



Forest soil challenges in Europe: Solutions through sustainable forest management and monitoring

Summary of the messages

1. Further measurements and sharing of soil data, models, and expertise are needed to reduce uncertainty in carbon stock changes in GHG inventories.
2. Enhancing soil carbon sequestration on mineral soils and reducing emissions on peatlands can help meet LULUCF climate targets in the EU.
3. Reducing harvests, increasing stocking density and extending rotation length, as well as sustainable post fire management practices, can increase soil carbon stock.
4. Partial peatland hydrology restoration and emission reduction in drained peatland forests can be combined with timber production through continuous cover forestry, avoiding further ditching.
5. Forest restoration to more resilient mixed and broadleaf dominated stands enhances adaptation to climate change.
6. Readily available methods for assessing soil biodiversity, functional redundancy, and community resilience facilitate implementation of the proposed Soil Monitoring Law.

" Among the major drivers of forest soil degradation are unsustainable forest management, peatland drainage, atmospheric nitrogen and sulfur deposition, forest fires, and deforestation."

Introduction

Soil degradation threatens sustainable provisioning of ecosystem services that are essential for human wellbeing. Among the major drivers of forest soil degradation are unsustainable forest management, peatland drainage, atmospheric nitrogen and sulfur deposition, disturbances which replace stands, such as forest fires, and deforestation. The overall quantified annual costs of soil degradation in the EU are estimated to be up to 28 billion € due to soil carbon (C) loss and erosion (EU Commission 2023).

The EU Soil Strategy for 2030 provides concrete steps towards protecting and restoring soils, and ensuring their sustainable use. As part of this, a proposed Soil Monitoring Law (SML) will create a coherent monitoring framework for all soils and make sustainable soil management the norm in the EU. Additionally, the EU Nature Restoration Law, LULUCF regulation, Common Agricultural Policy (CAP), and proposed Forest Monitoring Law all support advancing soil monitoring, mitigating degradation and fostering restoration. However, effective implementation of all these regulations requires enhanced understanding of soil processes and their drivers, ecosystem restoration practices, and soil monitoring frameworks.

Refined measurements and data sharing can reduce uncertainty in soil GHG inventories

Increasing C sequestration in forest soils and reducing net greenhouse gas (GHG) emissions is crucial to achieve EU climate targets set in the Paris Agreement. The EU's LULUCF regulation sets binding climate targets for the land sector, and establishes principles for GHG inventories to be used in reporting by EU Member States. Latest regulation directs countries to reduce uncertainty by advancing their land sector GHG reporting to higher Tier levels, according to IPCC guidelines. Higher Tier levels are also requested when mapping spatially explicit C stock changes with high C stock areas (i.e. peatland soils) and with high biodiversity value areas.

However, according to the 2022 UNFCCC submission, the Tier 1 approach is used by 19 out of 27 Member States in C stock change reporting on upland forest soils, while few countries use Tier 2 (3/27) and Tier 3 (5/27) methods, which are based on either dedicated measurements or modelling. ICP Forests has developed a harmonized forest soil monitoring protocol, which is already shown to be applicable across the EU. If countries with large forest areas—like Austria (AUT),

Spain (ESP), Portugal (PRT), and Italy (ITA)—were to develop inventory methods towards those in the more accurate Tier 3, the overall estimate of the European forest soil carbon sink would change (Fig 1).

In the EU, drained peatland forests have total emissions of 25 million tons of CO₂ eq., with the greatest emissions reported by Finland (FIN) and Sweden (SWE) (Fig. 1). An increasing number of Member States that have drained peatland forests

" In C stock change reporting on upland forest soils, only 5 countries out of 27 use methods that are based on either dedicated measurements or modelling."

