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Integrating carbon sequestration and biodiversity impacts in forested ecosystems: Concepts, cases, and policies

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Abstract The challenges posed by climate change, biodiversity loss, and land-use are deeply interconnected and integrated solutions are needed. This paper presents results from 11 contributions to a special issue covering topics of integrated modeling and spatial prioritization, mass-balance studies, Earth Observation techniques, research infrastructure developments, and evaluation of policy measures and economic compensation schemes. The spatial scale of the studies ranges from detailed site-specific to a European scale. This paper briefly summarizes the main findings of these studies, makes some general overall conclusions, and identifies topics for further research and methods developments.

Keywords Biodiversity · Carbon neutrality · Ecosystem services · Forests · Land use · Policy

INTRODUCTION

This special issue in *Ambio* brings together insights and experiences from 11 studies focusing on evaluation and integration of carbon (C) and greenhouse gas (GHG) processes, and biodiversity impacts mainly in boreal forested ecosystems. The multidisciplinary approaches include integrated modeling, mass-balance studies, Earth Observation (EO) techniques, research infrastructure developments, and evaluation of policy measures and economic compensation schemes. Although the focus is on forested ecosystems due to their large C storage and sequestration potential, importance for biodiversity, and often dominating role in the landscape, some of the papers also have a landscape approach, considering also other ecosystems (agricultural, wetland, and freshwater ecosystems) and GHG emissions from anthropogenic sources. The spatial scale of the articles ranges from detailed site-specific to a European scale.

Previous work has shown that the challenges posed by climate change, biodiversity loss, and land use are deeply interconnected. This has been documented in several recent high-level publications and reports (e.g., Diaz et al. 2019; IPCC and IPBES 2021; IPCC 2023a, b). These topics are currently also high on the policy agenda, such as the EU Green Deal (European Commission 2021a), EU biodiversity Strategy 2030 (European Commission 2020), and national climate change mitigation and sustainability policies. GHG emissions-induced climate change and accelerating anthropogenic changes in land use are projected to cause further significant deterioration and loss of natural ecosystems and biodiversity, as well as impacts on regional C and GHG budgets. Reaching the global target of limiting the global average temperature increase (Paris Agreement: 1.5 °C and well below 2 °C) requires both rapid transformation of national energy, industrial and land-use sectors, and large-scale deployment of negative emissions technologies and other land-based measures (Friedlingstein et al. 2020; IPCC 2023a, b). The projected economic mitigation potential of options in the global land sector between 2020 and 2050 is 8–14 Gt CO_2eq a^{-1} (IPCC 2023b). Successful co-managing of these tangled drivers requires innovative methods that can prioritize and target management actions against multiple criteria, while also enabling cost-effective land-use planning and impact scenario assessment.

Recently, governments have introduced concepts such as “C neutrality” and “net zero emission” where the aim is to achieve a balance between sources and sinks of CO_2 or GHGs by a target year (e.g., European Commission 2021b). Governments also have plans to stop the loss of biodiversity and implement the internationally agreed sustainable development goals (SDGs). Evaluations of C neutrality therefore require information on both the reduction potential of anthropogenic GHG emissions, including the preservation of existing carbon storages, and developments of the key land-based sinks at different spatial scales, while biodiversity and sustainability issues are simultaneously considered (Forsius et al. 2023). The Regulation for the Land Use, Land Use Change and Forestry (LULUCF) sector (European Commission 2021b) creates the legislative framework for emissions and removals from the land-use sector in the EU.

Forested ecosystems thus play a central role in the global efforts of mitigating climate change and halting biodiversity loss. Forests (trees and soil) store carbon and absorb a significant proportion of the CO_2 emissions, and forest management choices influence wood production, C sequestration, biodiversity conservation, and resilience of forests (Soimakallio et al. 2022; IPCC 2023b; Mäkelä et al. 2023). Through the identification of areas important for biodiversity and C processes, protection of existing forests can be strategically targeted to regions that best support meeting both the national and international biodiversity and climate targets (Forsius et al. 2021, 2023; Kujala et al. 2023). For countries with large forest cover, spatial mapping of biodiversity and C values is an essential technique to estimate the amount of C stored in, or sequestered by forest stands, as well as to evaluate the importance of forest stands for species of conservation interest (Kujala et al. 2023). Novel techniques where data from intensive research sites are extrapolated to regional scales of relevance for the policy-process are also needed (Minunno et al. 2019; Holmberg et al. 2021, 2023). Scenario-based information is needed for climate change adaptation measures and identification of tipping points (e.g., Forsius et al. 2013; Lenton et al. 2019; Mäkelä et al. 2023). Furthermore, various economic instruments (e.g., payment for ecosystem services) can be used to enhance implementation of biodiversity and C-related policies (Kangas and Ollikainen 2023).

