INTRODUCTION

Some options for Climate-Smart Forestry in Europe's mountain regions[1]

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Papers collected in this special issue of the *Canadian Journal of Forest Research* are presenting selected results of the European program for Cooperation in Scientific and Technology (COST) action on "Climate-smart forestry in the mountain regions", or "CLIMO", COST project number CA15226 (2016–2020). In particular, they represent a sample of the scientific papers presented at the CLIMO workshop held in Stará Lesná, Slovakia, 9–11 September 2019. The scientific interest in climate-smart forestry, which has risen in the last decade, resulted in the CLIMO COST action that encompassed 28 member countries, five observers from nearby countries, and five international partner countries (https://www.cost.eu/actions/CA15226/). A "COST action" is an interdisciplinary research network that brings researchers and innovators together to investigate a topic of their choice for 4 years. COST actions are typically made up of researchers from academia, private enterprise, public institutions, and other relevant organizations or interested parties. The main objective of the CLIMO COST action was to enable forestry to challenge the adverse impacts of climate change, taking into consideration both mitigation and adaptation strategies.

The CLIMO action aimed to translate the concept of "climate-smart agriculture" into an equivalent set of options for mountain forestry. It proposed three main pillars: (*i*) improving the livelihood of inhabitants in mountain regions by sustainably increasing ecosystem services; (*ii*) enhancing adaptation and resilience to climate change; and (*iii*) optimizing the climate change mitigation potential of mountain forests, focusing on the most efficient and cost-effective mitigation options and capitalizing on adaptation–mitigation synergies (http://climo.unimol.it/).

As "climate-smart forestry" (CSF) is a new term, its definition took much effort and included knowledge from different disciplines. Since "climate-smart agriculture" aims at increasing agricultural productivity while adapting to climate change, translated to forest management, the idea of CSF applicable to mountainous regions was defined as follows (Bowditch et al. 2020):

> Climate-Smart Forestry is a sustainable adaptive forest management and governance to protect and enhance the potential of forest to adapt to, and mitigate climate change. The aim is to sustain ecosystem integrity and functions and to ensure the continuous delivery of ecosystem goods and services, while minimizing the impact of climate-induced changes on mountain forests on well-being and nature's contribution to people. . . .In summary, Climate-Smart Forestry should enable both forests and society to transform, adapt to and mitigate climate induced changes.

The CSF definition was achieved by considering the following criteria for sustainable forest management, selected from the Forest Europe set of criteria and indicators (https://foresteurope.org/sfm-criteria-indicators/) — C1: Forest Resources and Global Carbon Cycles; C2: Forests Health and Vitality; C3: Productive Functions of Forests; C4: Forest Biological Diversity; C5: Protective Function (Soil and Water); C6: Socioeconomic Functions. Additional indicators added by CLIMO participants included Management system; Slenderness coefficient; Vertical distribution of tree crowns; and Horizontal distribution of tree crowns. Papers in this special issue are addressing some of the criteria used in defining CSF: management systems, socioeconomic functions, forest resources and the global carbon cycle, forest biological diversity and protective functions (namely, soil) characteristics.

Two papers in this issue are considering the need for advanced forest management strategies to adapt to and mitigate climate change, which would also benefit forest production. This approach requires accurate and updated information about forest resources. Santopuoli et al. (2021) analyzed a set of 10 indicators regarding mitigation and adaptation proposed by this project, with an aim to assess the status of CSF in Europe (1990–2015) based on national reports. In this study, forest damage, tree species composition and carbon stocks were the most important indicators. One of the biggest issues found by the authors was the lack of data. Santopuoli et al. (2021) propose a subset of indicators as the minimum for developing a practical toolbox for integrating the goals of CSF in national and European forest policy-making.

