Forecasting and managing multi-risks in Mediterranean, temperate and boreal forests: comparison between North-American and European approaches: conference proceedings

Cecile Robin, Kaysandra Waldron, Eric Rigolot, Philippe Deuffic, Claude Durocher

Forecasting and managing multi-risks in Mediterranean, temperate and boreal forests

comparison between North-American and European approaches

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TABLE OF CONTENTS

First session: "Toward approaches considering multi-risks, interaction between risks, and cascades effects in forest socio-ecosystems"

Second session "Toward facilities devoted to survey and monitor multiple risks including emergency devices for major risks"

Third session: "toward strategies for multi-risks mitigation and vulnerability reduction in forest socio-ecosystems"

INTRODUCTORY REMARKS

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OPENING OF THE CONFERENCE

Enhancing resilience of European forests based on state-of-the-art disturbance evidence, disturbance scenarios and forest modelling approaches used in the I-Maestro and RESONATE projects

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Abstract

Forest disturbances are increasingly affecting European forests and it is widely perceived that forest management needs to enhance forest resilience to safeguard ecosystem service provisioning under climate change. Knowledge on how management influences resilience and disturbance risks is still incomplete, and thus forest simulation models are needed to explore possible management responses. Approaches developed in the RESONATE and I-Maestro projects allow to model forest development under changing climate, increased disturbance risks and alternative forest management. We present latest disturbance data compiled with remote sensing methods for the period 1986-2020 and based on ground-based assessments from 1950 to 2019. Forest disturbance scenarios were developed in I-Maestro to simulate forest ecosystem service provisioning in landscape- to national scale case studies in France, Poland, Slovenia and Germany. Windstorm scenarios were constructed based on the reported empirical storms data, with storm extent and direction estimated in the form of geographic rectangles specified by coordinates, width, length, and direction. Impact linker functions were then used to compute tree damage probability for forest stands with storm incidence each year. We provide an outlook how disturbance data and scenarios will be applied in simulation studies in the two projects to explore management options and inform stakeholders how to enhance forest resilience.

Introduction

Natural disturbances are increasingly affecting European forests (Senf et al., 2018; Senf et al., 2021) and their impacts are projected to further increase under climatic change (Seidl et al., 2017), potentially disrupting the provisioning of forest ecosystem services to society (Lindner et al., 2010;

Thom and Seidl, 2016). We need knowledge and practices for making European forests, the services they provide, and related economic activities more resilient to future climate change and disturbances. Developing and disseminating scientific evidence to achieve this is a key objective of the Horizon2020 project RESONATE (www.resonateforest.org). The Forest Value Era-net project I-Maestro (www.i-maestro.inrae.fr) is a related project, which applies a range of different forest simulation models to a set of case studies (landscape-scale cases Bauges (France), Milicz (Poland), Snežnik (Slovenia) and country-scale simulations (France, Germany, Poland and Slovenia)) to develop forest management strategies for a resilient bioeconomy under climate change and disturbances.

To develop decision support on resilient forest systems and simulate forest ecosystem service provisioning we need robust data regarding current forest disturbance regimes and how they are changing. Moreover, we also need to project future disturbance regimes to drive forest simulation models for assessing disturbance impacts on forests. In this paper we report on recent efforts in the RESONATE and I-Maestro projects on characterizing past and present disturbances in European forests and how to derive disturbance scenarios from this observational evidence. We conclude with an outlook on how disturbance data and scenarios will be applied in simulation studies in the two projects to explore management options and inform stakeholders how to enhance forest resilience through management.

Mapping forest disturbance hotspots 1986-2020

Using remote sensing data and methods documented in Senf and Seidl (2021), forest disturbance regimes were mapped across Europe (Fig. 1), indicating considerable regional differences in disturbance size, frequency and severity.

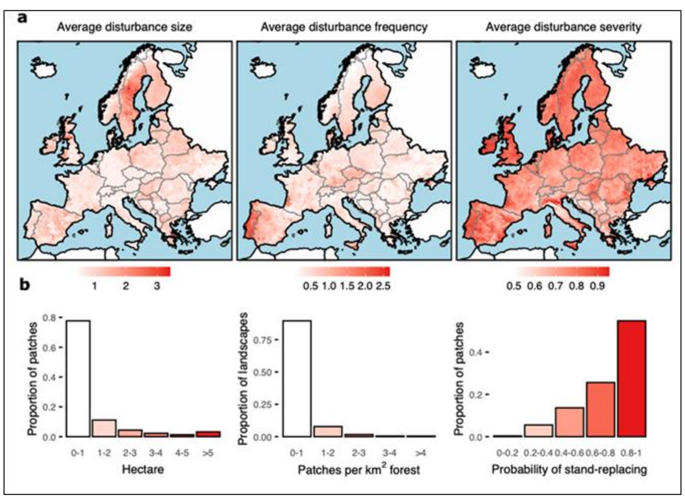


Figure 1: Forest disturbance regimes 1986-2016 (Senf and Seidl, 2021).

The analysis in RESONATE expanded the analysis of Senf and Seidl (2021) up to 2020 and allowed to map dynamic regional patterns of disturbances by different agents – here illustrated with results of 2020 (Fig 2.). The distinct temporal and spatial disturbance patterns are crucial to consider in management responses aiming at enhanced resilience.

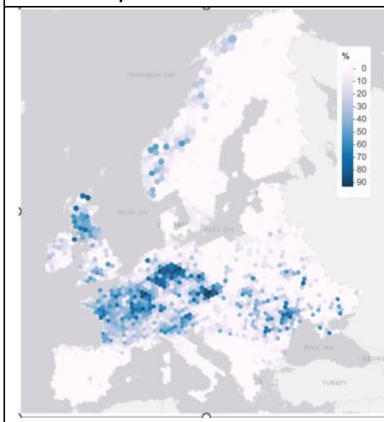
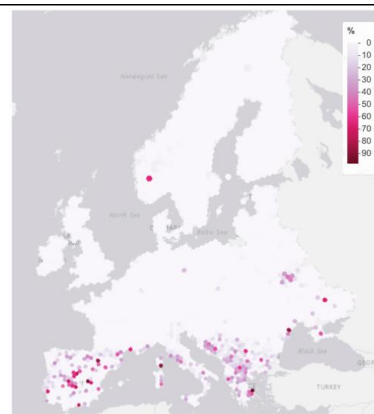
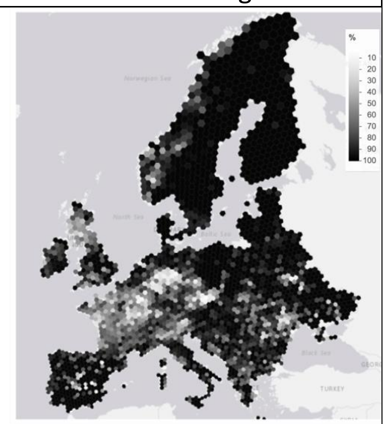
Prevalence in 2020		
Biotic/wind disturbance	Fire disturbance	Harvesting
		

Figure 2: Annual disturbance hotspots in 2020, percent of area affected in hectagons of 2,165 km².

Ground-based forest disturbance observations from 1950 to 2019

In the I-Maestro project, ground based disturbance observations were collected to update the Database of Forest Disturbances in Europe (DFDE; (Schelhaas et al., 2003)), which now covers 34 European countries for the period of 1950 to 2019 (Patacca et al., submitted manuscript).

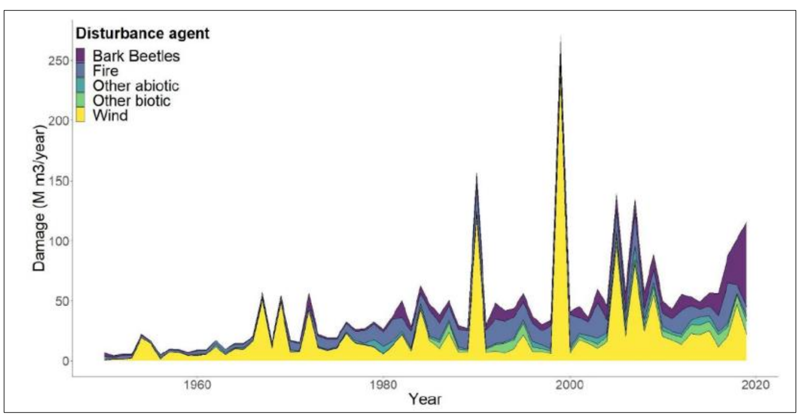


Figure 3: Reported damage caused by natural forest disturbances in Europe between 1950 and 2019 (Patacca et al., submitted manuscript).

All disturbance agents showed increased damages over the 70-year observation period (Fig. 3). The most important damage agents in European forests was wind, which showed strong stochastic singular events especially in the 1990s and 2000s. The strongest increases in damage were caused by bark beetles and other biotic damages (Fig. 4).

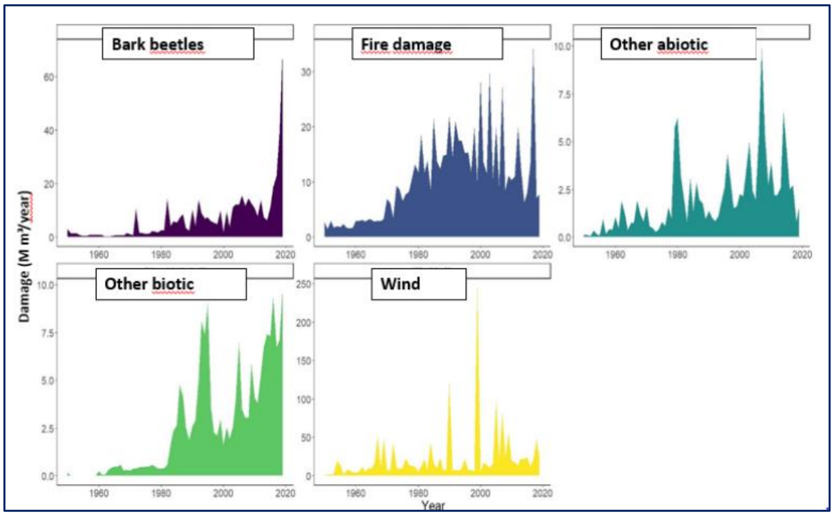


Figure 4: Temporal development of natural forest disturbance causes in Europe between 1950 and 2019 (Patacca et al., submitted manuscript), note the different y-axis scales, indicating significant differences in the magnitude of damages by agent.

Developing disturbance scenarios: example of windstorm disturbance projections

Different approaches have been used to project forest disturbances using forest simulation models under climate change (Hanewinkel et al., 2010; Schuler et al., 2019). In I-Maestro a new approach was developed to create disturbance scenarios based on the improved evidence on observed disturbance distributions derived from the DFDE. We illustrate the approach for the development of wind disturbance projections (Fig. 5).

From the compilation of observed wind storm events, future disturbance incidences are created using random draws of past wind storm events, which are modified using several corrections to the location and the characteristics of the drawn disturbance event: the location of the lower left corner was modified up to plus or minus 1 degree, the wind direction was randomly adjusted by up to 22.5 degrees in both directions, and the length and width of the storm was modified by up to plus and minus 100 km. All randomness factors were assumed to have a uniform distribution.

The scenario generation process produced varying numbers of storms affecting National Forest Inventory locations. Fig. 6 indicates regional differences in storm frequency over the investigated countries of France, Germany, Poland and Slovenia. Storm frequency is clearly decreasing from North-western to South-eastern Europe.

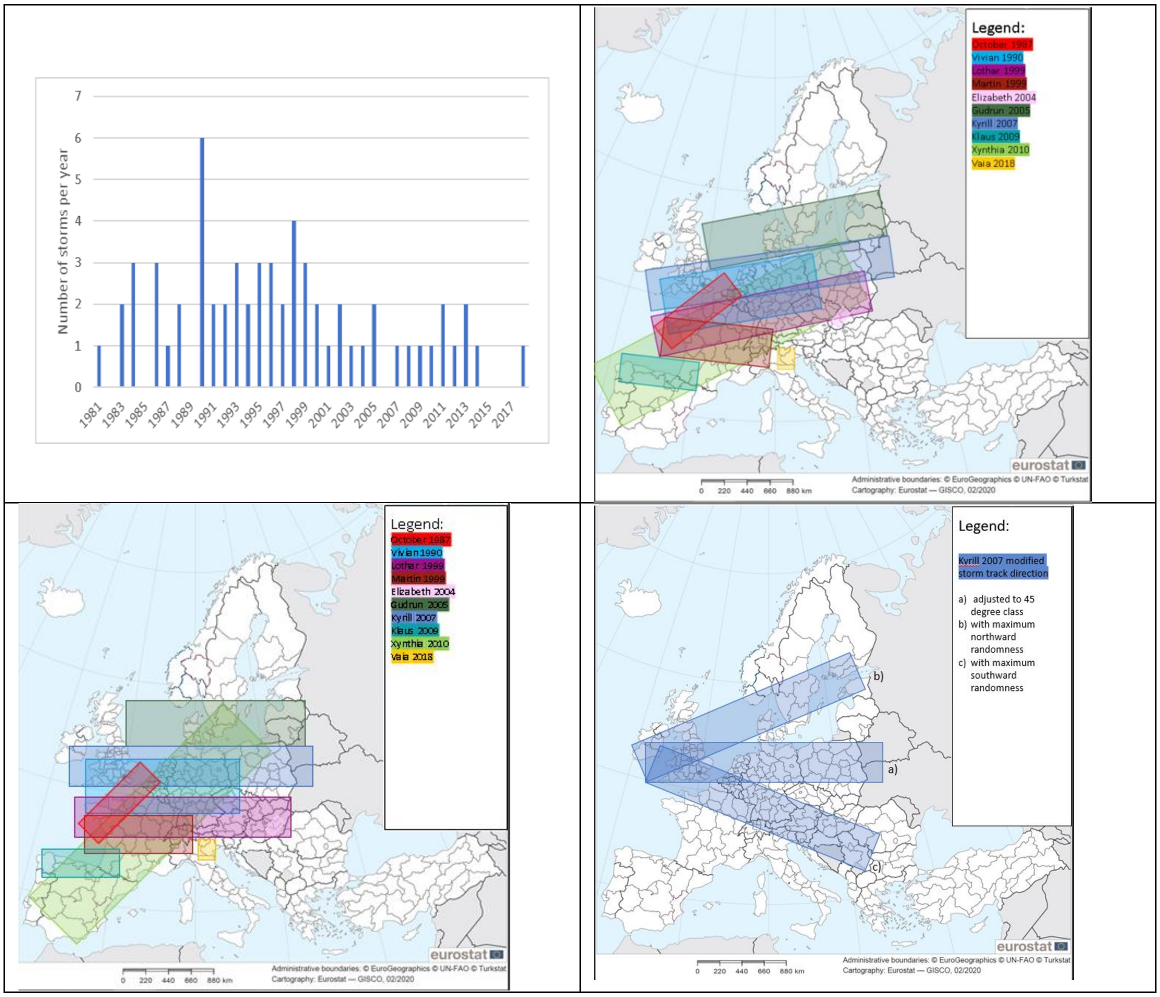


Figure 5: Generating scenario windstorms from observations. The observation record includes 62 storm events larger than 11.000 m³ of damaged timber (between zero and six per year) from 1981 to 2019 (top left). Storm affected areas are approximated with rectangles (top right), with wind direction adjusted in steps of 45 degrees (bottom left) and random corrections applied to the location, wind direction, and spatial extent - here illustrated for the wind direction of historical 2007 storm Kyrill (bottom right).

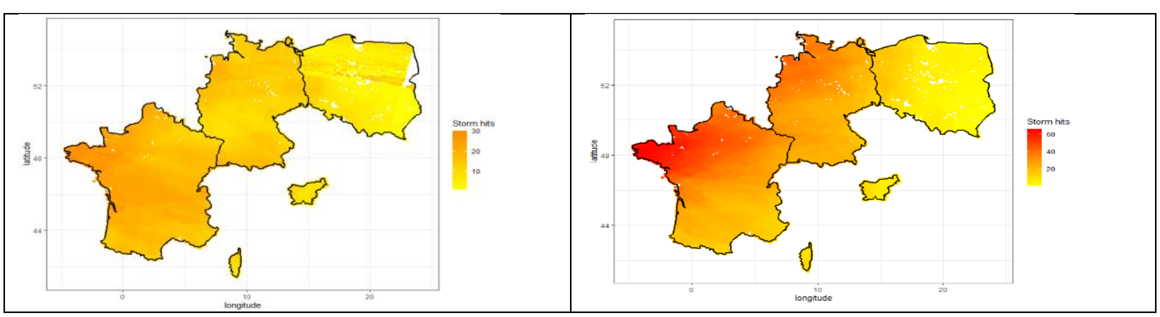


Figure 6: Storm frequency over Europe in the baseline (left) and Climate change (right) scenarios. The maps display the number of storm hits affecting National Forest Inventory plots during a 100-year simulation period. Under climate change, every year had a 50% probability that an extra storm would occur, based on findings by Outten and Sobolowski (2021).

To project impacts of wind disturbance scenarios on forests, forest models need to implement windstorm impact linker functions. Two linker functions were tested in I-Maestro: the first one is based on Stadelmann et al. (2019; corrected equation):

$$PTR = (S * TE) * (1 - \frac{e^{\alpha}}{1 + e^{\alpha}})$$

S is storm severity, *TE* reflects the topographic effect at the stand level, and α is a factor depending on forest structure, DBH and conifer proportion (Stadelmann, 2019).

I-Maestro models finally used the Schuler et al. (2019) function:

$$\log\left(\frac{P_{coh}}{1 - P_{coh}}\right) = a + c \cdot S \cdot DBH_{coh}^{b}$$

where P_{coh} is the probability of windthrow for cohort coh within the cell, DBH_{coh} is diameter at breast height of the cohort, and a, b and c are species-specific parameters that relate to tolerance to wind.

The evaluation of the projected damage amounts projected with the linker functions revealed that the linker function had to be calibrated to obtain realistic amounts of damage. Damages were scaled to account for storm severity: no damage was assumed to occur below 100 km wind speed, and the proportion of plots impacted by the storm in a storm affected landscape decreased with lower storm severity. This stresses the importance of regionally validating impact linker functions taken from the literature, as these are sensitive to forest characteristics and context (e.g. wind exposure and topography).

Integrating disturbance data and existing forest simulations of climate change impacts for assessing forest resilience

Many climate change impact studies have been carried out across Europe over recent years. In RESONATE, simulations from 17 models, 19 contributors, 2283 unique locations and 700,000 simulations (including a total of 53 Million data points) were compiled to synthesize these simulations by means of deep learning (Rammer and Seidl, 2019) and some auxiliary information. This will allow making AI-based projections of Europe‘s forest future based on the assimilated wealth of local climate change simulations, integrated with (climate-sensitive) disturbance models (see below) to produce transient predictions of future forest disturbance regimes (Fig. 7).

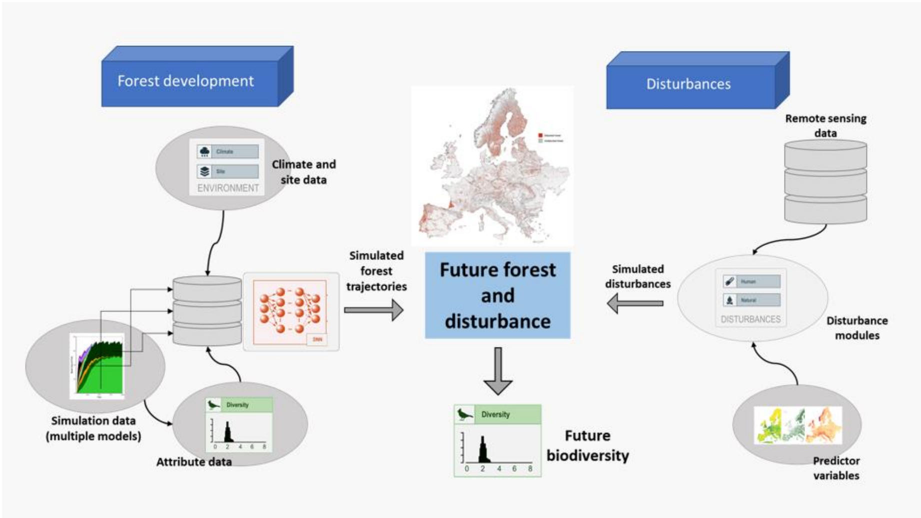


Figure 7: Conceptual overview of the integration of forest development under climate change derived from a deep learning algorithm synthesizing existing climate change impact assessment studies and future disturbance trends generated from climate sensitive disturbance models as implemented currently in the RESONATE project.

Outlook: exploring management options to enhance resilience

New methodological developments and comprehensive data collection efforts have recently improved our scientific evidence on natural and human forest disturbance impacts in European forests. The ground-based and remote-sensing derived disturbance data have complementary strengths, and it will be crucial in future to integrate both types of observations to achieve near real-time monitoring of different disturbance impacts that capture spatial disturbance patterns and accurately attribute them to different causes. Multiple disturbance agents are often interacting (e.g. drought followed by bark beetle damage or fire) and better attribution of such disturbance interactions affecting forests stands over several years deserves further research.

