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Editorial

Forest Functioning under Climate Warming and Future Perspectives on Forest Disturbances

Any Mary Petritan [1,*] and Mirela Beloiu Schwenke [2,*]

[1] Department of Ecology, National Institute of Research and Development in Forestry 'Marin Dracea', Closca 13, 500040 Brasov, Romania
[2] Department of Environmental Systems Science, Institute of Terrestrial Ecosystems, ETH Zurich, 8096 Zurich, Switzerland
* Correspondence: apetritan@gmail.com (A.M.P.); mirela.beloiu@usys.ethz.ch (M.B.S.)

Abstract: The Special Issue "Impact of climate warming and disturbances on forest ecosystems" underscores the critical importance of understanding how forests respond to these environmental challenges and the legacy of past management practices. Forest ecosystems are facing significant challenges due to ongoing climate change, characterized by rising temperatures and increased frequency of extreme events. The rapid pace of climate change is altering disturbance patterns and the adaptability of forests, which have a direct impact on ecosystem services that contribute to human well-being. This Special Issue features 11 research papers from nine countries. Some key outputs from these research papers include evidence on how climate change is already impacting forest ecosystems. For instance, the climatic envelope of many forest species has shifted due to global warming, making species more vulnerable, especially in lower elevations and at the edges of their distribution. Urgent adaptive measures in forest management are necessary to address this challenge. Climate change also affects vegetation phenology, tree growth, stand productivity, reproduction rates, and stand regeneration. Remote sensing data and ecological modeling techniques play a crucial role in monitoring and understanding these changes, especially in remote regions where field measurements are limited. The rising frequency and intensity of extreme events like droughts, windstorms, and forest fires require enhanced prediction and automatic monitoring. Leveraging machine learning tools and remote sensing data is imperative. This Special Issue provides insights into the intricate relationships among forests, climate change, and human interventions. We provide further research recommendations for the quantification and automated monitoring of forest fires and the management of forests to better withstand storms and increase their resilience to climate change.

Keywords: climate change; forest management; forest resilience; drought; old-growth forests; forest fires

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1. Introduction

Forests are invaluable ecosystems that have long been recognized for their multifaceted contributions to biodiversity and society. Forest dynamics are generally determined by changes in forest structure and composition over time, including their response to anthropogenic and natural disturbances. Yet, global climate change is affecting disturbance regimes and the adaptive capacity of forests at an accelerating rate [1,2]. (Disturbances such as droughts, storms, and fires have significant impacts on forests and the ecosystem services that they offer. Although there are numerous frameworks proposed for the automatic monitoring of forests [3–6], there is still a pressing need to enhance our capacity for actively detecting ongoing disturbances and predicting the future impact on forests and tree species. In this context, ground truth data and new technologies such as remote sensing, machine learning, and ecological modeling offer new opportunities for monitoring, quantifying, and predicting the impacts of climate change and disturbances on forest ecosystems [7,8].

Further, rapid climate-induced changes in disturbance regimes, combined with the ongoing legacy of past forest management (e.g., plantation of tree species outside of their natural distribution and different management types), have resulted in a complex and poorly understood interplay of factors that affect tree growth [9].

2. Overview of Contributions

The Special Issue "Impact of climate warming and disturbances on forest ecosystems" aimed to collect scientific research covering the following topics:

- Forest disturbance regimes (e.g., drought, forest fire, storms, and pathogens);
- Climate change impacts;
- Forest resilience and dynamics;
- Forest management practices;
- Old-growth forests.

This Special Issue, entitled "*Impact of Climate Warming and Disturbances on Forest Ecosystems*", features 11 original research papers by 67 authors from nine countries on three continents: Asia (China, India, Syria, Saudi Arabia), Europe (Belgium, Poland, Romania, Greece), and North America (USA). They provide examples of different regions of the globe on how climate changes and anthropogenic pressure could affect the structure, growth dynamic, and functionality of the forests and thus their ability to continue to provide the ecosystem goods and services and contribute to the well-being of society.

