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Causal inference of the CO_2 fertilisation effect from ecosystem flux measurements

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Land ecosystems play an important role in the carbon cycle, and hence the climate system. The engine of this cycle is Gross Primary Production (GPP), the assimilation of CO_2 via photosynthesis at the ecosystem scale. Photosynthesis is directly affected by rising CO_2 levels which, in turn, is expected to increase GPP and alter the dynamics of the carbon cycle. However, there is substantial uncertainty about the magnitude and geographical variability of the CO_2 fertilisation effect (CFE) on GPP.

We use a large collection of eddy covariance measurements (317 sites, 2226 site-years), paired with remotely sensed information of vegetation greenness to estimate the effect of rising CO_2 levels on GPP. We propose a hybrid modelling architecture, combining a physically-grounded process model based on eco-evolutionary optimality theory and a deep learning model. The intuition is that the process model represents the current understanding of the CFE, whereas the deep learning model does not implement explicit physical relations but has a higher capacity to learn effects of large and fast variations in the light, temperature, and moisture environment. The hybrid model is set up to learn a correction on the theoretically expected CFE. This makes it more effective in distilling the relatively small and gradual CFE.

Our study investigates inherent limitations of different models when it comes to drawing conclusions about the CO_2 fertilisation effect. Often, these limitations are due to the presence of latent confounders that give rise to spurious correlations. A promising avenue to address them is therefore the use of causal inference techniques. We show that one way to investigate causality is to test whether the trained hybrid model and its estimate of the CFE is stable across different ecosystems, as expected for a causal physical relation.

In summary, we study how causal inference, based on a combination of physics-informed and statistical modelling, can contribute to more reliable estimates of the CO_2 fertilisation effect, derived from ecosystem flux measurements.