Alternative implementations of randomness factors and linker functions applied to empirically based disturbance scenarios should be validated against baseline disturbance data at regional and national level. In empirically derived disturbance scenarios, there is furthermore a need to include smaller abiotic and other biotic disturbances as random events to represent years with smaller amounts of damage in between larger disturbance events. Climate change effects on disturbance risks is projected to increase and there is work underway to better estimate such impacts and incorporate them into AI based modelling pipelines, e.g. for wildfire disturbances (Grünig et al., submitted manuscript).

The I-Maestro and RESONATE projects provide alternative methodological approaches for simulating impacts of climate change and disturbances on European forests. Using these simulation approaches, the focus in these projects is now shifting towards exploring management options how to enhance forest resilience using different tree species, adaptive silviculture, and targeted disturbance prevention measures.

Acknowledgements

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FIRST SESSION: “TOWARD APPROACHES CONSIDERING MULTI-RISKS, INTERACTION BETWEEN RISKS, AND CASCADES EFFECTS IN FOREST SOCIO-ECOSYSTEMS”

Developing Generic Open Source Models for Predicting Wind Damage Risk to Forests and Trees in a Changing Climate

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Abstract

Wind damage to trees and forests has important economic, ecological, social and environmental impacts. In Europe wind is known to cause more than 50% by volume of all damage to forests, to have severe economic effects on the forestry business, and very important societal consequences. These impacts are also found across northern boreal forests, all areas affected by typhoons and hurricanes, and in any part of the world subject to strong winds.

The change in wind patterns and strength in the changing climate is not totally clear but there is evidence of increasing storm intensity, increased thunderstorm and associated gust front intensity, and the tracking of strong typhoons and hurricanes to higher latitudes. To mitigate the impact of these changes in wind pattern and to manage planted forests requires tools for predicting the impact of both forest management and the wind climate.

Over the last 20 years a hybrid-mechanistic forest wind damage model called ForestGALES has been developed and refined. The model was originally designed for uniform conifer stands but is now able to calculate the risk to both stands and individual trees and for a range of broadleaves and conifers. This allows calculation of the risk to mixed species and mixed age forests. The model has been extensively tested in France, Scotland, and Canada and has been adapted and used in a number of other countries. The model is freely available as a R library called fgr with extensive documentation and help.

In this talk we will demonstrate how the model has been used in different environments to answer questions on forest vulnerability and the impact of management. We will also demonstrate the benefits of working in different forest environments to validate the model and to make it globally useful.

Mountain forest and natural hazard prevention: Are Forest-based Solutions grandmothers of Nature-based Solutions

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Abstract

Life in the middle and high mountains has always been intimately linked to the "whims" of nature. Thus, man has always sought to protect his people and his property from natural phenomena. To do this, he has settled either in sectors where there was no known natural hazard, or in areas sheltered by natural obstacles, or in sectors where he built structures to be safe. Forests are part of the natural ramparts behind which man has always sought shelter. Thus, he defined the first forests with a protective function. Today, in the management of natural risks and the reduction of natural disasters worldwide, but especially in the mountains, forests are increasingly considered as equal to technical or engineering measures. Forest-based solutions (FBS) can, for example, increase slope stability and reduce risks to an acceptable level in many locations. Where forests are present, the implementation of engineering measures is often redundant or less costly. Good examples are the numerous forests in the Alps which prevent the triggering of avalanches instead of expensive snow racks, the large-scale afforestation of the late 19th century which today prevents erosion and sedimentation problems in the Alpine catchment areas. Thus, the mountain land restoration policies developed at the end of the 19th century are the ancestors of today's Nature-based Solutions (NBS), even if they initially differ in their biodiversity component.

Context

Life in the middle and high mountains has always been intimately linked to the "whims" of nature. Thus, man has always sought to protect his people and his property from natural phenomena. To do this, he has settled either in sectors where there was no known natural hazard, or in areas sheltered by natural obstacles, or in sectors where he built structures to be safe. Forests are part of the natural ramparts behind which man has always sought shelter. Thus, he defined the first forests with a protective function. In mountain areas, forests are thus ecosystems whose heritage aspects are the most marked. A heritage is the whole of the goods, rights and charges of a person. For centuries the mountain population has sought the protection (of goods and people) that the forest offers against natural hazards (rock fall, etc.) but it has also been an important source of supply for the development of mountain territories (construction wood, energy wood, timber, source of food products, etc.). In addition to these two traditional functions of mountain forests, the evolution of society and the important role of leisure activities within it have given mountain or lowland forests new heritage assets such as the protection of landscapes, biodiversity and a new recreational function based on the reception of the public. Thus, they should no longer be considered only as primary production units (wood production and financial income) serving private interests, but also as heritage and cultural assets. They thus serve the interests of the community. All of these services must be taken into account when planning and managing these forests. Their economic value, the functions they must provide and the management that must be implemented to conserve and improve these functions make them a true societal heritage (notion of socio-territory).

The forest evolves (dynamics) and only certain stages of its natural development fulfill the various roles expected of it. The management of mountain forests, influenced by the strong constraints of the natural environment, has become more difficult and delicate because of man and his activities. In particular, urbanization and leisure activities create new constraints in terms of land use and management. Simply managing forests according to the principle of sustained yield, i.e. not exploiting them more than they can produce, is no longer sufficient to guarantee these new trends.

However, if the goods and human activities threatened by natural hazards are mostly and increasingly located outside natural areas and downstream of them (they are called "target areas"); hazards, on the other hand, have their origins in natural environments located further upstream and which often undergo an abandonment of agricultural, forestry or pastoral activity due to the economic context and urban migration (they are called "source areas").

In this scheme, prevention can be achieved through two complementary policies:

1. An active defense through an adapted management of the natural environment at the source of the hazard, whose objective is to prevent the phenomenon from occurring.
2. A passive defense of the "target areas", whose objective is to prevent the natural hazards from harming. In this framework of action, the protective structures (the forest stands are then considered as natural protective structures) have a role of obstacle favouring the loss of energy and the trapping of the materials in movement.

The sectors most sensitive to natural hazards (roads, habitat areas) have often been the object of specific civil engineering protection (nets, racks, dikes, ...). On the other sectors, the silvicultural management of these forest slopes has so far allowed to maintain the forest and thus to limit the consequences of these natural phenomena. All over the world, and in the Alpine area, forests are thus considered as natural protective structures offering, according to the nature and intensity of the risks generated by gravity hazards (rock falls, landslides, avalanche erosion), a protection equivalent to that of engineering and civil engineering techniques and structures. On slopes where forests are present, the implementation of technical measures for the reduction of natural hazards is often less expensive and can be redundant.

The high costs of implementation and maintenance of civil engineering works and the desire to optimize public investments have re-initiated in the countries of the Alpine arc a discussion on the adoption of preventive measures and the valorization of natural environments as natural protective works. It should be emphasized that in this context of reaffirmation of the protective role of forest vegetation against risks, the relative decline in the value of wood is leading to the simplification or even the abandonment of forestry in various mid-mountain and mountain regions. Wood production is not only lower, but also of lower quality. Thus, by analogy with the agricultural sector, one can speak of forestry abandonment and a concentration of forestry activities on the most favorable areas, economically speaking. This "decline" of forest management can be explained by different reasons such as the disappearance of the rural world and its uses, economic difficulties of the timber industry in mountain areas or private land status. The abandonment of cultivation practices generates an aging of the forest stands with a consequent evolution of the structure of these stands and of their floristic composition. This evolution facilitates the fragility of these stands in the face of climatic hazards (e.g. storms, fires, avalanches) and also limits the protective service that these forest stands could play until now. Essential protective functions may therefore no longer be provided by forest stands that are too roughly exploited or insufficiently maintained. However, very often, only the disappearance of forest stands and the activation or reactivation of natural phenomena generating risks allow managers to appreciate their protective role a posteriori. It is thus advisable to anticipate these catastrophic evolutions and to avoid "running after the emergency". To do this, it is necessary, from the point of view of minimal, optimized and integrated management, to target as well as possible the place and the nature of the interventions to be carried out. To meet these requirements, it is necessary to have solid scientific and technical knowledge to locate, qualify and quantify the protective role of forest stands.

A forest stand has modes of action that differ according to the hazards (nature, intensity, frequency of occurrence), its location in relation to the area surveyed by a hazard, the scale of analysis (tree scale, slope, watershed) of the species present (diameter, ages, etc.) and the spatial organization of the trees. Even if the forest cannot avoid everything, it at least acts according to the principle of "divide and conquer" towards the various types of hazards. The knowledge of these interactions between the forest stand and natural hazards is one of the pillars of the construction of a sustainable and effective protection strategy. Thus, the choice of a strategy of prevention and protection of natural risks, makes indispensable in mountain areas, a reflection on the protection that the forest can offer. This requires the classification and characterization of stands according to their protective role, the realization of a cartography of these stands and the determination of priority zones for silvicultural interventions. These zones must include both the notion of priority according to the nature of the threatened stakes and the notion of urgency according to the degree of stability of the stands. The protection function of a forest is maximal when it maintains a natural hazard to a potential activity (notion of "extinction" of a phenomenon). It is consequently important for the managers of a territory to be able to identify the zones subjected to this type of hazard (zone of departure, zone of flow, zone of arrival). This location must have a double objective: the recognition of the protection service in land use planning documents and more particularly those relating to the implementation of natural risk prevention policies, and ultimately the implementation of a silviculture adapted to the maintenance and improvement of this ecosystem service (sustainable management of the service provided).

In parallel to this observation, the management of natural and semi-natural environments is becoming a major issue in national and international policies. It is based on the notion of sustainable management, multi-functional management, values of uses and services of ecosystems. In this respect, the preservation and enhancement of the protective role of forests against natural hazards are essential in the protection strategies of the inhabitants, users and economic activities of Alpine territories. Moreover, if forests are also deposits of a renewable raw material, wood, they are also recreational and cultural spaces and reservoirs of biodiversity. The 6 EU Ministerial Conferences on the Protection of Forests in Europe held since 1990 have all stressed the need for a common approach to value forest ecosystem services (FES) as a basis for the development of sustainable forest management. The prioritization of FES should be made based on societal needs. The reduction and prevention of natural hazards is one of them.

Mapping, valorisation, sustainable management and public awareness of the risk protection service of the forest stands of a territory are among the main objectives of the Integrated Natural Risk Management (INRM) strategy. Locating and quantifying the risk protection service of the forests present on a territory are the necessary steps to develop a territorial intelligence dedicated to the integrated management of natural risks.

The protection function of the forest is currently integrated in France in the practical guidelines for land management, but in a heterogeneous way. At the forestry level, the Guide de Sylviculture de Montagne (Ancelin et al, 2006) proposes specific recommendations for stands identified as having a marked protective role. In terms of natural hazards, the construction of hazard maps is based on the hypothesis of a phenomenon taking place on bare ground but the risk maps can be nuanced by incorporating the beneficial effect of the forest. However, no method is prescribed by regulation for the consideration of the forest, only some indications are given in the guide MEZAP (2022). It should be noted that in France, since the 2001 forestry orientation law, it is possible to integrate silvicultural rules for the management of forests with a protective function into the Plans for the prevention of foreseeable natural risks :

Plans for the prevention of foreseeable natural risks established in application of articles L. 562-1 to L. 562-7 of the environmental code, whose purpose is to prevent floods, land movements or avalanches, can provide for rules of management and forestry in the risk zones that they determine. The approved regulations are binding on forest owners and operators as well as on the authorities responsible for approving forest management documents drawn up in application of books I, II and IV of the present code or for examining cutting authorizations provided for by the present code or by the town planning code. In this case, forest owners and users benefit from the guarantees provided for by Article L. 413-1 and the texts taken for its application. (Article L425-1).

In this context, the scientific objective of producing knowledge on the qualitative and quantitative evaluation of natural risks for which forest ecosystems can offer a mitigating or aggravating role, is thus carried by the societal demand for improvement of natural risk prevention based, among other things, on a better consideration of the services rendered by forest ecosystems. This prevention policy is built with the objective of sustainable development of the territories concerned, implementing biological engineering techniques and ecological engineering approaches associated with spatial analysis for a better involvement of man in his own vulnerability. Ecological engineering is defined as the techniques and strategies for managing forest ecosystems in order to perpetuate and optimize their protective service against risks. It should allow for the best and most cost-effective use of public investments, in a context of climate change and increasing anthropogenic pressure and vulnerabilities. Ecological engineering approaches thus offer an opportunity to transfer knowledge (ecology, geomatics, spatial analysis, modelling, etc.) to "engineering knowledge" and to the benefit of "territorial intelligence" for a reasoned and integrated management of the services provided by forest ecosystems. Taking into account the biodiversity dimension, ecological engineering has evolved towards the concept of Nature-based Solutions (NBS). The International Union for Conservation of Nature defined NBS in 2016 as actions to protect, sustainably manage and restore natural or modified ecosystems to directly address societal challenges in an efficient and adaptive manner, while ensuring human well-being and producing biodiversity benefits. According to this definition, a NBS must meet three main requirements:

- Contribute directly to an identified societal challenge, other than biodiversity conservation;
- Be based on the functioning of ecosystems;
- Present benefits for biodiversity.

In view of this definition, we are entitled to ask ourselves if prevention/protection strategies and actions built on the use of the forest are not the precursor of the current NBS. Before NBS, weren't there the Forest-based Solutions that inspired the concept of NBS?

To answer this question, it is necessary to have an overview of the historical evolution of the perception and management of natural hazard protection forests.

Historical synthesis on the forests with a protective function in France

Summary based on studies by Mougin (1919), Deveze (1979), Couvreur (- 1982), de Crécy (1982, 1995), Charlier (1982), Bonnet (1983), Noel (1984), Sonnier (1991), Liévois (1996), Berger et al (2014).

The definition and legislation of forests with a protective function have evolved along with the nature and location of issues over time. Since forests are a means of combating natural hazards, the history of forests with a protective function cannot be dissociated from that of natural hazard management. The most important stages in this evolution are the promulgation of the various laws that serve as the legislative basis for the policy of Mountain Land Restoration. In his article on the birth of Mountain Land Restoration, De Crécy (1995) considers that four major stages can be defined:

- Before 1800 : a self-sufficient management.
- From 1800 to 1859: an awareness by the central power.
- From 1859 to 1960 : the golden age of the Mountain Land Restoration.
- From 1960 to 1991: the tourist explosion - A new demand.

In addition to these 4 stages recognized by all the authors, we can highlight 3 additional stages directly related to my research work from 1995 to 2022:

- From 1991 to 2001: the will to valorize the function of risk protection of the forest heritage in the policy of prevention of natural risks via the cartography and the notion of Green Zones.
- From 2001 to 2013: the acquisition and formalization of new knowledge via the mountain forestry guides.
- From 2013 to the present day: the desire to harmonize methodologies and criteria for the zoning of forests with a protective function at the European level.

Before 1800: A self-sufficient management

This first period was marked at the scale of the kingdom of France by a community management of natural risks, which resulted in a reasoned management and a restriction of the right to use the forests initially established by the users themselves and then extended to the duchies of the mountain areas. Thus for the Duchy of Savoy:

- ''the woods and trees, of whatever kind, which are suitable for supporting the snow and preventing avalanches and landslides, may never be cut, unless it is in places where the avalanches and landslides cannot cause any damage''
- ''It shall not be permitted to anyone to uproot or burn the trunks of the trees that support the banks of the rivers, only the liberty of pruning the branches and the top when they are seven years old, in such a way that they are left at least eighteen common feet (four meters) above the ground.''

The threatened stakes are local stakes, localized to the mountain valleys. But the needs caused by the demographic growth and the industry have multiplied the uses and the users of the forest. Thus, the exploited forest surface, the clearings are more and more important and the restriction of the rights of use is about to be forgotten.

From 1800 to 1859: A new awareness by the central power

Although the legislation of the first Empire preserves the one in force for the forests with a protective function, the overexploitation of the forests and the clearings are very important at the beginning of the 19th century. One can observe an increase in torrential floods and erosion. Thus, more and more frequently, the access roads were cut, the land was washed away, when it was not the houses themselves. Napoleon's military engineers increased the network of communication routes and moved the main routes from the sides of the slopes to the bottom of the valley, thus exposing them to torrential phenomena. The representatives of the State will thus be able to become aware of the threats which weigh on the mountain populations. The travelers who crossed the Alps did not fail in their accounts and correspondence to describe the dangers they encountered. The sources and the volume of information, of varying quality, therefore increased. The central power, located in Paris, will be able to perceive the state of the situation regarding natural risks in the mountains.

However, the local population has an increasing need for wood, while the (wood) resource is becoming increasingly scarce. Despite this, some municipalities ask for the setting aside of certain cantons. The inhabitants of Beaufort-sur-Doron (73) thus obtained to fix the directives of exploitations: only the trees of more than 45 cm of diameter at 1 m of the ground are exploitable, the height of the stumps must be of 1 m and finally no exploitation will be carried out if the exploitable woods will not have been inventoried and marked by the forestry agent and his clerk.

Surrel, an engineer of the Ponts et Chaussées in service in the Hautes-Alpes studied the mechanisms of erosion recovery, its causes and consequences. The enormous success met by the publication of his results in 1842 finally allows the State to become fully aware of the problems related to torrential phenomena. In this work, the author recommends reforesting the mountains because he believes that the clearing of land and excessive grazing are the causes of these phenomena. On the other hand, if these practices were maintained and no reforestation was done, Surrel and his supporters predicted great floods in the plain. The floods of 1856 to 1859 of the great rivers coming down from the mountains, the Loire, the Rhône, the Garonne and the considerable damage they caused, proved Surrel right. They also made the State aware of the necessary solidarity between upstream and downstream to prevent natural disasters.

The year 1859 also corresponds to the drafting of a new forestry code. An article of this code specifies that the opposition of the forestry administration can occur if the conservation of the woods is recognized as necessary for the maintenance of the lands on the mountains and the slopes; for the defense of the soil against the erosions and the invasions of the rivers or torrents; for the existence of the springs and the streams.

This second period corresponds to a worsening of the situation regarding natural risks in the mountains. The forests are overexploited and the clearing of land is increasing due to farming and breeding practices. Moreover, there is no effective legislation to protect the forest against these practices. The catastrophic floods that resulted made the State aware of the seriousness of the situation and of its role in the management of natural risks. But for the State the socio-economic stakes are in the low valleys and the plain. It is therefore going to take measures to protect exclusively these stakes from the damages caused by the water divagation. The foresters drew up plans that excluded any abusive cutting, and the forest cantons that served as a screen against rock falls and avalanches were removed from exploitation. In these cantons, only "rotten and decaying" woods were exploited. For the first time, the term "protective series" was used in forestry planning. The forester opposes the clearing of private woods by referring to the forest code of 1859. But the forester still lacks a legislative text to oppose the abuse of exploitation that generates natural risks.

From 1860 to 1960: The golden age of Mountain Land Restoration

The year 1860 was marked by an important event: the first known law in Europe on mountain reforestation. The State was to help foresters by promulgating a series of laws defining the legislative basis of the mountain land restoration policy. The Emperor Napoleon III, in view of the damage caused in the large cities of the plains by the floods, promulgated a law on the reforestation of the mountains on July 28, 1860. It made the reforestation of land located on the summit or the slope of mountains mandatory "due to the state of the soil and the resulting dangers for the lower regions". Thus, the first reforestation perimeters were defined. These reforestations are considered as a task of public interest, essentially intended to protect the populations of the large valleys more than the mountain dwellers themselves. To carry out this work, the mountain reforestation service was created within the Administration of Water and Forests.

On June 8, 1864, a new law allowed for the "regrass" of the mountains. Indeed, the foresters in charge of reforestation quickly realized that well-maintained pastures were an effective way to control erosion. This law allowed the communes to substitute grassing with reforestation, and thus to reduce the costs of the work while maintaining the presence of the herds in these sectors.

The law of April 4, 1882, on the restoration and conservation of mountain land, completed by the law of August 16, 1913, will fully define the bases of the action of restoration of mountain land. This law created, from the service in charge of reforestation of the mountains, that of Mountain Land Restoration of the Administration of Water and Forests and it defined three orientations:

- The conservation measures: putting in defense of the rangelands and regulation of the communal pastures in the mountains.
- Restoration measures: either compulsory and carried out by the State after acquisition of the land by amicable agreement or by expropriation, or optional and simply subsidized by the State.
- Development works: of pastures and woodlands.

The compulsory works are only made necessary "by the degradation of the soil and the born and current dangers". The Mountain Land Restoration perimeters, thus defined, are limited to sites where natural hazards are declared and active. There is therefore no preventive action, and this limitation allows natural hazards that could have been controlled at the beginning at a lower cost, to become natural hazards requiring heavy and costly work to protect the public. These Mountain Land Restoration perimeters will give birth to the Mountain Land Restoration state series which will be partly grouped in Mountain Land Restoration state forests.

The Mountain Land Restoration laws of 1860, 1882 and 1913 only concern, from a forestry point of view, the afforestation and reforestation of land. The management service of the Administration des Eaux et des Forêts (Water and Forestry Administration) must deal with the management of stands and silvicultural work. As such, it will be required to manage Mountain Land Restoration reforestation, except when the plantations are linked to protection works. But the forester still lacks a legal status that would allow them to manage other stands already established and with a protective function. This legal status will finally arrive with the law of April 28, 1922, known as the Chauveau law. It allows the legislator to define the term of forest with protection function and to create, among others, peripheral protection zones around and in addition to the torrential correction zones, defined by the previous laws.

