geographical distribution shows also papers in various regions outside Europe (60).

Focusing on Europe, overall European-wide based papers are in number of 6, continental biogeografical region is presented with 14 studies, boreal region with 10 studies, atlantic region with 8 studies, while mediteranean region is covered by 6 studies. For almost 60 papers the geographical affiliation was not a relevant criteria.

From the total of 162 scientific references, 32 of them have been funded by national institutions. Most of them are public institutions e.g. universities and other research bodies, ministries, national agencies or even research agencies. In only two cases the research has been funded by private companies. On the other hand, amongst the 23 papers mentioning EU financing sources, seven were financed by European Research Council via H2020, four by FP7 programme, two were financed by a COST action, two by ERDF, and the remaining by other sources (European Biodiversity Partnership, European Investment Bank). In fact, most of the studies were financed by European Commission research-development funds. In general, we can state that public money was largely dominant to finance climate change-based research in forestry adaptation/mitigation in the two last decades.

4 Results

Following the described methodology, the identified barriers and opportunities for implementation of mitigation and adaptation measures in forestry in Europe are described in a summarized way in this chapter.

4.1 A summary of the adaptation/mitigation measures

The main adaptation/mitigation measures in forestry are structured in the following blocks:

a) Measures to increase forest-based mitigation effects (technical solutions)
b) Measures to facilitate adaptation of forests and forestry to climate-change (technical solutions)
c) Measures to increase the social and policy up-take of the technical solutions, the acceptance of new strategies and planned advisory services (socioeconomic measures)
d) Measures to facilitate institutional innovation and integrative policies (political, legal and administrative measures).

In the following paragraphs, each group of adaptation/mitigation measures is related to the most relevant scientific-technical publication(s).

4.1.1 Measures to increase forest-based mitigation effects (technical solutions)

1. Maintaining or increasing forest area (Sharma *et al*. 2013);
2. Increasing stand- and landscape-level carbon (C) density (Sharma *et al*. 2013);
3. Providing timber, fiber or energy from sustainable forest management to store C in long-lived products and displace the production of more emissions-intensive products (Sharma *et al*. 2013);
4. Assessing land use categories for their actual C sequestration (and compare against each other) (Agrawal *et al*. 2014);
5. Using biodigesters to reduce the use of firewood and the quantity of CO_2 released in the atmosphere (Nganje and Larwanou 2019);
6. Implementing sustainable intensification of cropping systems to better take into account the risks of trade-offs between productivity, ecosystem services and biodiversity in landscape planning in agricultural areas (Forsius *et al*. 2013);
7. Adopting the attitude of active management for the development and implementation of new forest models that include climate change uncertainty (Petr *et al*. 2014).

4.1.2 Measures to facilitate adaptation of forests and forestry to climate-change (technical solutions)

1. Facilitating a shift towards more climate adapted species (Bouriaud *et al*. 2015, Jandl *et al*. 2019);
2. Changing the rotation or the thinning schedule (Bouriaud *et al*., 2015; Jandl *et al*. 2019);
3. Replacing monospecific forests and promoting mixed forests (Bouriaud *et al*. 2015, Giuggiola *et al*. 2013) by increasing the species composition diversity by planting ponderosa pine as a potential replacement species for red pine, given the physiological and ecological similarities between the two species (Muller *et al*. 2019);
4. To improve the resilience of forests to storm damage by enhancing individual-tree stability and by reducing top height of stands (Bouriaud *et al*. 2015);
5. Regulating tree density for an improved water use efficiency of the remaining trees and a decreasing fire risk (Bouriaud *et al*. 2015);
6. To potentially replace with species adapted to drought and to future disturbance regimes and climate conditions (Muller *et al.* 2019);
7. Using ecological models to address ecosystem vulnerability (Wang *et al*. 2019);
8. Establishing a non-management network composed of old-growth patches (Fouqueray *et al*. 2019);
9. Maintaining forest heterogeneity, avoiding forest-use intensification and natural habitat loss (Fouqueray *et al*. 2019);
10. To promote urban green infrestructures (Nganje and Larwanou 2019);
11. Restorating degraded landscapes to alleviate the current and future negative impacts of climate and anthropogenic disturbances or catastrophes (Nganje and Larwanou 2019);
12. Taking action to reduce or manage natural or human-induced perturbances, such as pests, droughts and storm risks (Petr *et al*. 2014); and specially taking measures for wildfire management. The benefits of thinning in reducing drought and fire vulnerability have been broadly demonstrated (Vilà-Cabrera et al., 2018). In fire management in Mediterranean area, a land management approach and fuel management measures are recommended (Fernandes 2013), as far as the fire regime will be largely driven by local meteorological conditions. Management should focus on fire severity prevention and forest resilience as well as on fire suppression insfraestructures (Fernandes, 2013).
13. To foster afforestation, reforestation and sustainable forest management, in particular in regions with high risk of fire-prone pioneer tree species (e.g. pines) and shrub communities regeneration (Resco de Dios *et al*. 2007), as well as forest expansion on agriculture marginal lands (Rojas-Briales *et al*. 2023, Belgado-Artés *et al*. 2022).

4.1.3 Measures to increase the social and policy up-take of the technical solutions, the acceptance of new strategies and planned advisory services (socioeconomic measures)

1. To launch programs or initiatives to educate the society, employees of vulnerable economic sectors, and government officials to reduce the challenges posed by uninformed (or misinformed) people on forest adaptation to climate change (Wang *et al*. 2019);
2. To increase public awareness of climate change impacts on forests (Wang *et al*. 2019);
3. To improve the accessibility and dissemination of research findings, models, and management tools for enabling researchers and resource managers to address areas where knowledge gaps exist (Sterrett 2011, quoted by Wang *et al*. 2019);
4. Communities expressed their needs for in-depth training in sustainable forest management practices (Ofoegbu *et al*. 2019);
5. To involve local stakeholders in planning for adaptation to socioecological changes for the strengthening of local efforts in dealing with climate change challenges and livelihood resilience against climate risk (Ofoegbu *et al*. 2019);
6. Establishing suitable mechanisms and information systems for sustainability of ecosystem services (Chow *et al*. 2019);
7. To deal with uncertainities: social and climatic categories should help forest policy-makers to prioritize, avoid, accept or better communicate specific uncertainties in policy documents, especially for climate change adaptation (Petr *et al*. 2014).