There are great expectations on EO systems providing standardized, spatially complete, and cost-effective information for detection, quantification, and forecasting of C processes and biodiversity at large scale (Lausch et al. 2016; Vihervaara et al. 2017; Kattenborn et al. 2019). EO techniques are also at the core in EU policy processes for mapping land-use changes. Yet, the potential of EO data in ecological research remains underutilized (Pettorelli et al. 2016). Also, the expectations concerning the outcomes of EO methods are often contradictory and highly scale dependent. The concept of essential biodiversity variables (EBVs, Pereira et al. 2013) is typically linked to satellite-based EO systems that provide global data with high temporal coverage. These types of data can be capable of supporting global monitoring schemes but are of little value for local conservation decisions that require more detailed data (Lehtomäki et al. 2015; Tanhuanpää et al. 2023). High-resolution EO datasets have typically limited spatial coverage but are capable of object-level detection of ecologically significant forest components (e.g., Heinaro et al. 2021; Mäyrä et al. 2021). Furthermore, historical maps offer valuable insights for detecting environmental change, as they provide essential information on long-term land use and land cover (LULC) trends and identification of features that may not be readily accessible through remote sensing data (Mäyrä et al. 2023).

The collection of papers of this special issue aims at answering the following questions:

- How can areas valuable for both C and biodiversity be identified in forested ecosystems and are there synergies or tradeoffs between these values in the landscape, considering both spatial and dynamic aspects?
- Can policy targets for climate mitigation and biodiversity conservation be achieved considering current land-use trajectories and climate change impacts?
- How do spatial, temporal, and resolution uncertainties and interactions between ecosystem processes influence the evaluation results?
- How should developments of measurement systems and ecosystem research infrastructures be organized in an optimal way?
- How can advanced techniques such as EO and deep learning methods be used for indicator developments and for detecting changes in the landscape?
- How should economic instruments be developed to support the implementation of integrated biodiversity and C policies?
- How are forest policy coherence requirements linked to knowledge production?

In the following sections, we briefly summarize the individual contributions to the special issue, make some overall conclusions across the studies, and identify key needs for further work in this sector.

ARTICLE CONTRIBUTIONS

Role of land cover in Finland's greenhouse gas emissions

The European Commission strives to achieve net-zero GHG emissions by 2050, and Finland has an even more ambitious target of carbon neutrality by 2035. To implement national and global targets of climate mitigation, regional (spatially) explicit information on the relative importance of different land cover forms on net greenhouse gas (GHG) emissions and carbon stocks is needed. Using data and model parameters that represent the period of 2017–2025, Holmberg et al. (2023) provide spatially explicit information on the emissions of all main land cover types (artificial surfaces, cropland, forests, waterbodies, and wetland) in 18 regions in mainland Finland, and discuss the role of the different land cover categories, evaluating the uncertainties of the category-specific estimates.

Their results show large regional contrasts that reflect both long-term economic developments and natural factors. At the national level, while the role of forests amounted to 42% of total country emissions due to carbon losses in timber, energy wood harvest, and soil emissions from drained peatland, the artificial surfaces (energy production, industrial processes, road traffic, agriculture, machinery and off-road transport, waste management, peat production, residential combustion) caused 31% of total emissions. On the contrary, forests acted as the main sink, which contributed to 96% of total carbon sequestration. Finland's total emissions to the atmosphere were 147.2 ± 6.8 $TgCO_2eq$ $year^{-1}$ and after subtracting a total sequestration of 93.2 ± 13.7 $TgCO_2eq$ $year^{-1}$, the net remaining emissions were 53.9 ± 15.3 $TgCO_2eq$ $year^{-1}$ (= net GHG flux per capita of 9.8 $MgCO_2eq$ $year^{-1}$). This means that the remaining gap to reach climate neutrality in Finland currently amounts to 37% of emissions. The results could support the implementation of regional climate roadmaps and sustainable land use, and thereby assist reaching also national targets. However, the authors conclude that there are still large uncertainties in the spatial GHG information that need further work, e.g., regarding the current state of the forest, and proxies for distributing emissions from artificial surfaces.

