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Lakes amplify nitrogen and phosphorus imbalances in inflows

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Lakes are a global sink for nutrients and thus supply an important ecosystem service in the form of nutrient retention. However, it is unclear how the relative availability of nitrogen (N) and phosphorus (P) affects nutrient retention. To address this, we performed experiments with the lake model PCLakePlus on 9 lake archetypes that represent lakes of different mixing regimes (mono-, di-, and polymictic) in different climates. We forced the model with stochastically generated inflows and N and P loads to examine how the N:P ratio in inflow affects the N:P ratio in the lake outflow. In these model experiments, lakes tended to amplify imbalances between N and P in the inflow. At intermediate inflow N:P (~30), the outflow N:P was similar. However, at low inflow N:P, the outflow N:P was equal or lower, and at high inflow N:P, the outflow N:P was equal or higher. This amplification effect was most sensitive to high N input loads. This suggests that lakes either maintain or amplify N:P imbalances rather than buffering or compensating them. We explain these differences in nutrient retention with the lake phytoplankton and sedimentation dynamics. When input N:P is imbalanced, the phytoplankton biomass is generally limited by the nutrient in shortest supply, which limits the phytoplankton's capacity to uptake the non-limiting nutrient. Consequently the nutrient in shortest supply is retained most efficiently, amplifying any stoichiometric imbalances. Since phytoplankton have a higher capacity to uptake and store excess P than excess N, high N:P ratios were amplified more than low N:P ratios. We further analysed a global dataset from the Global River Water Quality Archive and BasinATLAS, using boosted regression trees to identify the effect of different drivers and catchment characteristics on the molar TN:TP ratio in river and stream water. This showed that drivers and catchment characteristics associated with human impact increased N:P ratios, with a stronger effect at high N:P. The lake model subsequently showed that lakes further amplified this anthropogenic increase in N:P ratios, so that human induced stoichiometric imbalances from N pollution resonate through the landscape. These results shed light on the mechanisms behind the widespread phenomenon that lakes retain P preferentially over N. The successful management of P inputs into waterways has probably decreased N retention efficiency. Our research suggests that managers should reduce N inputs, for instance by employing nature-based solutions, to maintain a stoichiometric balance and protect sensitive downstream ecosystems and coastal zones.