4.1.4 Measures to facilitate institutional innovation and integrative policies (policy, legal and administrative measures)

1. Maintaining more resilient and sustainable land-use systems (Wang *et al*., 2015);
2. Integrating climate change adaptation into normal sustainable development planning (Silwal *et al*., 2019);
8. The adaptation to climate change emphasis on forest stands level could be a brake for managing ecological connectivity (Fouqueray et al. 2019);
3. (policy) precautionary measures for sustainable forestry are to be preffered (Fouqueray *et al*., 2019);
4. Improving the current governance structures by ensuring the continuity of research projects (Chow *et al*., 2019);
5. Adopting or adapting pathways for implementation of forest-related climate initiatives, including REDD+ pilot projects (Nganje and Larwanou 2019);
6. Assessing the carbon balance of any bioenergy production system over the life cycle of the product (Vanhala *et al*. 2013);
7. Adopting climate risk maps to gain legitimacy for climate change adaptation measures independent of their practical functions for decision-making (von Detten and Faber 2013);

8. Improving organizational dialog regarding the criteria of how to assess the different measures, strategies and decision-support tools concerning climate change adaptation (von Detten and Faber 2013);
9. Increasing financial incentives to promote wider adoption of climate friendly best practices in agriculture, forestry, agroforestry and pasture management (Dhillon *et al*. 2013);
10. Considering multiple purpose land use would help to prevent potential conflicts between 'development' and 'conservation' (Nijnik *et al*. 2013);
11. Assessing the actual implementation of climate change related forest policy measures in order to assess their effects on biodiversity (Storch and Winkel 2013);
12. To assess the risks associated with anticipated changes in fire regimes prior to implementation of a conservation strategy aimed at climate change mitigation (Sharma *et al*. 2013);.
13. Deeply understanding ecosystem forest C dynamics and prognosis for future CO_2 sequestration or natural release in order to identify which protected areas are most likely to provide sustained climate change mitigation (Sharma *et al*. 2013).

4.2 A summary of the barriers

The main identified barriers are structured in the following blocks:

a) Environmental constraints
b) Conflicts in the forest utilisation and land-use system, and their trade-offs
c) Implementation gaps
d) Social acceptability and preferences
e) Addressing uncertainties and lack of information
f) Financing
g) Barriers to long-life, high-value forest products

Each barrier is related to the most relevant scientific-technical publication(s).

4.2.1 Environmental constraints to adaptation according to the biogeographical region

EU forests will probably experience disturbances of higher intensity and higher frequency (Seidl et al. 201, 2017, Senf and Seidl 2018). Early signs of declining forest resilience under climate change spark concerns about the future state of forests (Liu et al. 2019, Senf et al. 2018, Forzieri et al. 2022). Satellite-based data show higher variability in radiometric indices during 2000-2020. This increase in variability is a sign of reduced resilience towards climate variability, in particular, the recent droughts. According to Senf et al. (2020) the recent increase in canopy mortality observed throughout Europe is largely linked to drought. But their 2018 study (Senf et al., 2018) also showed that the inferred satellite-based canopy mortality had a very regional variability component, which pointed to the strong influence of the forest type and the management system. Thus, despite undeniable large-scale trends, the actual intensity will vary locally depending on several environmental factors.

The forests from Boreal region

Noticeably, boreal forests do not show similar trends in mortality compared to temperate forests. This further underlines the fact that many determinants of the forest response to disturbance factors (even to the large-scale abiotic ones) is largely influenced by local factors. Boreal forests may benefit from warmer conditions and a continued nitrogen deposition that globally improves the fertility, resulting in increased productivity. This increase in productivity (Kellomäki et al. 2018, Kauppi et al. 2022) is also largely sustained by the projected increase in precipitation (Ruosteenoja et al. 2016). The threats in boreal forests therefore differ from that of temperate forests in that it could be related to (Reyer et al., 2017; Venäläinen et al. 2020): higher frequency of snow damages; extensive wind damages; outbrake of new pests, that would benefit from higher temperatures.

The forests in the Atlantic region

The Atlantic region is one of the most heavily populated and intensely managed areas in Europe. Many natural and semi natural habitats are now fragmented patches in a largely artificial landscape. After decades of deforestation, many of the forests in western Europe's Atlantic region are plantations, and these forests sustain competitive wood-using sectors and have rapid growth rates by European standards (Mason and Meredieu, 2011). In the nineteenth century Sitka spruce was one of the species which had been introduced in Atlantic Europe (e.g. Ireland, United Kingdom, Norway, France and Denmark). Yet, increasing the structural and species diversity of Sitka spruce forests is a goal of many countries' forest strategies; these steps are also recommended to help with climate change adaptation and risk management (Mason and Perks 2011).

In the case of forest ecosystems there are some trends highlighted into litterature:

- From northern France to boreo-nemoral Sweden, the studies (Reinecke et al., 2016) related to shifts in the pH niche show that differentiating between acidophilic and neutrophilic species is crucial to identify general patterns and underlying mechanisms. For example, with increasing latitude, neutrophilic species tended to retreat from acidic sites, indicating that these species retreat to more favorable sites when approaching their range margin. Alternatively, these species might benefit from enhanced nitrogen deposition on formerly nutrient-poor, acidic sites in southern regions or lag behind in post-glacial recolonization of potential habitats in northern regions. Most acidophilic species extended their niche toward more base-rich sites with increasing latitude, indicating competitive release from neutrophilic species. Alternatively, acidophilic species might benefit from optimal climatic conditions in the north where some have their core distribution area (Reinecke et al, 2016).

- Recent growth trends of conifers across Western Europe are controlled by thermal and water constraints and favored by forest hetero-geneity (Clémentine et al, 2020). Native forests showed a more heterogeneous forest structure as compared to introduced forests that, in line with observed positive dependence of tree growth trends onto both water availability and forest heterogeneity, appears to modulate the competitive pressure on water resources with ongoing summer maximum temperature increase (Clémentine et al, 2020).

- the futures of forest systems are uncertain because change may come mainly from socio-economic, and not ecological, drivers (Schoene and Bernier 2012). Adaptation strategies must therefore move away from single technical solutions and must not rely on one-size-fits-all mechanisms (Mora et al, 2014). The authors identified drought resistance and soil fertility as important environmental constraints for forest adaptation to climate change, the soil fertility being very much influenced by the forest management intensity.

More extreme changes are expected in the southern areas of the UK, where severe summer droughts will become more frequent. Current climate change prognoses suggest that most native broadleaf species from southern England may become less suitable for timber production on some soils (Broadmeadow et al., 2005). However, the genetic diversity of the local native populations could generate some adaptation features.

Woodland managers are aware of some changes, especially concerning tree disease, even if they are generally not convinced they need to adjust to climate modifications (Lawrence & Marzano, 2014). Although species choice is the main focus of adaptation, there are still divergent opinions. However, to preserve woodland cover and guarantee a sustainable hardwood timber sector, the planting of non-native species should be considered.

Adapting Atlantic forests to climate change presents a number of challenges, but eight of them are applicable to the entire Atlantic region (Massion and Meredieu 2011). Therefore, they refer to (Masson et al. 2009a):

1. Create methodologies in order to help forest managers in identifying the sites and stands most vulnerable to climate change.

2. Development of a data base/knowledge on how various species are expected to respond to climate change, matched by research on how their populations and distributions are actually changing

3. Improved understanding of the regional factors that will become limiting for species

4. Testing of species/provenances/genetically improved varieties that may be suitable for the current and projected Atlantic climates

5. Improved understanding of how climate change will affect wind, fire, pest, and disease disturbance regimes

6. Improve wind climate prediction and adapt existing wind risk models to predict vulnerability of more diverse stand structures.

7. Adapting growth models developed for even-aged single-species forests to more diverse forest types and/or providing more flexible models

8. Improved comprehension of appropriate decision-making methods, including methods for dealing with uncertainty and integrating multiple societal values

The forests from the Continental region and Alpine region

The European bark beetle constituted the dominant pest (Grégoire and Evans 2007) with a huge impact on Central European forests (Hlásny *et al*. 2019). The increase in temperatures could increase voltinism and favour the expansion of the pests.