3. Summary of Main Outputs and Findings

The already changed climate has been highlighted by Mihai et al. [10] for different provenances and regions in Romania, by different forest types. The authors showed that the climatic envelope of many forest species has already changed and become less suitable due to climate warming, which increases the vulnerability of species, especially at lower elevations or at the edges of their distribution. For instance, the annual mean temperature has risen by 1.33 °C nationwide, with a clear warming pattern in the plains (Figure 1). The authors warned that climate change appears to be occurring faster than species can adapt or migrate and argue that adaptative measures in forest management are urgently needed. Chandra et al. [11] analyzed changes in the habitat suitability of vulnerable species such as orchids under different climatic scenarios using ecological niche modeling. Their results indicated a reduction in highly suitable areas under future climate conditions and acknowledged the importance of identifying viable habitats to conserve vulnerable species and prevent local extinctions.

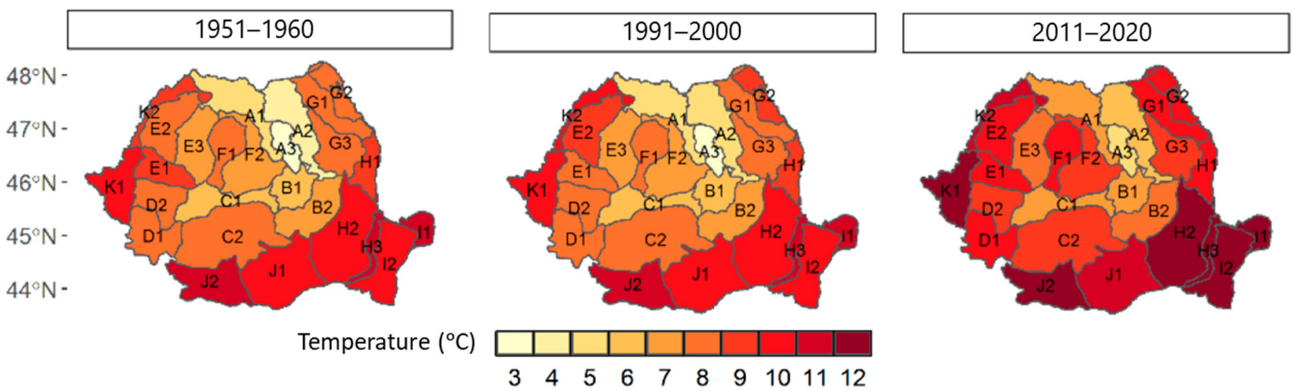

Figure 1. Changes in the mean annual temperature in Romania across different regions. Adapted from Mihai et al. [10].

Other papers published in this Special Issue have shown that climate changes affect vegetation phenology [12], tree growth [13] and stand productivity [14] but also the reproductivity rate [15] or stand regeneration [16]. Using remote sensing data, such as MODIS together with vegetation indices and vegetation gross primary productivity [12,14], allows the identification of changes in vegetation changes and the link to climate change. This is of great relevance, particularly in remote regions where field measurements are limited. To this end, using the MODIS gross primary productivity model, moving average trend analysis, linear regression analysis, and the climate tendency rate method, Aili et al. [14], analyzed the variation in the vegetation gross productivity of forests in Altay Mountains, China, in response to the daily temperature and precipitations. Dugesar et al. [12] investigated the change in vegetation phenology along an elevation gradient in the main forest types of the western Himalayas and observed a delayed trend for all vegetation types. A Normalized Difference Vegetation Index time series was used for this purpose. Because phenology responded differently in heterogeneous mountain landscapes to climate change, the authors concluded the importance of comprehensive observations at the local level to our improve understanding of forest response to climate change.

Using dendrochronological methods, Qi et al. [13] attempted to determine the main climate factors that influence the radial growth of two coniferous tree species. The study showed the growth response is species-specific and the drought during the growing season is a decisive negative factor. In addition, the authors stressed the importance of studying the effect of climatic factors not only over long periods but also over short periods of time, such as the decadal scale. The results of an experimental study in a common garden [15] indicated that water limitation led to the reallocation of resources toward reproduction rather than growth, an effect that is still present two years later. Respectively, treated shrubs showed a higher germination rate, an adaptive trait that should ensure survival under stress conditions. The authors concluded that the delayed effects of drought on reproductive traits in woody species may add more complexity to the consequences of climate change on species distributions and forest survival.

