informa SCIENCE-BASED INTEGRATED FOREST MANAGEMENT FOR CLIMATE MITIGATION
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Does Forest Management Enhance Carbon Sequestration in European Forests? Examining the Trade-offs with Other Ecosystem Services

Human society benefit greatly from ecosystem services (ES) provided by forests. These can be enhanced through forest management. One key ES is carbon sequestration. However, there is a need for a systematic integration of the available knowledge about the impact of forest management on enhancing forest carbon sequestration across Europe. Furthermore, not all management regimes favor the different ES the same way. Tradeoffs and synergies among different ES may arise when managing forests to boost carbon sequestration, and these should be accounted when designing and planning forest management practices. In this review, we will gather the most recent observations on the benefits of forest management in terms of carbon sequestration, comparing managed stands with similar unmanaged ones. We will also assess the interactions of these management regimes with other key ES provided by forests, and discuss their spatial distribution across Europe.

Forests provide multiple ecosystem services (ES), making them essential for human well-being. These services include large scale climate related ones (carbon sequestration and carbon stocking, cooling, albedo, regulation of water fluxes over land), water regulation and purification, soil development and protection, avalanche prevention, biodiversity preservation, wood and non-wood products provision, rural employment and landscape, recreational, cultural and spiritual benefits.

Notably, forests act usually as carbon sinks, partially counteracting anthropogenic CO_2 emissions and mitigating global warming. Effective forest management practices may enhance carbon sequestration potential. These practices range from bolstering forest resilience against disturbances like droughts, windthrow, pest or forest fires (Fig. 1), to increasing carbon residence time in above- and below-ground biomass or in the soil, substitution of fossil fuels by biomass combustion, or production of long-lived wood and other forest products (e.g. bamboo, rubber, cork).

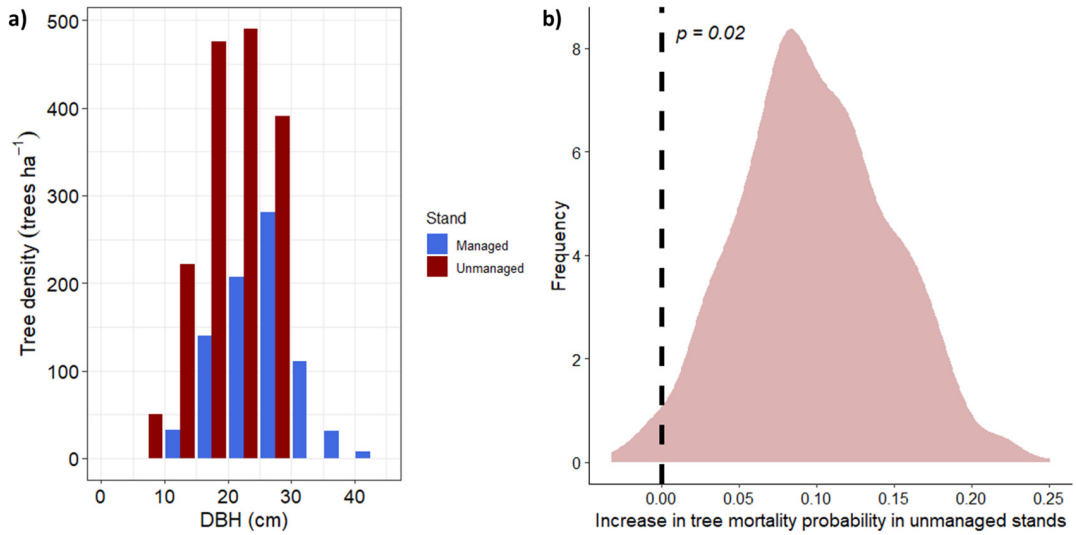

Figure 1: Comparison of stand structure and tree mortality in managed and unmanaged *Pinus pinaster* stands. (a) Average stand structure and (b) difference in tree mortality between managed (last intervention: year 2008) and unmanaged stands for six *Pinus pinaster* stands in Prades, Catalunya, NE Spain. These stands are part of a 62-ha afforestation heavily affected by bark beetle (*Tomicus destruens*) infestation and extreme drought co-occurring during year 2023. Widespread mortality occurred, but it was significantly lower in managed stands, underscoring their reduced vulnerability to pests due to a better tree health promoted by forest management due to the reduction of interception (more water available) and less competition for the available water (more water available per tree).

Effective forest management planning must consider interactions with other ecosystem services, which can be synergistic, conflicting or neglectable. These services include reducing vulnerability to forest fires and drought stress, preventing avalanche or flood damage, and ensuring water purification and provision, pests or windthrow, among others. Additionally, management practices must account for the potential reduction in specific and structural diversity compared to old-grown forests or forests grown without a significant human intervention on its structure during the last decades. While practices like monocultures may increase carbon sequestration per area, they often make forests more vulnerable to natural disturbances like fires and pest infestations. Also, unmanaged relatively young stands resulting from the abandonment of the traditional agriculture since the Second Industrial Revolution can be particularly susceptible to forest fires. A carbon-oriented management strategy is of little benefit if the captured carbon is likely to be released back into the atmosphere due to these disturbances. Therefore, depending on regional particularities, such as climate regime and socio-cultural heritage of the landscape, management practices that minimize the risks of widespread tree mortality and generate a community with different co-occurring tree life strategies, can promote a more resilient forest structure. This resilience may ensure that the carbon captured in vegetation and soil remains stored and is not released back into the atmosphere.