Forest fire comes with indirect effects of increased temperatures and increased droughts. The decrease of the surface soil layers will increase susceptibility to fire. Projection show that the area of forest subjected to fire will increase as a result of the climate changes, making its apparition in regions so far relatively immune (Venäläinen *et al*. 2014). In particular, eastern and southern Europe seem more exposed to a rise of fire danger.

Drought is perhaps the most ubiquitous threat. Mountainous forests will probably suffer more than lowland forests due to the differential dynamics of temperatures and precipitations. According to Pepin *et al*. 2022, mountains experience enhanced warming compared to lowlands, but the precipitation trends is not different from that of lowlands. Therefore, the drought trends will probably be exacerbated in the Alpine region of Europe. The large-scale decline of Scots pine in the Alps could be taken as an example of the large-scale mortality that could be triggered by a rapid increase in drought.

According to Forzieri *et al*. (2021), the increase in disturbance hazards is not homogeneous throughout Europe but rather shows a "hotspot" thought to be located at the border of the climate envelope namely southern and northern European forests.

The forests in the Mediterranean region

Data show that climate change has already noticeably increased the fire risk in Mediterranean forests (Raftoyannis *et al*. 2014). The increase in extreme events and the increase in the length of the growing season seem to be the main drivers of this enhanced fire risk (Moriondo *et al*. 2006).

Simply put, the trends towards hotter and dryer conditions are exacerbating the Mediterranean stress (Valladares *et al*. 2014) despite the very high resilience of these forests well suited to the climate. Forest fragmentation emerges as an important factor that could reduce the adaptability of forests (Valladares *et al*. 2014).

Responses to drought and heat however show a very high resilience, which points to acclimatization to even larger temperatures (Lacopetti *et al*. 2022).

The Mediterranean region could see a differentiation in climate trends, such that the currently wettest sites could evolve towards drier conditions, whereas the dry sites could have only minor increases of the drought intensity (Ruffault *et al*. 2012).

The maps of disturbance shown by Senf and Seidl (2018) show a high spatial variability and underline the fact that, beyond trends, local conditions will alter largely these trends. The "one size fits all" is largely challenged here.

4.2.2 Conflicts in the forest utilisation and land-use system, and their trade-offs

1. Nature conservation versus timber production represents the main conflict line (Bouriaud *et al*. 2015), with a lack of trust foresters and conservationists (Buizer and Lawrence 2014);

2. Adaptation is slow, often intangible, a constantly moving goal, and challenging because it has to engage with both social and ecological complexity and value conflicts (Buizer and Lawrence 2014);
3. Trade-offs between targeted measures to reduce impacts and improve adaptive capacity (Seidl and Lexer 2013);
4. Balancing these relatively new management concerns with the traditional concerns about biodiversity and ecological integrity will be a new and challenging task for protected area managers just as it is for land resource managers in many other jurisdictions (Sharma *et al*. 2013);
5. Successful forest-based climate mitigation will require policies that are cognizant of fundamental trade-offs in forest ecosystem C dynamics and the provisioning of other forest ecosystem services (Giebink *et al*. 2022).
6. Adaptation objectives might conflict with the processes at the ecosystem level. Adaptation strategies aim at decreasing the risk of natural or human-induced disturbances and promoting resistance in the short-term, but long-term resilience is rather neglected. Focusing on short-term benefits frequently has unintended consequences on other adaptation objectives and untargeted ecosystem components (Vilà-Cabrera *et al*. 2018).

4.2.3 Implementation gaps

1. The gap between the intended objectives set up in the regional forest policies and their practical implementation (Bouriaud *et al*. 2015);
2. Climate change adaptation seems to be impeded or slowed down in cases where decisions on adaptation measures need to go through a whole political process, involving high political-level decisions (Bouriaud *et al*. 2015);
3. Knowledge and strategies to adapt forests to climate change are not enough if there are insufficient quality action plans and legislation to transform this knowledge into action (Wang *et al*. 2019);
4. Action plans are often fragmented, lacked of comprehensive solutions, focused on specified sectors, and failed to address long-term mitigation and adaptation to climate change (Wang *et al*. 2019);
5. People have weak capacity to participate meaningfully in forest management in terms of skills, education, knowledge of forest regulation legislation, and community organization (Ofoegbu *et al*. 2019);
6. Difficulty of decoupling household livelihood activities from destructive forest-use practices in the rural areas (Ofoegbu *et al*. 2019);
7. The lack of adaptation to climate change measure ready for implementation (Fouqueray *et al*. 2019);
8. Forest management agencies corruption and lack of local community engagement (Chow *et al*., 2019);
9. The gap between technical potential and realized GHG mitigation, due to a gap caused by barriers in implementation and economic constraints (Dhillon and Wuehlisch 2013);

10. Costly investments in planting, especially with non-traditional species, such as black cherry or bitternut hickory (Muller *et al*. 2019);
11. Policy itself often works in a fragmented, piecemeal fashion (Agrawal *et al*. 2014);
12. Weak law enforcement capacity, including the regulation of other actions, such as game browsing, overgrazing, illegal logging, or unsustainable agroforestry practices (Bouriaud *et al*. 2015).

4.2.4 Social acceptability and preferences

1. Preferences and current practices of stakeholders (forest managers and land owners) are the main impeding factors of adaptation (Bouriaud *et al*. 2015);
2. Mobilizing forest owners to adaptative actions remains one of the most crucial future tasks (Mostegl *et al*. 2019);
3. Traditional concepts of silviculture are insufficient to prepare the forests for future conditions (Jandl *et al*. 2019);
4. Insufficient awareness about ecological requirements and sustainable management practices of forests may constrain their adaptive capacity for future climate change (Wang *et al*. 2019);
5. Education and awareness-raising are the issues of greatest concern, with 'public awareness' knowledge on climate change lacking the most scientific support (Wang *et al*. 2019);
6. Some „old" practices (e.g. the planting of foreign tree species) are proposed as solutions without an apparent (micro) political reasons (von Detten and Faber 2013);
7. Dialogue between forest owners and civil society: high risk of non-acceptance of adaptation projects, need to ensure concertation and possibly co-creation of projects at the local level (I4CE 2020, Luhas *et al*. 2021).
8. Institutional stability, that is pending on the preferences and current practices of internal stakeholders in the 'action arena', by a stable process of forest management planning and by the ability of external actors to provide expertise and trigger changes in forest management practices; if the current management satisfies the most influential and powerful existing stakeholders, there are no incentives for adaptation (Bouriaud *et al*. 2015).
9. Policymakers should involve local communities in the design and implementation of future climate change mitigation and adaptation strategies (Luhas *et al*. 2021).

4.2.5 Addressing uncertainties and lack of information

1. The lack of landmarks when selecting patterns of interaction variables (Bouriaud *et al*. 2015);
2. Silvicultural approaches as part of transition treatment, e.g. planting a suite of both native and novel future climate-adapted species, address the challenges and uncertainties associated with forest sustainability and climate change (Muller *et al*. 2019;.