This law allows to define as forest with protection function the wooded lands whose maintenance in wooded state is recognized as necessary to maintain the lands on the mountains and on the slopes, to defend against avalanches and against the invasion of water and sand and to defend against erosion.

In addition to this definition, it proposes a procedure for classification as a protection forest and the implementation of a special forestry "regime" for classified forests. This classification can concern large forests. At the end of this classification, a special forestry regime is established. It concerns :

- The conservation and protection of the wooded area.
- The measures are very strict because, as the law states, "no clearing, no excavation, no extraction of materials, no raising of the ground or deposit and no public or private infrastructure may be carried out unless the equipment is essential for the development and protection of the forest.
- In addition, the prohibition of frequentation by the public may be regulated or prohibited by prefectural order, to ensure the maintenance of the wooded state.
- The administration in charge of forests may carry out all the works deemed necessary to consolidate the soil, to protect against avalanches, to restock the voids, to improve the stands, and may control the frequentation of the public in order to maintain the biological balance. The execution of these works is the responsibility of the State.
- The management of the forest.
- The classification as a protection forest makes it possible to avoid abusive felling in private forests. In fact, cutting in classified forests cannot be done without a prefectoral authorization. But this classification is not able to oblige the owners to apply a management adapted to the reasons of the classification. Indeed, "the exploitation regulations are in no way obligatory".
- Rights of use and grazing.
- For protection forests not subject to the forest regime, no right of use may be granted without the authorization of the prefect. For all protection forests (whether or not subject to the forest regime) grazing is limited to areas where cutting is prohibited.

In summary, this third period saw the legislator lay down the legislative bases for the policy of restoring land in the mountains. He thus created the Mountain Land Restoration Service, a specialized service of the Water and Forestry Administration. For this service, the forest is not the goal to be reached but only one of the means to fight against the distant risks of floods and against the close risks of torrential origin. The classification of forests with a protective function complements the actions of mountain land restoration and corresponds to the final touch of the legislative and regulatory edifice set up in 1860. Unfortunately, this classification procedure only defines the legal basis. Thus, it does not make it possible to answer essential questions such as the definition of a management and a forestry adapted to the protection against natural risks. Its implementation is laborious, which explains, in part, its low use. For the first time, the State became aware of the need to identify and map natural hazards. To do so, it used the remarkable network of observers constituted by the field agents of the Water and Forestry Administration. Until then, the policy of mountain land restoration was essentially dedicated to torrential phenomena. The development of tourism from the 1960s onwards changed the public's demand for safety.

From 1960 to 1991: the tourist boom - A new demand

Until the 1960s, the main risk to combat was torrential overflow, which was confined to relatively fixed geographical areas known to the Mountain Land Restoration managers. But the development of tourism, linked to that of winter sports, means that the public goes to the mountains and very often in areas that, traditionally, man abandoned in winter.

To accommodate these tourists, the capacity of the villages and ski resorts is being increased. To this real estate development is added that of the access roads. Thus to the torrential overflows come to be added avalanches and rock falls. The acquisition by the State of the zones where the risks arise is now inadequate, taking into account the surface to be treated. Indeed, it would be like nationalizing the whole mountain! Moreover, the public is looking for absolute and immediate security.

It is therefore necessary to localize the risks to determine the nature and priority of the interventions necessary to guarantee the safety of the public. The disaster of Val d'Isère on February 10, 1970, which caused the death of 38 teenagers and injured 39 others, will encourage the State to equip itself with the necessary means to proceed to the localization and the posting of the risks. It will thus develop the Plans of Zones Exposed to Natural Risks, the Plans of Exposure to Risks and finally the Plans of Prevention of foreseeable natural risks.

At the same time, the legislator replaced the Chauveau law by the law of July 10, 1976. It only modifies the definition of protection forests by enlarging it to "woods and forests, whatever their owners, located on the outskirts of large agglomerations, as well as in areas where their maintenance is necessary, either for ecological reasons, or for the well-being of the population".

The evolution of the needs in the field of localization and the display of the risk are the main facts of this fourth period. The Mountain Land Restoration services, in addition to the programming of works related to natural hazards, have become recognized experts in the field of natural hazards both in punctual prevention actions and during periods of crisis. They are also one of the interlocutors for the Plan de Prévention des Risques Naturels en Montagne. If an initial mapping of forests with a protective function has been carried out, it is unfortunately not exhaustive because it only concerns state-owned forests that have been subject to regulatory classification or that have "a direct and marked physical protection role" as defined in the Sonnier survey of 1988. This first survey allowed for an inventory to be made, marking a desire to enhance a natural heritage with a public utility function. It also highlighted the lack of knowledge and tools to carry out risk mapping considering the action of forest stands on the dynamics of natural hazards. This period is also marked by the progress made in the field of Computer Assisted Cartography, then of geomatics and in parallel in that of modelling (computing power, modelling of hazard dynamics in 1 and 2D).

From 1991 to 2001: the will to valorise the function of risk protection of the forest heritage in the policy of prevention of natural hazards via the cartography and the notion of Green Zones

The high costs of setting up and maintaining civil engineering works and the desire to optimize public investments have re-initiated, since 1991, in France and in all the countries of the Alpine arc, a reflection on the adoption of preventive measures and the valorisation of natural environments as natural protection works. Within this framework of reflection, France (Berger 1997), Austria (Plonner and Sonser 2000), and Switzerland (Medico 2000) have developed similar methodologies for zoning forests for protection against natural hazards. Based on work carried out from 1991 to 1996, Cemagref of Grenoble proposed in 1996 a first method of zoning forests with a protective function based on the use of a Geographic Information System (GIS). This first study made it possible to estimate, by considering the zones of potential avalanche and rock fall departure currently masked by the forest and for which no activity has been observed to date, that a third (order of magnitude) of the French mountain forests is able to have an effective protection role with respect to natural risks (Berger F. 1996).

If we consider the figures of the Ministry of Agriculture and for the department of Savoie alone (Sonnier survey of 1986), the total surface area of forests having been classified as having a protective function is only 3319 ha, i.e. 5.5% of the 60,000 ha studied. Consequently, if only the forest areas classified as protection forests under the Chauveau law are taken into account, then the total area actually occupied by forests with a protection role is greatly underestimated.

During this work, a state of the art on the scientific knowledge of forest-natural hazard interactions was carried out and served as a basis for the drafting by the ONF of the first French guide specifically dedicated to forest management and natural hazards (Hurand 1994). This guide offers French managers a synthesis based for the first time on dendrometric parameters for which threshold values are proposed (resulting from a bibliographic analysis and the empirical knowledge of practitioners).

This work was used as a basis for the drafting of the January 2001 Forest orientation law (Law n°2001-602 of July 9, 2001). It is only since this law, with the modification of articles L423-1 (possibility of subsidizing certain forestry works) and L425-1 (possibility of recognition of the service of protection of forest stands in the Plans for the prevention of foreseeable natural risks) of the forestry code, that the forest is considered as a natural protection structure requiring an adapted management and allowing to guarantee the effectiveness of this protection in time. It is important to specify that if the 2001 forestry orientation law offers the possibility of enhancing the protection offered by the forest cover, none of the first methodological guides for the realization of the Plans for the prevention of foreseeable natural risks elaborated in 1999 takes into account this effect of the forest cover. To do so, it will be necessary to wait for their revisions, which was decided in 2015 by the Ministry of Ecology, Sustainable Development and Energy (MEDDE) and scheduled for 2016, with the participation of forestry experts in the steering committees.

In addition, the publication in 1996 of the book Instructions - Soins minimaux pour les forêts à fonction protectrice by the Swiss Federal Office for the Environment, Forests and Landscape (SAEFL, which has since become the FOEN) and in 1999 of the first edition of the Guide des Soins Minimaux pour les forêts protectrices (Guide to Minimum Care for Protective Forests) marked an important step for mountain silviculture at the scale of the Alps. Indeed, for the first time in the history of forest management, a silviculture guide proposes, for each of the natural hazards present in the Alpine zone, criteria and thresholds allowing the definition of objectives for the sustainable management of stands. This definition is based on the characterization of the efficiency of the protection they offer and on the natural evolution (without silvicultural interventions) of this protection in 10 to 50 years. Based on the feedback from the implementation of this guide on a Swiss scale, the foresters of the Alpine arc were unanimous in recognizing the need for such a manual, which does not give recipes to the practitioner, but which encourages him to make the necessary observations and steps before planning and intervening. The use of this first guide has made it possible to define new lines of research in direct relation to the requests of the practitioners.

From 2001 to 2013: acquisition and formalization of new knowledge through modeling and mountain forestry guides.

This period is marked by the rise of modeling and geographic information systems (GIS) to assist in the zoning and sustainable management of forests with a protective function. In France, the effort to acquire knowledge on the interactions between forests and rapid gravity events focused on the characterization of the mechanical resistance of a tree during the dynamic impact of a rocky projectile, by equipping itself with a unique research tool: the experimental site of Vaujany. The knowledge acquired has been formalized in different types of models and publications. These publications were used for the first revision in 2005 of the Swiss guide to Minimum Care for Swiss Protective Forests (since renamed Sustainable Management of Protective Forests) and the models were used for the first edition of the French guides to mountain silviculture for the Northern Alps (2006) and for the Southern Alps (2012). In parallel, the 1996 zoning methodology (rocky and avalanche risks) was optimized by developing models, compatible with a GIS platform, which were lacking to automate the production of maps for expert appraisal.

From 2013 to the present: the desire to harmonize methodologies and criteria for the zoning of forests with a protective function at the European level.

The year 2013 is a key date in the construction of the European Union (EU) forestry strategy. Indeed, until 2013, the EU forestry strategy developed in 1998 was in force. Its framework of action aimed for the sustainable management of forests and their functions. In total and for the period 2007-2013, 5.4 billion euros were made available by the European Agricultural Fund for Rural Development for sustainable forest management. It soon became apparent that the allocation of these funds required harmonization at the European level of the definitions, indicators and methodologies used by each EU member state.

The European Commission proposed that the states agree in 2014 on the setting of "harmonized" criteria for forest protection. On September 20, 2013, was presented the draft of the new European forestry strategy for the period 2014-2020. While sustainable forest management is still at the heart of the European forestry strategy, the novelty is to integrate an approach built on the concept of "value chain" (i.e. how forest resources are used to produce goods and services that strongly influence forest management). It emphasizes the need for a holistic approach that requires consideration of the full range of ecosystem services provided by European forests at regional, national and transboundary scales. The sustainable management of forest ecosystem services is thus considered as one of the pillars of rural development. Finally, this new strategy also calls for the establishment of a forest information system and reaffirms the need for harmonized information collection at the European level. The approval process of this new European forestry strategy was closed on April 28, 2015 with the adoption of the report of Kostinger. With regard to forests with a protective function, the most important articles and suggestions of this report (Kostinger 2014) are the following:

- The need to determine the value of forest ecosystem services in a more systematic way and to take it into account in the decision-making process of the public and private sectors;
- The realization that only healthy and stable mountain forests can fully fulfill their protective functions for man and nature by preventing avalanches, mudslides and by playing their role as natural flood defences; stresses that cross-border exchange is particularly necessary in this context;
- The need to oppose any attempt to link forestry to the competence of the European Union and that the local and regional character of the sector and the legal competence of the Member States in this field must be respected, while seeking coherence between the respective competences of the European Union and the Member States;
- Urging Member States to design their forestry policies in such a way as to take full account of the importance of forests in protecting biodiversity, preventing soil erosion, ensuring carbon sequestration and air purification and maintaining the water cycle;
- The call for strengthening the harmonized monitoring of European forest resources including all wood and non-wood products and services as a basis for sound policy and decision making for sustainable forest management; therefore, underlines the need for an instrument based on existing bodies and organizations to ensure the resilience of future European forests by reducing the impact of disturbances through the consideration of forest risk in forest and land management.

In the end the new European forestry strategy can be summarized as: harmonization/valuation of ecosystem services/bioeconomy/sustainable management. In the context of the valuation of the ecosystem service of risk protection, the economic evaluation of this service will be one of the key points of the development of the future European approach, bioeconomy, for mountain forest territories. This economic evaluation will require the integration, in the diagnosis, of the dynamics of forest stands with or without human intervention, and the economic evaluation of the consequences of these scenarios. Thus, the new European forestry strategy relies on the contribution of modelling and models for the diagnosis of ecosystem services and to help formalize management choices.

Conclusion

The definition of forests with a protective function in France has changed very little over time. Generally, this definition includes the action of the forest on the regulation of the water regime, avalanches and rock falls. But at the end of the 19th century, until the day after the Second World War, the French State focused on its role of protection against water-related risks. It thus set the legislative bases of the policy of restoration and conservation of mountainous lands and created the Mountain Land Restoration services. These services, for which the forest is a means and not an end, are once again promoting biological engineering techniques after having gradually abandoned them in favor of civil engineering techniques. This transition from one technique to another has been, and still is, dictated by the evolution of the nature of socio-economic issues and societal demands. We have thus gone from proximity issues to delocalized issues in the valleys of the plains to finally return to proximity issues. But in the meantime, the users of the mountain have changed. The growing share of tourism and the development of communication routes and transnational exchanges, whatever the season, means that today the protection sought must be maximum and instantaneous. To guarantee the safety of the public, the state has developed a policy of displaying natural risks by means of zoning plans. The last to date Plan for the prevention of foreseeable natural risks, has benefited from the criticisms made to the previous plans, from the progress of technical and scientific knowledge, from the contribution of modeling and geomatics. The plan is also, among other things, the result of a simplification of procedures. The first methodological guides for the realization of the Plans for the prevention of foreseeable natural risks were elaborated in 1999 and do not take into account the effect of the forest cover in the regulatory zoning. In view of scientific and technical advances (knowledge, modelling, tools, etc.), legislation, and exchanges of experience at both national and international levels, the planned revision of these guides should make it possible to remedy this shortcoming.

Even if the Mountain Land Restauration, a specialized service of the ONF, has benefited since its creation from the evolution and modification of legislation and regulations concerning the policy of prevention of natural hazards, it is not the same for the forest management service. Indeed, despite a good definition of forests with a protective function by the legislator, the classification procedure and the classification itself are unsuitable for a management dedicated to the control of natural risks. Foresters had to wait for the revision of the forestry orientation law in 2001 before they were finally offered the possibility of having this protective function recognized in the Plan for the prevention of foreseeable natural risks. Furthermore, it is a pity that, at a time when work is being done to display the risk, no exhaustive assessment of the protective role of mountain forests other than state forests has been drawn up for all French mountain territories. Such a document would make it easier to consider the protection service provided by the forest, the implementation of the Guide des Sylvicultures de Montagne and, if necessary, the allocation of subsidies to cover the management deficits linked to the implementation of silvicultural interventions necessary for the perpetuation and optimization of the protection function of forest stands. The realization of such a cartography requires the development of models adapted to the scale of a territory, or even of a region, but also to the resolution of the available topographic data. Moreover, these models should not only locate forests with a protective function but also allow to qualify and quantify the efficiency of the protection offered by the forest stands. This mapping work will also have to be in line with the European will and strategy to harmonize indicators of sustainable management of ecosystem services.

In the end, the reforestation of the French mountains initiated in 1860 and in the logic of ''Imitate Nature, hasten her work (Adolphe Parade 1802-1864)'' are indeed one of the ancestors of Nature-based Solutions. Indeed, the implementation of these Forest-based Solutions meet all the requirements defined by the IUCN:

- Contribute in a direct way to an identified societal challenge, other than the conservation of biodiversity: in this case the prevention of natural hazards and the protection of goods and people.
- Rely on the functioning of ecosystems: afforestation, reforestation, silviculture as close to nature as possible to ensure the permanence of forest cover.
- Present benefits for biodiversity: the afforestation and reforestation works have restored and enriched the biodiversity in the concerned sectors.

Thus, at the beginning of the Nature-based Solutions were the Forest-based Solutions!

To conclude, let's leave to the engineer of Water and Forests, Prosper Demontzey (1831-1898), the word of the end: ''I know of no nobler mission than that of helping nature to reconstitute in our mountains the order that she had so well established and that only the improvidence of man has changed into an inevitable chaos.''

A biophysical approach of fire risk following biotic and abiotic disturbances in forests: the examples of bark beetles and drought

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Abstract

The behavior of forest fires strongly depends on weather and fuel conditions. In particular, the fuel structure, i.e. the quantity of fine material (needles, leaves, twigs) and its distribution (vertical and horizontal continuity), as well as the fuel moisture content (live and dead parts) are key factors of the spread, intensity and severity of wildfires. Biotic (e.g. insects) or abiotic (e.g. storms, drought) disturbances profoundly modify these factors, as they affect the spatial arrangement of fuel elements and they can increase the fraction of dead fuel or decrease the live fuel moisture content. These modifications, which can be highly heterogeneous at plot scale, induce interactions between the antecedent disturbance and the subsequent fire.

FIRETEC is a physics-based fire behavior model, which represents the fuel with a spatial resolution of about 2m and accounts for its moisture. It therefore allows to explicitly take into account the impacts of the antecedent disturbance on the fuel and in turn on the fire behavior.

We will present example studies of bark beetles/fire interactions that allowed us to analyze in detail the nature of the interaction between disturbances. This interaction can be synergistic, antagonistic or neutral, depending whether damages are higher, lower or equal to those generated by the two disturbances separately considered. This depends on the weather conditions, the intensity of the beetle attack and the lag between attack and fire, highlighting the complexity at play in multiple disturbance interactions.

Similar approaches can be applied to the drought/fire interaction. We will present pioneering studies on the impact of water content on fire behavior. Also, the dynamics of live fuel moisture content in response to drought, as well as the xylem cavitation causing increase in the fraction of dead elements, can be simulated with a biophysical plant hydraulic model called SUREAU. This offers interesting perspectives for the study of drought/fire interaction.

Introduction

The behavior of forest fires strongly depends on weather and fuel conditions. In particular, the fuel structure, i.e. the quantity of fine material (needles, leaves, twigs) and its distribution (vertical and horizontal continuity), as well as the fuel moisture content (live and dead parts) are key factors of the spread, intensity and severity of wildfires. Biotic (e.g. insects) or abiotic (e.g. storms, drought) disturbances profoundly modify these factors, as they affect the spatial arrangement of fuel elements and they can increase the fraction of dead fuel or decrease the live fuel moisture content. These modifications, which can be highly heterogeneous at plot scale, induce interactions between the antecedent disturbance and the subsequent fire. These interactions can be synergistic, antagonistic or neutral, depending whether damages are higher, lower or equal to those generated by the two disturbances separately considered.

FIRETEC is a physics-based fire behavior model (Linn et al. 2005), which represents the fuel with a spatial resolution of about 2m and accounts for its moisture. It therefore allows to explicitly take into account the impacts of the antecedent disturbance on the fuel and in turn on the fire behavior. It is hence a relevant tool to investigate the effects of fire following disturbances leading to modification of fuel structure and properties.

Here, we will present example studies of bark beetles/fire interactions that allowed us to analyze in detail the nature of the interaction between disturbances. Then, we will present pioneering studies on the impact of water content on fire behavior, as well as an ecophysiological modelling of the dynamic of live fuel, which can be used to assess the Live Fuel Moisture Content (LFMC), a key parameter of fire spread.

Bark beetles and fire interaction, the example of ponderosa pine stands (Sieg et al. 2017)

Bark beetle attacks induce tree mortality resulting in a drying of the pine canopy that becomes red ('red stage'), before dead needles fall on the ground, remaining only 'grey' trees. The whole process typically takes around 2 years depending on wind. During the 'red' stage, the low moisture induces more flammable fuels leading to increase in fire line intensity (Fig. 1). This increase can typically reach what would be observed for live trees, but with a wind twice as fast. When the needles fall on the ground, the potential for crown fires become more limited but wind speed increases, leading to quite high spread rates, but fires with less intensity.

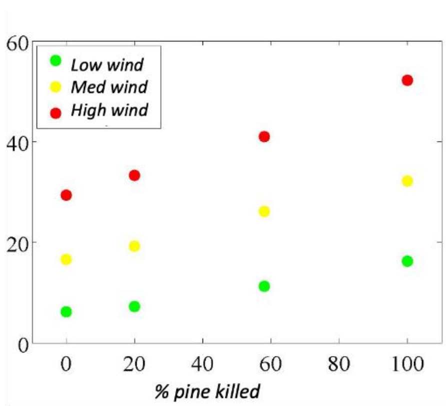

Figure 1. Fire line intensity (in MW/m) as a function of % pine killed by beetles for different wind speeds at red stage.

In order to evaluate the nature of interactions between the two disturbances at the two different stages, we computed a metric based on live canopy fuel loss to characterize if the linkage is antagonistic (net bark beetle and fire severity being less than if the two disturbances occurred independently) or synergistic (greater combined effects than independent disturbances). As shown in Fig. 2, 'red stages' are generally synergistic especially in low wind conditions, when the presence of dead trees increases fuel consumption in closest live trees, leading to aggravation of damage. On the contrary, 'grey stages' are generally antagonist, as the reduction of crown fire potential limits the damage to remaining live trees. The interactions between such disturbances depend on the weather conditions, but also on the intensity of the beetle attack and the lag between attack and fire, highlighting the complexity at play in multiple disturbance interactions.