Quantification of forest carbon flux and stock uncertainties under climate change and their use in regionally explicit decision making: Case study in Finland

Multiple studies have shown that the uncertainty in net ecosystem exchange estimates is high. Regional-level uncertainty analyses therefore improve confidence in forest carbon balance projections used in national and regional policy planning. Using a process-based forest growth model PREBAS, Junttila et al. (2023) estimated the forest net biome exchange (NBE) and accumulated ecosystem carbon stocks under multiple management and climate scenarios. Major sources of uncertainty for all the 18 administrative regions of mainland Finland over the period of 2015–2050 were estimated. The authors demonstrated that Monte Carlo simulations can be used to propagate input and parameter uncertainty, as well as variability in weather conditions and harvest levels, to generate time-dependent carbon balance uncertainty distributions. In this study, sampled forest initial state values, model parameters, harvest levels, and global climate models (GCMs) served as inputs in Monte Carlo simulations. The results reveal that the main sources of uncertainty varied with time, by region, and by the amount of harvested wood. Combinations of uncertainties in the representative concentration pathways (RCP) scenarios, GCMs, forest initial values, and model parameters were the main sources of uncertainty at the beginning, while the harvest scenarios dominated by the end of the simulation period, combined with GCMs and climate scenarios especially in the north. The study also recommends that to achieve carbon neutrality at national and international levels, decisions should be based on multiple modeling approaches supplemented with uncertainty estimates, not only on one model with a deterministic point value result.

Effect of forest management choices on carbon sequestration and biodiversity at national scale

Mäkelä et al. (2023) analyzed the combined impact of prescribed forest management rules and country-wide harvest levels on C balance and biodiversity-related indicators in Finland. The forest management scenarios (management-driven, demand-driven, and forest owners' preference) were simulated on a wall-to-wall grid in Finland until 2050 with the forest growth and C balance model PREBAS. Authors used constraints on total harvest: business as usual, low harvest, intensive harvest, and no harvest to analyze the impacts of harvest intensity. Biodiversity was analyzed with previously published habitat suitability indices for selected species together with deadwood volume and birch volume. The central finding of this study was that the harvest level is key to C stocks and fluxes, regardless of any additional management actions taken and allowing for a moderate extension of strictly protected forest. Biodiversity was more dependent on other management variables than harvesting levels, and relatively independent of C stocks and fluxes. Results also indicated that there is some potential to increase biodiversity even under the current harvest intensity, both through directed management actions and through extension and proper allocation of protection areas. However, reduced harvests are needed to guarantee that the forests remain as C sinks in the next few decades. Likewise in all modeling studies, results are conditional on the model and assumptions used. A proper process-based description of soil C and nitrogen interactions is still under development for the PREBAS model.

Modelling the regional potential for reaching carbon neutrality in Finland: Sustainable forestry, energy use and biodiversity protection

Finland has an ambitious national target to reach C neutrality by year 2035. Forsius et al. (2023) integrated results of three spatially distributed model systems to evaluate the potential to reach this goal at both national and regional scale in the country, by simultaneously considering protection targets of the EU biodiversity strategy. Modeling of both anthropogenic emissions and forestry measures were carried out, and forested areas important for biodiversity protection were identified based on spatial prioritization. The results indicated that the probability to reach the overall policy target of C neutrality by 2035 (and net negative GHG emissions thereafter) was influenced by the assumptions on the impacts of climate change on future forest growth. Assuming continuation of the current climate, the C/GHG target could only be reached by a combination of strong mitigation measures of the anthropogenic GHG emissions and low forest harvesting intensity clearly below the current averages. Strong emission mitigation measures and modeled increasing forest growth due to climate change would potentially make these climate targets less demanding. The estimated future net GHG balances in the different administrative regions of Finland varied greatly, due to differences in the distribution of anthropogenic point and areal emission sources, forest resources, and forest harvesting intensities. These results thus emphasized the need for regional cooperation in reaching national climate targets. It was furthermore shown that, following the EU 10% protection target, potential new protected areas for forest biodiversity would provide a significant C storage and sequestration potential by 2050, indicating complementarity of emission mitigation and conservation measures.