3. Lack of guidance when making decisions on forest management with long-term implications (Jandl *et al*. 2019);
4. It is often impossible to use unmanaged reference forests as a benchmark for the most appropriate strategy of adaptive forest management (Jandl *et al*. 2019);
5. An important challenge for the forestry sector is to respond to a lack of scientific support, particularly a lack of understanding of locally predicted climate change scenarios (Wang *et al*. 2019);
6. A lack of accessibility and understanding of the tools available for climate change adaptation may also contribute to a perceived lack of scientific support (Wang *et al*. 2019);
7. Local stakeholders and the facilitators have limited technical knowledge about loss of species, low productivity of forests and the outbreak of invasive species, therefore involving experts is necessary (Silwal *et al*. 2019);
8. Limitation of knowledge on potential measures to deal with climate change impacts (Silwal *et al*. 2019);
9. One of the challenges is to develop predictive models founded on physical principles and capable of working with the constraints of available data that are also consistent with empirically observed mechanisms (Forsius *et al*. 2013);
10. Future uncertainty is a major issue in developing long-term forest management strategies (Seidl and Lexer, 2013);
11. A key challenge for adaptation is to balance between anticipating expected future conditions and building the capacity to address unknowns and surprises in the future (Seidl and Lexer 2013).
12. Data limitations for C stock densities in national park forests (Agrawal *et al*. 2014, Kašanin-Grubin and Burton 2021);
13. Acknowledgement of adaptation-related uncertainties involved in forest management due to climate change (Buizer and Lawrence 2014);
14. High uncertainty about the climatic category and the randomness of nature is a cause of inertia to climate change adaptation in forest planning (Petr *et al*. 2014);
15. The ability to control and regulate the risks is probably a key reason for the inertia to climate change adaptation in forestry (Petr *et al*. 2014).

4.2.6 Financing

1. Investments: cost of restauration of degraded stands (Stanturf *et al*. 2015), especially in the context of climate change impact and resilience: need for diversified plantations (Muller *et al*. 2019), risk of death of young plants, need for protection against wildlife (Wang *et al*. 2019).
2. Costs of enabling actions and infrastructures, e.g. research and development; experimentation (Wang *et al.* 2019); transfer of knowledge from science to practice; need for tools or climate services to support practitioners' decision making (Financing 'boundary spanners', 'facilitators') (von Detten and Faber 2013, Wang *et al*. 2019, Silwal *et al*. 2019, Ofoegbu *et al*. 2019)

3. Financial incentives to promote wider adoption of climate friendly best practices in agriculture, forestry, agroforestry and pasture management. (Dhillon and von Wuehlisch 2013)

4.2.7 Barriers to long-life, high-value forest products

1. Emergency harvests may hamper the transformation for long-life forest products, especially timber, e.g.lesser quality and smaller diameter than expected. They could still be used in long-life hard wood products (HWP) but not in all kind of products, at least not without some technical adjustments (I4CE 2020);
2. Transformation woodworking industries should be able to adapt to a more diverse (in terms of species) and less predictable resource (in terms of diameters and quality) in the future (I4CE 2020);
3. Higher energy prices may deflect part of the resources towards energy uses and make energy use more attractive (I4CE 2020);
4. Insulating panels are still more expensive than classic materials and would probably need public support or a strong industry development to be competitive (I4CE 2020);
5. Innovation is likely to be neglected or suppressed if considered potential objections within the organization or from the social environment (von Detten and Faber 2013).

4.3 A summary of the opportunities

The main identified opportunities are structured in the following blocks:

a) Opportunities to trigger a change depend on governance factors
b) Opportunities for forest adaptation stay in the current state of forests and ongoing forest-related policy processes
c) Opportunities for long-life high-value forest products

In the following subsections, each opportunity is related to the most relevant scientific-technical publication(s).

4.3.1 Opportunities to trigger a change depend on governance factors

1. Ability of the external stakeholders' to intervene in the decision-making process (Bouriaud *et al*. 2015);

2. The collective-choice-level of decision is the level at which the rules should be modified to make adaptation occur (Bouriaud *et al*. 2015);
3. The ownership pattern may facilitate the implementation of planned measures of adaptation, if several other conditions exist e.g. beliefs in climate change, freedom in forest-related decision, system openness to participation (Heltorp *et al*. 2018);
4. The beliefs and expectations of forest owners and managers (Blenow *et al*. 2014, Heltorp 2019).

4.3.2 Opportunities for forest adaptation stay in the current state of forests and ongoing forest-related policy processes

1. Age class structure of forests are an opportunity to adapt without additional costs. Old forests arrived at the regeneration age offer the opportunity for adaption when based on natural regeneration (Bouriaud *et al*. 2015);
2. Take advantage of degraded forests and policy support to make the right adaptation decisions and resilience choices: this sound obvious but is not necessarily the case. Need for knowledge transfer from science to practice and political decision-makers to make the most informed decisions, even in a context of uncertainty (Cook *et al*. 2013).
3. Recovery plans and climate policy funding. Strong focus on carbon sinks and opportunities for financing adaptation strategies (Verschuuren 2018).

4.3.3 Opportunities for long-life high-value wood products

1. Climate policies: should heavily focus on building renovation for the next 20-30 years to meet climate targets, with a huge potential for panels and insulation materials, which are under-exploited today. Resources that are currently used for energy purposes could be directed towards those type of products (cascade use of wood) (Brunet-Navarro *et al*. 2018).
2. New regulations to limit carbon emissions from the building sector are also promoting the increased use of bio-based products, including alternative innovative and advanced wood-based and cork products, in construction (Lange *et al*. 2021).
3. Hardwood transformation potential is being identified and targeted in some recovery plans, e.g. France (I4CE 2020). So, there is an opportunity for better material use and products industrial transformation (e.g. HWP).
4. Development of long-life bio-based products is part of several climate strategies in Europe as a way to increase carbon sinks, especially in construction, but also in furniture, packaging or paper products.
5. Carbon certification mechanisms (especially at the UE level) could help bring financial incentives for the use of local long-life forest products in circular economy (recovering and recycling), including substitution effect of other energy intensive materials with hiogher GHG emissions (e.g. steel, concrete, plastics) (I4CE 2020).

4.4 Matching measures, barriers and opportunities

Opportunities to trigger a change in the sustainable forest management strategy depends on different levels of decision (Bouriaud *et al*. 2015) and on the power-relationship present at every level of decision-making. The current state of forests (legacies, planning system, age, restoration needs, prevention of disturbances, etc.) and ongoing forest-related policy processes represent opportunities for both adaptation and mitigation. There are plenty of opportunities for long-life high-value forest products driven by policies and markets.

Literature proposes different type of adaptive management scenarios. They can be classified (as suggested by Hörl *et al*. 2020) in resistance-type strategies (mostly recommended thinning, prescribed burning, and decreased rotation length) and resilience-oriented strategies (mostly recommended species composition changes). In our review, we distinguished between the first level type of technical solutions (measures) and enabling measures.

The available technical solutions to increase forest-based mitigation effects or facilitate the adaptation of forests and forestry to climate change face several types of barriers:

1. Implementation gaps (13)
2. Social acceptability and preferences (10)
3. Addressing uncertainties and lack of information (15)
4. Conflicts in the forest utilization and land-use system and trade-offs (7)
5. Financing (2)

However, the literature review shows that there are measures tested or suggested to cope with these barriers, via two kinds of enabling measures:

1. Measures to increase the social and policy up-take of the technical solutions, the acceptance of new strategies and planned advisory services (7)
2. Measures to facilitate institutional innovation and integrative policies (14).