Synergistic index	Low wind	Med. wind	High wind
Red stage, 20 %	2 (0)	3 (0)	1 (0)
Red stage, 58 %	**53 (+++)**	**10 (+)**	2 (0)
Red stage, 100 %	**89 (+++)**	**12 (+)**	2 (0)
Grey stage, 20 %	**16 (+)**	**-15 (-)**	-3 (0)
Grey stage, 58 %	**-13 (-)**	**-20 (--)**	**-9 (-)**
Grey stage, 100 %	**-15 (-)**	**-24 (--)**	**-24 (--)**

neutral (0), synergistic (+), antagonistic (-)

Red stage:
- 53 - 89 % increase in damage in low wind conditions
- Neutral under high wind

Grey stage:
- 10 - 25 % decrease in damage
- with the exception of the weak wind: 16 % increase

Figure 2. Synergistic indices for the different simulations of fire severity for 3 wind conditions and various beetle attacks with different characteristics

Drought and fire

Drought induces a drastic decrease in live fuel moisture content, which is one factor of fire behavior. There is surprisingly not that much literature on the role of live fuel moisture on the rate of spread of fires, which often focuses on dead fuel moisture content, with a few exceptions (e.g. Marino et al. 2012). In particular, the significance of this parameter has for long been ignored, given the difficulties to estimate its effects in field conditions, due to a variety of reasons (Pimont et al. 2019). Among them, experiments are often carried out in a range of moisture that is too humid to observe the effect of LFMC for obvious safety reasons. Hence, studies regarding the impact of live fuel moisture content on fire behavior are mostly modelling studies (Jolly et al. 2016; Banerjee et al. 2020) due to the difficulty to set adequate fire experiments in severe drought conditions, but there is more and more consensus on the key role of this factor, which effects highly depend on the fuel type and the range of LFMC (Figure 3).

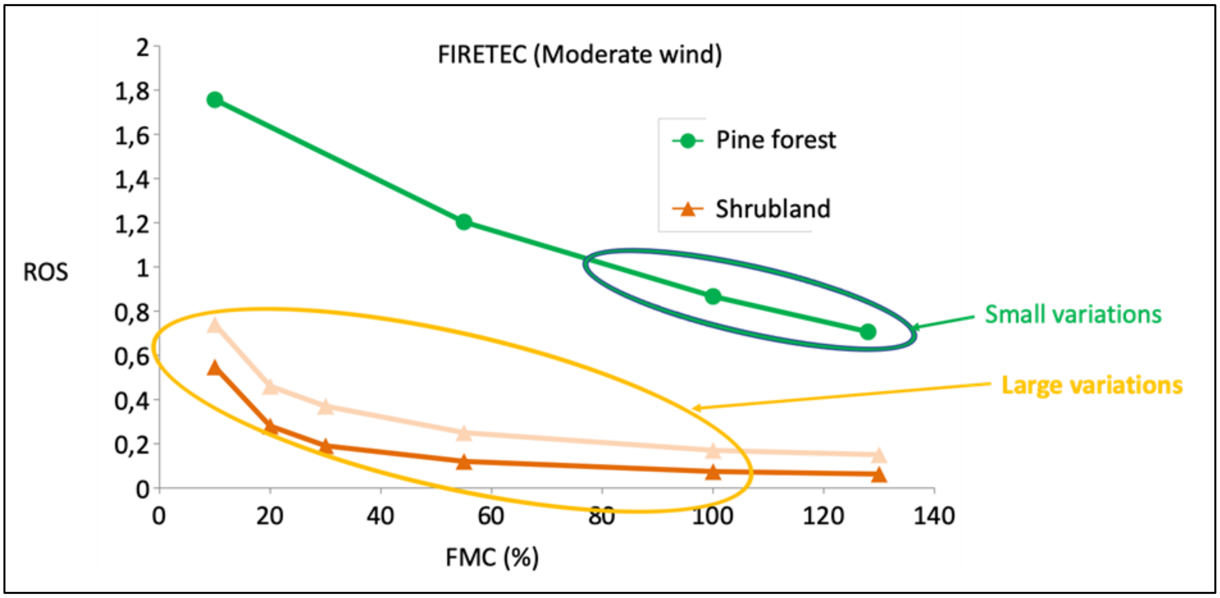

Figure 3. Relative effect of Fuel Moisture Content (FMC) on rate of spread (ROS) for different fuel types.

Another important research field as hence be the development of model able to predict Live Fuel Moisture content given the weather conditions and plant and soil parameters (Jolly and Johnson 2018). A good example of that is the Sureau model (Cochard et al. 2019; Ruffault et al. 2022a&b), as shown in Figure 4.

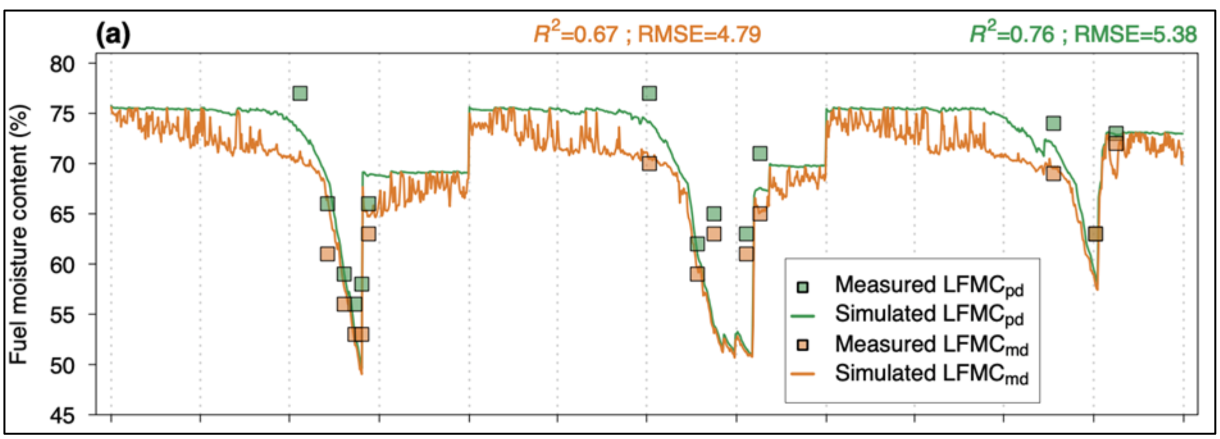

Figure 4. Comparison between simulation of LFMC with Sureau with field data (Ruffault et al. 2022b).

Conclusion

Interactions between disturbances are fairly complex as they depend on the weather conditions, but also characteristics of both disturbances. These interactions can be synergistic, antagonistic or independent. Several tools, from physics-based models of fire behavior to ecophysiological models of plant functioning are available to study these interactions in details.

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Wildfire and forest disease interaction

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Abstract

Northern hemisphere forests are increasingly relied upon to meet the carbon sequestration goals. However, these systems are increasingly impacted by tree mortality events and increasingly impactful wildfire events. Often the management approaches to mitigate or maximize fire safe conditions and forest carbon sequestration are in opposition. These challenges are magnified by disparities between the scales where management is applied, often at the stand scale, and the landscape scale where wildfire and biological tree mortality occur.

We use a series of examples to illustrate the complexity, opportunities, and challenges inherent to overcoming these intertwined problems. We demonstrate the impacts of biological tree mortality, wildfire, and forest management on forest carbon sequestration using a simple set of heuristic carbon models. These results are contextualized with several management experiments which demonstrate the scale and efficacy of interventions. Finally, we combine our understanding of current management tools with the biophysical dynamics of several tree mortality events and wildfire to identify questions central to maximizing management benefits as well as the pace and scale of these efforts.

Both North American and European forests are increasingly managed with the goal of increasing atmospheric carbon sequestration and meeting an ambitious set of goals to cap greenhouse gas emissions (Woodbury et al. 2007, Bellassen and Luyssaert 2014, Jandl et al. 2015). At the same time, arid as well as more mesic forests in these regions are experiencing increased wildfire frequency, intensity, and overall impacts (Penman et al. 2014, Mitsopoulos et al. 2015, Williams et al. 2019). The changing dynamics and impacts of wildfire threaten these forest carbon stores and the attendant management goals in multiple ways. Fire, of course, directly volatizes many components of the forest carbon pool such as soil carbon, dead organic matter, and living biomass (Hurteau and Brooks 2011, Restaino and Peterson 2013, Cobb et al. 2016). Fire also can kill individual trees or substantial portions of above ground biomass thereby converting living to dead biomass and arresting the flow of CO_2 from the atmosphere to terrestrial ecosystems, again threatening management goals (Metz et al. 2013, Earles et al. 2014, Hood et al. 2018). But wildfire problems do not occur alone, rather a host of biological tree mortality agents, drought and other factors associated with global change overlap in time and space with wildfire. The result is that these disturbance events not only overlap, but also interact in ways and on multiple time scales, often leading to even more extreme impacts of one or multiple disturbances (Chen et al. 2015, Johnstone et al. 2016, Cobb 2022). Thus, the theater of contemporary natural system management, research, and policy is one with a set of multiple risks, or a 'multi-risk' landscape including the overlap as well as the interaction of disturbances.

Policy makers and vegetation managers are increasingly well informed about the intensification of disturbance events, which is reflected in an increased effort to adapt management actions or increase the scale of their application (Forest Management Task Force 2021, Schwartz and Syphard 2021). However, for these efforts to be successful, the responses require a combination of efficacy, realistic logistics, and stakeholder buy-in (Cobb et al. 2017b). Here, I use several of these examples to contextualize several overlapping and interacting forest threats to contextualize the multi-risk challenge of contemporary forest management and argue that disturbance interactions are one of the risks in a 'multi-risk' perspective on natural systems. Researchers, policy makers, and natural system managers are increasingly aware of the magnifying effect of climate change on biological tree mortality, wildfire, and drought, which were previously the three most significant forest threats in isolation for many forests, particularly in western North America. Of course, these disturbances remain the most significant threats to forests in many arid regions, but the modifying effects of climate change and the increasing overlap among them demands that the community addressing these challenges adapt its vision, perhaps by treating them holistically.

When are forest ecosystems resilient in the face of climate change?

Understanding the degree of resiliency for any natural resource is increasingly important given that an interconnected human population relies on the resources provided by forests. In terms of carbon, we can expect some forest carbon pools will be more resilient than others because many of these resources have been stably locked within long-lived trees such as giant sequoia or redwood (Brown and Swetnam 1994, Busing and Fujimori 2005, Sillett et al. 2010). That many forest systems have been robust to the considerable variation in climate over thousands of years is evidence they can be resilient to a changing climate and the associated changes in disturbance regimes. On the other hand, the degree of climate change in regions such as California, the nature of anthropogenic drivers of this change, and the interaction of climate change and disturbance raises meritable questions regarding the degree of stress which can be absorbed and when undesirable shifts in forest resources will occur (Tepley et al. 2016, Williams et al. 2019, 2022, McLauchlan et al. 2020). Climate change appears to be redrawing many important aspects of disturbances and changing the boundaries of ecological transitions; these changes have potential for profound alternations of natural resources (Millar and Stephenson 2015, Cobb 2022).

Although there is clear evidence for resilience in many forests, there is much evidence that a greater diversity and distribution of forests across the globe appear susceptible to ecosystem conversion (Allen et al. 2015, Cobb et al. 2017b, Fei et al. 2019). Given the long time horizon of silvicultural treatments, it is likely that many forests will need to be restored when disturbance impacts exceed the capacity to recover (Van Lear et al. 2005, Cobb et al. 2017b, Rodman et al. 2020). Conversion from one forest type to another or replacement of one ecosystem structure with another that does not have the same carbon storage capacity is likely to create a need for the costly and difficult work of restoration intervention to achieve a desired state (Hemstrom et al. 2002, Ruthrof et al. 2013, Cobb et al. 2017a). Restoration interventions can be highly worthwhile but expensive. Thus, it becomes critical to understand the conditions which force ecosystem conversion, such as the multi-risk landscape of contemporary natural resource management. This provides some of the framework needed to identify which systems can be bolstered prior to conversion and help prioritize restoration treatments as well (Millar and Stephenson 2015, Cobb et al. 2017b).

To better understand the role of human systems – management, policy, and research – on forest resiliency, I along with numerous collaborators envision a coupling of a hierarchical human system with a set of natural feedbacks (Figure 1). In our rendering, top-down and bottom up forces drive actions on the human side while natural systems are a set of partial to fully reciprocal feedbacks (Liu et al. 2007, Spies et al. 2014, Cobb 2022). Immediate human experience has been shown to drive a substantial portion of risk perception and willingness to incur costs to avoid losses (Freeman 1989, Shafran 2008, 2012). Thus, the behavior of the natural system has a clear causal pathway to influence human behavior, for example by increasing the perception of risk after experiencing a natural disaster such as wildfire (Shafran 2008, Lecina-Diaz et al. 2021).

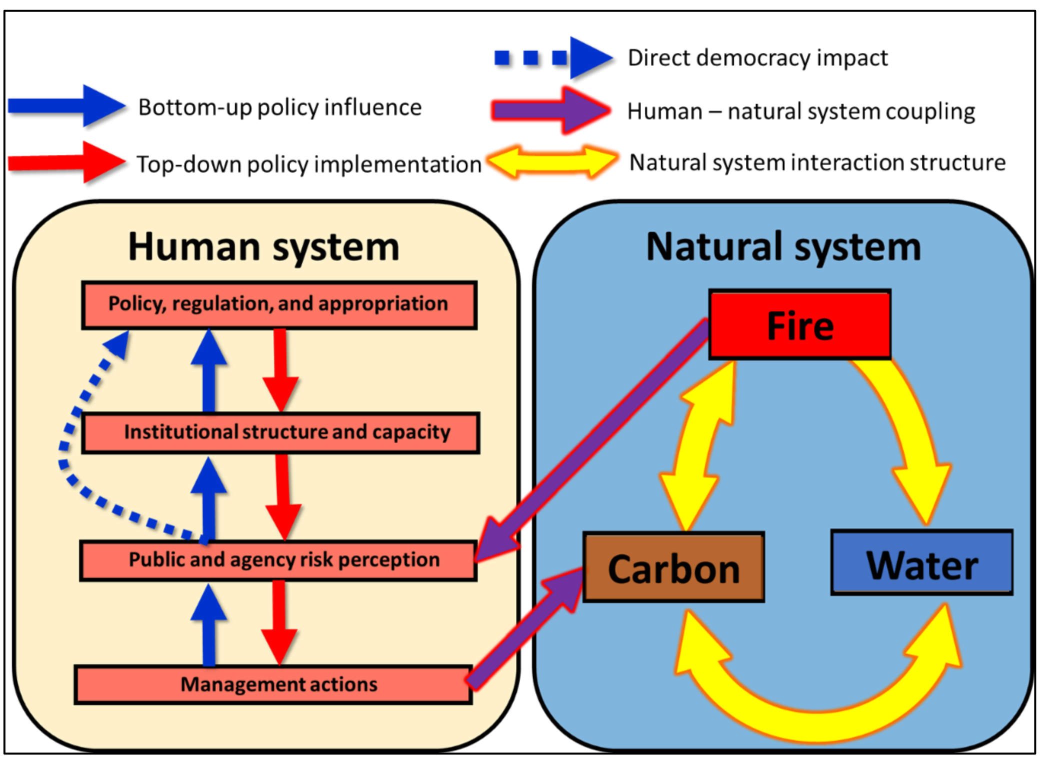

Figure 1. The structure of coupled human natural systems in California's wildfire and tree mortality crisis with several defined dynamics and couplings. Here the human system has a more easily defined hierarchy of scales while the natural system is rendered without a defined scale.

This framework gives some structure for testing hypotheses of natural system – human system interaction, such as that large investments in wildfire risk reduction is likely to alter dynamics of the natural system, specifically carbon storage and wildfire dynamics (Hurteau et al. 2008, Hurteau and North 2010, Boisramé et al. 2017). This is, after all, the goal or the point of costly management projects. In a representative democracy, bottom-up forces can influence or drive top-down initiatives such as the substantial current investments by the state in fuels reduction treatments. However, management actions are still largely advocated by, planned, and applied by individual actors or agency departments (individual landowners, non-profit landholders, federal or state agency districts, etc). What factors determine the capacity of these actors? Under what conditions can these actors successfully implement policy initiatives? When are these actions sufficient to mitigate a multi-risk landscape, including non-linear disturbance interactions? Substantial investments into forest treatments are a critical step to realizing forest resiliency. For example in California, investments in the forest sector aimed at addressing climate change are synergistic with efforts to address the state's wildfire crisis (Forest Management Task Force 2021). However, funding is of little use if the treatments are ineffective or where local actors lack the capacity or interest to undertake the large projects advocated by the state.

Muti-risks vs disturbance interactions: different flavors of the same problem

Recognition of co-occurring, overlapping, or interactive disturbances has gained attention with problematic increases in forest damage resulting from individual disturbance events (Lindner et al. 2010, Jactel et al. 2012, Metz et al. 2013, Buma 2015, Johnstone et al. 2016, Cobb 2022). Researchers who have focused on disturbance interactions have tended to focus on quantification of the interactive effects (potential or realized) of common disturbance events as these have only been identified as forest threats during the past ~20 years (Bebi et al. 2003, Kulakowski and Veblen 2007, Cobb et al. 2016, Simler-Williamson et al. 2021). Disturbance interactions have been visualized from several perspectives (Buma 2015, Johnstone et al. 2016, Simler-Williamson et al. 2019), but for the purposes of framing these as a category of 'risk' in a multi-risk landscape I highlight three useful illustrations (Figure 2). I ask the reader to imagine three distinct but familiar disturbances, such as wind-caused mortality, harvest, and wildfire. The specific disturbances are interchangeable or substitutable for this thought experiment. In many forests across the globe, each of these example disturbances are impactful events which shape many characteristics of a linked natural-human forest system. However, the degree of impact from disturbance interactions, their importance in a multi-risk landscape, and the capacity of management actions to mitigate them are each contingencies dependent on the timing, type of disturbance involved, and ecological dynamics inherent to the forest in question.

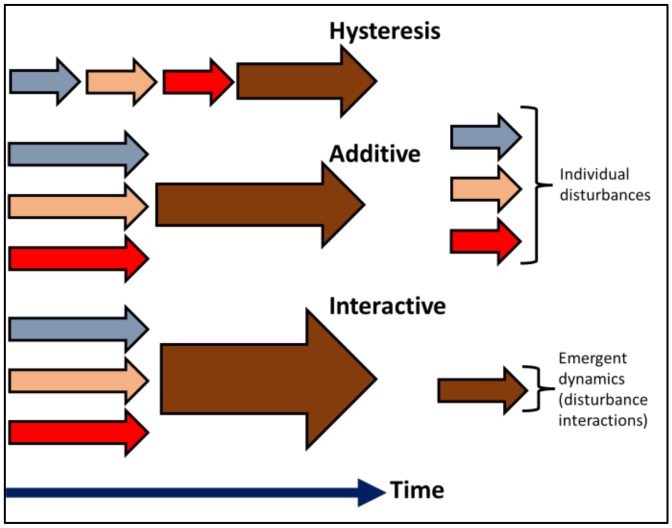

Figure 2. Several multiple forest risk frameworks with contextualization of disturbance interactions as a multi-risk. Disturbance interactions can emerge due to a sequence of historical events (Hysteresis), alter the likelihood of overlapping disturbances without changing the individual disturbance impacts (Additive), or act as a non-linear or multiplicative modifier of disturbance impacts (Interactive).

Three broad pathways for disturbance interactions to occur illustrate how these are distinct from or bound within the multi-risk framework (Figure 2). Hysteresis is a broadly recognized force shaping the structure, composition, and function of many ecological systems (Foster et al. 2002, Cunniffe et al. 2016, Mausolf et al. 2020). Historical factors which shape forest composition are critical drivers of future disturbances ranging from biological to biophysical (Foster and Orwig 2006, Lindner et al. 2010, Cobb 2022). Historical factors also include, of course, past management actions which is a clear link between the human and natural dynamics. Predisposition of forests to future threats due to historical factors, such as those related to a changing climate, have received appropriately strong attention and can be categorized as a set of disturbances linked in time (Allen et al. 2015, Millar and Stephenson 2015, Seidl et al. 2017). Disturbance interactions emerge as a distinct threat when the chain of disturbance events set the stage for a new kind of disturbance or alter the magnitude of impact of disturbances which are inherent to the landscape. For example, changes in species composition can predispose forests to emergence of novel pathogens and insects (Foster et al. 2002, Foster and Orwig 2006, Cunniffe et al. 2016). Changes in species composition also influence susceptibility to windthrow and alter fire dynamics and/or impacts (Whitney et al. 2002, Dolanc et al. 2014, McLauchlan et al. 2020). These disturbance interactions will merit research, policy, and management attention when they degrade important natural resources or create novel post-disturbance conditions that threaten future forest resilience.