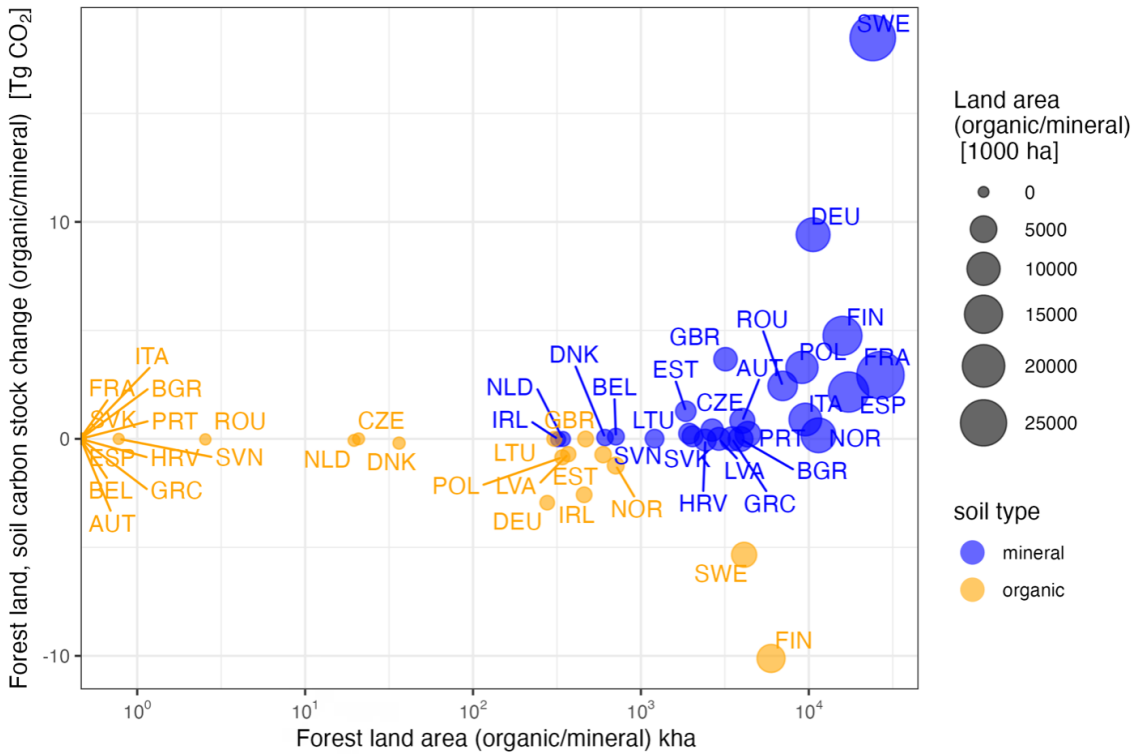


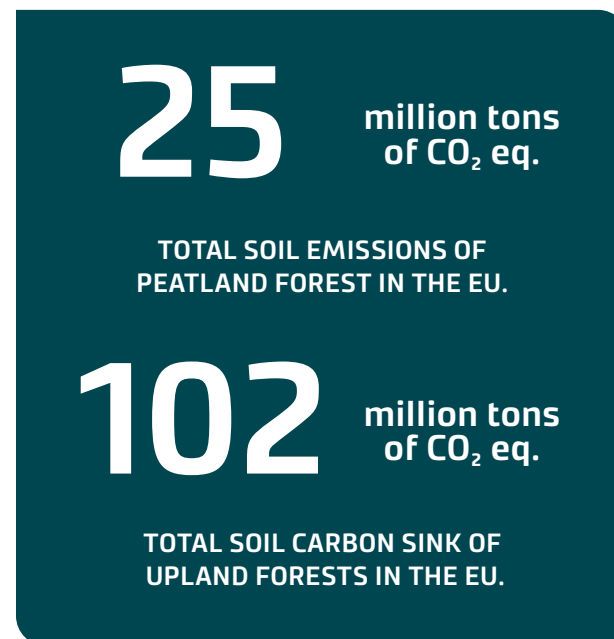
Figure 1 | Soil C stock change [Tg CO₂] for mineral soils (including litter and deadwood, blue) and organic soils (yellow) according to land area in forest land. Note that the scale of x-axis is logarithmic. Positive values are sinks and negative values are emissions. Across all reported countries, the total emissions of organic soils were 25 Tg CO₂ eq and the total sink of mineral soils was 102 Tg CO₂ eq (including deadwood and litter). Data obtained from 2024 submissions to the UNFCCC (latest year for reporting is 2022).