Irrespective of the measures proposed, there are implicit trade-offs: as expressed by Hörl *et al.* (2020), none of the climate change recommendations in the literature is robust if considering multiple ecosystem services.

5 Conclusions and implication for WP1 and WP4

5.1 Pre-existing conditions and arrangements determine barriers and opportunities

The maps of climate-change enhanced disturbance in Europe (Senf and Seidl 2018) show a high spatial variability and underline the fact that event there are general trends, local conditions will alter largely these trends. For this reason, implementation of the planned adaptation measures depends on their scope and their level of congruence with local existing forest management practices (Bouriaud *et al*. 2015). Usually, the measures tend to be defined in accordance with the current legal frame of forest management and / or European forest and nature-related policy recommendations. Thus, the adaptation measures do not substantially break with the existing practices (Bouriaud *et al*. 2015), which fits with the debate about incremental versus punctuated change (Mahoney and Thelen 2010): policy instruments are accepted as long as they do not involve a change in the current management practices (Serbruyns and Luyssaert 2006). Foresters's traditional attitudes based on long years of experience in forest management in Europe are favoured by the dominance of planned top-down decision-making and the wider command-and-control culture of forest management (Lawrence 2009, Lawrence 2017).

Each stage of the rational decision-making process has its own type of limits to adaptation (Moser and Ekstrom 2010). While revieweing the literature on adaptation, the barriers are analysed in general at the implementation stage. However, the forest owners' and managers' strength of belief in local effects of climate change are critical for adopting adapted measures (Yousefpour *et al*. 2013, Blennow *et al*. 2014), but so it does their implication in forest management decisions (Heltorp 2019). Also, the demand for competing ecosystem services influences the decision-making process and the scope of adaptation measures proposed in dictating the conflict lines in forest utilization. Thus, pre-existing frames and beliefs (Williamson *et al*. 2012) and pre-existing institutional arrangements (Lukasiewicz *et al*. 2016; Abrams *et al*. 2021) determine the barriers or opportunities for adaptation or mitigation.

An aspect that is not well developed in the literature is the fact that some demographic, political or economic factors could represent as either a barrier or opportunity (e.g. the dependence on forests for livelihood, for firewood, the age of the forests, the needs for restoration, etc.). Also, there is a room to advance in the direction of matching barriers and opportunities, e.g. how to transform a barrier/challenge into an opportunity for better organizational, economic or technical solutions coping with the negative effects of climate change. Some of the barriers to the measures proposed need to be declined in immediate actions and enabling actions. For example, the generic 'financial barriers' to adaptation strategies include both the need to fund forestry climate-change sound measures, especially when dealing with privately owned forests and the need to ensure the "enabling actions" which will allow forest investments themselves. Those enabling actions often need human resources within public institutions (researchers, public forest managers, etc).

5.2 Multilevel governance is an opportunity for changes

Institutional stability may be a serious barrier to adaptation if the forest policy formulation process is not open to external expertise. External stakeholders may use the opportunities at the next level of forest policy-making in order to lobby for adaptation/mitigation measures (Bouriaud *et al*. 2015). More room should be created for the internal and external local expertise to achive local-based adaptation (Adger *et al*. 2005, Sharma *et al*. 2013). In multi-level governance, adaptation is subject to the infuence of locally or regionally powerful interests, dependent upon resources and strategic interventions from powerful higher-level actors, and limited by temporal factors including the long-term nature of infrastructure changes and the short-term nature of political attention to environmental change" (Abrams *et al*. 2021).

5.3 Perceived need to change and the power to change are both barriers and opportunities for implementation

Forest management adaptation to climate change is limited by the perceived need to change. If forest management is perceived as being able to provide the same degree of forest goods and services in a future affected by climate change, there is no need to implement alternative adapted management strategies (Bouriaud *et al*. 2015). The more perceived risk of negative effects (disturbances, lose of forest species, loss of productivity), the more incentives exist for adaptation. The beliefs in the negative effects of climate change are an essential factor in adapting behaviour (Blennow and Persson 2009; Blennow *et al*. 2012; Lawrence and Marzano 2014). Sociological instruments, such as questionnaires or interviews can be used to understand the propensity to change forest management practices.

5.4 The typology of barriers suggests that an enabling environment is needed, but the departure point for researchers is dealing with legacies and communicating about uncertainty

The literature review shows that there are governance, political and financial drivers to allow for the adaptation and/or mitigation of forest-based strategies to happen. However, while technical solutions exist to trigger adaptation and/or mitigation, their implementation is affected by forest sector intrinsic conservationism, uncertainty (relative effectiveness and efficiency of the measure), **side effects** (such conflicting values on forest ecosystem provision and their trade-offs) and lack of institutional enabling environment. **Financial and technical barriers** (poor information, poor infrastructure, lack of access to capital for adaptation, high costs of uncertainties) co-exist with **regulatory and legal barriers** (forest management planning rules or legal rules may impede innovation in adaptation to climate change) and knowledge and attitudinal barriers (scarcity of research, lack of forest management skills climate-sound in silviculture, fire/storm risk, planning, disregard for climate change, climate sketpticism of climate fatalism, lack of political will, lack of training sources, guidance and advice, lack of networking, trust or cooperation). A major problem for uptaking in practice adaptation or mitigation measures remains also in the fact that different assumptions and modelling frameworks can give very different conclusions regarding the effectiveness of forest-based climate mitigation or climate adaptation techniques.

The implications for WP1 and WP4 are that:

1) INFORMA project needs to deal with uncertainity and to be able to communicate with stakeholders about this (e.g. finding indicators);
2) INFORMA project needs to consider local expertise, perceptions, trade-offs and controversies to increase research-results uptaking in practices, and to properly communicate the trade-offs and risks associated with the measures proposed;
3) INFORMA project needs to be aware of legacies when selecting the appropriate climate change adaptation and mitigation strategies: every region and case study has its own particularities.

For the reasons above, it is likely that the proposed measures and strategies will address stakeholders' expectations to a higher extent if the models will consider real management practices and will make a place for local expertise.

6 References

Abrams, J., Huber-Stearns, H., Steen-Adams, M., Davis, E.J., Bone, C., Nelson, M.F. and Moseley, C., 2021. Adaptive governance in a complex social-ecological context: emergent responses to a native forest insect outbreak. *Sustainability Science*, *16*(1), pp.53-68.

Adger, W.N., Arnell, N.W. and Tompkins, E.L., 2005. Adapting to climate change: perspectives across scales. *Global Environmental Change*, *15*(2), pp.75-76.

Adger, W.N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D.R., Naess, L.O., Wolf, J. and Wreford, A., 2009. Are there social limits to adaptation to climate change?. *Climatic change*, *93*(3), pp.335-354.

Agarwal, B., 2010. *Gender and green governance: the political economy of women's presence within and beyond community forestry*. OUP Oxford.

Alonso, L., Picos, J. and Armesto, J., 2022. Automatic Identification of Forest Disturbance Drivers Based on Their Geometric Pattern in Atlantic Forests. *Remote Sensing*, *14*(3), p.697.