Forest management, especially under conditions of climate change, relies on accurate estimates of forest structural parameters, which can be achieved using novel methodologies and devices that enable continuous monitoring of forest sites. Monitoring of long-term and (or) large-scale restoration effects can be challenging because it is often time-consuming, expensive, and requires trained technicians. An alternative approach that reduces the need for field measurements employs remote sensing and digital image processing techniques that are widely used and highly efficient. Applications in forestry are numerous; for example, digital cameras provide both measurements of the physiological state of a forest canopy at high temporal and spatial resolutions, but also complement CO_2 and water exchange measurements, increasing the overall knowledge of ecosystem processes (Ahrends et al. 2009). Both light detection and ranging (LiDAR) and high-resolution imagery acquired from unmanned aerial vehicles (UAVs) can be useful in classifying land cover; in determining canopy topography, biomass, timber volume, tree species identity, land cover use and

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[1]This is the introduction for the partial special issue containing a collection of papers presented at the CLImate-Smart Forestry in MOuntain Regions (CLIMO) workshop held in Stará Lesná, Slovakia, 9–11 September 2019.

planning; and in monitoring forest recovery (Reis et al. 2019). Although gaining wide application, this methodology is still not fully developed (Zhao et al. 2012; Weinstein et al. 2020). As part of the CLIMO action, Torresan et al. (2021) propose use of a wireless sensor network (WSN) that could be a part of "the internet of things" and which could make data available in real time to foresters, forest managers, scientists, and citizens. The authors suggest that the new generation of sensors, data transmission, and processing tools, in combination with ground-based measurements, provides a technology that is sufficiently mature to enable real-time, large-scale monitoring of forests, but the shortcoming is a high total price. This problem can be addressed by the remodeling of existing technologies for operation in harsh forest environments, innovative combinations of existing technology suites, identification of alternative data sources, and the novel conflation of existing data (Torresan et al. 2021). Alvites et al. (2021) used data from airborne laser scanning (the most widespread application of LiDAR) to assess carbon stocks at the tree level to classify 31 forest stands into four complexity categories. The authors show that the combined use of two unsupervised techniques greatly improves monitoring of forest ecosystems, and they propose more accurate ways of collecting CSF indicators to facilitate forest management.

Ecosystem services represent direct and indirect contributions of ecosystems to human well-being; these benefits primarily refer to provisioning, regulating, cultural, and supporting services (Costanza et al. 1997). Forests are widely recognized as principal ecosystem service providers (Pohjanmies et al. 2017). Up to 100 different forest ecosystem services, including food, timber and fuel production, water conservation and regulation, nutrient retention, carbon sequestration, biodiversity protection, climate regulation, ecotourism, and spiritual and traditional values are listed in different national reports (Millennium Ecosystem Assessment 2005). Research into forest ecosystem services is highly relevant, with environmental science, biological science, and social science receiving the most attention. Furthermore, in contrast with other forest research areas, the multidisciplinary character of forest ecosystem services analysis embraces relevant social sciences and economics (Aznar-Sánchez et al. 2018). Payment for ecosystem services (PES) is recognized as a vital policy incentive that promotes the sustainable provision of forest ecosystem services and can be an effective use of available finances in biodiversity plans (Karousakis 2012). Since research about PES related to mountain forest ecosystems in Europe is lacking, Brnkalakova et al. (2021) conducted a study analyzing the use of PES for sustainable and climate-smart forestry in Iceland based on intensive afforestation efforts there over the last 30 years. The well-being of local people in Iceland is improved by voluntary participation of local farmers while meeting global climate change targets. The authors discuss how PES in combination with CSF is a crucial strategy for long-term sustainable forest management.