The rising global temperature together with the increase in the frequency, severity, and duration of extreme events such as droughts, windstorms or fires, followed by various associated disturbances, have already negatively affected forest ecosystems worldwide [17–19]. (An example of such events is the extreme and long-lasting hotter drought and heatwaves from 2018 and 2019 that affected forests in Central Europe [20,21] or windstorm Klaus, one of the most devasting windstorms in Europe [22]. As such events left a significant footprint in forest stands, followed by large economic and ecological losses, modern tools such as machine learning [22] or remote sensing and geographic information systems [23] are very useful to build better models to predict forest damage caused by windstorms [22] or to accurately monitor fire intensity and damages [23]. As such extreme events are expected to occur more frequently in the future, improving their prediction and monitoring will be essential for better planning.

In addition to climate change, human disturbance can negatively affect stand characteristics. As reported in another paper published in this Special Issue, some structural stand traits and soil microclimates were altered by the first silvicultural interventions carried out in a former virgin forest [24]. The changed microclimate conditions in the former virgin forest led to greater CO_2 soil emissions (Figure 2). Moreover, stand dynamic trough canopy gaps are influenced by topography, with forest gaps occurring more on slopes between 10 and 20 degrees and at higher elevation [25]. Topography also plays an important role in the relationships between climate and different vegetation traits [12].

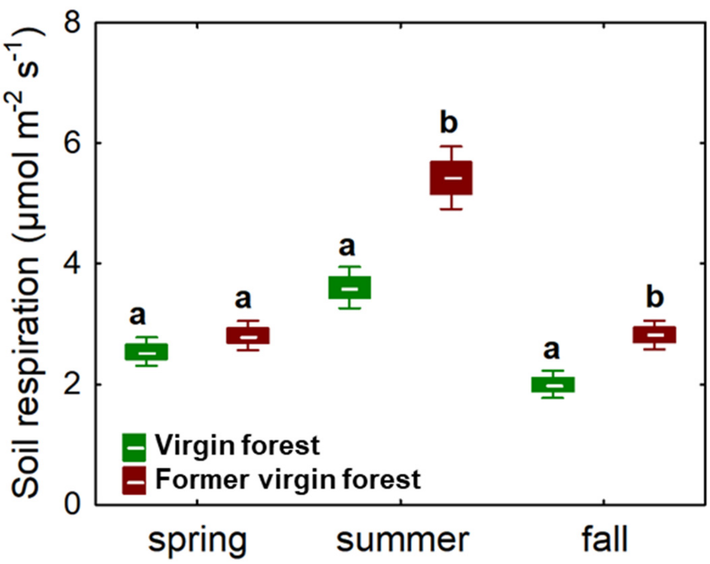

Figure 2. Differences in soil respiration between virgin and former virgin forests. Adapted from Braga et al. [24].

4. Challenges and Future Work: Forest Fires and Storm Disturbances

4.1. Forest Fires

In recent years, forest fires have captured global attention due to their increasing frequency, severity, and their far-reaching ecological, economic, and social impacts. Forest fires have left their mark on diverse ecosystems across the world. Millions of hectares burned in the last few years, ranging from the Amazon rainforest (e.g., in 2019–2020, 0.9 mil. ha) in South America to the boreal forests of Siberia (e.g., in 2019, 3 mil. ha), and the wildfire-prone regions of British Columbia (e.g., in 2017 and 2018, a total of 2.6 mil. ha were burnt), California (e.g., in 2018, 0.7 mil. ha), and Australia (e.g., in 2019–2020, 18.6 mil. ha) [26,27]. These mega-fires are often exacerbated by climate change, prolonged droughts, heatwaves, increasing aridity [28–30], forest management, deforestation [31], and shifts in weather patterns, creating a formidable challenge for forest ecosystems and the communities that depend on them. The occurrence of forest fires varied over time, with 2021 being the worst year in terms of the area burnt. In 2020, forest fires occurred mainly in southern Europe, while in 2021, they also occurred in northern regions and had a higher intensity and burnt area compared to 2000 (Figure 3). Both field observations and remote sensing data are essential to map forest fires. Forest fires ($\geq$30 ha) are mapped globally using MODIS satellite sensors. Since 2018, Sentinel-2 imagery was incorporated, which allowed mapping fires $\geq$ 5 ha in Europe [32].