The merit of applying precious attention to disturbance interactions is straightforward to evaluate when contrasting their emergence as “additive” or “interactive” impacts (Figure 2). In both cases, multiple risks occur in a system simultaneously, but the outcome of this overlap determines if the emergent impacts can be understood as a simple function of each disturbance alone (additive) or if nonlinear effects and/or impacts emerge (interactive). In the additive scenario, each disturbance has a constant effect on a resource in question and can be understood or predicted given the impacts of the individual events or conditions (Buma 2015, Johnstone et al. 2016, Cobb and Metz 2017). In the case of additive dynamics, a theater of forest threats is probably best thought of a multi-risk problem where reducing or avoiding one or more disturbances can be effective natural resource management (Cobb et al. 2017b). In contrast, non-linear or non-additive interactive impacts result in new threats or risks to sustainable natural resource management (Figure 2). Non-linearities resulting form disturbance interactions have received more attention in the last decade because of their potential to magnify the outcomes of preexisting, sometimes crisis-level, problems. For example, strong evidence supports the role of climate change in increasing biological tree mortality and wildfire (Temperli et al. 2013, Williams et al. 2019, Cobb 2022). However, the overlap of these events has also been shown to result altered impacts of one or the other disturbance, often but not exclusively magnifying the impacts of one or both disturbances (Metz et al. 2013, Sieg et al. 2017, Simler-Williamson et al. 2021, He et al. 2021).

Conclusions

Surprises are often problematic in natural resource management, particularly that of forests where resources are managed for long-term returns on investment. Interactive, or non-additive, impacts of multiple disturbances hold the greatest potential for undesirable surprises – that is, future unanticipated challenges to critical resources such as timber, water, and carbon storage. These future challenges which will undoubtedly reach crisis levels in many cases, are more likely to emerge in a multi-risk landscape, particularly one where non-additive interactions occur among disturbances which are linked in time and space. These emergent dynamics will likely reduce ecosystem resiliency, possibly simultaneously compromising economic resiliency of industries and communities.

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Anticipating and managing multiple risks to boreal forests and forestry under a changing climate: a Finnish Case study

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Abstract

Climate change induces multiple risks to forests and forestry globally. In Finland, the greatest abiotic risks to forests are expected to be caused by windstorms, drought and forest fires, and extreme snow loading on trees. The warmer climate is also expected to increase biotic risks to coniferous forests by many insect pests and pathogens of trees, and especially by European spruce bark beetle (Ips typographus) in Norway spruce (Picea abies) and wood decay by Heterobasidion root rot in Norway spruce and Scots pine (Pinus sylvestris). However, the occurrence of risks may vary largely depending on region and the severity of projected climate change. Wind damage risk is expected to increase especially in the south, because of the shortening of the soil frost period under a warming climate, and despite of any change in wind climate. The risk of snow damage is anticipated to increase in the north in opposite to the south. The warmer climate is also expected to increase drought, which may further boost the risk of large-scale forest fires. The warmer climate is also expected to increase the risk of European spruce bark beetle outbreaks and damages by Heterobasidion root rot especially in the south. The probability of detrimental cascading events, such as those caused by a large-scale wind damage followed by a widespread bark beetle outbreak, are also expected to increase. Different kind of risk management solutions may be needed, depending on geographical region and time span. Simulation models and other decision support tools, which can address multiple risks and uncertainties in decision making could provide a valuable support for decision making in forestry. Ideally, know-how on the sensitivity (and uncertainties) of forest resilience and provisioning of multiple ecosystem services to management strategies and changing operative environment may help to avoid extremely poor outcomes in decision making.

Multi-species forestry to address multiple risks in forests

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Abstract

Forests are increasingly threatened by numerous hazards whose frequency and severity are growing due to global changes, such as droughts, storms, fires, pest outbreaks or biological invasions. These threats are further reinforced by the fact that these hazards often follow each other, accumulate or interact, aggravating their deleterious effects. This complexity makes it even more difficult to implement means of control or prevention because they must be generic. Genetic selection for resistance or the use of pesticides are, for example, measures that are too specific to be effective against the multiple agents of damage. A more promising approach is to change silvicultural practices to enhance the intrinsic resistance of forest ecosystems. In particular, recent research suggests that increasing the diversity of forest species, in certain mixture configurations such as combinations of deciduous and coniferous trees, can lead to a reduction in vulnerability to drought, windthrow, fires, infestations by some native and exotic insect pests, and diseases caused by certain pathogenic fungi. The question remains, however, whether this resistance induced by the mixture of tree species is also relevant for multiple hazards. I review three types of hazard combinations and illustrate how their combined effects can be mitigated by forest diversification using examples from our research on associational resistance against insect pests, with a particular focus on the maritime pine-birch mixture.

A first case is the pleiotropic effect of species mixing reducing multiple composite hazards (e.g. several insect pests of different trophic guilds like borers, defoliators, seed feeders), where the mixed forest is more resistant to each of the hazards separately, thus reducing the risk associated with their possible cumulative effect over time. A second case of generic resistance is given by the reduction of the impact of a hazard that itself increases the vulnerability to a second hazard (e.g. a gall maker galls favouring the contamination by a needle cast), and thus interrupting the cascade effect. A third case concerns the simultaneous reduction of sensitivity to two simultaneous hazards (e.g. a defoliating insect and a bark beetle) and therefore for which the resistance of species mixtures limits their synergistic impact on tree survival.

It should be remembered that risk also depends on the exposure, i.e. the values at stake that are exposed to the damage inflicted in hazard-prone forests. The exposure value is in principle very important in the case of monocultures because all trees belong to the same sensitive species,

whereas in a mixed forest it is more rare that all species have the same level of vulnerability to different hazards, preserving the possibility of survival and growth to a part of the trees.

It is therefore expected that forest diversity will reduce both vulnerability to different hazards and exposure to different types of damage, thus reducing the magnitude of multiple risks. These theoretical considerations now need to be verified experimentally to enable the design of mixed forest plantations that are more resilient to multiple hazards while ensuring the provision of expected forest ecosystem services.

An analysis of the risks associated with the range expansion of forest insect pests in relation to climate change

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Abstract

Predicting the impacts of climate change on earth's ecosystems is arguably one of the most challenging research questions of our times and is giving new impetus to many ecological questions. One of these questions relates to our understanding of the factors and processes that define the range of a species and how climate change may affect these factors and processes. A review of our current knowledge suggests that defining the range of many forest insect pests is not a trivial question because population structure at the range limits is often complex. Despite these difficulties, there are strong evidence that the distribution of some forest insects species have changed in the past decades. For a species to expand its range, it has to overcome the factors that limit its distribution and establish in its new territory. We review the physical and ecological barriers that may limit the range of a forest insect species and the demographic parameters that control its establishment in new areas. We argue that little can be known and inferred from studies that document change in only one parameter. Instead, we need to focus more on developing process-based understanding of species responses to climate change to better predict the risks associated with changes in the range of forest insect pests.

Fire deficit in boreal North America: causes, consequences, and future projections

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Abstract

Fire deficit, the lack of wildfire activity relative to what is expected in a given fire environment, is usually the result of fire-management policies aimed at extinguishing all wildfires. In boreal forests of Canada, where wildfires are generally stand renewing (i.e., lethal to trees), fire-deficit areas contain large tracts of continuous mature forests. This unnaturally old forest mosaic may have unintended effects on fire management by increasing the potential for large, high-intensity wildfires, a phenomenon coined as the 'fire paradox'. In boreal Canada, the fire deficit is generally high around human communities, given that fire-suppression activities prioritize areas where people live and work. Moreover, the density of ignitions is comparatively higher around communities—22 times greater considering a 5-km buffer—than in areas farther afield, putting exceptional pressure on fire-management resources to protect these communities from wildfire. While it is possible to pre-emptively mitigate the wildfire hazard through the modification of vegetation (e.g., fuel treatments, prescribed burning), the changing climate may further complicate community wildfire protection. Increasing extreme weather conditions lead wildfires to burn vegetation indiscriminately, thereby undermining the effectiveness of fuels-reduction strategies. Moreover, climate-induced phenomena such as mass tree mortality, unprecedented insect outbreaks, and accelerated permafrost thaw—all on the rise over the last half-century—will challenge both fire management activities and ecological resilience. Despite the ongoing changes and future uncertainly in the boreal biome, our understanding of these natural systems is growing more rapidly than ever. Given the magnitude of changes that have yet to happen, it is imperative that we become better equipped to live with large, high-intensity boreal wildfires.

SECOND SESSION “TOWARD FACILITIES DEVOTED TO SURVEY AND MONITOR MULTIPLE RISKS INCLUDING EMERGENCY DEVICES FOR MAJOR RISKS”

Opportunities and limitations of thinning to increase resistance and resilience of forests to global change

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Abstract

We reviewed recent literature to identify the positive and negative effects of thinning on both stand- and tree-level resistance and resilience to four stressors that are expected to increase in frequency and/or severity due to global change: i) drought, ii) fire, iii) insects and pathogens and iv) wind. There is strong evidence that thinning, particularly heavy thinning, reduces the impact of drought, and also the risk and severity of fire when harvest slash is burned or removed. Thinning also increases the growth and vigor of residual trees, making them less susceptible to eruptive insects and pathogens, while targeted removal of host species, susceptible individuals, and infected trees can slow the spread of outbreaks. However, the evidence that thinning has consistent positive effects is limited to a few insects and pathogens, and negative effects on root rot infection severity were also reported. At this point, our review reveals insufficient evidence from rigorous experiments to draw general conclusions. Although thinning initially increases the risk of windthrow, there is good evidence that thinning young stands reduces the long-term risk by promoting the development of structural roots and favouring the acclimation of trees to high wind loads. While our review suggests that thinning should not be promoted as a tool that will universally increase the resistance and resilience of forests, current evidence suggests that thinning could still be an effective tool to reduce forest vulnerability to several stressors, therefore creating a window of opportunity to implement longer-term adaptive management strategies such as assisted migration. We highlight knowledge gaps that should be targeted by future research to assess the potential contribution of thinning to adaptive forest management.

Health risks in forests: from forest monitoring data and risk factors improving decision-making support

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Abstract

The Epidemiological Plant Health Surveillance Platfom is in charge of improving plant health monitoring in France. Surveillance, analysis and advice are our main lines of action to cater to public policies or professionals in the plant health sector. Projects have been undertaken relating to two pests which impact forest: pine processionary and pinewood nematode.

The Platform has completed statistical analysis in order to reduce the number of plots into a national monitoring network of Pine processionary. The results obtained have allowed French Forest Health Department to optimize the monitoring network thus enabling them to minimize redundant information.

Furthermore, a relative risk analysis was conducted to survey the absence of Pinewood nematode. Areas with relative risk of entry and introduction were identified. An evaluation of the survey system implemented since 2000 will be carried out based on these risk-assessed areas. The results were used to improve decision-making support such as areas that must be monitored or the number of samples that must be realized.

Platform presentation

In 2010, the animal health epidemiological surveillance Platform (ESA) was launched. In 2018, the creation of the plant health epidemiological surveillance platform (ESV) and the food chain epidemiological surveillance platform (SCA) will follow [Figure 1].

Figure 1: The 3 epidemiological surveillance platforms in France.

The ESV Platform is the result of the collaboration of several partners: INRAE, Anses, Ministry of Agriculture and Food Sovereignty, ACTA, APCA, FREDON France, and Cirad. It has 11 operational staff: 7 from INRAE, 3 from Anses and 1 from Cirad; bringing together multiple disciplines: computer scientists, statisticians, epidemiologists, communication officer, and monitoring officer.

The ESV Platform currently participates in 11 working groups where it provides technical and methodological support. Five working groups focus on a specific pest: *Xylella fastidiosa*, huanglongbing, Fusarium tropical race 4, vineyard decline and pinewood nematode. Four working groups are shared between the 3 platforms: data quality, One Health, Surveillance evaluation and Communication. And finally, two working groups focus on cross-cutting topics: surveillance for regulated or emerging pests, French epidemic intelligence system [Figure 2].

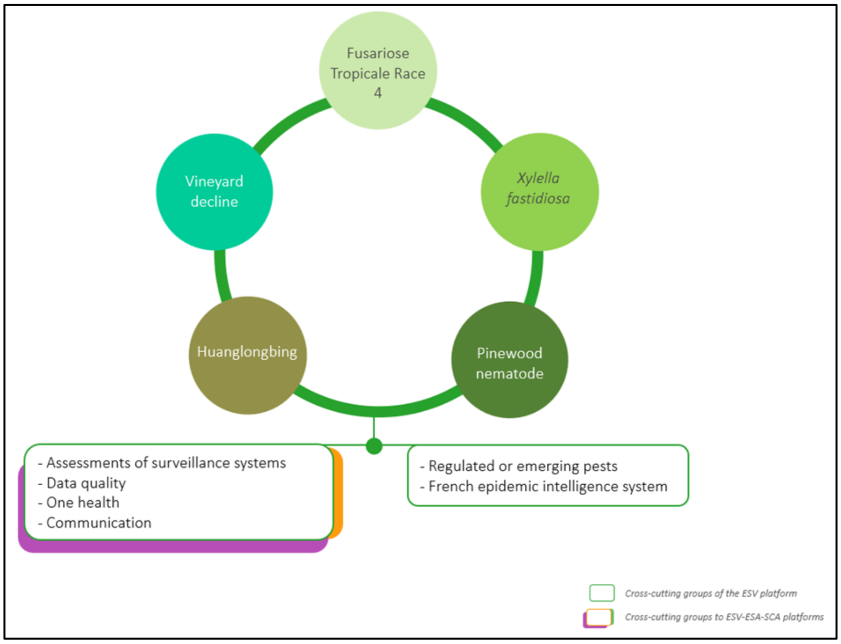

Figure 2: the 11 working groups supported by the ESV Platform.

The ESV Platform has carried out work on two forest pests: the pine processionary moth (*Thaumetopoea pityocampa*) and the pinewood nematode (*Bursaphelenchus xylophilus*). The objective of this work is to provide some answers on the improvement of surveillance strategies for these two harmful organisms in France and on the identification of areas at risk of introduction of the pinewood nematode in France.

Pine processionary moth

The Pine processionary moth is a harmful (non-quarantine) organism monitored in France by the Department of Forest Health (DSF) since 1989. This organism impacts the vitality of pines and the health of human beings by the production of stinging hairs on the caterpillar stage.

DSF corresponding observers have been monitoring this harmful organism in France since 1989 thanks to a network of active plots which, in 2020, numbered 514 plots. The number of nests created by the pine processionary moths is counted for 100 pines observed each year. Thus, the data centralized in the DSF database make it possible to highlight cyclical trends in the population dynamics of pine processionary moth according to the environment of the plots.

The ESV Platform came to support the DSF by proposing a method to optimize the monitoring network for the pine processionary moth. Indeed, some plots monitored each year did not provide additional information to the network. The objective of the ESV Platform was therefore to propose plots that could be removed from the network to limit information redundancy and to limit costs. For this, georeferenced data from observations of pine processionary nests for 100 pines observed between 2008 and 2020 were used. The analyzes were carried out independently for each major ecological region of metropolitan France (crystalline and oceanic Great West, semioceanic North Center, semi-continental Great East, Vosges, Jura, oceanic South-West, Massif Central, Alps, Pyrenees, Mediterranean, Corsica). The method consists in 1) characterizing the plots according to the years of observation, 2) applying an ascending hierarchical classification for each group, 3) gathering by hand the groups which are similar but not observed over the same years, 4) redoing the stages 2 and 3 on the groups not sufficiently discriminated. The results were compiled in an interactive dashboard available on the ESV Platform website (dashboard of the pine processionary page). For each major ecological region, the evolution curves of the number of nests per 100 pines observed for each plot gathered by group are presented one one hand. And on the other hand, it is possible to select one (or more) group(s) to visualize the IDs of the plots of the group and their coordinates, the curves of evolution of the number of nests for 100 pines observed for the plots of the group and the location of the group plots on a map [Figure 3].

Thanks to this dashboard, the DSF agents can visualize the redundant plots of the network (gathered together in the same group) and choose on several criteria (assembled in the same group therefore same population dynamics, location, knowledge of the plot thanks to their expertise) which eliminate plots from the network to limit information redundancy. Thus, the PACA and Occitanie regions have eliminated nearly 30% of the plots in the network based on this work.

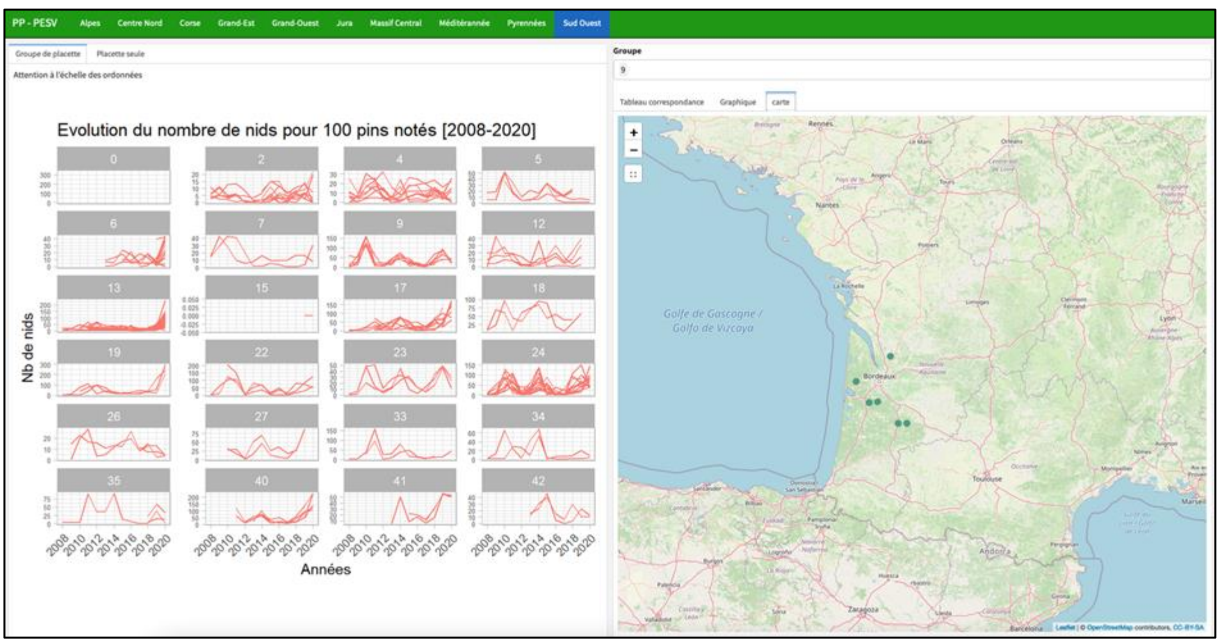

Figure 3: Overview of the dashboard for the South West region and group 9

Pinewood nematode

The ESV Platform supports the working group on monitoring the pinewood nematode in France. The pinewood nematode (*Bursaphelenchus xylophilus*) is a priority quarantine organism (OQP list) vectorized by Monochamus and currently absent from France. The working group brings together experts to reflect on the improvement and evaluation of the current monitoring system based on the identification of areas at risk of introduction of the pinewood nematode in France.

First, based on the article by Parnell et al. 2014 and on the equation Wi = Pi * R0i with, Wi the risk at place i depends on Pi the probability that the pathogen arrives at place i multiplied by R0i the size of the expected epidemic at place i; the members of the working group were able to define the criteria and data associated with the risk of entry (Pi) and the risk of establishment (R0i) of the pinewood nematode in France.

The data associated with the various criteria were then weighted by expert judgement. A multi-criteria analysis was carried out using the PROMETHEE software at two different scale levels: national and regional.

The results make it possible to highlight the areas (department or quadrat of 8 x 8 km) at relative risk of entry or introduction (entry + establishment) of the pinewood nematode in France.

The method and the results are explained and can be viewed in a dashboard available on the ESV Platform website (dashboard of the pinewood nematode page).

This work has made it possible to guide the choices concerning the places to be monitored in France by the actors in the monitoring of the pinewood nematode.

At the same time, work was carried out on the centralization of surveillance data. A mapping of the actors involved in the monitoring data pathway, from inspections and samples to the analysis results, was carried out. The data recorded by the various actors are centralized in the database of the ESV Platform continuously. Data quality work is carried out afterwards. To visualize this data and allow feedback to the actors, an R shiny application has been developed by the ESV Platform allowing the interactive visualization of sampling and trapping data in the form of graphs and maps. Due to the sensitive nature of this surveillance data, the application is reserved for actors with private access.

Then, the working group aims to assess the surveillance system based on the analysis of the relative risks as well as on various methods and tools. The group is considering the use of suitable mathematical models or the use of RIBESS, a tool developed by European Food Safety Authority (EFSA) to estimate the optimal number of samples and traps to be carried out according to the risk and other parameters (sensitivity of the method detection, maximum tolerated threshold of not detecting the pathogen, etc.).

Conclusion

To conclude, the ESV Platform supports surveillance actors and public decision-makers on various themes in metropolitan France and its overseas territories, including harmful organisms at risk for forests.

Monitoring forest health : what the Forest Health Department (DSF) does in France and which links exist with other risks

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Abstract

The DSF monitors the health of French forests through more than 250 forest health correspondent-observers, field foresters, mainly from the ONF (national forests office, in charge of public forests management), the CNPF (national center for forests properties, in charge of accompanying private foresters) and the State forestry services. This information is supplemented by health observations made by the National Institute of Geographic and Forestry Information (IGN). This system has made it possible to consolidate expertise and a health memory for the entire forestry sector and for long-term monitoring of the health of French forests. The expertise of the DSF is also based on close partnerships with research and reference laboratories (INRAE, ANSES, Universities), which use the data collected by the DSF and in return provide improved knowledge and support for the development of monitoring protocols.