are reporting their emissions. However, only Denmark (DEN) (Tier 1), Finland (Tier 3) and Ireland (IRL) (Tier 2) report emissions for drained peatland forests based on methods where emission factors per area vary over time (2023 submission under unfccc.int).

The use of highly uncertain Tier levels in reporting of EU forest soil C stock changes underlines the need for urgent compilation and sharing of data, models, and expertise to improve the quality of GHG inventory reporting across the EU. Similarly, LUCAS soil inventory data for forests (woodlands in the LUCAS), require higher quality and precision as well as appropriate coordination with site and tree stand measurements. For future field campaigns with LUCAS soil, both geolocation of repeated samples and soil layer differentiation (including litter and organic layer) must be done in an appropriate way to reduce uncertainty of the GHG inventory across countries (Ziche et al. 2022, Heikkinen et al. 2024).

Sustainable forest management increases soil carbon stocks

The HoliSoils project shows that forest management has major impacts on soil C stock and GHG emissions (Mäkipää et al. 2023). Intensive timber harvesting with removal of harvest residues results in soil C stock reduction, while high stocking density, extended rotations, and enhanced productivity or dominance of coniferous species increases soil C stock (Mäkipää et al. 2023). In boreal forests, nitrogen fertilization increases the soil C stock, while decreasing the methane (CH₄) sink (Mäkipää et al. 2023). In central Europe, where forest soils are nitrogen (N) saturated and acidified due to atmospheric deposition of nitrogen



"Forest management has major impacts on soil C stock and GHG emissions."



and sulfur (S), liming can advance soil health recovery and increase soil carbon stocks (Grüneberg et al 2019). In southern Europe, sustainable post-fire management practices can enhance soil health and microbial recovery after forest fires (Garcia-Pausas et al. 2022). HoliSoils results show that prescribed burnings increase the resistance to possible wildfires and to severe droughts (Vilà-Vilardell et al. 2023), but with neutral or negative impacts on soil C stocks depending on the intensity.

Improvements in accounting for the impact of management practices on soil temperature, moisture, nutrient balance, microbial and faunal community structure, and related processes in simulation models remain a challenge. This is crucial for science-based decision-making at stand, regional, and European scales.

Peatland water level management mitigates GHG emissions

EU countries are preparing for the implementation of the Nature Restoration Law by designing their national restoration plans; at the same time, managed drained peatland forests can also be targeted. Managed peatland forests offer significant potential for emission reduction (Mäkipää et al. 2024a). Peatland hydrology management (drainage, rewetting) strongly impacts GHG emissions of peatland forests. Higher water

levels correspond to lower CO₂ emissions (Escobar et al. 2022, Kwon et al. 2022, Mäkipää et al. 2023). Elevated water tables, however, may also result in higher CH₄ emissions, the effect of which on global warming potential (GWP) is in general compensated by reduced CO₂ emissions. After clearcutting, the total GWP of all GHG emissions (CO₂, CH₄ and N₂O) can be ten times higher than in peatlands with standing trees (Tikkasalo et al. 2025). Avoiding clearcutting and applying continuous cover forestry on peatlands allows timber production with a higher water level (and avoids further ditching), which can reduce GHG emissions (Lehtonen et al. 2023).

"Peatland hydrology management is a major driver of GHG emissions of peatland forests, with higher water level corresponding to lower CO₂ emissions."