To reduce the destructive effects of forest fires, they must be detected as early as possible. This requires early warning systems to predict the areas at high risk [33] and an active fire detection system to identify areas with forest fires [34,35]. This urges us to develop and refine fire behavior models to better predict fire spread, intensity, and behavior under varying climate conditions, including the influence of extreme events like heatwaves and prolonged droughts. Pezzatti et al. [36] proposed a novel metric to predict the risk of future forest fires. Early warning forest fire systems would help to identify regions at increased risk of forest fires and provide insights into adapting forest management strategies to mitigate these risks. Further, public awareness and cross-boundary collaboration are needed to mitigate risks and enhance community resilience.

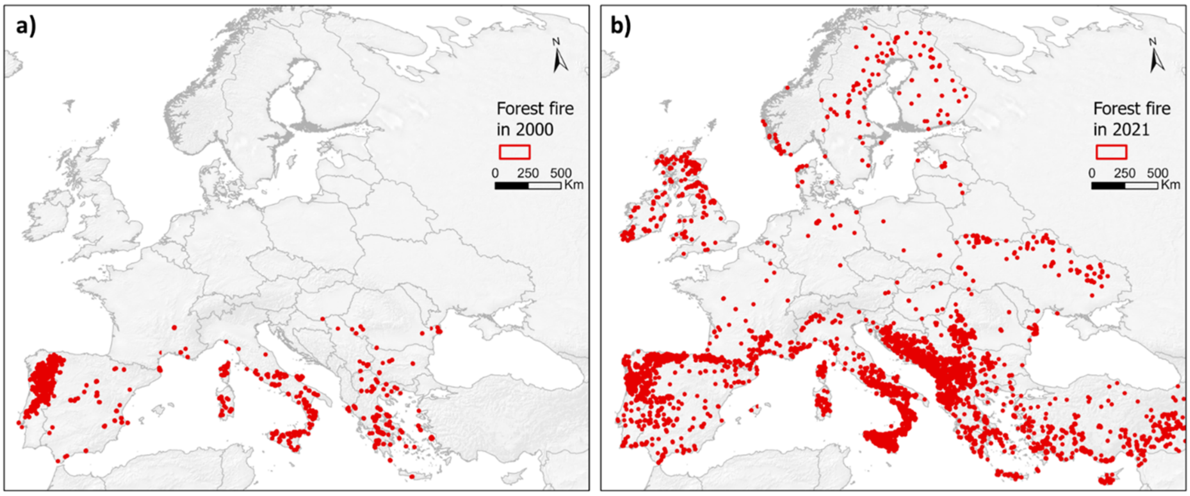

Figure 3. Burnt areas (≥30 ha) produced by forest fires in (**a**) 2000 and (**b**) 2021 based on the European Forest Fire Information System (EFFIS) data.

4.2. Storms and Forest Resilience

Storms induce long-term ecological impacts, including changes in forest structure and composition [37,38]. To face the upcoming storms, we need to identify strategies for enhancing forest resilience to storms, including silvicultural practices and landscape-level planning. The measurements in this regard are at the stand or landscape level. For instance, it is recommended to avoid heterogeneous crowns, gaps, and edges between stands [39]. Yet, with changing climate patterns, understanding the influence of climate change on the frequency and intensity of storms is essential for proactive management.

Forests and how they are managed are very diverse, depending on many factors such as tree species, ecological and environmental conditions, as well as societal demands. As also shown in this Special Issue, climate change affects forest ecosystems and its impact is modulated by forest management [9,40,41]. Therefore, in addition to increasing research that considers both past climate and forest management in modeling forest growth, productivity, and response, there is a strong need to identify such win–win forest management practices (including non-intervention, climate-smart forestry, adaptative management, assisted migration) to better cope with climate change.

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