In addition to a general health watch and the monitoring of regulated and emerging organisms, specific monitoring is organised for the most impacting health problems: spruce bark beetle, damage to young plantations, ash blight, oak defoliating insects, Douglas-fir needle midge, box tree borer, pathogens impacting poplar groves, pine and oak processionary moths, forest stand dieback due to multi-factorial causes, health problems of cork oaks. In terms of regulated and emerging organisms, the main concerns are pinewood nematode in Portugal and Spain, American oak wilt in the USA, phytophtora ramorum in the UK, pine canker in Spain and emerald ash borer in North America, East Asia, Russia and Ukraine.

Forest health problems can be triggered by other hazards (storms, snowfall, hail, droughts, ...) but can also increase the risks following them (fires, block falls, landslides, ...). The analysis of the interconnection of risks is a current issue.

Operational strategies for multi-risk management related to forest fires

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Abstract

Forest fire risk management in France is based on interdepartmental work and concerns 3 ministries and their operators (including ONF): Agriculture for prevention linked to the management of natural areas, Environment for prevention linked to the protection of people and property and the management of forest-habitat interfaces, Interior for firefighting and civil security.

Multi-risk management related to forest fires covers two aspects:

- The risks whose consequences can increase the risk of fire, in particular by increasing the available fuel (drought, heat wave, pest attacks, storms, etc.)
- The risks that are generated or increased by the passage of fire, in particular due to the loss of vegetation cover (falling trees, falling boulders, floods, mudslides, avalanches, etc.)

The presentation outlines the strategies implemented or under development for the forecasting and monitoring of these situations (mapping of the effects increasing the risk of fire to improve daily forecasting, rapid pre-diagnosis and post-fire studies, etc.) as well as the mitigation of post-fire risks.

Supporting annual allowable cut determination in Quebec through an integration of the multiple risks associated to natural disturbance and climate change

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Abstract

This paper details the ongoing work at Quebec's "Bureau du Forestier en chef"2 (BFEC) that seeks to support forest management decision-making in a context of uncertainty. Challenges to the integration of uncertainty into forest management are discussed. Recent developments on the ex-ante integration of natural disturbance (mainly wildfire) and climate change into forest modelling and analysis are presented. The synthesis of probabilistic information for consideration by decision makers is addressed. The focus of ongoing work is also presented.

Background

The principal responsibility of Quebec's Bureau du Forestier en chef (BFEC) is to determine annual allowable cut (AAC). AAC is the maximum volume of timber that may be harvested on an annual basis within each of the province's 57 management units (which together represent a total forested area of 42.5 million hectares). The process of determination can be divided into two main steps: (i) the estimation of maximum sustained yield (MSY) and (ii) AAC determination per se (Figure 1). MSY is the highest rate of wood harvest, measured in m3 of merchantable wood per year, that can be maintained over the long term (often 100 to 150 years), as estimated through modelling. To estimate the MSY, a forest estate model optimizes the selective application of management actions into the future, using as input the forest inventory and management constraints and objectives.

Based on the estimation of a management unit's MSY, the Chief Forester applies expert judgement to determine the maximum amount of wood volumes that may be harvested over time; this rate of forest harvesting is known as annual allowable cut (AAC). The work described in this report concerns principally the process of AAC determination.

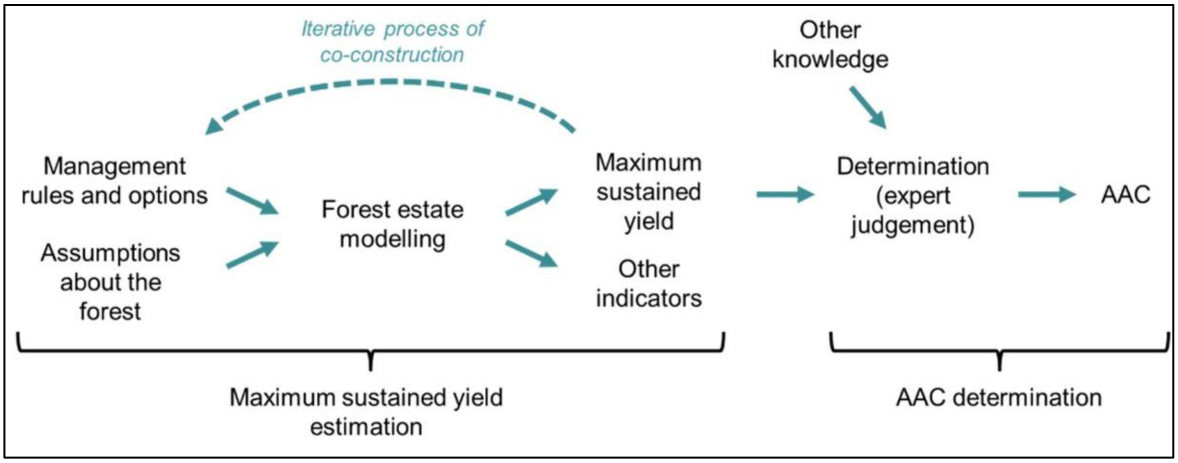

Figure 1. Diagram illustrating the process of MSY estimation (on the left) and AAC determination (on the right).

Motivations for the inclusion of uncertainty into AAC determination include the following.

- The Forestry Act and the Sustainable Forest Management Strategy of Quebec stipulate that climate change as well natural disturbance, both of which involve significant and inherent uncertainties, should be taken into consideration when determining AAC.
- Research (e.g., Savage et al. 2010) has suggested that adjusting AAC after large disturbances may, in certain cases, not ensure the sustainability of harvest rates over time.
- It is becoming apparent that in more constrained systems, where for example more demands are made on the forest in terms of multiple values, unplanned events such as wildfire may have greater social and economic impacts than in less constrained systems.

In this paper, three types of uncertainty are considered:

- Aleatoric uncertainty (or randomness): the uncertainty related to the randomness of natural and human systems.
- Epistemic uncertainty (or knowledge uncertainty): the uncertainty around our understanding of how natural and human systems function.
- Knightian uncertainty (or unknown unknowns): the uncertainty related to as-yet unknown future drivers of change.

Issues and challenges

As is the case with many aspects of forest management, AAC determination has been largely conceived in deterministic terms since its inception (Evelyn 1664). In Quebec and in most Canadian jurisdictions, the impacts of natural disturbance and climate change on AAC are generally considered after the fact (an “ex post” approach, sometimes called “a posteriori”), for example through the updating of forest inventory and sample plot data (permanent or temporary). Consequently, there has been limited discussion of uncertainty and little experience with the development of solutions as a function of that uncertainty. As the economic, social, and ecological demands on forest ecosystems increase, it is becoming apparent that our ability to overcome important and unexpected events through an ex post adjustment of management strategies decreases. Also, an unprecedented rate of climate change appears to threaten the resilience of forest ecosystems throughout Quebec (Boulanger et al. 2014 and 2017, Whitman et al. 2019). Thus, there is growing recognition that, under certain circumstances, a more explicit "ex ante" (before the event, sometimes called "a priori") integration of uncertainty related to natural disturbance may lead to a more sustainable management of forests (Savage et al. 2011, Daniel et al. 2017).

Experience to date

As mentioned previously, forest management and AAC determination have been largely conceived in deterministic terms. In most Canadian jurisdictions, and indeed in most management units in Quebec, when large disturbances occur the forest inventory is updated and a new AAC determination is undertaken in due time.

Starting in 2015, precautionary factors have been applied to the MSY at the time of AAC determination in two management units in Quebec (26-61 and 26-62) where the risk of fire is considered high. Recent work on natural disturbance applied a Monte Carlo approach to the stochastic modelling of interactions between wildfire and forest management in this region (Forestier en chef 2022). Analysis of results generated probabilistic qualifiers on the sustainability of a range of precautionary factors (Figure 2).

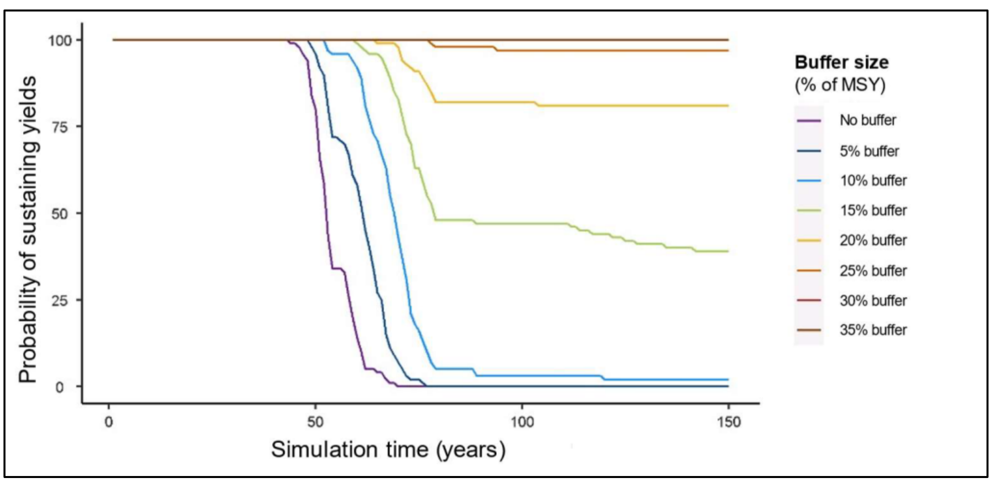

Figure 2. Probability of sustaining a range of AAC values, obtained through the application of a range of precautionary factors (from 0% to 35% reduction from MSY). Results are drawn from Forestier en chef (2022)

A pilot project initiated in 2018 at the BFEC3 sought to develop methodology to integrate climate change impacts into AAC determination. The project was also an opportunity to develop adaptations to climate change. An integrated forest landscape model was developed (Figure 3) for the project using the SELES landscape model building tool (Fall and Fall 2001). Many of the researchers whose work informed the landscape modelling participated in developing the approach and vetting modelling results (Bernier et al. 2016, Bouchard et al. 2015, Boulanger et al. 2014, D'Orangeville et al. 2018, Power and Auger 2019, Splawinski et al. 2019). The spatially and temporally explicit landscape model integrated natural disturbance (fire and spruce budworm), management actions (clear-cut harvesting, tree planting, precommercial thinning, and salvage logging), as well as the regeneration failure that resulted from the passage of fire through immature conifer dominated stands. Three climate scenarios (historical, RCP 4.5, and RCP 8.5), with outputs from three models (Can-ESM2, Hadley, and MIROC), influenced the behaviour of fire, spruce budworm, and stand productivity (Figure 3).

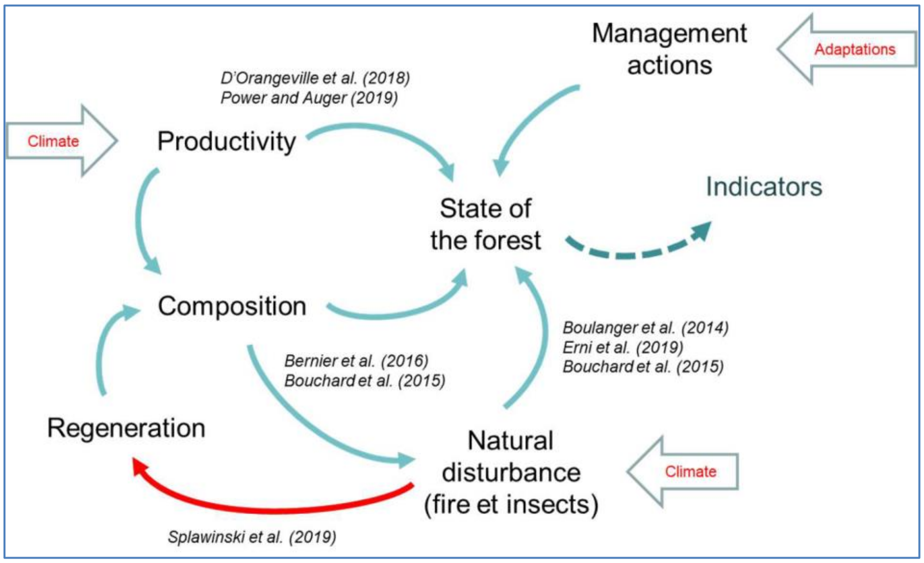

Figure 3. Conceptual representation of linkages within the forest landscape model used to model the impacts of climate change on AAC determination. Factors sensitive to climate (natural disturbance and productivity) are shown with arrows. Adaptation measures were developed and tested through control of forest management in the model. Illustration is drawn from Forestier en chef (2021).

Results from the climate change project (Forestier en chef 2021) show that, under status quo management (no climate adaptation), climate change is expected to impact AAC significantly, particularly under the RCP 8.5 scenario (Figure 4). In this project, climate model appeared to have little influence on the results (Figure 4), and only the Canadian model was retained for subsequent reporting.

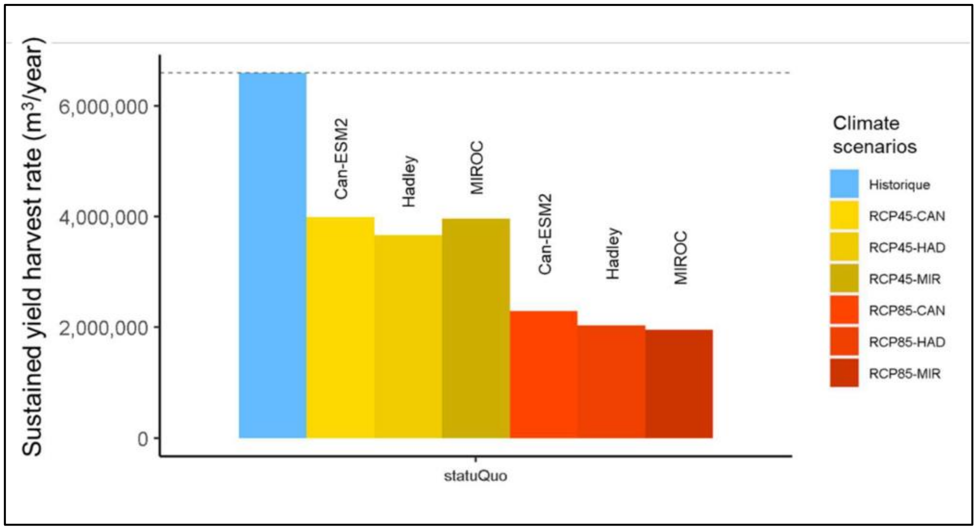

Figure 4: Maximum sustained yield for the status quo management scenario, under historical, RCP 4.5, and RCP 8.5 climate. Results are drawn from Forestier en chef (2021).

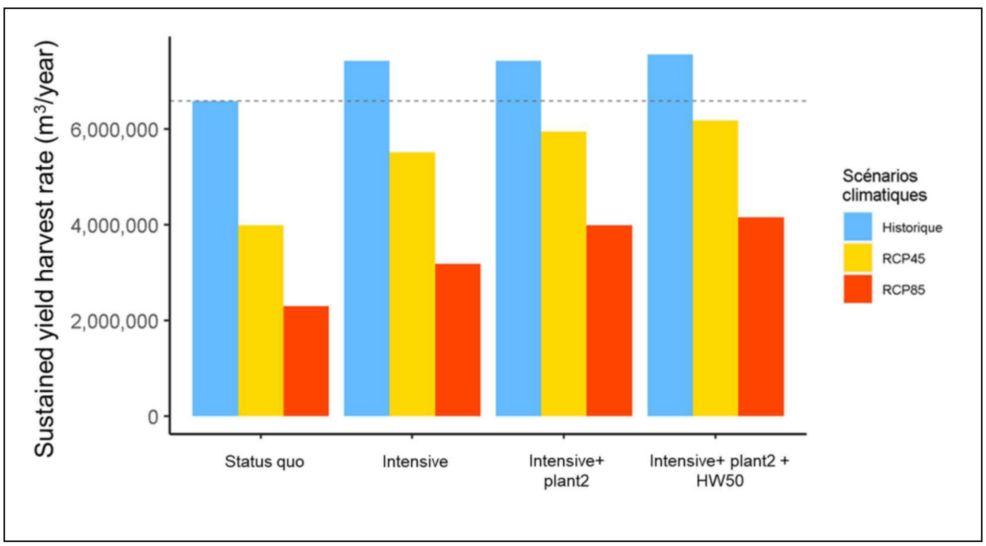

Figure 5. Maximum sustained yield under 3 climate scenarios for status quo management, intensified forestry (plantations focused solely on wood production), intensified forestry with increased extensive plantation, and intensification with greater plantation and hardwood enrichment. Results are drawn from Forestier en chef (2021).

Knowledge gaps

The work carried out on the integration of climate change and natural disturbance to AAC determination allowed for the identification of many knowledge gaps. These gaps included the following:

- An understanding of climate change effects on tree mortality, and how this mortality influences stand level productivity.

- Knowledge on the impacts of climate change and natural disturbance on regeneration and successional trajectories.
- The ability to predict the impact on annual burn rates of forest fuel composition and its spatial organization over the landscape.
- A better understanding of the influence of forest fuel impacts on the propagation or resistance to the spread of fire.

These gaps are being addressed through collaborative research projects. More clarity on these elements will help the BFEC develop more reliable projections of future forest states and a better estimation of the contribution of adaptation measures to the meeting of forest management objectives.

Moving forward

Certain ideas appear helpful as future work is developed and implemented in a context of decision support at the BFEC. The following details those ideas that seem most significant.

- Support decisions, don't predict the future

As a modeller, it is tempting to include as much detail as possible in a never-ending quest for realism. However, when the nature of linkages among forest ecosystem components into the future is highly uncertain, more mechanistic detail may not always be helpful in supporting decisions.

Also, parsimony, through its control on complexity, is important since simpler models are easier to explain and understand. As often paraphrased from Box (1976): all models are wrong, but some models are useful.

Some approaches to supporting decision-making may not require the explicit and mechanistic prediction of future states. Work based on the diversity-connectivity hypothesis (e.g., Aquilué et al. 2021) may provide the means to bolster resilience without requiring the explicit modelling of ecosystem processes.

The extension of TRIAD to climate change vulnerability (Roy-Tardif et al. 2021) is another example of a useful tool that does not necessarily require the modelling of underlying ecological process. Ecological collapse modelling may also provide some support to decision-making.

- Training will be helpful

We expect that training on climate change and natural disturbance, and how these interact with forest management and AAC determination, will be helpful as we move forward on this work. Such training should help to provide a common language for the integration of multiple risks, as well as empower analysts and partners in the development of adaptation strategies for the forests of Quebec.

- The process of decision support is important

As we present to decision-makers information that is based on an ever-increasing number of decision criteria, over multiple periods, for multiple scenarios, and for hundreds or thousands of equiprobable futures (through Monte Carlo trials, for example), the process of decision support becomes increasingly challenging and important. Bridging the gap between increasingly complex forest modeling and the support of actual decisions is crucial.

- Finance may provide tools

Financial analysis has successfully integrated uncertainty into language, analysis, and decision support. While practices may not be perfect, certain concepts, such as the avoid-reduce-transfer-retain approach to risk management (Figure 6) may be useful as we seek to support decision making in forestry.

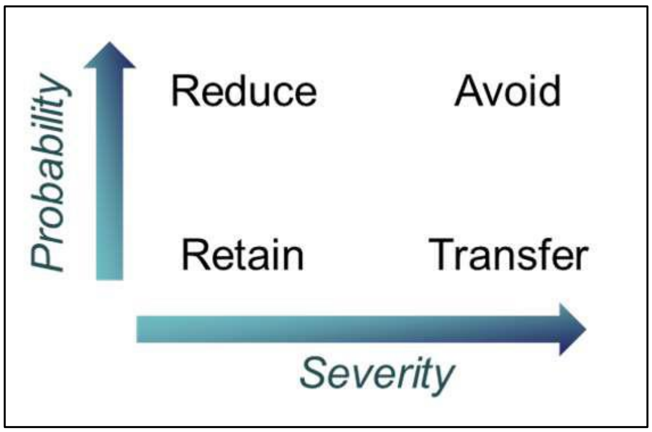

Figure 6: Illustration of potential risks along two perpendicular gradients (probability and severity), showing approaches to dealing with each class of risk: low probability and low severity risks (maintain the investment), low probability and high severity risks (transfer risk through insurance, for example), high probability and low severity risks (reduce the importance of such investments in the portfolio), and high probability and high severity risks (avoid such investments).

Conclusion

We will continue to develop methodology to integrate uncertainty related to climate change and natural disturbance to AAC determination at the BFEC. We expect that sustained interaction with other practitioners, researchers, and stakeholders will help to make these methods more helpful in sustaining the decision-making process as we move forward with the adaptation of forests and forests practices to climate change and natural disturbance.

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Overview of the complexity of integrated multi-risk approaches in forests

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Abstract

Foresters aim at managing forests to make them less prone to all types of risks. They have to take decision under uncertain environment where abiotic (storm, fires, drought..) and biotic risks can ruin their effort in producing wood and other ecosystem services. So taking advantage of 20 years of European projects and initiatives related to forest resilience, we address the following questions :

(i) what makes multi-risk management complex? (ii) what are the tentative approaches for integrated risk management? (iii) where is there room for improvement?

