Towards a climate -resilient society and sustainable environment through freshwater carbon knowledge

Impact story: BlueLakes – Digitizing the carbon sink potential of boreal lakes

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Introduction

Finland's boreal lakes are among the most distinctive elements of its natural heritage, shaping landscapes, livelihoods, culture, and wellbeing. They are also far more than scenic assets: lake sediments store organic carbon over millennial timescales, making inland waters important—but historically under recognized—components of national and European carbon budgets. BlueLakes was established to transform scientific understanding of these freshwater carbon sinks into actionable tools for climate mitigation, sustainable water management, and informed decision making across society.

By delivering the first national scale evidence on carbon burial in boreal lakes, pioneering assessments of freshwater "blue carbon" ecosystems, and embedding this knowledge in Finland's primary water quality and catchment model (WSFS Vemala), BlueLakes has made substantial contributions to a more sustainable, climate resilient society and healthy environment. The project demonstrates how environmental science, digital innovation, and multi stakeholder co-creation can jointly support the green transition and strengthen societal preparedness for climate change.

1. Impact Objectives

The objectives of BlueLakes were explicitly aligned with the OneHealth concept, building a sustainable society and enhancing environmental well-being. In relation to climate change mitigation and adaptation, responsible environmental stewardship, and knowledge-based governance, the main impact objectives can be summarized as:

- Strengthen society's capacity to mitigate climate change by quantifying the natural carbon sink potential of boreal lakes and identifying measures to safeguard and enhance it.
- Support sustainable land use and healthy environment by generating catchment-level evidence and tools that enable authorities to evaluate how land use decisions affect carbon dynamics in freshwater systems.
- Promote an inclusive and digitally enabled society through the co-development of open digital tools (WSFS Vemala) and openly accessible datasets that democratize environmental knowledge

These objectives directly promote a sustainable society by bridging scientific insights with the needs of policymakers, practitioners, environmental authorities, and the wider public.

2. Actions

BlueLakes performed a coordinated set of scientific, digital, and participatory actions designed to advance sustainable society and environmental well-being through both new knowledge and operational tools.

Action: Generating new scientific evidence for societal use

BlueLakes produced extensive new field, laboratory, and remote sensing datasets including:

- More than 200 lakes analysed for modern sediment carbon burial rates.
- New environmental measurements from open-water and vegetated littoral zones of key lakes.
- The first comprehensive Finnish datasets on carbon stocks in macrophyte dominated "teal/blue carbon" habitats.
- Macrophyte coverage maps (based on satellite data) for the pilot lakes (including time series of the seasonal evolution of macrophyte coverage) and more extensive maps covering all recognized lakes in Finland for which the method is applicable.

These fundamental scientific advancements establish an evidence base for higher-level outputs of the project and long-term sustainable water and climate policy. The project promoted open science and data stewardship. All new data were stored securely, curated, and published in open repositories (e.g., PANGAEA), supporting fairness, transparency, and long-term societal benefit.

Action: Developing digital technologies for public authorities

The project delivered a major digital innovation in the form of a new version of WSFS Vemala, including a module for macrophyte/blue carbon ecosystems and extended description of catchment-level carbon cycling.

Consequently, WSFS Vemala can now:

- Estimate carbon burial and remineralisation in lakes across Finland, including in macrophyte areas.
- Simulate climate and land use scenarios relevant to national climate objectives.
- Provide open-access outputs via interfaces such as vesi.fi (https://www.vesi.fi/en/) and public Vemala tools (WSFS-Vemala /Syke: https://metadata.ymparisto.fi/dataset/{7E6EB982-A3CA-4DE3-87C0-1B61462442DF})

In the near future, ongoing work from PhD and postdoctoral researchers in the consortium will deliver two further key innovations:

- Upscaled national macrophyte coverage products derived from Earth Observation and field calibration, supporting lake scale and catchment scale carbon stock assessments.
- Routines to estimate the spatial distribution of carbon in lake sediments from seismic and sediment geochemical data.

These digital advances support evidence based environmental governance, accelerate the digital transition in water management, and help authorities design climate robust policies.