Amaru, S. and Chhetri, N.B., 2013. Climate adaptation: Institutional response to environmental constraints, and the need for increased flexibility, participation, and integration of approaches. *Applied Geography*, *39*, pp.128-139.

Biesbroek, G.R., Klostermann, J.E., Termeer, C.J. and Kabat, P., 2013. On the nature of barriers to climate change adaptation. *Regional Environmental Change*, *13*(5), pp.1119-1129.

Biesbroek, R., Dupuis, J., Jordan, A., Wellstead, A., Howlett, M., Cairney, P., Rayner, J. and Davidson, D., 2015. Opening up the black box of adaptation decision-making. *Nature Climate Change*, *5*(6), pp.493-494.

Biesbroek, R., Klostermann, J., Termeer, C. and Kabat, P., 2011. Barriers to climate change adaptation in the Netherlands. *Climate law*, *2*(2), pp.181-199.

Birchall, S.J., MacDonald, S. and Slater, T., 2021. Anticipatory planning: Finding balance in climate change adaptation governance. *Urban Climate*, *37*, p.100859.

Blennow, K. and Persson, J., 2009. Climate change: Motivation for taking measure to adapt. *Global Environmental Change*, *19*(1), pp.100-104.

Blennow, K., Persson, E., Lindner, M., Faias, S.P. and Hanewinkel, M., 2014. Forest owner motivations and attitudes towards supplying biomass for energy in Europe. *Biomass and Bioenergy*, *67*, pp.223-230.

Blennow, K., Persson, J., Tome, M. and Hanewinkel, M., 2012. Climate change: believing and seeing implies adapting. *PloS one*, *7*(11), p.e50182.

Bouriaud, L., Marzano, M., Lexer, M., Nichiforel, L., Reyer, C., Temperli, C., Peltola, H., Elkin, C., Duduman, G., Taylor, P. and Bathgate, S., 2015. Institutional factors and opportunities for adapting European forest management to climate change. *Regional Environmental Change*, *15*(8), pp.1595-1609.

Broadmeadow, M. S. J., Ray, D., & Samuel, C. J. A. (2005). Climate change and the future for broadleaved tree species in Britain. Forestry, 78(2), 145-161.

Brunet-Navarro, P., Jochheim, H., Kroiher, F., & Muys, B. (2018). Effect of cascade use on the carbon balance of the German and European wood sectors. *Journal of Cleaner Production*, *170*, 137-146.

Clémentine Ols, Jean-Christophe Hervé, Jean-Daniel Bontemps. Recent growth trends of conifers across Western Europe are controlled by thermal and water constraints and favored by forest hetero-geneity. Science of the Total Environment, 2020, 742, pp.140453. 10.1016/j.scitotenv.2020.140453. hal-02892840v2

Cook, C. N., Mascia, M. B., Schwartz, M. W., Possingham, H. P., & Fuller, R. A. (2013). Achieving conservation science that bridges the knowledge–action boundary. *Conservation Biology*, *27*(4), 669-678.

Dannevig, H. and Aall, C., 2015. The regional level as boundary organization? An analysis of climate change adaptation governance in Norway. *Environmental Science & Policy*, *54*, pp.168-175.

DelgadoArtés, R., V. Garófano-Gómez, J. V. Oliver-Villanueva, E. Rojas-Briales. 2022. Land use/cover change analysis in the Mediterranean region: a regional case study of forest evolution in Castelló (Spain) over 50 years. Land Use Policy, 114, 105967. DOI: 10.1016/j.landusepol.2021.105967.

Dhillon, R.S. and von Wuehlisch, G., 2013. Mitigation of global warming through renewable biomass. *Biomass and bioenergy*, *48*, pp.75-89.

Eakin, H., York, A., Aggarwal, R., Waters, S., Welch, J., Rubiños, C., Smith-Heisters, S., Bausch, C. and Anderies, J.M., 2016. Cognitive and institutional influences on farmers' adaptive capacity: insights into barriers and opportunities for transformative change in central Arizona. *Regional environmental change*, *16*(3), pp.801-814.

Eisenack, K., Moser, S.C., Hoffmann, E., Klein, R.J., Oberlack, C., Pechan, A., Rotter, M. and Termeer, C.J., 2014. Explaining and overcoming barriers to climate change adaptation. *Nature Climate Change*, *4*(10), pp.867-872.

Fernandes, Paulo M. "Fire-smart management of forest landscapes in the Mediterranean basin under global change." *Landscape and Urban Planning* 110 (2013): 175-182.

Forzieri, G., Dakos, V., McDowell, N. G., Ramdane, A., & Cescatti, A. (2022). Emerging signals of declining forest resilience under climate change. *Nature*, *608*(7923), 534-539.

Forzieri, G., Girardello, M., Ceccherini, G., Spinoni, J., Feyen, L., Hartmann, H., ... & Cescatti, A. (2021). Emergent vulnerability to climate-driven disturbances in European forests. Nature communications, 12(1), 1081.

Grégoire, J.-C., & Evans, H. F. (2007). Damage and control of bawbilt organisms an overview. In F. Lieutier, K. R. Day, A. Battisti, J.-C. Grégoire, & H. F. Evans (Eds.), Bark and wood boring insects in living trees in Europe, a synthesis. Dordrecht, The Netherlands: Springer. https://doi.org/10.1007/978-1-4020-2241-8_4

Grothmann, T. and Patt, A., 2005. Adaptive capacity and human cognition: the process of individual adaptation to climate change. Global environmental change, 15(3), pp.199-213.

Hauge, Å.L., Hanssen, G.S. and Flyen, C., 2018. Multilevel networks for climate change adaptation–what works?. *International journal of climate change strategies and management*.

Heltorp, K.M.A., 2019. Forestry and forest management in an uncertain environment: adaptation to climate change in Norwegian forestry.

Heltorp, K.M.A., Kangas, A. and Hoen, H.F., 2018. Do forest decision-makers in Southeastern Norway adapt forest management to climate change?. Scandinavian Journal of Forest Research, 33(3), pp.278-290.

Hlásny, T., Krokene, P., Liebhold, A., Montagné-Huck, C., Müller, J., Qin, H., … Viiri, H. (2019). Living with bark beetles: Impacts, outlook and management options. From Science to Policy 8. European Forest Institute.

Hörl, J., Keller, K. and Yousefpour, R., 2020. Reviewing the performance of adaptive forest management strategies with robustness analysis. *Forest Policy and Economics*, *119*, p.102289.

Iacopetti, G., Selvi, F., Bussotti, F., Pollastrini, M., Jucker, T., & Bouriaud, O. (2022). Tree diversity and identity modulate the growth response of thermophilous deciduous forests to climate warming. Oikos, e08875.

Institute for Climate Economics (I4CE), 2020. Combining economic recovery with the climate. Annual Report 2019/2020. Web: https://www.i4ce.org/wp-content/uploads/I4CE-RA-2019-GB-web.pdf (accessed on 23.01.2023)

Ishtiaque, A., Eakin, H., Vij, S., Chhetri, N., Rahman, F. and Huq, S., 2021. Multilevel governance in climate change adaptation in Bangladesh: structure, processes, and power dynamics. *Regional Environmental Change*, *21*(3), pp.1-15.

