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Modelling nitrate concentration in a forest stream affected by bark beetle using hypothesis-driven Bayesian hierarchical modelling

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Vegetation and soil microorganism communities are important regulators of nutrient exports from forested catchments. Hence ecosystem disturbance can impact nutrient cycles. This study explores the response and resilience of the nitrogen cycle of a catchment located in the Bavarian Forest National Park, Germany, in the face of a severe bark beetle disturbance. The case is emblematic for the types of ecosystem disturbance we might increasingly expect as a result of climate change. Our study catchment had been dominated by Norway spruce, which is the major host tree of *Ips typographus*, a native bark beetle which exhibited two outbreaks in the past three decades killing up to 85 % of the trees. The concentration of nitrate (NO_3) measured during one outbreak increased twofold and the normal seasonal pattern was disturbed.

In order to model the NO_3 concentration in the river during the disturbance, we used generalised linear regression modelling with a log link function and, informed by the regression, a lumped catchment model, both with discharge and water temperature as predictor variables. This follows a "top-down" mode of model development in response to limited process understanding and data of nutrient cycle responses to disturbance. The models were fit to the data set in a Bayesian hierarchical modelling framework, in which the model parameters were inferred separately for each year, but modelled as realisations from the same (unknown) population distribution. While the Bayesian framework is the state-of-the-art approach to uncertainty quantification in hydrology, the hierarchical setup is rather novel, especially in a hydrogeochemical context. Our hierarchical models achieved high accuracy by allowing the parameters to vary across years, yet avoided overfitting by constraining the variability of the parameters through the common distribution.

The temporal evolution of the parameter estimates conveys important process information. Here it suggested changes in release and retention of NO_3 as a result of the disturbance. Specifically, the NO_3 concentration increased during the disturbance, likely due to nitrogen release from the decaying dead trees. In addition, we found evidence of the ecosystem function of the soil microorganisms retaining the NO_3 being enhanced when the availability of NO_3 increased. However, when the released NO_3 exceeded the retention capacity of the catchment, excess NO_3 reached the stream without being regulated. Under this condition, the variability of NO_3 was governed by discharge but hardly by temperature. Upon re-growth of the vegetation after the disturbance, excess nitrogen in the catchment was quickly consumed, thus decreasing the NO_3 concentration in the stream again.

The results of this study revealed that the nutrient regulation of the catchment played an important role in limiting excess NO_3 concentration in the stream during the insect infestation. The resilience of the vegetation community to the disturbance resulted in swift recovery of the ecosystem function retaining nutrients. Our study demonstrates the value of hierarchical Bayesian modelling for the efficient generation and comparison of hypotheses, which we could show can inform process-based model representations of nutrient cycling at the catchment scale.