Utilizing historical maps in identification of long-term land use and land cover changes

Knowledge in historical land use and land cover (LULC) is crucial for quantifying and comprehending the scale and impact of environmental changes and for better targeting management efforts. Intensification of human activities has resulted in both areal land changes and increases in linear infrastructure. Mäyrä et al. (2023) demonstrated how to utilize modern computer vision methods to efficiently derive georeferenced information from scanned historical maps to study historical LULC changes in the study area of 900 km^2 in Southern Finland between 1965 and 2022. They used U-Net (Ronneberger et al. 2015), a deep learning architecture originally developed for medical image segmentation and widely adapted to other domains, to automatically extract fields, mires, roads, watercourses, and water bodies from the historical maps, and then used these data, along with the recent topographic databases to quantify the LULC changes for the past 57 years. The proposed method proved to perform well. The results showed the increase with road and ditch networks, and the change in area of agricultural fields and mires. For example, the total area of fields decreased by around 27 km^2, and the total length of watercourses (ditches) increased by around 2250 km in the study area. The authors wish to further develop the methodological approach both by increasing the study area and by including more LULC classes.

Input data resolution affects the conservation prioritization outcome of spatially sparse biodiversity features

Spatial conservation prioritization is an analytical tool for seeking cost-effective solutions for the allocation of conservation areas (Sarkar and Margules 2002). The methodology relies on spatial datasets describing the ecologically essential qualities of subject areas. The accuracy of these datasets largely defines the quality of the analysis outcome. Spatial resolution is one key component defining the data quality. Tanhuanpää et al. (2023) investigated how changing the resolution of input data affects the conservation prioritization outcomes. The authors used remote sensing-based high-resolution datasets for deriving detailed tree species and deadwood maps. The tree-level data were generalized to grid-level using six different resolutions ranging from 16 m × 16 m to 96 m × 96 m. The grid-level data were used as input features in six resolution-specific analysis runs in spatial conservation prioritization software Zonation (Moilanen et al. 2022). The researchers showed that using coarse resolution input data favors the common and evenly distributed features over the scarce and scattered features in prioritization outcomes. On grounds of their results, the authors state that there is a trade-off between the inclusion of scarce ecologically significant phenomena and delineation of continuous and thus resilient areas for protection.

Role of data uncertainty when identifying important areas for biodiversity and carbon in boreal forests

Managing forests for biodiversity and carbon services requires knowledge on their spatial distribution. Typically, spatial data on biodiversity and C features of forests are produced using models, which always contain some level of uncertainty. In their paper, Kujala et al. (2023) explore how the different sources of forest data uncertainty affect the distribution estimates of individual species and C values, and how these in turn affect the location of priority forests for C and biodiversity. The authors iteratively simulated spatial forest data using the forest growth and C balance model PREBAS and quantified the changes in regional biodiversity and C values, and in the priority ranking forests. They found that even relatively small variations in forest variables could introduce large variability in C and biodiversity feature estimates. However, these variations rarely translated into large changes in the distribution of priority forests—although the priority ranking of individual forests could change drastically, the spatial patterns of the most important forest for biodiversity and C stayed rather stable. An important finding was that the amount of uncertainty in the modeled C or biodiversity data, whether measured by model fit of estimate variability, was a poor indicator of how much these data introduced variability in the priority rankings of forests. Instead, the influence of the individual C and biodiversity features was more dependent on their spatial rarity and co-occurrence with other values. Thus, even a small estimate variation in a very influential feature could have a large effect on the location of priority areas, whereas large uncertainty in a non-influential feature did not.