Action: Stakeholder co-creation for societal relevance

From inception, BlueLakes was co-designed with end users from:

- Regional authorities (ELY-Centre representatives)
- Water protection associations and river basin authorities
- Municipalities and regional planners
- Environmental consultancies
- Finnish Environment Ministry

Advisory Board meetings with these partners ensured continuous dialogue, guiding data needs, model functionalities, and communication strategies. This approach created strong societal ownership of the project outputs and ensured their immediate applicability.

Action: Public outreach and raising societal awareness

The project engaged wider society through:

- Public lectures (e.g., Lahti outreach events)
- Media articles and blog posts for lake restoration practitioners and environmental professionals
- Contributions to national trainings: VEMALA user days with ~120 professional participants annually
- BlueLakes end-user seminar “Hiilen jäljillä” with representatives from ministries, agencies, NGOs, consultancies, and research organisations-user seminar

These activities strengthened public understanding of freshwater carbon processes and their relevance for sustainable climate solutions.

3. Successes and Challenges

Successes:

Key scientific output 1: enhanced rates of modern carbon burial

The project confirmed that modern carbon burial in Finnish lakes is substantially higher than long-term Holocene averages and controlled by land use, lake type, ecological status, and sediment dynamics.

Key scientific output 2: significant carbon stocks in vegetated ecosystems:

Vegetated littoral zones ("teal carbon" areas) were shown to hold exceptionally high carbon stocks—on par with well-known marine blue carbon habitats—opening new possibilities for freshwater nature-based climate solutions.

High-value digital outputs:

WSFS Vemala was successfully expanded to include carbon cycling and macrophyte dynamics, creating a robust tool for climate and land use scenario analysis at national scale.

Strong stakeholder integration:

Collaboration with authorities, policy fora, and sector professionals ensured relevance, uptake, and continuity beyond the project's lifetime.

Challenges:

Temporal constraints:

The 3-year timeline limited the ability to observe multi-annual variability in carbon cycling and required that a relatively small number of sites were selected for intensive study. Furthermore, completion of PhD degrees started within the project extends beyond the 3-year timeline, requiring applications for additional resources.

Complexity of upscaling:

Modelling spatial heterogeneity of carbon burial on the whole-lake scale is dependent on extensive seismic data acquisition and sediment sampling. Similarly, upscaling estimates of carbon stocks in macrophyte areas requires robust remote sensing data and field calibration. In both cases, data availability limits the accuracy of estimates beyond the intensively studied areas.

Despite these challenges, strong consortium coordination and stakeholder commitment ensured that high quality outputs were delivered successfully.

4. Impact Mechanisms

BlueLakes identified several mechanisms by which its activities and results generate environmentally relevant societal impact:

Knowledge transformation into decision tools:

Scientific evidence on carbon burial and remineralisation was implemented directly into WSFS Vemala, turning research findings into operational digital solutions for authorities.

Enhanced predictive capability:

The updated model enables catchment scale carbon budgeting and simulation of future climate and land use scenarios, supporting regulatory compliance (e.g., Water Framework Directive), restoration planning, and climate adaptation.

Strengthened cross-sectoral dialogue:

Continuous engagement with policymakers, regulators, researchers, and civil society helped align environmental governance with emerging carbon management approaches.

Capacity building:

WSFS Vemala training sessions, open datasets, and digital interfaces equip regional authorities and consultants with new skills to address sustainability challenges. The training of junior researchers during the project also contributes to capacity building of future professionals.

Catalysing broader ecosystem restoration measures:

Results highlight the importance of protecting macrophyte belts and reducing eutrophication not only for biodiversity, but also for carbon sequestration—helping integrate climate aspects into freshwater management.

5. Medium and Long-Term Impacts and Systemic Effects

Over the coming years, the knowledge and digital tools developed in BlueLakes are expected to reshape how Finland manages its lakes, creating lasting improvements in sustainable society and environmental well-being. In the medium term (1–5 years), authorities and consultants are likely to integrate the updated WSFS-Vemala carbon modules into everyday planning, permitting, and restoration processes. As more users adopt the model—supported by future

trainings and open access interfaces—carbon burial, sediment processes, and macrophyte habitat functions will become standard considerations alongside ecological status assessments and nutrient targets. This shift is grounded in the project's demonstrated findings concerning the role of catchment land use in lake sediment carbon accumulation and the roleof vegetated littoral zones as important carbon stores, aligning with both Finnish and international research. Together, these changes can guide actions that enhance lake resilience, improve water quality, and support communities' long-term environmental security.

