BlueLakes: digitizing the carbon sink potential of boreal lakes

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The project *BlueLakes: digitizing the carbon sink potential of boreal lakes* was funded by the EU's Recovery and Resilience Facility (RRF) via the Research Council of Finland from 2023 to 2025 to investigate modern carbon accumulation in the sediments of inland waters in Finland. The project combined expertise from research groups at University of Helsinki (UH), Geological Survey of Finland (GTK) and Finnish Environment Institute (Syke). The aim was to improve understanding of the overall magnitude of carbon storage in lake sediments, of spatial heterogeneity in sediment carbon within large lakes, and of the catchment-level drivers of carbon storage.

Inland waters and the carbon cycle

Since the pioneering work of Cole et al. (2007), inland waters have been considered as important lateral conduits in the carbon cycle of the Earth surface system. Inland waters also mediate exchange of carbon vertically between the atmosphere, hydrosphere and lithosphere. As part of this function, sediments accumulating in lakes act as vectors for long term carbon burial on timescales of thousands to millions of years, depending on the climatic and geomorphological setting (Fig. 1a). In the region of the Salpausselkä I and II ice marginal formations in southern Finland, modern freshwater sedimentation was initiated during the isolation of lakes from the proto-Baltic Sea at around 11–10 ky BP (Valpola & Ojala 2006). The accumulating sedimentary material is typically poorly consolidated gyttja facies in which carbon is present as diffuse organic matter (OM).

Data from sub-bottom profiling show variable thickness of the post-isolation gyttja, with accumulation up to tens of meters in the deepest areas of lakes in southern Finland (Fig. 1b). However, detailed surveys of the distribution of organic-rich facies, and understanding of their relationship to bathymetric properties, shoreline ecosystems and catchment area land use are still lacking. Hence, the overall importance of lake sediments as carbon stores remains uncertain. Improving quantification of carbon cycling and accumulation in watershed-scale loading models will assist authorities to plan actions in accordance with legislation such as the EU Restoration Law, Water Framework Direc-