Leveraging research infrastructure co-location to evaluate constraints on terrestrial carbon cycling in northern European forests

The on-going environmental change calls for climate change mitigation and adaptation policies. Effective measures need high-quality data to rely on, that ultimately stem from diverse in situ (site-based) measurements. Joint research infrastructure offers an efficient way to collect and facilitate such data and an effective means to distribute it openly. Futter et al. (2023) highlights the potential of research infrastructure networks in providing diverse time series data for observing terrestrial C sinks and C balance. Research infrastructures, such as ICOS (Heiskanen et al. 2022) and ACTRIS,[1] offer an efficient way to produce standardized and harmonized in situ data. Such data can be utilized in various remote sensing and modeling applications aiming at investigating the C dynamics. The authors also present a thorough conceptual model for co-locating the future research infrastructure and propose how such arrangements could support, e.g., EU Green Deal strategy for reaching C neutrality (European Commission 2021a). The authors conclude that reaching the set climate goals will require effective means for bringing the scientific facts and developments into the policy processes. Hence, the existing co-located research infrastructures should be supported, and further on, the concept should be applied in a wider network of research sites.

Quantification of the effect of environmental changes on the brownification of Lake Kukkia in southern Finland

Brownification of surface waters is often explained by changes in large-scale anthropogenic pressures and ecosystem functioning, including acidification, climate change, and land-use changes. Rankinen et al. (2023) quantified the effect of past environmental changes on the brownification of an important lake for birds, Lake Kukkia, located in a boreal forested catchment in southern Finland. The authors studied the past trends of organic carbon loading from catchments based on observations taken since the 1990s. Catchment-scale eco-hydrological models (PERSiST, INCA-C; Futter et al. 2007, 2014) were calibrated to three small, well-studied catchments at the Lammi long-term ecological research area and the calibrations transferred to the neighboring Lake Kukkia catchment. The long-term brownification process of the lake was then studied with a process-based multi-year simulation model for lake thermo- and phytoplankton dynamics (MyLake model; Saloranta and Andersen 2007). Finally, the authors created hindcasting scenarios for atmospheric deposition, climate change and land-use change to simulate their quantitative effect on the brownification of Lake Kukkia. Their results indicated that changes in forest cuttings have a significant effect on water quality, and are shown to be the primary reason for the brownification. The decrease in acidic deposition has resulted in a higher leaching of total organic carbon (TOC) but in the Kukkia catchment area the effect is very small. In the lake catchment area, while the annual mean temperature has increased by 2 °C since 1985, annual precipitation remained the same. Due to the smaller runoff, the TOC leaching from terrestrial areas is smaller than it would have been without the increasing trend in temperature.

Reforming a pre-existing biodiversity conservation scheme: Promoting climate co-benefits by a carbon payment

Payments for ecosystem services (PES) schemes are commonly used to promote biodiversity conservation in private forests, and including C as another target may be a cost-efficient way to achieve the goals of the EU Biodiversity Strategy and the requirements of the LULUCF regulation. Kangas and Ollikainen (2023) used the Finnish METSO forest conservation program as a case study for a reform where a carbon payment is added to a pre-existing forest biodiversity conservation PES scheme to achieve

[1] www.actris.eu.

synergy gains for both biodiversity conservation and climate change mitigation goals. Using a site selection model, authors examined how the proposed scheme could promote biodiversity and C values, and what level of the C payment would provide the highest synergy gains. The results indicated that introduction of the C payment increases the efficiency of the whole mechanism by improving the landowners' incentives to participate in the scheme and promotes both targets. The C payment should primarily be paid for C storage instead of C sink, and the highest synergy gains are obtained in most cases by a second-best payment level of 10–20€ tCO_2^{-1}. Introducing an additional incentive-based instrument in forest conservation may likely promote voluntary conservation for a wider group of forest owners, and will incentivize landowners to offer sites that would not have been offered for the program otherwise.

Coherent at face value: Integration of forest carbon targets in Finnish policy strategies