First we illustrate the diversity of temporal and spatial scales to address, as well as possible interaction and trends. Then we introduce the diversity of agents and organisations involved in prevention, response and post management of crisis in forest, concluding on the transdisciplinary effort required in addition to the simple forest management skills. Then the integrated risk management is illustrated by showing how decision have to been taken at all scales from the forest tree to the national level, showing that the state is one of the main player for integrated management.

The presentation concluded with the main avenues for improvement:

- game control by closer cooperation with hunter and farmers,
- multidisciplinary assessment of communication related to forest risks
- improved zoning at landscape level for better landscape planning, including urban areas
- better interaction and application of national contingency plans
- better control of world trade containers (wood component with stowaways) and horticultural material at risk for forest

Change Management under the Pyroscène – the Portuguese Integrated rural fire experience

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Mainland of Portugal in a nutshell

Mainland of Portugal has roughly 8.9 million hectares, of which 8.5 million hectares can sustain fire to some degree of severity. It is located in the Iberian Peninsula, from about 32ºN to 42ºN and 6ºW to 9ºW, from sea level to 1991 meters. Mostly Mediterranean climate, with areas of temperate maritime climate (NW) and semi-arid climate (lower Alentejo), one of the warmest territories in Europe, with a daily mean from 8ºC to 22ºC, and average low of 4.5ºC to an average high of 29ºC. Mainland of Portugal annual rainfall varies from about 3200 mm on the Peneda-Gerês National Park (NW) to as little as 400 mm or less in south Alentejo. Most forested areas are covered by Eucalyptus, Maritime Pine and Cork Oak (over 70 %). Primary productivity is high and combustible landscapes account for no less than 2/3 of the territory.

A very diverse landscape, very susceptible to wildland / rural / forest fires[1] due to landcover, Mediterranean x Atlantic (north and center) climate influence, existence of forest spaces without management and valorization, and fire culture. High primary productivity, extreme weather and extended summer condition (more dry fuel and hotter days) expected ahead will increase rural fire risk.

Fire regime (when, how and why)

20,000 ignitions and 100,000 ha burnt occur per year. The main causes of ignitions are negligence (73 %), due to bonfires and burning (67 %) not registered or authorized (mainly for pastoral purposes); and 17 % intentional (arsonism and others).

1 The term rural fire will be used in this text as it follows the Portuguese terminology to include all possible types of wildfire

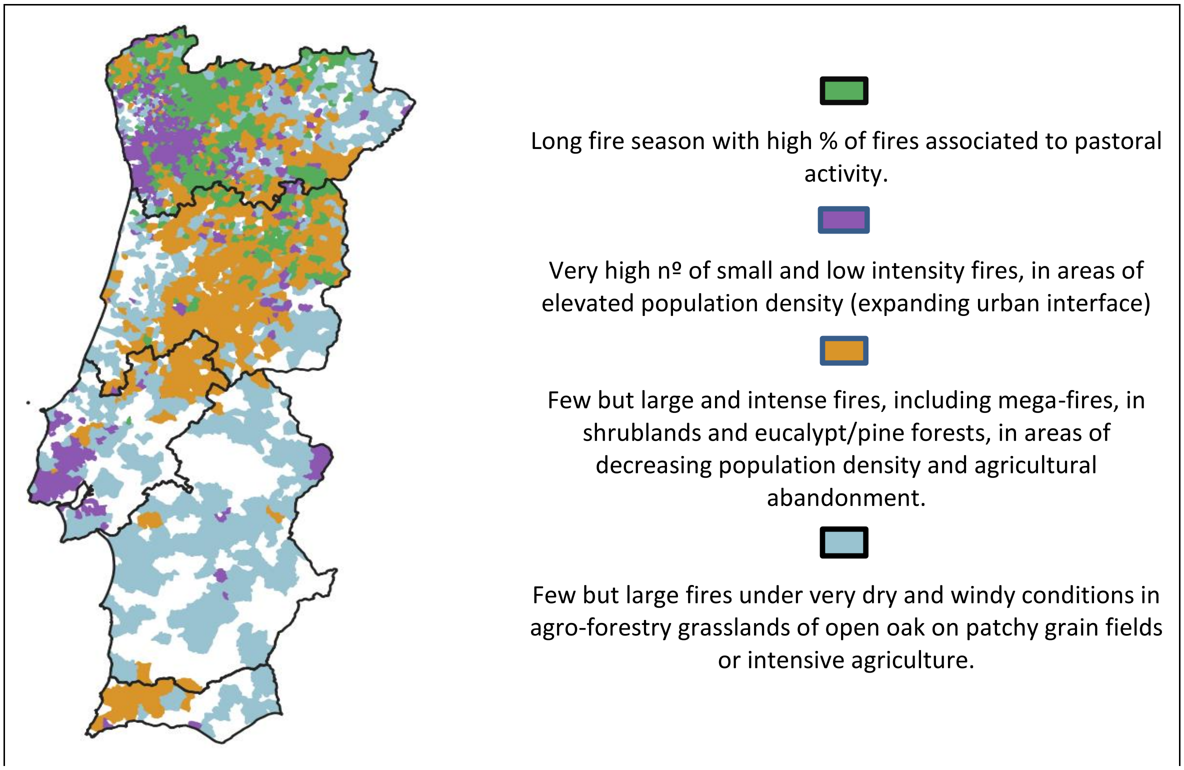

Figure 1: fire regime mapping (1980-2017) from: https://www.agif.pt/pt/estudos

Emergence of megafires

The growing trend, in recent years, in Portugal (2003, 2005, 2013, 2017), of increasing size and surface area affected by forest fires, affecting more people, causing more victims and greater impact on natural and built heritage implies a greater number of people and property to be protected as a priority during this emergency.

In addition to the size, there has also been an increase in fires with extreme behavior, referred to in some literature as megafires, due to their extraordinary size, intensity that exceeds any extinction capacity, and with high socio-economic impacts, with human fatalities and high economic losses inside and outside the forest sector.

These situations require greater prioritization in the protection and rescue of people and property, often affecting the availability of resources to contain the spread of fire in forest areas, thus increasing its extent and the likelihood of affecting more people and property.

In 2017, several of these situations occurred in Portugal, with several megafires that exceeded, in some cases for several hours, any extinction capacity, limiting the possibility of interventions exclusively to help people, not allowing the execution of fire containment actions.

In the rural fire of Pedrogão Grande, which occurred between June 17 (start at 14:30) and June 20, 2017, fire behavior parameters and impacts rarely observed were recorded between 19:00 and 21:00 of the first day, namely:

- average propagation speed of 3.9 km/h, reaching momentarily 15.2 km/h (downburst); frontal intensities between 20,000 and 60,000 kW/m (considered extreme behavior above 10, 000 kW/m);
- speed of perimeter expansion of about 3500 ha/hour;
- pyro-cumulonimb formation
- displacement of the fire column at a speed of 5 km/h, reaching an altitude of 13 km (overcoming the troposphere and reaching the tropopause);
- occurrence of 48 (75 %), of the total of 64 registered fatalities in the period between 20:05 and 20:15 (10'), along about 11 Kkm.

It was at that time the largest forest fire registered in the country, having been covered by the fire, between June 17 and 20, about 50,000 ha.

During the summer, after the Pedrogão fire, several other great forest fires (occurrences of over 100 ha) would be registered, but the worst situation would occur on October 15, under the influence of hurricane Ophelia - strong and dry winds with high temperatures - and the state of severe drought in most of the country (81 %). On that day, 440 fire starts were registered, which caused about 50 deaths, burned thousands of houses and destroyed more than 500 company facilities, many of them located in industrial polygons. That day and the two that followed, about 225,000 hectares burned. During this year, 214 fires of more than 100 ha were registered (responsible for 93 % of the burned area), of which 62 with areas greater than 1000 ha each, and 11 greater than 11,000 ha. In this year, record fire weather index values were recorded (Fire Weather Index, from the Canadian system adapted for Portugal).

Besides meteorological issues, what other causes could be at the origin of these catastrophic events of disproportionate size? Firstly, the clandestine use of fire (about two thirds of occurrences are due to negligence), in burning - often without any practical sense or rational purpose, which must be reduced and preferably eliminated - or burning, mostly for grazing, which must be framed and supported so that they are carried out properly. Structural conditions will also have an increasing influence on the difficulty of suppression and the exposure of populations to risk, caused, in particular by the homogenization of the landscape, which resulted from the abandonment of extensive agrarian activities, and the large fires of 2003 and 2005, which occurred in these regions and eliminated many of the previously existing mosaics.

Traditional interventions at the prevention and firefighting level are limited in terms of effectiveness by the intensity of the fire front. Extreme events such as those that occurred in 2017 in Portugal often exceed the extinction capacity. In these circumstances, standard or regulatory preventive actions do not cause changes in the intensity of the fire that considerably reduce its intensity, not contributing to improve the chances and probabilities of successful firefighting. Fires with extreme behavior create pyro-environments and often spread by secondary focuses (fire spottings), several hundred or even thousands of meters away. These exceptional situations have been increasing and, given climate change, it is expected that they will occur more frequently, requiring new ways of acting, at the level of lands, people and firefighting devices.

Assuming that there are limits to the extinction capacity, in extreme situations (even less complex than megafires), what to do and how to do when this capacity is exceeded, and when simultaneously there are forest areas on fire and people's lives and property at risk? Is it possible to simultaneously fight, protect, and assist, with the same type of teams and the same professionals? How to organize the system to give immediate responses (HELP) and prevent the rural fire from continuing to spread or at least be prepared (by anticipation) to intervene when there are opportunities for firefighting?

In ecosystems where fire is naturally present (as in the Mediterranean climate), the creation of mosaics using low intensity fires promotes excellent conditions for different plant and animal communities (habitats) and is extremely useful in helping to contain high intensity fires beyond suppression capacity (Cochrane and Bowman 2021).

To reduce catastrophic fires, we must change behaviors - eliminating occurrences (ignitions) on days of extreme meteorological danger - create mechanisms to promote the rational and framed use of fire (prescribed burning, support for traditional burning activities), and implement strategies for managing the progression and expansion of low-impact occurrences in areas with high recurrence.

The implementation of an Integrated Management System for Rural Fires (SGIFR)

The analysis by the Independent Technical Commissions (CTI 2017) of the megafires that occurred in 2017 gave rise to a series of proposals for improving the forest fire defense system, and the Agency for the Integrated Management of Rural Fires (AGIF, www.agif.pt/en) was created to promote, facilitate and coordinate its implementation. Some of the proposes for the implementation of an Integrated Management System for Rural Fires (SGIFR) are: a system based on the training and accountability of its agent; priority in the protection of people and goods with civil protection forces focused on their mission; management of rural fires focused on prevention and incorporation of knowledge; promotion of the territory's sustainability.

The main issue is to protect Portugal from extremely rural fires. A National Plan for Integrated Management of Rural Fires (PNGIFR, https://www.agif.pt/en/about-sgifr), with a National Action Program for 2020-30 (PNA), has been approved and is being implemented. Another directory mission for this integrated approach is the implementation of a new qualification plan for the functions and activities in the rural fires, the National Qualification Plan for the agents of the Integrated System for Rural Fires Management (PNQ_SGIFR https://www.agif.pt/pt/plano-nacional-de-qualificacao-do-sgifr-pnq_sgifr).

To deeply know everything that is associated with the occurrence of rural fires, and their interconnection, particularly mega and simultanueous fires, one of the essential conditions is to work in their mitigation in an efficient way. The increase in its complexity and severity has led that, there has been in recent years an important evolution in the knowledge of the inherent processes, in parallel with more and better predictive and operational information, greater availability of technological tools, more investments and allocation of more and better resources. The complexity of the phenomenon, associated with greater availability of information, tools and resources, has consequently increased the difficulty and complexity of decisions, requiring, for their effective management, a high level of knowledge and skills, which should be promoted through training programs properly adjusted to this multiplicity and to their recipients. The depth of knowledge to be transmitted, for the full use of this complex potential, requires high levels of training, integrated into the higher education system.

It is also necessary to capitalize, in the entities, the high but dispersed knowledge that exists. One part of this knowledge has been occasionally disclosed in scientific articles or other publications. However, it must be seized by the professionals with decision-making responsibilities in the SGIFR, namely by integrating it in the education system, in a systematic, directed and binding way, through formats of training disclosure and incorporation in the normal training processes.

The need to integrate the activities developed throughout the different phases of the process chain of the Integrated Rural Fire Management System, from planning, through prevention, preparation, pre-suppression, suppression and relief, to post-event, which form the basis of the new SGIFR philosophy, led to the analysis and presentation of qualification proposals for all stages of the rural fire process chain. An exhaustive identification of all the key functions and activities of each phase of the process chain of the Integrated Rural Fire Management System (SGIFR) was carried out, with the identification of qualification needs for each on.

High need for specific certifiable higher education level training have been identified, particularly in fire analysis, to qualify the fire professionals responsible for the key functions and activities of the SGIFR, often associated with the decisions and strategies to be implemented in the various stages of the process chain. In the higher-level certified training, the currently existing offer is quite reduced, being limited to the accreditations of prescribed fire and suppression fire for technicians. Aligned with the European model of micro-credentials or micro-diplomas which aims to stimulate modular training of higher education, which promote continuous learning and the acquisition of new skills, particularly in close collaboration with public and private entities. These higher-level training actions must undergo a sector-specific certification process in order for the qualification to be recognized by the SGIFR entities.

The teaching format, of collaboration between higher education institutions, collaborative laboratories and SGIFR entities, with simultaneous valorization of the professional experience of trainees, can contribute to the existence of a common platform for collaboration and sharing. Suc a platform could bring together researchers and decision makers, promote the interconnection between both with gains in the efficiency of applied and targeted research, and contribute to improve the desired and necessary professionalization and specialization.

For Portugal, this is a new stage, and therefore a huge challenge, in the provision of high-level training on rural fires, especially in its analysis components, so it will be necessary to count on the collaboration of existing experts in these matters, regardless of their origin, inside or outside the country.

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Coupling fire intelligence models to fire growth modelling through Firehawk

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Abstract

Fire agencies suppression effectiveness is greatly supported by fast and efficient decision-making based on comprehensive situational awareness. Indeed, when a new fire is detected, the agency in charge wants to evaluate its chances of success, the quantity and type of suppression resources needed, and it wants to know if some values, infrastructures, or even lives are at risk. To answer these questions the agency can use fire growth modelling to forecast where, when, and with what behaviour the fire will burn. However, other information such as estimation of resource needs and threat still needs to be coupled to fire growth modelling. This decision-making process is complex, necessitating experienced resources that can integrate the information in a timely manner. To help supporting this, we are developing a web platform with the capacity to integrate fire growth from the Canadian Fire Behaviour Prediction System, through Prometheus Software as a Services (PSaaS), to other spatially explicit fire intelligence models. This platform is called Firehawk. Firehawk aims at providing comprehensive and objective information to support decision makers in answering some of the previously mentioned questions. In this presentation, we will go over the current developments of Firehawk's features, including a demo, and we will explain the future developments and vision for this tool.

THIRD SESSION: “TOWARD STRATEGIES FOR MULTI-RISKS MITIGATION AND VULNERABILITY REDUCTION IN FOREST SOCIO-ECOSYSTEMS”

How do forest stakeholders perceive and cope with multiple risks? An exploratory survey in the Gascony forest

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Abstract

The Landes of Gascony is a homogeneous forest, covered at 85% by maritime pine (Pinus pinaster) which is the dominant variety. The forest is exposed to several biotic and abiotic hazards due to its monospecific stands. The ecological and biological impacts of those risks have been well studied one by one in the past. Nowadays scientists search to analyse how those risks interact and what consequences they could have on the functioning of forest stands. However, the economic impact and the attitudes of non-scientist forest stakeholders towards multiple risk interactions are unknown. To fulfil this gap, we carried out a qualitative survey with 34 forest stakeholders in summer 2021 and we asked them to classify risk perception by monitoring the macro-cartography of risk by audit (MCRA). We also questioned them about their possible strategies to break chains of risk interactions. Unlike ecologists and biologists' perception of multiple risk, most of the interviewees insisted on the socioeconomic impacts of multiple risks and their cascading effects on the forest sector. They also identified four major chains of risk for the Gascony forests. However, the interactions have been perceived differently according to the stakeholders' profiles, depending on their financial capacity to anticipate and overcome multiple risks. It also seems that multiple risk management in the Gascony forest would benefit from a better structuration and coordination of the wood sector to cope with a higher occurrence of multiple risks in the future that could seriously hamper the forest ecosystem and the forest sector.

The social dimensions of managing old and new forest risks in a changing societal context

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Abstract

This talk is about people's perceptions of multiple threats to the forest and how these perceptions are relevant for management. Studies conducted in Sweden of the general public, private forest owners, and the responsible agency will be used to illustrate key points. People's subjective perceptions of threats depends both on the characteristics of the event itself e.g., a storm, and the psychological processes involved in making this assessment. In addition, threat perceptions are formed in a social and societal context indicating that e.g., how others perceive threats and the characteristics of advisory services are relevant for perceptions. When asked about multiple risks, forest owners in Sweden perceived storms, followed by browsing damage and insect outbreaks to be the greatest threats to their forest, but even these were not considered very serious. Climate change was not perceived to be a serious threat to the owners' forest. However, the general public perceived climate change to be a somewhat greater threat to the forest in Sweden than the owners did. Given the tendency to focus on threats here and now, it is especially important for forest advisors to highlight more long-term threats associated with climate change to ensure that these are mitigated in management. Climate change adaptation of the forest may be employed to prevent multiple damages to the forest in the future. The level of climate change adaptation among owners has been found to be limited in Sweden, but there are signs that this may be changing. Psychological factors such as forest values with implications on owner identities, and knowledge have been found to be important for climate change adaptation in terms of diversifying the forest. To conclude, the management of multiple threats requires an understanding of the social-ecological system, including the forest, institutions, stakeholders' perceptions, and psychological processes.

If we want to improve the way we prepare for multiple risks in forestry, there is a need to understand the decision making around these risks and the determinants of actions to mitigate risks. In countries with a lot of privately-owned forests, private forest owners, also labelled family forest owners or non-industrial private forest owners, are important decision makers and the owners' threat perceptions influence how they prepare for forest risks. However, not only those with authority to make management decisions are important for an understanding of risk management, but also the perceptions of other societal groups. For example, the general public's threat perceptions are important for the acceptability of forest policy and management with implications on the extent to which the management of forest risks is perceived to be legitimate.

Overall, the management of forest threats is determined by psychological and social processes, but also structural and institutional factors, as well as forest characteristics. This paper is about threat perceptions and links to forest risk management, the role of institutional factors, and climate adaptation as a way of managing multiple forest risks. Empirical data from Sweden is used to illustrate important issues for an understanding of the social dimensions of forest risk management.

Subjective evaluations of threats

People make subjective evaluations of threats, rather than objective, systematic evaluations. The subjective evaluations depend both on characteristics of the event itself, such as the magnitude and how sudden the event is, and the psychological processes involved in making this assessment. Threat perceptions include cognitive components reflecting for example the perceived consequences of the threat and the perceived likelihood that the event will happen. Cognitive biases have been found to influence these cognitive components. One common bias is the availability bias making people more inclined to perceive a threat they have more experience of and hear more about as more serious. Given that people emphasize different values in the forest e.g., production, biodiversity, recreation, or cultural values the perceived consequences of forest threats vary depending on the emphasis placed on these values and how the event is perceived to influence diverse forest values. Threat perceptions also have emotional components since threats tend to evoke e.g., worry, fear or frustration in people. Whereas emotions may help to make people more engaged in managing risks, too strong negative feelings may in contrast lead to apathy and disengagement. But why is it important to learn about how people evaluate threats when these do not align with objective evaluations? There are several reasons for this. For example, subjective threat perceptions are associated with the acceptability of forest risk management in the general public and with the actual forest risk management behaviors of forest owners.

Factors important for forest threat perceptions

Threat perceptions are influenced by different psychological factors, but perceptions are not formed in a vacuum but in a social and societal context indicating that the people we meet and interact with have significant influences on these perceptions. For example, we tend to use others to inform us about what is considered acceptable and normal in a specific context, so called normative influences. Society also have structures that have an impact on how we perceive threats and characteristics such as gender and education can be used as proxies to reflect these structures. Institutional factors, such as the strategic work on forest threats by the forest government agencies play a role for how actors in the forest sector perceive and prioritize threats. Finally, forest characteristics (e.g., age, tree composition, previous management) further has an impact on forest threat perceptions. Factors with an impact on threat perceptions thus range from psychological to social processes, as well as structural and institutional factors in addition to forest characteristics.

Empirical illustrations from Sweden

Data from Sweden will be used to illustrate key points of the decision making relevant for the management of forest risks. Almost 70% of Sweden is covered with forests and the dominant tree species are conifers, mainly Norway Spruce and Scots pine. About half of the forest is owned by private forest owners and the owners are given a large degree of freedom to manage their forest in line with their objectives. Although the forest policy emphasizes production and environmental objectives to the same degree, the forest sector is relatively production oriented. The forest in Sweden is damaged by storms, but also insects, fungi and more frequently also fires. With a changing climate, forest damages are expected to increase. In this paper, analyses based on an interview study of advisors at the Swedish Forest Agency conducted in 2014 (Eriksson, 2017a) and three large survey studies of representative samples of private forest owners and the general public are utilized, including a study of private forest owners from 2014 (Eriksson, 2017b), a study of the general public from 2015 (Eriksson et al., 2018) and a study of private forest owners from 2018 (Eriksson and Fries, 2020; see also Eriksson, 2018; Eriksson and Sandström, 2022). Details of the methods and analyses can be found in the published studies.

