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Assessing the impact of time-varying factors on soil respiration: normalizing long-term data for temperature and moisture using machine learning

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Abstract

Soil respiration exhibits high spatial and temporal variability. This process is strongly dependent on soil temperature and moisture, making direct comparisons of data obtained either at different times or from remote sampling sites particularly challenging. Increasing the number of spatial replications and minimizing time gaps between measurements within the study area can only partially mitigate this issue. However, when analyzing long-term data—especially when assessing the impact of dynamic factors (e.g., ecosystem recovery following reduced industrial pollution)—inter annual variations in conditions can lead to erroneous conclusions. Valid cross-year comparisons require recalculation of measured values to standardized temperature and moisture.

This study is based on long-term measurements of CO_2 emissions in forests near two copper smelters (Middle and South Urals, Russia), where emissions sharply declined after 2010. Over 6,000 soil respiration measurements were conducted on 60 sample plots along pollution gradients in 2010–2013, 2018, 2023, and 2024. To account for environmental variability, soil respiration was modeled as a function of temperature and moisture using nine classical regression models and Random Forest (RF).The log Response Ratio quantified the effect size.

The best-performing classical regression model (R^2=0.45, *MSE*=3.32) and RF (R^2=0.95, *MSE*=0.55) showed different accuracy in modeling soil respiration. Standard conditions were set at 15°C soil temperature and 0.4 m^3/m^3 soil moisture. Raw (i.e., non-normalized) data suggested a recovery trend in soil respiration from 2010 to 2024, with some years showing no difference between polluted and background sites. However, normalized data (using both approaches) revealed persistent pollution-induced suppression of soil respiration, with no recovery following emission reductions. Thus, normalization effectively eliminated the confounding effects from asynchronous environmental fluctuations, enabling accurate assessment of long-term soil respiration trends and preventing data misinterpretation.

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Categories

Forests

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Keywords

soil respiration, machine learning, industrial pollution, forests