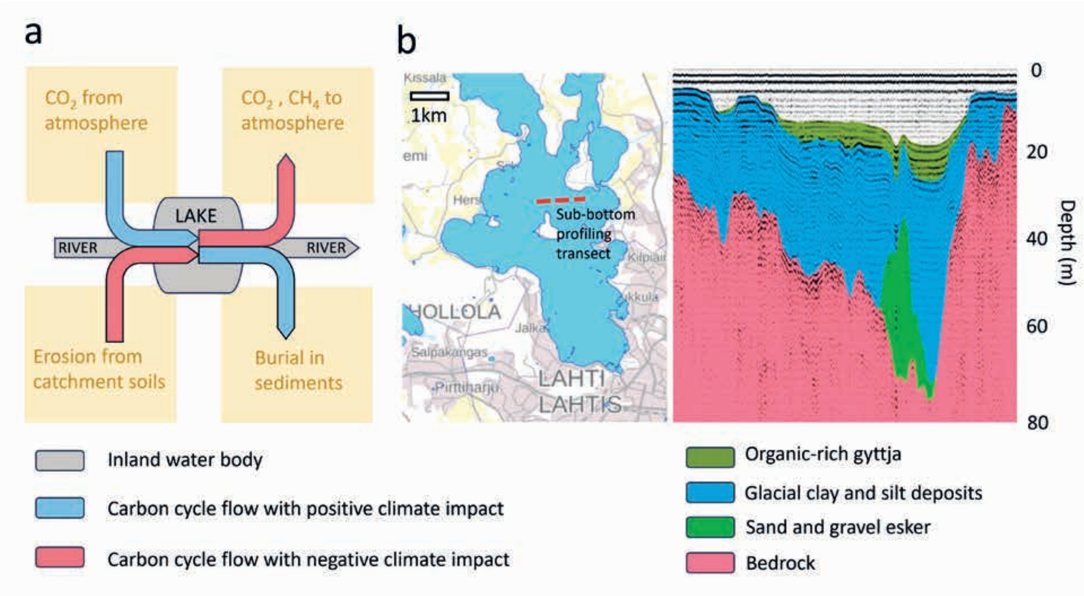

Figure 1. a) Conceptual visualization of the role of inland waters in the carbon cycle, based on Cole et al. (2007) and Regnier et al. (2013). Colors indicate flows leading to net removal of CO_2 from the atmosphere, such as photosynthesis and burial of organic matter (climate positive) or net emission of CO_2 or CH_4 to the atmosphere, such as respiration (climate negative). Note that burial in lake sediments may constitute a long-term carbon sink depending on the geological setting. b) Accumulation of organic-rich gyttja sediments during the lake phase (10.2 ky BP–present) of Lake Vesijärvi, Lahti, Finland identified with 3–9 kHz CHIRP sub-bottom profiling (modified from Hämäläinen 2018). Transect length is approx. 1.5 km.

Kuva 1. a) Sisävesien roolin käsitteellinen visualisointi hiilen kierrossa, perustuen Cole et al. (2007) ja Regnier et al. (2013) -lähteisiin. Värit osoittavat virtauksia, jotka johtavat CO_2:n nettopoistumiseen ilmakehästä, kuten yhteyttäminen ja orgaanisen aineksen hautautuminen (ilmastopositiivinen) tai CO_2:n tai CH_4:n nettopäästöihin ilmakehään, kuten respiraatio (ilmastonegatiivinen). Huomaa, että hautautuminen järvisedimentteihin voi muodostaa pitkäaikaisen hiilinielun geologisesta ympäristöstä riippuen. b) Orgaanispitoisen pohjasedimentin kertyminen Lahden Vesijärven järvivaiheessa (10,2 ky BP – nykyhetki), tulkittu 3–9 kHz:n CHIRP-kaikuluotaimella tehdystä pohjaprofiilista (muokattu Hämäläinen 2018:sta). Poikkileikkauksen pituus on noin 1,5 km.

tive (WFD) and the national Climate Act of Finland.

The *BlueLakes* project included three work packages (WP), whose goals were, respectively:

1. to estimate the importance of vegetated shoreline areas to carbon storage in lake sediments (lead: UH)
2. to determine the land use drivers of modern carbon accumulation rates in a dataset of >200 Finnish lakes (lead: GTK)
3. to implement carbon cycling into the national scale catchment and nutrient loading model WSFS-Vemala (lead: Syke)

Not blue, but teal carbon

Research into coastal vegetated ecosystems, including mangroves, seagrasses and salt marshes, has demonstrated the importance of such areas in sequestering carbon dioxide from the atmosphere and trapping diffuse particulate organic material into fine-grained sediments. Carbon storage in such ecosystems has been dubbed *blue carbon* (Macreadie et al. 2021). Equivalent research into freshwater *teal carbon* systems, located along vegetated lake shorelines, is still in its infancy. However, unpublished results from