Over the next 100 years, climate change will have a significant impact on forest ecosystems, and therefore, it is necessary to evaluate long-term effects and the efficacy of response measures (Spittlehouse and Stewart 2003). One priority will be adapting to forest disturbances while preserving the genetic diversity and resilience of forest ecosystems. Because genetic resources are listed among the core indicators for forest biological diversity, one of the important topics CLIMO has investigated was the genetic diversity of pure beech stands across Europe, as described in the paper by Höhn et al. (2021). Analyzing samples from 12 pure beech stands using nuclear microsatellite markers, the authors found that genetic diversity is high, and it increases with the geographical distance among stands. Genetic divergence was also found to reflect differences in local stand growth characteristics. Höhn et al. (2021) underline the important role of high heterozygosity, because highly heterozygous trees might respond to climate change more successfully than trees that are not.

There are still knowledge gaps on the future impact of climate change on forest growth and productivity, and on soil properties. In this special issue, four papers are concerned with this topic. Ježík et al. (2021) emphasize the importance of studying short-term weather fluctuations in dendrochronology. The authors identified the main seasonal windows influencing growth of spruce and beech and conclude that there are clear species-specific differences in the response to weather fluctuations. Jocher et al. (2021) also demonstrate the difference between carbon exchange dynamics of beech and spruce stands during a severe drought period. The authors found that spruce ecosystems suffered in drought conditions, while beech stands and mixed-species stands were able to tolerate these conditions. With droughts expected more frequently under climate change, forest management systems should consider these results in choosing tree species and in managing stand composition. Moisture input and temperature are the principal drivers of plant growth and litter decomposition (Perry 1994) and the balance between them influences soil organic matter cycling and related microbial processes (Kirschbaum 1995). The amount of litterfall and decomposition in forest ecosystems is important for ecosystem functions such as primary production and carbon and nutrient cycles, and data obtained are used in models that estimate the carbon stocks of soil in the ecosystem (Liski et al. 2005). Sarginci et al. (2021) found an interesting contrast in litter decomposition dynamics between beech and chestnut stands, and conclude that these data can be extrapolated to regions with similar settings. Their study shows that litter decomposition in beech stands became progressively higher in the first year and lower in second year with increasing elevation, while litter decomposition in chestnut stands was increasingly more rapid in the second through fourth years as elevation increases.

Soil-quality assessment includes determination of soil properties and processes related to the ability of soil to function efficiently as a component of an ecosystem. It is a value-based concept related to the objectives of ecosystem management and, therefore, is management- and ecosystem-dependent (Schoenholtz et al. 2000). Two papers in this issue are concerned with forest soil properties in pure beech stands across Europe. The paper by Dinca et al. (2021) analyzed microbial soil biodiversity and the paper by Kašanin-Grubin et al. (2021) assessed the erodibility properties of forest soils on different types of bedrock. Because soil microbiology is crucial for soil system functioning, it is important to analyze it in the context of predicted climate change. Dinca et al. (2021) demonstrate that microbial communities could play a crucial role in forest adaptation to environmental change. The authors conclude that the correlation between soil microbial community attributes and the physical and chemical properties of soil should be considered in CSF strategies. Studying physicochemical forest soil properties is important because even though a well-established root system and closed canopy can prevent soil erosion, this might drastically change under a changing climate. Kašanin-Grubin et al. (2021) analyzed 76 soil samples from 20 beech forests developed on five bedrock types for a range of physicochemical properties. The authors found that soil susceptibility to erosion follows the order granite > andesite > sandstone > quartzite > limestone and that deeper soil horizons on granite are more susceptible to erosion than surface horizons are, with the opposite trend found for soils on limestone.

Collectively, the papers in this special issue illustrate the diversity of forest attributes and ecological processes that need to be considered as we endeavor to make mountain forests more resilient to climate change. Though representative of only a small portion of the overall research undertaken, these 10 papers provide examples of how the COST action CLIMO program has successfully leveraged an impressive network of researchers and forest managers to identify a number of effective strategies that can be immediately employed to help forests adapt to a warming world and to harness their ability to help mitigate growing CO_2

concentrations in the atmosphere. However, this research program has also pointed out that many questions remain to be answered, and there are probably many more CSF options that have yet to be developed and applied.

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