After screening the literature, including over 4100 papers published in the last 20 years on forest management impacts on several ES across Europe, we found a significant trend on focusing on its benefits regarding biodiversity, resulting in an over-representation of such studies in the literature in contrast with the other ES (Fig. 2). Moreover, our initial screening suggested that uncertainty still persists regarding the performance of unmanaged forests compared to managed forests on similar sites, especially concerning their carbon sink potential in relatively mature development stages and under severe disturbance regimes. Evidence-based policymaking requires a quantitative and informed understanding of the effects of forest management on carbon sequestration and carbon stocks. Therefore, research on the impacts of forest management on carbon stock and sequestration, and its interaction with other ES, has reached a stage where synthesis is both beneficial and necessary.

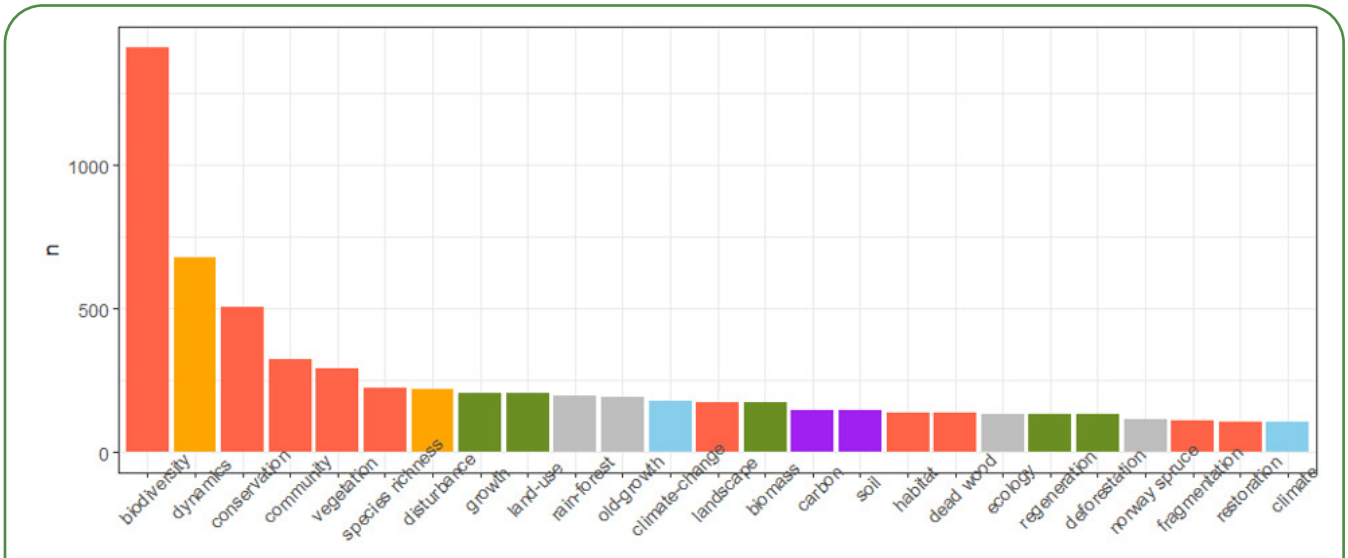

Figure 2: Keyword analysis from a literature screening on 4097 papers in the Web of Science, addressing ecosystem services provision of managed forests respect to unmanaged forests across EU.

After reframing our search for the studies addressing directly the effect of management on forest carbon balances, we selected a total of 374 potential candidate studies with empirical measurements regarding the impacts of management on forest carbon sequestration potential. Following the ROSES systematic review protocol, we aim to compile the necessary scientific knowledge from these studies into a database, and then to analyze the impact of management on forest carbon sinks in the five European bioregions defined by the INFORMA project, which are likely to present different management needs and challenges. It is reasonable to expect that carbon as

the lead driving force for forest management might not be the silver bullet of EU policy regarding forestry, as in many areas of Europe other key ES (e.g. soil protection and water flow regulation, biodiversity hotspots, green urban infrastructure, forest fires prevention) might be more relevant for those areas, especially under global warming. Our study will inform EU Commission policy actions not only about the benefits of forest management, particularly its impact on forest carbon sink capacity, but also identify which ecosystem services, or forest resilience itself, could be negatively affected by a carbon-oriented forest management policy at a regional level if not sufficiently tuned regarding other societal demands and long-lasting resilience.

Lessons learned

1. There are numerous studies on the impacts of forest management on biodiversity, but fewer address its effects on carbon stocks and their interaction with other ES at the European level. Moreover, the results of such studies require a systematic integration to inform at regional level about the potential benefits for a carbon-oriented forest management.

2. Often, the increase in forest carbon sequestration through management is addressed in isolation, without considering its impacts on other key ecosystem services, including resilience to disturbances.

3. Systematic integration of knowledge about forest management's impact on carbon sequestration in Europe is needed, as well and its impacts on other key ecosystem services provision. Different bioregions are expected to present different needs and challenges regarding forestry, that may or may not align with a carbon-oriented forest management policy.

Takeaway

Forest management has the potential to increase forest carbon sink in Europe. However, the impacts of a carbon-oriented forest management practices should not just be evaluated by themselves, but its impacts on other key forest ecosystem services and resilience should be accounted.

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