Jansson, H., 2022. Knowledge as a national tool to influence institutional changes: A study of the barriers and opportunities of national authorities to support collaborative action within climate change adaptation on the municipal level.

Jones, L. and Boyd, E., 2011. Exploring social barriers to adaptation: insights from Western Nepal. *Global environmental change*, *21*(4), pp.1262-1274.

Juhola, S. and Westerhoff, L., 2011. Challenges of adaptation to climate change across multiple scales: a case study of network governance in two European countries. *Environmental science & policy*, *14*(3), pp.239-247.

Kalesnikaite, V., 2019. Keeping cities afloat: Climate change adaptation and collaborative governance at the local level. *Public Performance & Management Review*, *42*(4), pp.864-888.

Kašanin-Grubin, M. and Burton, P.J., 2021. Some options for Climate-Smart Forestry in Europe's mountain regions. *Canadian Journal of Forest Research*, *51*(12), pp.v-vii.

Kellomäki, S., Strandman, H., Heinonen, T., Asikainen, A., Venäläinen, A., & Peltola, H. (2018). Temporal and spatial change in diameter growth of boreal Scots pine, Norway spruce and birch under recent-generation (CMIP5) global climate model 4 projections for the 21st century. Forests, 9(3), 118. https://doi.org/10.3390/f9030118

Lange, L., Connor, K. O., Arason, S., Bundgård-Jørgensen, U., Canalis, A., Carrez, D., ... & Vieira, H. (2021). Developing a sustainable and circular bio-based economy in EU: by partnering across sectors, upscaling and using new knowledge faster, and for the benefit of climate, environment & biodiversity, and people & business. Frontiers in bioengineering and biotechnology, 1456.

Lawrence, A. and Marzano, M., 2014. Is the private forest sector adapting to climate change? A study of forest managers in north Wales. *Annals of forest science*, *71*(2), pp.291-300.

Lawrence, A., & Marzano, M. (2014). Is the private forest sector adapting to climate change? A study of forest managers in north Wales. Annals of forest science, 71, 291-300.

Lawrence, A., 2009. Forestry in transition: Imperial legacy and negotiated expertise in Romania and Poland. *Forest Policy and Economics*, *11*(5-6), pp.429-436.

Lawrence, A., 2017. Adapting through practice: Silviculture, innovation and forest governance for the age of extreme uncertainty. *Forest Policy and Economics*, *79*, pp.50-60.

Liu, Y., Kumar, M., Katul, G. G., & Porporato, A. (2019). Reduced resilience as an early warning signal of forest mortality. Nature Climate Change, 9(11), 880-885.

Luhas, J., Mikkilä, M., Kylkilahti, E., Miettinen, J., Malkamäki, A., Pätäri, S., Korhonen, J., Pekkanen, T.L., Tuppura, A., Lähtinen, K. and Autio, M., 2021. Pathways to a forest-based bioeconomy in 2060 within policy targets on climate change mitigation and biodiversity protection. *Forest Policy and Economics*, *131*, p.102551.

Mahoney, J. and Thelen, K., 2010. A theory of gradual institutional change. *Explaining institutional change: Ambiguity, agency, and power*, *1*, pp.1-37.

Mason, B. and Perks, M.P., 2011. Sitka spruce (Picea sitchensis) forests in Atlantic Europe: changes in forest management and possible consequences for carbon sequestration. *Scandinavian Journal of Forest Research*, *26*(S11), pp.72-81.

Mason, W.L. and Meredieu, C., 2011. Silvicultural Strategies, Sustainability, and Adaptation to Climate Change in Forests of the Atlantic Region of Europe (< Special Issue> Multipurpose Forest Management). *Journal of Forest Planning*, *16*(Special_Issue), pp.67-77.

Mason, W.L., Nicoli, B.C. and Perks, M.P., 2009a. Mitigation potential of sustainably managed forests. In: Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds) *Combating climate change: a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change*. The Stationery Office, Edinburgh: 100-118

McDonald, J., 2011. The role of law in adapting to climate change. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(2), pp.283-295.

Mora, O., Banos, V., Regolini, M. et al. Using scenarios for forest adaptation to climate change: a foresight study of the Landes de Gascogne Forest 2050. Annals of Forest Science 71, 313–324 (2014). https://doi.org/10.1007/s13595-013-0336-2

Moriondo, M., Good, P., Durao, R., Bindi, M., Giannakopoulos, C., & Corte-Real, J. (2006). Potential impact of climate change on fire risk in the Mediterranean area. Climate research, 31(1), 85-95.

Moser, S.C. and Ekstrom, J.A., 2010. A framework to diagnose barriers to climate change adaptation. *Proceedings of the national academy of sciences*, *107*(51), pp.22026-22031.

Mukherjee, U., 2018. Climate change adaptation in urban India through traditional practices. An empirical research on the impacts of climate change on the Mega cities of India and the institutional barriers or opportunities that exists to adapt to climate change by using traditional practices.

Ofoegbu, C., Chirwa, P.W., Francis, J. and Babalola, F.D., 2019. Assessing local-level forest use and management capacity as a climate-change adaptation strategy in Vhembe district of South Africa. *Climate and Development*, *11*(6), pp.501-512.

Ostrom et al., 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems, Science 325, 419 (2009); DOI: 10.1126/science.1172133)

Ostrom, E., 1990. *Governing the commons: The evolution of institutions for collective action*. Cambridge university press.

Ostrom, E., 2012. Polycentric systems: Multilevel governance involving a diversity of organizations. *Global environmental commons: Analytical and political challenges in building governance mechanisms*, pp.105-125.

Ostrom, E., Gardner, R., Walker, J. and Walker, J., 1994. *Rules, games, and common-pool resources*. University of Michigan press.

Oulahen, G., Klein, Y., Mortsch, L., O'Connell, E. and Harford, D., 2018. Barriers and drivers of planning for climate change adaptation across three levels of government in Canada. *Planning Theory & Practice*, *19*(3), pp.405-421.

Pepin, N. C., Arnone, E., Gobiet, A., Haslinger, K., Kotlarski, S., Notarnicola, C., ... & Adler, C. (2022). Climate changes and their elevational patterns in the mountains of the world. Reviews of Geophysics, 60(1), e2020RG000730.

Primmer, E., 2011. Analysis of institutional adaptation: integration of biodiversity conservation into forestry. *Journal of Cleaner Production*, *19*(16), pp.1822-1832.

Raftoyannis, Y., Nocentini, S., Marchi, E., Sainz, R. C., Guemes, C. G., Pilas, I., ... & Lindner, M. (2014). Perceptions of forest experts on climate change and fire management in European Mediterranean forests.

Reinecke, J., Wulf, M., Baeten, L., Brunet, J., Decocq, G., De Frenne, P., Diekmann, M., Graae, B.J., Heinken, T., Hermy, M., Jamoneau, A., Lenoir, J., Plue, J., Orczewska, A., Van Calster, H., Verheyen, K., Naaf, T., 2016. Acido- and neutrophilic temperate forest plants display distinct shifts in ecological pH niche across north-western Europe. Ecography 39, 1164–1175.. https://doi.org/10.1111/ecog.02051

Resco de Dios, V., Fischer, C. and Colinas, C., 2007. Climate change effects on Mediterranean forests and preventive measures. *New forests*, *33*, pp.29-40.