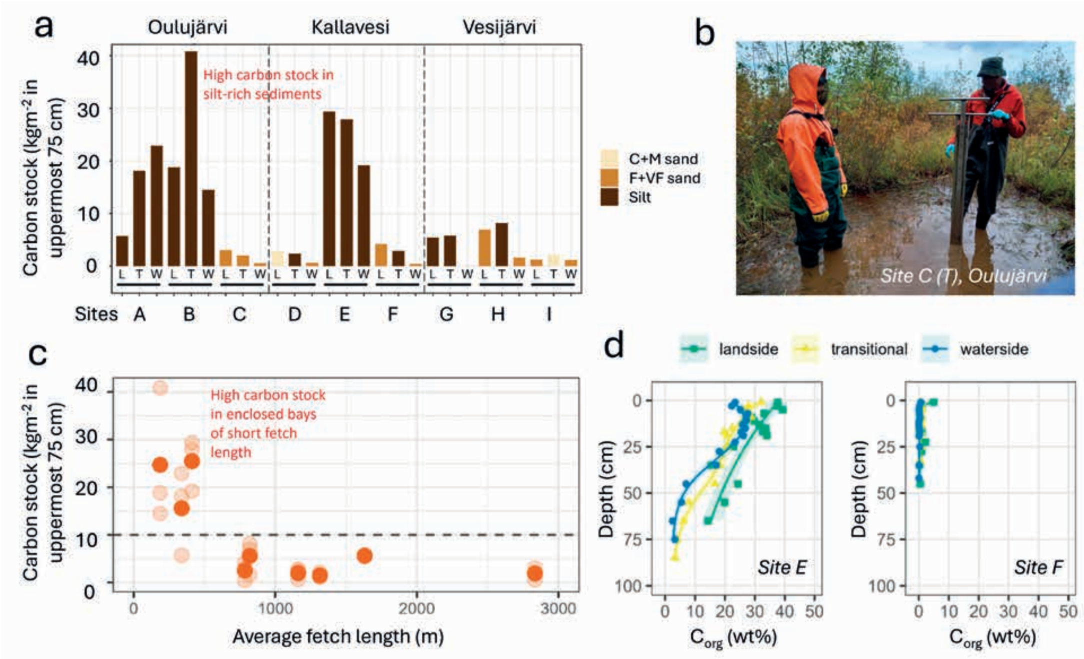

Figure 2. a) Carbon stocks in vegetated shoreline areas of three large lakes. For each lake, three sites were sampled (A–I). At each site, sediment cores were taken from the landside (L), transitional (T) and waterside (W) zones of the vegetated area. Dominant grainsize of the inorganic fraction of each core is indicated by the colors. b) Sampling with a box corer in Oulujärvi. Photo: Ana Lúcia Lindroth Dauner c) Carbon stocks plotted against fetch length of the vegetated shoreline. d) Example profiles of weight % organic carbon (Corg) in the dry matter at two sites. Modified from Lindroth Dauner et al. (2026).

Kuva 2. a) Kolmen suuren järven kasvillisuuden peittämien ranta-alueiden hiilivarastot. Jokaisesta järvestä otettiin näytteet kolmesta kohteesta (A–I). Jokaisella paikalla otettiin sedimenttinäytteitä kasvillisuuden maavyöhykkeeltä (L), siirtymävyöhykkeeltä (T) ja vesivyöhykkeeltä (W). Kunkin näytteenoton epäorgaanisen fraktion vallitseva raekoko on merkitty väreillä. b) Laatikkonäytteenottoa Oulujärvellä. Kuva: Ana Lúcia Lindroth Dauner. c) Hiilivarastot kasvillisuuden peittämän rantaviivan pyyhkäisymatkan funktiona. d) Esimerkkiprofiileja orgaanisen hiilen (Corg) painoprosentista kuiva-aineessa kahdella paikalla. Muokattu julkaisun Lindroth Dauner ym. (2026) pohjalta.

BlueLakes showed that carbon stocks in the uppermost 10 cm of the sediment column in vegetated shoreline areas of lakes in Finland (dominated by rooted macrophytes such as *Phragmites, Carex and Equisetum*) exceed those of open water areas by a factor of 3–5. The main variable controlling the magnitude of the carbon stock in vegetated areas appears to be shoreline exposure. In enclosed bays of <500 m fetch length, quiescent sedimentation of fine-grained materials favors accumulation of OM (Fig. 2a, c, see also Lindroth Dauner et al. 2026). In contrast, open shorelines with longer fetch are characterized by sandy, organic-poor sediments regardless of the density of vegetation. Interestingly, the organic-rich sediment layer below the sampled vegetation stands is typically <1 m in thickness, likely indicating a zone of temporary storage rather than permanent accumulation in these systems (Fig. 2d). Ongoing work aims to generate whole lake estimates of shoreline carbon stock using remote sensing data of vegetated areas.