Reliable monitoring of forest soil biodiversity and functioning requires state-of-art methods

The proposed Soil Monitoring Law requires soil biodiversity monitoring in all Member States, using nationally set indicators and threshold values. In forests, the spatial heterogeneity of soils that arises from physical conditions, the co-existence of trees, ground vegetation, and soil biota, as well as from stand management, poses a substantial challenge that makes soil biota difficult to sample. The HoliSoils project developed state-of-the-art methods for soil biodiversity assessment and elaborated a comprehensive protocol for harmonized forest soil sampling and biodiversity analysis. The ability to apply the sampling scheme across a wide range of EU forests, from Mediterranean to Boreal, allows for robust testing and refinement, and provides sampling protocols that can be readily applied, for example in the analysis of soil microbial (Richy et al. 2024) and faunal community (Biryol et al. 2024) responses to forest management. Moreover, the methods are not unique to forests, and EU Member States can decide to use the developed protocols to monitor soil biodiversity at sites across different land uses.

"Reliable monitoring requires state-of-the-art soil biodiversity assessment methods and a comprehensive protocol for harmonised forest soil sampling and biodiversity analysis."

References

Biryol, C., Trap, J., Prévosto, B., Dupouyet, S., Baldy, V., & Santonja, M. 2024. Managing both overstory and understory vegetation mitigates the impact of drought on soil nematode communities in a Mediterranean pine forest. *Applied Soil Ecology* 202, 105585. <https://doi.org/10.1016/j.apsoil.2024.105585>

Escobar, D., Belyazid, S. & Manzoni, S. 2022. Back to the Future: Restoring Northern Drained Forested Peatlands for Climate Change Mitigation. *Frontiers in Environmental Sciences* 10:834371. <https://doi.org/10.3389/fenvs.2022.834371>

EU Commission 2023. Impact assessment report accompanying the proposal for a Soil Monitoring Law SWD(2023) 417 final. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023SC0417>

Garcia-Pausas, J., Romanyà, J., & Casals, P. 2022. Post-fire recovery of soil microbial functions is promoted by plant growth. *European Journal of Soil Science* 73, 13290. <https://doi.org/10.1111/ejss.13290>

Grüneberg, E., Schöning, I., Riek, W., Ziche, D., Evers, J. 2019. Carbon Stocks and Carbon Stock Changes in German Forest Soils. In: Wellbrock, N., Bolte, A. (eds) Status and Dynamics of Forests in Germany. *Ecological Studies*, vol 237. Springer, Cham. https://doi.org/10.1007/978-3-030-15734-0_6

Kwon, M. J., Ballantyne, A., Ciais, P., Qiu, C., Salmon, E., Raoult, N., Guenet, B., Göckede, M., Euskirchen, E. S., Nykänen, H., Schuur, E. A. G., Turetsky, M. R., Dieleman, C. M., Kane, E. S., & Zona, D. 2022. Lowering water table reduces carbon sink strength and carbon stocks in northern peatlands. *Global Change Biology* 28. 6752-6770. <https://doi.org/10.1111/gcb.16394>

Heikkinen, J., Kostensalo, J., Keskinen, R., Soinne, H. and Nuutinen, V., 2024. Temporal trends in Finnish agricultural soils: A comparative analysis of national and LUCAS soil monitoring datasets. *European Journal of Soil Science* 75, e13525. <https://doi.org/10.1111/ejss.13525>

Lehtonen, A., Eyvindson, K., Härkönen, K., Leppä, K., Salmivaara, A., Peltoniemi, M., Salminen, O., Sarkkola, S., Launiainen, S., Ojanen, P., Rätty, M. & Mäkipää, R. 2023. Potential of continuous cover forestry on drained peatlands to increase the carbon sink in Finland. *Sci Rep* 13, 15510. <https://doi.org/10.1038/s41598-023-42315-7>