The increasing pressure to mitigate climate change requires the policy domains (e.g., forest policy, bioeconomy policy, and biodiversity policy) to integrate and operationalize climate considerations in their agendas. Despite the explicit claims about policy coherence, few genuine attempts have been made toward integration and coordination among the domains. Previous studies (e.g., Sarewitz 2004; Sivonen and Syväterä 2023) have reported that a notable challenge in environmental governance is that scientific knowledge is used strategically to serve political purposes, rather than to relieve environmental disputes. Bearing this in mind, Pitzén et al. (2023) addressed the coherence of forest policy by analyzing the content and knowledge claims in forest, bioeconomy, and biodiversity strategies of Finland to investigate how they recognize the need to maintain forest C sinks and secure C sequestration, and how they adopt C as an object of governance. Results revealed that the policy domains remain largely disconnected and rely on differentiated knowledge bases. Knowledge used in the policy design and implementation processes should be discussed thoroughly, and thereby integrated. Authors also suggested that policy strategies with sectoral foci facilitate incoherent policymaking due to unresolved tradeoffs and knowledge disagreements. As recommendation, the study suggested three further research avenues on policy coherence: firstly, the different epistemologies behind the politicized knowledge claims on forest carbon should be studied in more detail; secondly, the strategic utilization of scientific knowledge in policy processes requires further research, especially in the context of sustainability transformations connecting multiple socio-environmental challenges; and finally and most importantly, policy coherence requires the interconnection of environmental policy analyses and environmental science-driven trade-off analyses.

CONCLUSIONS

We identify three main interconnected groups of issues based on the individual contributions. First, we analyze evaluation and modeling of C- and GHG-processes in these forested landscapes. The studies clearly indicate that reaching C neutrality at the national and regional levels requires both efficient reductions of the anthropogenic GHG emissions and maintenance of the C sinks via modest forest harvesting policies. The potential mitigation and land-use measures differ widely by region, and the identified C neutrality gap can be quantified by the techniques developed and presented in these papers (Forsius et al. 2023; Holmberg et al; 2023; Junttila et al. 2023; Mäkelä et al. 2023; Rankinen et al. 2023). Mäkelä et al. (2023), Junttila et al. (2023), and Forsius et al. (2023) also show that decreasing forest harvesting levels will increase C storage in the Finnish forest ecosystems and that the current C storage levels are far below the maximum potential. According to Mäkelä et al. (2023), the national C budget of these systems is driven by the harvest level, not the management strategy, and that current national forest management recommendations do not support C storage/ sequestration. Regionally explicit uncertainty analysis is a useful approach for planning regionally fair policy actions, fulfilling national targets (Junttila et al. 2023). More work is needed to link C and N processes and evaluate climate change impacts in the boreal forested ecosystems.

Second, some overall conclusions can be made on integrating C and biodiversity processes and impacts at the landscape level. Using different methodological approaches, both Mäkelä et al. (2023) and Kujala et al. (2023) show that relaxing harvesting levels benefit both C storages and biodiversity. Kujala et al. (2023) also show that the different spatial distributions of C and biodiversity values have strategy implications, resulting in numerous options for increasing C pools and fluxes, whereas many of the biodiversity values are spatially confined. Previous work in Finland has come to similar conclusions (Forsius et al. 2021). Furthermore, C losses in these systems may be temporary but local biodiversity values may be unique to the area and lost permanently, if affected (Heikkinen et al. 2021; Mäkelä et al. 2023). These and other studies (UN 2019) also show that tradeoffs between C and biodiversity values and between biodiversity/climate protection and economic return exist and need to be acknowledged. This indicates that, although biodiversity conservation strategies are increasingly coupled with climate mitigation targets, biodiversity should remain as the primary focus when prioritizing areas for protection. On the other hand, the study of Forsius et al. (2023) showed that additional protected areas for biodiversity provided a significant C storage and sequestration potential by 2050 (close to the maximum reduction potential of the anthropogenic GHG emissions), indicating potential complementarity of emission mitigation and conservation measures in the long term. Thus, both the spatial and temporal variability of these processes need to be considered. New techniques based on remote sensing and artificial intelligence can produce spatially detailed data on biodiversity values and indicators, as well as on LULC change over large areas (Mäyrä et al. 2023; Tanhuanpää et al. 2023). The papers of this special issue provide methods and databases for designing optimal solutions for co-managing climate and biodiversity aspects in the landscapes.