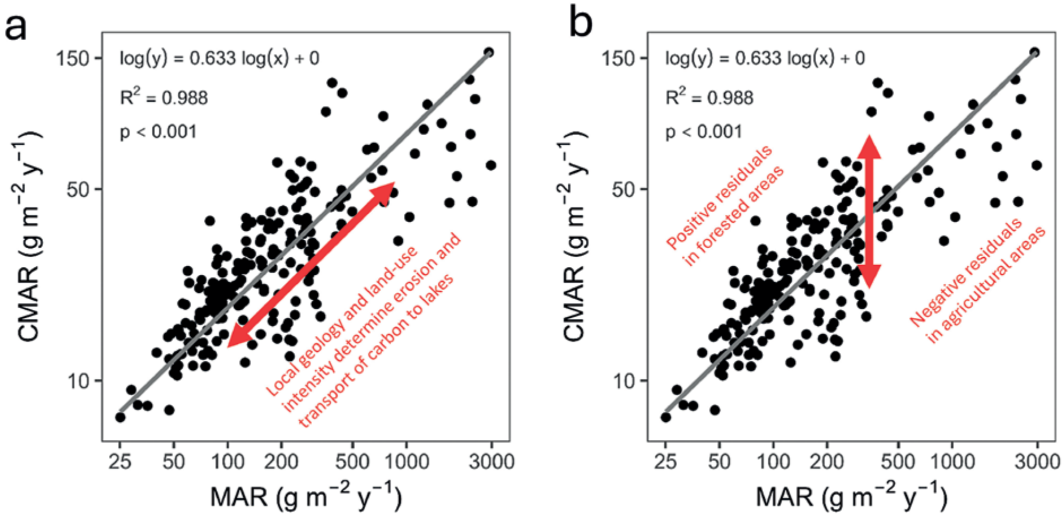

Figure 3. a) Carbon mass accumulation rate (CMAR) plotted against bulk mass accumulation rate (MAR) for 208 lakes in Finland, from the GTK database. The magnitude of carbon burial is primarily determined by accumulation of bulk sediment. b) The same visualization highlighting clusters of lakes with positive or negative residuals from the CMAR vs. MAR regression. Modified from Junna et al. (2025).

Kuva 3. a) Hiilen massakertymisnopeus (CMAR) esitettynä kokonaismassan kertymisnopeuden (MAR) funktiona 208 Suomen järvelle GTK:n tietokannasta. Hiilen hautautumisen suuruus määräytyy ensisijaisesti sedimentin kokonaiskertymisen perusteella. b) Sama visualisointi, joka korostaa CMAR vs. MAR-regressiosta saatuja positiivisen tai negatiivisen residuaalin omaavia järviryhmiä. Muokattu julkaisun Junna ym. (2025) aineiston pohjalta.

Connection between land use and carbon storage

Previous estimates of carbon mass accumulation rates (CMAR) for Finnish lakes from the work of Kortelainen et al. (2004) suggest values in the range 1.0–5.7 g $m^{-2} y^{-1}$ for the entire Holocene deposition. *BlueLakes* used a new database of sediment carbon content and mass accumulation rates derived from ^{137}Cs dating for 208 lakes in Finland, to estimate modern values of 7.4–157.5 g $m^{-2} y^{-1}$, with a median value of 24.5 g $m^{-2} y^{-1}$ indicating a roughly 5-fold increase in the modern era (Junna et al. 2025). This increase is caused by enhanced rates of erosion of catchment soils due to intensified land use (Mäkinen et al. 2012). The overall mass accumulation rate (MAR) is thus the key predictor of CMAR in any given lake, with highest rates in regions of extreme erosion such as agricultural areas in clay-rich soils in southern Finland (Fig. 3). However, the type of land use has an influence on the efficiency of carbon burial. Lakes in agricultural areas typically show negative residuals from the CMAR vs. MAR regression indicating relatively low rates of carbon burial. This may be explained by the presence of easily degradable organic matter, derived both from crop and grassland areas, and from autochthonous organic matter production in eutrophied inland waters. Meanwhile, relatively refractory organic matter from forested catchments is buried more efficiently, causing positive residuals from the CMAR vs. MAR regression. It should be noted that, overall, a significant fraction of eroded carbon is expected to be lost to the atmosphere through respiration during transport to lakes (Fig. 1a). Ongoing work aims to generate whole lake estimates of open water carbon stock using seismic data of gyttja sediment thickness.