Looking further ahead (5–20 years), BlueLakes provides a foundation for including lake-sediment carbon in national carbon accounting discussions. As consideration of inland waters as human-impacted environments becomes commonplace, Finland may begin to quantify freshwater carbon sinks as part of its broader LULUCF greenhouse gas reporting. Such integration could support climate neutrality efforts by revealing previously uncounted mitigation potential in lakes. Over time, decision-makers may also use WSFS Vemala's scenario tools to compare land-use or climate pathways, helping anticipate how carbon retention might change with forestry practices, catchment modifications, or restoration investments.

The project's influence is also expected to expand beyond its immediate user base. Open datasets, modelling scripts, and transparent workflows lower barriers for adoption by other sectors, such as consulting companies, municipal planners, and environmental service providers, who can embed freshwater carbon insights into design and advisory work. At the same time, national and regional authorities (Syke, LVV (former ELY Centres), ministries) can help accelerate uptake by mainstreaming carbon-aware practices in river-basin planning, restoration programmes, and public reporting through platforms like vesi.fi.

Systemically, BlueLakes has the potential to catalyse broader cultural and structural changes in water governance. By linking carbon sequestration with eutrophication control, biodiversity goals, and climate adaptation, the project's results help bridge traditionally separate policy domains. Over time, this integration can encourage a shift towards ecosystem-based, climate-aware freshwater management, reinforcing sustainable environmental well-being by safeguarding the natural assets that communities depend on. The likely development trajectory—supported by previous research and early stakeholder adoption—is that the outputs of BlueLakes will continue to influence digital tools, policy frameworks, and restoration strategies long after the project ends, contributing to a more resilient, knowledge-driven freshwater governance system nationally and, increasingly, across Europe.

6. EU-Level Impact

BlueLakes has strengthened cross-border research collaboration through joint activities established during implementation, including data sharing and joint field sampling with Horizon Europe projects (Future Lakes, FERRO) and Water4all projects (Festival and Pluralakes).

On the longer term, BlueLakes contributes to implementation of EU policy priorities, including the Green Deal, the Nature Restoration Law objectives and to the Mission "Restore our Ocean and Waters". BlueLakes is a signatory of the charter for this Mission. The project outputs and scientific results provide knowledge that can be scaled to a European level, thus providing solutions for nature restoration activities and climate-wise management practices for inland waters and the Baltic Sea through cooperation with the Baltic Marine Environment Protection Commission (Helsinki Commission - HELCOM).

7. Monitoring and Evaluation Indicators

To date, the project has not implemented an evaluation framework to assess its short- and long-term impacts against sustainable society or (environmental) wellbeing criteria. However, to facilitate such an evaluation, BlueLakes proposes indicators aligned with the Pathway to Impact framework:

Activity indicators

- Structured co-creation with water authorities and environmental agencies
- Participation in scientific conferences and national training events
- Collaboration with multiple research consortia and other outreach activities

Output indicators

- Number of open-access datasets published
- Scientific and non-scientific publications
- Release of enhanced WSFS Vemala carbon modules
- Number of stakeholder engagements

Outcome indicators

- Use of model outputs by authorities (LVV (former ELY Centres), municipalities, consultants)

- Actions to protect macrophyte areas in lake management plans
- Uptake of lake carbon budgeting tools in restoration and permitting processes

Impact indicators

- Evidence of freshwater carbon burial in national climate policy instruments
- Decision-making informed by Vemala carbon scenarios
- Improved monitoring protocols integrating carbon cycling parameters

Conclusion

BlueLakes demonstrates how cutting-edge science, digital transformation, and sustained stakeholder engagement can collectively advance a sustainable society and environmental wellbeing. By revealing the true carbon sink potential of boreal lakes, developing powerful digital tools to quantify it, and ensuring that these tools are integrated into practice, the project strengthens societal resilience, climate preparedness, and data-driven governance. In a rapidly changing climate, the freshwater ecosystems that define Finland's landscape have emerged as vital allies in the pursuit of sustainability. BlueLakes has not only uncovered their hidden potential but has built the scientific, digital, and societal foundations necessary to safeguard and enhance this potential for generations to come.