Mäkipää et al. 2023. How does management affect soil C sequestration and greenhouse gas fluxes in boreal and temperate forests? - A review, *Forest Ecology and Management* 529,120637. <https://doi.org/10.1016/j.foreco.2022.120637>

Mäkipää, R., Bruun, O., Lehtonen, A., Peltoniemi, M. and Kulovesi, K., 2024a. We need targeted policy interventions in the EU to save soil carbon. *Frontiers in Environmental Science*, 12, p.1354695. <https://doi.org/10.3389/fenvs.2024.1354695>

Mäkipää, R., Menichetti, L., Martínez-García, E., Törmänen, T. & Lehtonen, A. 2024. Is the organic carbon-to-clay ratio a reliable indicator of soil health? *Geoderma* 444, 116862. <https://doi.org/10.1016/j.geoderma.2024.116862>

Richy, E., Fort, T., Odriozola, I., Kohout, P., Barbi, F., Martinovic, T., Tupek, B., Adamczyk, B., Lehtonen, A., Mäkipää, R., Baldrian, P. 2024. Phosphorus limitation promotes soil carbon storage in a boreal forest exposed to long-term nitrogen fertilization. *Global Change Biology* 30, e17516. <https://doi.org/10.1111/gcb.17516>

Tikkasalo, O.-P., Peltola, O., Alekseychik, P., Heikkinen, J., Launiainen, S., Lehtonen, A., Li, Q., Martínez-García, E., Peltoniemi, M., Salovaara, P., Tuominen, V., Mäkipää, R. 2025. Eddy-covariance fluxes of CO₂, CH₄ and N₂O in a drained peatland forest after clear-cutting, *Biogeosciences*, 22, 1277-1300. <https://doi.org/10.5194/bg-22-1277-2025>, 2025

UNFCCC, National Inventory Submissions 2022 and 2023. <https://unfccc.int>

Ziche, D., Grüneberg, E., Riek, W. and Wellbrock, N., 2022. Comparison of the LUCAS 2015 inventory with the second National Forest Soil Inventory: Comparability and representativeness of two soil inventories conducted in Germany. *Johann Heinrich von Thünen Institut, Thünen-Report*, 94, p.62.

Vilà-Vilardell, L., De Cáceres, M., Piqué, M., Casals, P. 2023. Prescribed fire after thinning increased resistance of sub-Mediterranean pine forests to drought events and wildfires. *Forest Ecology and Management* 527, 120602. <https://doi.org/10.1016/j.foreco.2022.120602>

Policy Brief 2025 | Forest soil challenges in Europe: Solutions through sustainable forest management and monitoring

Authors:

Mäkipää, R.¹, Adams, S.², Baldrian, P.³, Casals Tortras, P.⁴, Curiel Yuste, J.⁵, Guenet, B.⁶, Luyssaert, S.⁷, Santonja, M.⁸, Wellbrock, N.⁹ and Lehtonen, A.¹

Affiliations:

¹ Natural Resources Institute Finland (Luke)

² European Forest Institute (EFI)

³ Institute of Microbiology of the Czech Academy of Sciences (IMIC)

⁴ Forest Science & Technology Centre of Catalonia (CTFC)

⁵ Basque Centre for Climate Change (BCB)

⁶ French National Centre for Scientific Research (CNRS)

⁷ Vrije University Amsterdam (VU)

⁸ Aix Marseille University (AMU)

⁹ Thuenen Institute

This project 'Holistic management practices, modelling and monitoring for European forest soils' - HoliSoils - is funded by the European Commission's Horizon 2020 research and innovation programme under grant agreement no. 101000289.



We build sustainable future and well-being
from renewable natural resources.



Luke Policy Brief 1/2025

ISSN 2343-4252

ISBN 978-952-419-028-2 (print)

ISBN 978-952-419-029-9 (online)

URN urn.fi/URN:ISBN:978-952-419-029-9