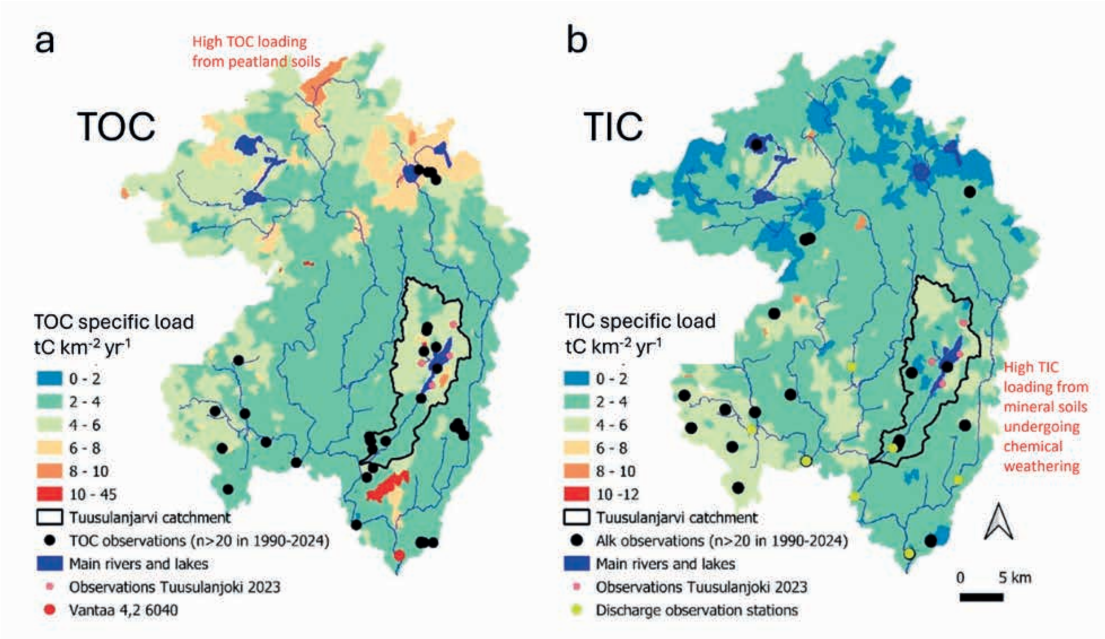

Figure 4. Loading of a) total organic carbon (TOC) and b) total inorganic carbon (TIC) from the catchment of Vantaanjoki, including the sub-catchment of Lake Tuusulanjärvi, in southern Finland. Values are estimated from soil type, land use and climate data using the WSFS-Vemala carbon model. Modified from Korppoo et al. (2026).

Kuva 4. a) Orgaanisen hiilen kokonaismäärän (TOC) ja b) epäorgaanisen hiilen kokonaismäärän (TIC) kuormitus Etelä-Suomen Vantaanjoen valuma-alueelta, mukaan lukien Tuusulanjärven osa-alue. Arvot on arvioitu maaperätyyppi-, maankäyttö- ja ilmastotiedoista käyttämällä WSFS-Vemala-hiilimallia. Muokattu julkaisun Korppoo ym. (2026) aineiston pohjalta.

Can we model it?

The national scale nutrient loading model WSFS-Vemala (Huttunen et al. 2016) has been used by water managers throughout Finland to simulate surface-water loading of nutrients (nitrogen and phosphorus) to lakes, to aid target setting for water quality within the WFD. Until recently, carbon cycling had not been included in Vemala. *BlueLakes* aimed to improve the simulation of carbon loading through implementing a description of both total inorganic carbon (TIC) and total organic carbon (TOC) loading on the sub-catchment scale (Fig. 4, see also Korppoo et al. 2026), and by revisiting the biogeochemical module for in-lake carbon cycling. This included adding shoreline vegetation as a separate sub-module and improving parameterization of OM degradation rates using field data from the other work packages. The updated version of the model is expected to be available to users in the near future.