Third, we conclude regarding implementation of economic instruments and policy measures. Payments for ecosystem services (PES) schemes provide landowners incentives to manage their lands in a more environmentally friendly manner, e.g., via protection or restoration. As Kangas and Ollikainen (2023) point out, the application of current PES schemes to forest lands entails two weaknesses. First, current PES schemes typically target the delivery of a single ecosystem service, like biodiversity or C but not both at the same time. Second, by compensating mechanically for the conservation costs instead of paying for direct provision of ecosystem services, PES mechanisms seldom provide the best economic incentives to forest landowners. Their study results show that introducing a C payment to a biodiversity conservation program with an equivalent increase in conservation budget increases supply of sites and promotes synergy between biodiversity and C targets. The study of Kujala et al. (2023) shows that biodiversity values and stand age correlate more with the C storages than the potential sinks, which needs to be considered in the design of the PES schemes. In transformative societal shifts, a lot of hinges observed on national level politics and policies. The findings of Pitzén et al. (2023) that show sectoral differentiated knowledge bases and selective use of scientific results to support political agendas are worrisome but not surprising, and they go to show that further work is still needed before climate and biodiversity targets can be implemented in a truly cross-sectoral manner.

The papers in this special issue also identify key topics for future research and technical improvements. Several papers in this issue rely on the results from dynamic forest modeling, also under future climate scenarios. This introduces major sources of uncertainty into the predictions, due to the complex physiological and biochemical processes involved and increasing risks caused by various external drivers, such as pests and forest fires (e.g., Anderegg et al. 2020; Venäläinen et al. 2020). Developing the models and process understanding to better predict forest growth under climate change conditions is thus a clear priority for further research. This also includes developments of techniques for quantifying and displaying uncertainty estimates at the regional scale (Minunno et al. 2019; Junttila et al. 2023). In this context, development of reliable scenarios for both the key drivers (climate, energy use, etc.) and the use of natural resources under changing conditions is always a key need for the modeling work. Utilization of highly detailed EO data and machine learning techniques would improve regional databases and landscape prioritization efforts (Kujala et al. 2023; Mäyrä et al 2023; Tanhuanpää et al. 2023). Detailed and long-term spatial data derived from remote sensing and historical maps play a vital role in understanding the impacts of LULC change on biodiversity, C storage, and ecosystem dynamics. Expanding the spatial extent of analyses in the future will provide information for conservation strategies, policy decisions, and sustainable land-use practices over wider geographical areas. Yet, methodological challenges, data integration complexities, and the importance for interdisciplinary collaboration need to be addressed to fully harness the potential of these data sources.

Consideration of nutrient limitations is also a key issue for quantifying C processes in forest ecosystems. Nitrogen and C cycles in forest and other ecosystems are closely linked because growth requires nutrients, in particular N. However, N cycling in the ecosystems involves complex processes such as atmospheric deposition, recycling of organic N by microbes, and biological N fixation (Nadelhoffer et al. 1999; Luyssaert et al. 2021). Due to these interactions, the magnitude of the C sink of old forests, as well as sustainability of the C sink strength of young and managed forest, has recently been intensively discussed (Gundersen et al. 2021; Luyssaert et al. 2021). The impacts of climate change will further increase the need to improve the knowledge on these C–N and other nutrient interaction processes.

A related issue is that measurement systems and formal research infrastructures are currently to a large extent implemented based on different scientific disciplines. This leads to a situation where multisectoral integrating ecosystem-based studies on the same locations are difficult to carry out. As Mirtl et al. (2018) and Futter et al. (2023) clearly show, much could be gained by improved collaboration and co-location of these different research infrastructures. As an additional benefit, this would also save scarce financial and personnel resources.

The magnitude of land-based measures and implementation of negative emission technologies needed to comply with the global GHG mitigation targets and the efforts to stop the biodiversity decline (Diaz et al. 2019; IPCC and

IPBES 2021; IPCC 2023b), and related national targets, emphasize the need to develop market mechanisms for both C and biodiversity protection, as well as integrated economic instruments for combined biodiversity protection and C sequestration/storage (Assmuth et al. 2021; Kangas and Ollikainen 2023). Private companies are showing increasing interests to decrease the environmental impacts of their businesses and support developments in this field. The general need to transform the economic system toward sustainability and more efficient use of renewable resources and energy is also clearly recognized (Girardin et al. 2021; OECD 2022). In this context, removal of subsidies for harmful economic and land-use activities (e.g., use of fossil fuels, ditching of peatlands) would be a priority, as well as improvement of general policy coherence for such activities. As Pitzén et al. (2023) suggest, connection of environmental policy analyses and science-driven trade-off analyses would in this respect be a key priority.

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