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Improving the scaling up of canopy photosynthesis by accounting for leaf physiological gradients based on a Bayesian approach

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Forests play a major role as global carbon sinks, and in order to understand global carbon cycles, it is necessary to determine climate change effects on the sink strength of forests. While ecophysiological processes at the molecular and leaf level are well understood, it remains controversial how they can be integrated over space and time to net ecosystem exchange of CO_2 (NEE). In particular, vertical gradients of leaf physiological traits in forest canopies represent a challenge for scaling up to the canopy. We tested whether accounting for independent gradients of maximum carboxylase rate (Vcmax) and photosynthetic electron transport (Jmax) improves NEE estimates by comparing three scaling schemes: (1) constant Vcmax and Jmax, (2) increasing Vcmax and Jmax from bottom to the top, and (3) increasing Vcmax and decreasing Jmax from the bottom to the top of the canopy.
In the growing seasons 2017 and 2018, we measured photosynthetic capacity (Amax), chlorophyll (Chl) and nitrogen (N) concentrations of foliage at four canopy heights of Fagus sylvatica, Fraxinus excelsior, Abies alba and Picea abies growing in a mixed forest in Switzerland. In addition, we characterised the vertical light gradient using hemispherical images. We used the light gradient, N and Chl concentrations to parametrise a process-based soil-plant-atmosphere (SPA) model that provides NEE at a high temporal resolution. We calibrated the model with the three scaling schemes to half-hourly data of NEE derived from eddy covariance (EC) measurements for three years (2013–2015) using a Markov chain Monte Carlo procedure and validated the models with two subsequent years of NEE data from EC measurements (2016–2017).

Higher light availability at a specific height in the canopy was correlated with higher leaf N ($p < 0.05$), but lower Chl concentration ($p < 0.01$), which corresponds well to increasing Vcmax and decreasing Jmax in the canopy (scheme 3). During the two validation years, the goodness-of-fit, indicated by normalised root mean squared error and the index of agreement was indeed best for scheme (3), while scheme (2) was superior to scheme (1). All three models underestimated NEE during overcast days and overestimated it during hot sunny days, but the percent bias was lowest for scaling scheme (3). We conclude that identifying and incorporating independent gradients of Vcmax and Jmax in scaling models clearly improves performance. In late April 2017, however, a late frost event during leaf unfolding delayed leaf maturation, resulting in reduced NEE during spring 2017. None of the schemes of the SPA model captured this event appropriately and overestimated NEE by up to 21%. This underlines the necessity to account for seasonal variation in leaf physiological traits.