Connecting to the end-users

The research performed in *BlueLakes* aimed to improve basic understanding of processes in the carbon cycle, but a key strength of the project implementation was the involvement of stakeholders from the outset. Obligations within the EU Restoration Law, Water Framework Directive (WFD) and the national Climate Act of Finland necessitate quantification of human impacts on the aquatic carbon cycle alongside those on water quality (Tammeorg et al. 2024). Therefore, representatives of water protection associations, economic development centers (formerly ELY-centers), local foundations and government ministries took part in an advisory board that guided the project towards management-relevant outputs such as the new version of the Vemala model.

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The WP leads of BlueLakes were Tom Jilbert, Karoliina Koho and Marko Järvinen, respectively. Consortium principal investigator was Karoliina Koho. In addition to the authors listed above, other project partners contributed to the three articles summarized in this piece. Their details can be found in the bibliography.

Tiivistelmä

BlueLakes: boreaalisten järvien hiilinielupotentiaalin digitalisointi

BlueLakes: boreaalisten järvien hiilinielupotentiaalin digitalisointi -hanketta rahoitti EU:n elpymis- ja palautumistukiväline (RRF) Suomen Akatemian kautta vuosina 2023–2025. Hankkeessa tutkittiin hiilen nykyistä kertymistä Suomen sisävesien sedimentteihin yhdistämällä Helsingin yliopiston (UH), Geologian tutkimuskeskuksen (GTK) ja Suomen ympäristökeskuksen (Syke) tutkimusryhmien asiantuntemusta. Tavoitteena oli parantaa ymmärrystä järvien sedimenttiin varastoituneen hiilen kokonaismäärästä, suurten järvien sedimentoituneen hiilen alueellisesta heterogeenisyydestä ja valuma-aluetasolla hiilen varastoitumiseen liittyvistä taustatekijöistä. Hankkeen tulokset osoittavat, että kasvillisuuden peittämät ranta-alueet ovat tärkeitä sedimenttien hiilen varastointialueita, vaikka pitkäaikainen hautautuminen tapahtuu syvemmillä alueilla. Ihmisen toiminta valuma-alueilla on lisännyt hiilen kertymisnopeutta järvisedimenttiin maaperän eroosion kautta, vaikka suuren osan mobilisoituneesta hiilestä uskotaan päätyvän ilmakehään kulkeutumisen aikana. Hankkeessa kehitetty uusi versio WSFS-Vemala-mallista kykenee simuloimaan hiilen kiertokulkua valuma-alueen mittakaavassa.

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Juhlaseminaari- ja illallinen 23.10.2026

Suomen Geologinen Seura juhlistaa 140. toimintavuottaan juhlaseminaarilla ja -illallisella perjantaina 23. lokakuuta 2026.

Juhlaseminaari järjestetään noin kello 12–16 Tieteiden talolla Helsingissä. Seminaarin teemana on veden merkitys ja sen moninaiset näkökulmat. Puhujina esiintyvät erikoistutkija Lotta Purkamo (Geologian tutkimuskeskus), kirjailija Jenni Räinä, ympäristögeologian professori Peter Österholm (Åbo Akademi), logistiikan professori Katri Kauppi (Aalto-yliopisto) ja hydrogeologian tutkimusprofessori Kirsti Korkka-Niemi (GTK; Helsingin yliopisto).

Seminaariin ei tarvitse ilmoittautua, mutta tilaan mahtuu noin 115 osanottajaa. Seminaaria voi seurata myös etäyhteydellä; linkki julkaistaan seuran verkkosivuilla ennen tapahtumaa.

Juhlaillallinen pidetään ravintola Kaartissa, Helsingissä, kello 18 alkaen. Ilmoittautumisen ja illallisen maksun määräaika on maanantai 28.9.2026.

Lisätietoja juhlapäivästä ja ilmoittautumisesta päivitetään seuran verkkosivuille: https://www.geologinenseura.fi/fi/ajankohtaista/juhlaseminaari-ja-illallinen-23102026