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Author(s):
Hagedorn, Frank; Rhyner, Timo; Storck, Florian; Brunmayr, Alexander Sohrab; Flury, Roman; Minich, Luisa; Zobrist, Jürg; Eglinton, Timothy Ian

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Rising dissolved inorganic carbon in Alpine rivers evidence enhanced soil respiration driven by climatic warming over the past decades

Frank Hagedorn[1], Timo Rhyner[2], Florian Storck[3], Alexander Brunmayr[4], Roman Flury[1], Luisa Minich[1], Jürg Zobrist[5], and Timothy Eglinton[2]

[1]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland (frank.hagedorn@wsl.ch)
[2]Geological Institute, ETH Zürich, 8092 Zürich, Switzerland
[3]Hydrology Division, Federal Office for the Environment, 3003 Bern, Switzerland
[4]Department of Physics, Imperial College London, SW7 2AZ London, UK
[5]Emeritus Scientist, Swiss Federal Institute of Aquatic Science and Technology, 8600 Dübendorf, Switzerland

Anthropogenically-induced climate change is rapidly altering Earth's carbon cycles. However, information on long-term and large-scale responses of soil respiration—a key process releasing CO_2—remains limited. Soil CO_2 production, driven by rhizosphere and microbial respiratory activity, is inherently temperature sensitive. Yet, thermal adaptation, substrate depletion and other constraints such as drought may dampen responses to climate warming. Assessing soil respiration at broader temporal and spatial scales is hampered by its high variability and the labor-intensive nature of CO_2 flux measurements. Consequently, evidence for longer-term enhancement of soil respiration in response to ongoing climatic warming remains scarce.

Here, we analyze 50-year long records of dissolved inorganic carbon (DIC) from Swiss rivers draining Alpine catchments to infer long-term and large-scale responses of soil CO_2 production. Riverine DIC flux originates from CO_2 dissolved in water, with approximately half derived from belowground respiratory activity and the remainder released through weathering processes. Our radiocarbon and stable isotope analyses confirm these sources in Swiss rivers.

Long-term records from the Swiss national river surveillance program reveal that average DIC concentrations in rivers draining the Swiss Alps (Rhine, Inn, Ticino) have increased by 1.6% per decade since the 1980s. This decadal-scale rise in DIC concentrations correlated significantly with the increase in water temperatures by approximately 1.3°C in this period. The DIC increase is not linked to multi-annual variations in river discharge, which drive interannual variability. Analyzing the relationship between discharge and DIC concentrations shows that, for a given discharge, DIC concentrations in the Rhine, Inn, and Ticino have increased in recent decades compared to levels observed in the 1980s and 1990s.

Export of DIC by Swiss rivers only accounts for approximately 2% of the CO_2 released from Swiss ecosystems. Nevertheless, the decadal-scale increase in DIC indicates that CO_2 production in the

soil must have increased. The DIC increase occurred despite a decreasing CO_2 solubility with rising water temperatures. Linking the observed DIC increase to the warming of 0.35°C per decade yields a temperature dependency (Q_{10}) of 2.2. This aligns with values from annual monitoring efforts and short-term soil warming studies across Swiss ecosystems, ranging between 2.3 and 5.3. Our finding indicates a sustained, large-scale stimulation of soil respiration in Alpine environments driven by climate warming, with little thermal adaptation over decadal timescales.