Reyer, C., Bathgate, S., Blennow, K., Borges, J. G., Bugmann, H., Delzon, S., … Hanewinkel, M. (2017). Are forest disturbances amplifying or cancelling out climate change-induced productivity changes in European forests? Environmental Research Letters, 12(3), 034027. https://doi.org/10.1088/1748-9326/aa5ef1

Rojas-Briales, E.; Oliver-Villanueva, J.-V.; Lerma-Arce, V.; Fuente, D.; Lorenzo-Sáez, E. Improving Sustainable Forest Management of Pinus halepensis Mill. Mid-Aged Stands in a Context of Rural Abandonment, Climate Change, and Wildfires. Forests 2023, 14, 527. https://doi.org/10.3390/f14030527

Ruffault, J., Martin-StPaul, N. K., Rambal, S., & Mouillot, F. (2013). Differential regional responses in drought length, intensity and timing to recent climate changes in a Mediterranean forested ecosystem. Climatic Change, 117(1-2), 103-117.

Ruosteenoja, K., Räisänen, J., Venäläinen, A., & Kämäräinen, M. (2016). Projections for the duration and degree days of the thermal growing season in Europe derived from CMIP5 model output. International Journal of Climatology, 36, 3039– 3055. https://doi.org/10.1002/joc.4535

Sanga, U., Sidibé, A. and Olabisi, L.S., 2021. Dynamic pathways of barriers and opportunities for food security and climate adaptation in Southern Mali. *World Development*, *148*, p.105663.

Schoene DH, Bernier PY (2012) Adapting forestry and forests to climate change: a challenge to change the paradigm. Forest Policy Econ 24:12–19.

Seidl, R., & Lexer, M. J. (2013). Forest management under climatic and social uncertainty: trade-offs between reducing climate change impacts and fostering adaptive capacity. *Journal of Environmental Management*, *114*, 461-469

Seidl, R., Schelhaas, M.-J., Rammer, W., & Verkerk, P. J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. Nature Climate Change, 4(9), 806– 810. https://doi.org/10.1038/nclimate2318

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., … Reyer, C. P. O.(2017). Forest disturbances under climate change. Nature Climate Change, 7, 395– 402. https://doi.org/10.1038/nclimate3303

Senf, C. & Seidl, R. 2018. Natural disturbances are spatially diverse but temporally synchronized across temperate forest landscapes in Europe. Global Change Biol. 24, 1201–1211 (2018).

Senf, C., Pflugmacher, D., Zhiqiang, Y., Sebald, J., Knorn, J., Neumann, M., ... & Seidl, R. (2018). Canopy mortality has doubled in Europe's temperate forests over the last three decades. Nature Communications, 9(1), 4978.

Serbruyns, I. and Luyssaert, S., 2006. Acceptance of sticks, carrots and sermons as policy instruments for directing private forest management. *Forest policy and Economics*, *9*(3), pp.285-296.

Sharma, T., Kurz, W.A., Stinson, G., Pellatt, M.G. and Li, Q., 2013. A 100-year conservation experiment: Impacts on forest carbon stocks and fluxes. *Forest Ecology and Management*, *310*, pp.242-255.

Sietz, D., Boschütz, M. and Klein, R.J., 2011. Mainstreaming climate adaptation into development assistance: rationale, institutional barriers and opportunities in Mozambique. *Environmental Science & Policy*, *14*(4), pp.493-502.

Stanturf, J.A., Kant, P., Lillesø, J.P.B., Mansourian, S., Kleine, M., Graudal, L. and Madsen, P., 2015. *Forest landscape restoration as a key component of climate change mitigation and adaptation* (Vol. 34, p. 34). Vienna, Austria: International Union of Forest Research Organizations (IUFRO).

Stern, N. and Stern, N.H., 2007. *The economics of climate change: the Stern review*. cambridge University press.

Teixido, A.L., Quintanilla, L.G., Carreno, F. and Gutierrez, D., 2010. Impacts of changes in land use and fragmentation patterns on Atlantic coastal forests in northern Spain. *Journal of Environmental Management*, *91*(4), pp.879-886.

Temperli, C., Bugmann, H. and Elkin, C., 2012. Adaptive management for competing forest goods and services under climate change. Ecological Applications, 22(8), pp.2065-2077.

Termeer, C., Dewulf, A. and Breeman, G., 2013. Governance of wicked climate adaptation problems. In Climate change governance (pp. 27-39). Springer, Berlin, Heidelberg.

Valladares, F. Benavides, R., Rabasa, S. G., Díaz, M., Pausas, J. G., Paula, S., & Simonson, W. D. (2014). Global change and Mediterranean forests: current impacts and potential responses. Forests and global change, 47-75.

Venäläinen, A., Korhonen, N., Koutsias, N., Xystrakis, F., Urbieta, I. R., & Moreno, J. M. (2014). Temporal variations and change in forest fire danger in Europe for 1960–2012. Natural Hazards and Earth System Sciences, 14(6), 1477– 1490. https://doi.org/10.5194/nhess-14-1477-2014

Venäläinen, A., Lehtonen, I., Laapas, M., Ruosteenoja, K., Tikkanen, O. P., Viiri, H., ... & Peltola, H. (2020). Climate change induces multiple risks to boreal forests and forestry in Finland: A literature review. Global change biology, 26(8), 4178-4196.

Verschuuren, J. (2018). Towards an EU regulatory framework for climate-smart agriculture: the example of soil carbon sequestration. Transnational Environmental Law, 7(2), 301-322.

Vilà-Cabrera, A., Coll, L., Martínez-Vilalta, J. and Retana, J., 2018. Forest management for adaptation to climate change in the Mediterranean basin: A synthesis of evidence. *Forest Ecology and Management*, *407*, pp.16-22.

Wang, J., Samsura, D.A.A. and van der Krabben, E., 2019. Institutional barriers to financing transit-oriented development in China: Analyzing informal land value capture strategies. Transport Policy, 82, pp.1-10.

Weber, E. and Khademian, A.M., 2008. Managing collaborative processes: Common practices, uncommon circumstances. Administration & Society, 40(5), pp.431-464.

Williamson, T.B. and Nelson, H.W., 2017. Barriers to enhanced and integrated climate change adaptation and mitigation in Canadian forest management. *Canadian Journal of Forest Research*, *47*(12), pp.1567-1576.

Yousefpour, R., Temperli, C., Bugmann, H., Elkin, C., Hanewinkel, M., Meilby, H., Jacobsen, J.B. and Thorsen, B.J., 2013. Updating beliefs and combining evidence in adaptive forest management under climate change: A case study of Norway spruce (Picea abies L. Karst) in the Black Forest, Germany. Journal of environmental management, 122, pp.56-64.

Zea-Reyes, L., Olivotto, V. and Bergh, S.I., 2021. Understanding institutional barriers in the climate change adaptation planning process of the city of Beirut: vicious cycles and opportunities. *Mitigation and Adaptation Strategies for Global Change*, *26*(6), pp.1-24.