Threat perceptions and forest risk management

Analyses of threat perceptions among private forest owners (n = 1,482) and in the general public, including those with a forest owner in the household (n = 177) and those without (n = 837) reveal differences both depending on what is evaluated, i.e., threat to own forest versus the Swedish forest in general, and between the stakeholder groups (Eriksson, 2018). Results showed that a range of different threats (e.g., storm, insects, fungi, new pests and pathogens) were perceived to constitute greater threats to the Swedish forests compared to when threats to own forest were evaluated. Private forest owners and the general public perceived storms to be the greatest threat to their own forest and the Swedish forest, respectively, but even storms were not perceived to seriously threaten forests. Damages by insects were perceived to be the second most serious threat in all groups, but among the forest owners, browsing damage was considered as serious as insect damage was. Climate change was not considered a very serious threat, particularly among owners assessing threat to own forest.

Further analyses of the owners show that threat perceptions, in terms of cognitive evaluations and worry were associated with the level of past forest risk management of storm, browsing damage and climate change as well as intention to manage the forest to reduce the risk of these damages in the future (Eriksson, 2017b). Physical characteristics associated with the forest (e.g., region) were important for threat perceptions. In addition, social factors were associated with in particular perceptions of coping e.g., in terms of response efficacy (belief that there are measures to undertake) and self-efficacy (belief that the individual him or herself have the ability to implement measures).

Advise from public advisory services to forest owners

An interview study of advisors at the Swedish Forest Agency provides further insights into the institutional dimensions of forest risk management (n = 27) (Eriksson, 2017a). Results showed that there are instrumental reasons for advice since the public advisory service is important to fulfil the Swedish forest policy. In addition, advice was given based on a normative rationale since the advisors wanted to provide the owners with advice to ensure that the owners are able to make appropriate management decisions. A range of risk topics were addressed in the advice, including damage by storms, insects, and browsing. Results further showed that over time the emphasis on risks associated with climate change was emphasized to a greater extent, as was damage to ecological values. Finally, quality of relations between the advisors and the owners were emphasized to ensure that advice would have intended impacts, with trust being a key factor. However, one potential concern for the future was that budget cuts in the public advisory services may lead to less emphasis on advice on future risks associated with e.g., climate change.

Climate adapted forest management

Climate adapted forest management in terms of risk spreading and risk reducing strategies can be considered a way to mitigate not one single but multiple forest risks. Studies of forest owners' climate adapted forest management provide insights on psychological predictors that in addition to threat and coping perceptions play a role for climate adaptation (n = 1,251) (Eriksson and Fries, 2020) and how the frequency of these practices have changed over time (Eriksson and Sandström, 2022).

Climate adaptation was examined in terms of increasing the diversity of the forest through e.g., increasing the share of mixed and deciduous forests and site adapted forestry. Results showed that different types of knowledge but also the values emphasized by the owners are important for climate adaption (Eriksson and Fries, 2020). Procedural knowledge covering facts about climate adaptation, but also confidence in own knowledge about adaptation were important for climate adapted management. Basic values, in terms of the extent to which collective values (i.e., emphasizing others' and the environments' interests) and forest values in terms of production and biodiversity values were relevant. However, values had indirect effects on management since these factors were no longer significant predictors of adaptation when identity perceptions were considered. For example, results showed that owner identities reflecting an emphasis of consumption and public goods in the forest (e.g., hunting, public benefits), being a more social owner, as well as a less distant owner were associated with higher levels of climate adaptation. In analyses of change in climate adapted management among forest owners, results revealed an increase from 2014 to 2018 (Eriksson and Sandström, 2022). Results further revealed an increased emphasis on biodiversity values among the forest owners, and that this greater emphasis on biodiversity values explained the increase in climate adaptation over time.

The study of the general public highlights that forest values were also important for the acceptability of using forest diversity as a risk management tool in the general public (N = 1,026) (Eriksson et al., 2018). The public was generally in favor of diversifying the forest and stronger ecological values in the public, but also the preference for deciduous trees were positively associated with acceptability of diversifying the forest.

Concluding remarks

The management of multiple threats requires an understanding of the social-ecological system. With regard to the social system, there are systematic effects that can help us understand the actors and the social system. Social science theories and research of perceptions, interactions and formal governance can provide guidance on the factors that are important. Whereas multiple threats are already considered in forest management since e.g., forest owners and managers are considering threats when managing forests, subjective threat perceptions have boundaries. For example, only the threats they are aware of and consider serious will be considered in management. Hence, management for multiple risks in forestry requires threats to be integrated in our frames of thinking about management. One potential way of doing this is to consider forest threats (current and future) in terms of potential barriers to achieve management objectives, at a strategic policy level but also all the way down to the forest property level. As a consequence of this framing of threats, it becomes evident that forest threats need to be addressed to achieve management objectives. This can be done by proactively preparing for multiple risks already when planning for the management of forests.

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What are novel decision approaches and their outcomes to deal with multiple risks and uncertainties in forest resource management?

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Abstract

Forest management is characterized by very long-term decision outcomes due to its long production time. This imposes ecological and economic risks to forest management to deal with the changes in bio-climatic conditions, occurrence of natural hazards, and time-dependent economic rationale. Experiences in European forestry developed over time and led to classical management approaches, e.g. monocultures, to cope with the long-term effects of decisions on the sustainability of forest goods and services. The traditional forestry systems, however, assume a steady state climate and risk patterns among others. The assumption may not hold any more due to global change and the dynamics of demand on forest goods and services. The nature of the expected changes in 21st century is uncertain and asks for novel approaches to find the best solutions including new demands e.g. carbon dioxide mitigation. The novel approaches shall take into account the plausible climate change scenarios, their effects on forest processes and services, and the changes in risk patterns. Moreover, behaviors of decision-makers in dealing with the deep uncertainty of forest forecasts shall be accounted for in the process of decision-making. Here, we demonstrate some examples of novel DSS systems adopted from other fields for forest resource management. Depending on the objectives of managing forests, behaviors of decision-makers, and the expected impacts of climate, the result may differ and ask for diversifying strategies in a landscape level to establish a resilient and robust forested landscapes for the society. The outcomes of applying such novel approaches in Europe show a strong need for the diversification of forest management strategies including species admixture and application of robust decision approaches in selecting the optimal decisions under multiple risks and associated uncertainties. The latter trades optimality for certainty to avoid unexpected high losses under the worst future conditions e.g. high climate change and other forest disturbances.

Forest decisions are ultimately about allocation of forest resources in multiple scales form stand to landscape to provide multiple ecosystem goods and services for the society. Optimizing forest allocation asks not only for integration of multiple services but also taking into account multiple risks affecting forest processes and functions. Moreover, climate change is challenging forest resilience and expected to change the severity and frequency of biotic and abiotic disturbances. Multi-risk assessment of forest ecosystem is the key to adapt forest resources to the future conditions and society's demands for ecosystem services.

Forest processes are subject to uncertainty because of the dynamics of natural systems and inherent deep uncertainty of future climate change. The latter is forming a deep uncertainty as we are not able to assign probabilities to the set of all plausible climate change scenarios. These scenarios all affect future forest conditions and the expected provision of ecosystem services. Therefore, process-based modeling approaches are essential to consider the changes in climate and the impacts of forests.

Expectations about forest management outcomes in the future are built based on the dynamics of forest ecosystems and the timing of management interventions over planning horizon. Therefore, any economic expectation shall take into account the future cash flows (costs and revenues) and discount them to a reference time to decide about alternative forest management solutions. Concepts of Net Present Value (NPV) and Land Expectation Value (LEV) are used in forestry to account for the time preferences using a discount rate.

Decision-making approaches are needed to deal with the dynamics of forest ecosystems under climate change and its impacts and considering the uncertainty of the system dynamics. Robust decision-making provides a unique opportunity to optimize the forest outcomes under deep uncertainty. It trades nominal optimality for robustness under worst conditions subject to a set of climate change scenarios, management options, and forest conditions. However, the study of Hörl et al. (2020) reviewing the current recommendations for adaptive forest management under climate change revealed that the majority of the strategies are far from robust especially regarding multiple objectives of forest management.

Adaptation of forest resources to multi-risk necessitates simultaneous integration of risks and their uncertainties in assessing the alternative strategies seeking to reach multiple set of goals and constraints over time. Forests are managed to avoid undesired disturbances and balance the needs for multiple conflicting or synergic goals. Therefore, a careful preparation of decision processes is essential to deal with risks and ensure a robust and optimal outcomes in the future.

Quantifying the uncertainty of decision factors such as interest rate, model parameters uncertainty, and other economic and ecological processes is the first step to find robust solutions. In return, the expectations are not any more an average and fixed figures bit rather a probability distribution of expected outcomes regarding goals -8e.g. NPV). There, applying robustness criteria is useful to find solutions with the greatest outcomes under multiple risks. Such solutions are recently developed to realize European climate smart forestry (Yousefpour et al., 2018). It allocates the forest mitigation potential of European forestry among European countries and depending on their specific economic (labor, wood price, interest rate) and ecological (species) conditions. Apparently, Eastern and Northern European countries can afford the greatest carbon mitigation measures. Southern European conditions are the last choices because of the high wood value and low forest growth rates.

Robust decision-making for biodiversity purposes among others offers diversifying solutions for landscapes to maintain and improve forest biodiversity features under climate change and multiple risks. A study by Augustynczik et al. (2018) show that more forest reserve area and a higher level of diversification with multiple management options with low to high intensity are crucial to realize the robust conservation goals.

For direct policy search of efficient decisions about payment for ecosystem services is also possible applying robust decision analysis. A study by Radke et al. (2020) realized that the uncertainty of carbon sequestration level in a single European beech stand (Fagus sylvatica) is so high that a robust carbon price over 25 € per ton carbon is essential to reach a confidence interval level of 95% about the carbon mitigation outcomes. Any price below this may result in an uncertain (low-high) mitigation effect without being able to assess the outcomes.

Forest decisions are, on the other hand, behavioral ones and depend on the past experiences, past and current observation, and how future expectations can be accounted for in the decision analysis. Yousefpour et al. (2017b) categorize the decision-making to four different types depending on the level of information processed and integrated in making adaptive decisions. Figure 1 below, provides an illustration of climate change expectations "now," i.e., ENow(Climate) to the several decision points in the future. The colors illustrate the different expectations of decision-making types. Blue is the observed and unique change in the past. Red is the expectation under "nochange decision making," where past treatments are repeated as long as they appear to work. The black expectation refers to "reactive decision making," where decisions are changed based on the observed change in the past. Green refers to "trendadaptive decision making," where adaptation to the predicted trend occurs. Blue-grey shadows denote "forward-looking adaptive decision making," where a range of possible futures is expected and where the expectations get broader, i.e., more uncertain, as we go more distantly into the future.The no-change and reactive types of decision making base decisions at any point in time on available information about past and present climate states only. The decisions do not depend on expected and predicted future fluctuations, trends, or asymptotic behavior of the climate. They differ in whether beliefs are updated to the currently observed climate or not (the point "now" in Figure 3). No-change decision making assumes that past climate will persist, and any temporary variation is just considered trendless fluctuations, so the best guess of the future is the original starting point. The reactive decision making type notices the present state of climate (Hoogstra 2008), and the expectation is that it will prevail. Here current fluctuations play a large role. Therefore, adapting and reacting to already experienced climate change impacts is possible by changing business-as-usual (BAU) to a new set of reactive strategies that are adapted to current conditions.Trend-adaptive decision making takes into account expert predictions of the most likely climate change scenarios and its impacts on forest, e.g., projection of future forest conditions under the most likely representative concentration pathway (RCP) scenario. The decisions also consider the presently observed climate and forest conditions, but are not based on the belief that the past repeats itself. Thus, they look forward and react to beliefs about the trends. However, when making a management decision, the uncertainty characterizing the situation is not fully taken into account, and the decision-making process is not designed to include learning. We return to this type of decision making in our discussion of simulation-optimization studies. Finally, in forward-looking adaptive decision making the state of the climate and the forest, as well as recent and ongoing climate change are observed, but instead of formulating expectations in the form of a single trend or scenario, the uncertainty inherent in the predictions of climate change and particularly in the likely impacts is acknowledged. Therefore, a spectrum of outcomes is considered, and most importantly, a repeated evaluation process is used to make new projections in the future based on improved observations that have the ability to modify decisions at future points in time according to observed changes. Already when evaluating current decision alternatives, the possibility of future adjustments is taken into account. Thus, decision making is dynamic in this mode and fully adaptive; forward-looking decision makers redesign AFM strategies taking full advantage of the information available on climate change and from monitoring impacts on forests. We use this case to illustrate a way on how beliefs can be systematically updated.

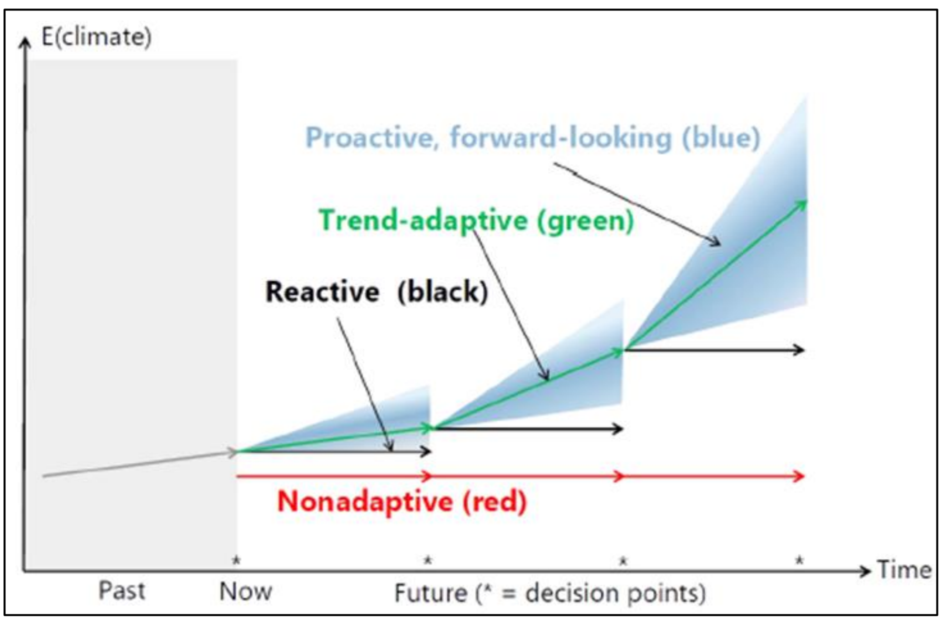

Figure 1: Decision-making types under climate change (Source: Yousefpour et al., 2017b)

Nonaadaptive (determinist) decisions may chose different forest strategies and thereby risk achieving the expected outcomes. As shown in Figure 2 and from economic point of view, all decision-making types are valid if their benefits exceeds the costs of adaptation (Yousefpour et al., 2017a). Robust decisions impose the highest costs, however, the greatest safety under worst conditions. Therefore, they are especially relevant for highly values ecosystems. Low value forests or forests that are not expected to be consider ably affected by climate change and risks may rely on reactive adaptations and react as the risk is realized. Proactive adaptation is conditional on the expected future conditions and subjective to the beliefs of decision-makers about future conditions. As the figure 2 shows, it is valid for a range of ecosystems subject to a moderate level of climate change impacts. As stated above, behaviors of decision-makers play a major role in deciding upon adaptive decisions. The higher the risk aversion coefficient of them, the higher the chances for proactive and robust decisions under climate change.

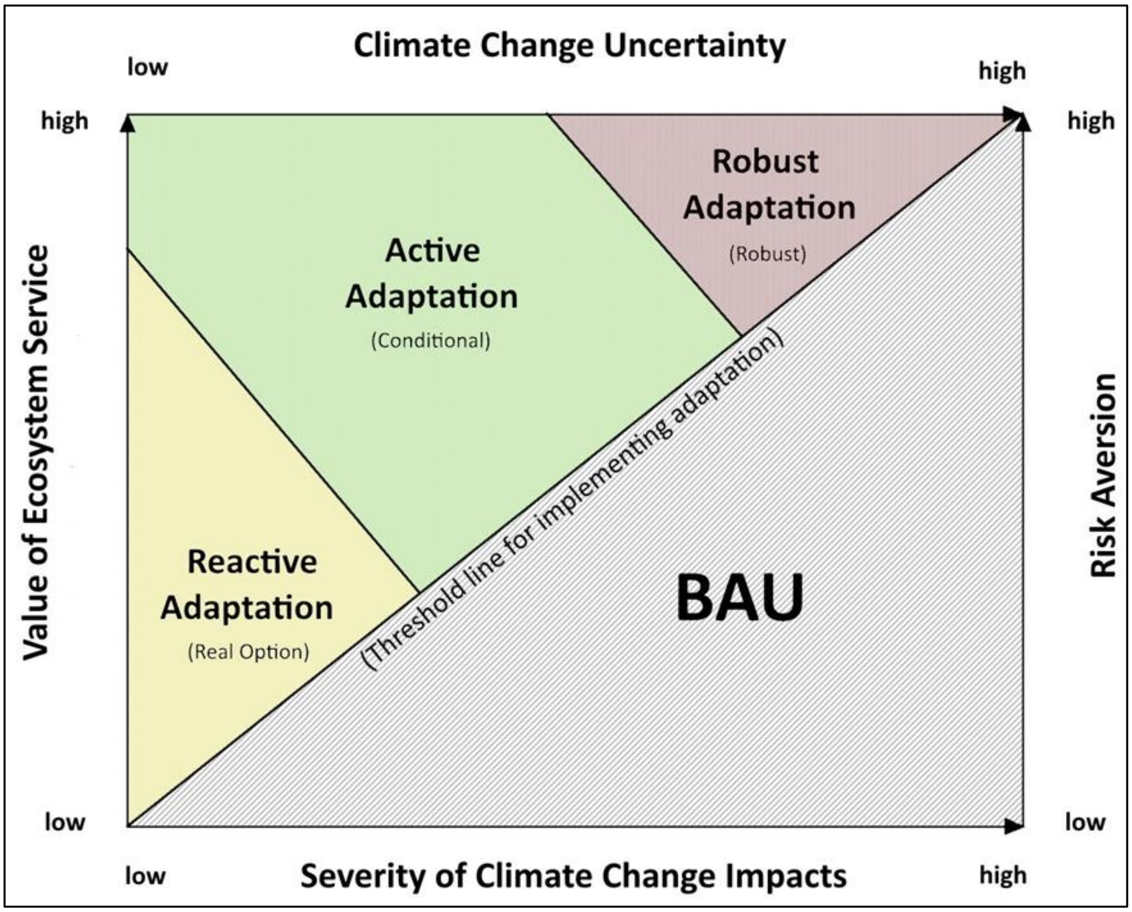

Figure 2: Pertinence of adaptive forest management strategies under risk and uncertainty of climate change and subject to the value of ecosystem and risk attitude (aversion) of decision-makers (sources: Yousefpour et al., 2017a)

Regarding the risk attitude (aversion) and the effects on adaptive behaviors, Deng et al. (2017) found that the individual experience (know how) and valid evidences affect the final adaptive behaviors more than positive perceptions about climate change and water saving urgency. In line with this study, Brunette et al., 2020 studied the adaptive behavior in action of forestry professionals in Southestern Germany and eastern France and found that exactly the risk aversion attitude of professionals hinders their adaptive action. This has been a surprise outcome but correlating risk and uncertainty attitude of respondents to the set of questions about their behaviors revealed that the perceived risk and uncertainty of changing business as usual strategy is higher that climate change and its impacts for professionals.

The behavioral studies in forest decision process are rare but emerging and show the great value of such understanding in supporting decision-makers. The main outcomes of the behavioral studies agree that valid and transferable evidences are crucial to persuade forestry professionals to proactively adapt to future forecasted conditions. However, the behaviors may differ after realizing risk and the urgent need for alternative and cost efficient strategies. Hereby, the integration of behavioral factors in supporting the final adaptive decisions is suitable to generate optimal and if needed robust strategies under multi-risk and uncertainty.

In summary of this report, adaptive forest management is a comprehensive decision processes and asks for true integration of multi-risk and forest objectives. For this, understanding forest processes and their responses to future global change is essential to build a realistic build of future forest conditions, process-based models may be a good choice to build such economic expectations as well. There are novel decision-making approaches that forestry can borrow from other disciplines such as robust decision-making and adopt it for forest decision-making purposes. Such robust approach can be used for direct policy search and realize climate smart forest decisions. Moreover as highlighted in the study of Petr et al. (2020) there are differences between forest decision support tools in the way the present many sources of uncertainty and the way decision-makers need to integrate them in the decision-making process. Equipping forest decision support systems with modules quantifying uncertainty and integrating multi-risk relevant to local conditions is the crucial step to provide essential knowledge base for forest decision-makers.

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