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INVITED COMMENTARY

The impact of anthropogenic nitrogen deposition on global forests: Negative impacts far exceed the carbon benefits

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Humans have drastically altered the nitrogen (N) cycle during the past century, enriching ecosystems from the tropics to the tundra with inputs of novel nitrogen (Galloway et al., 2008). These inputs can be direct and intentional, mainly in agricultural or forestry settings where various N-containing fertilizers are actively applied to enhance production. However, fertilizers, fossil fuel combustion, and manures associated with livestock management also have caused emissions of reactive N (NO_y and NH_x) to skyrocket during the past century, resulting in a redistribution of N into terrestrial environments near and far from emissions hotspots. Negative impacts of atmospheric N emissions and deposition have been known for a long time, including N_2O serving as a potent greenhouse gas (i.e. ca. 300 times more potent than CO_2 per molecule), as well as reactive N deposition contributing to terrestrial acidification, eutrophication, and biodiversity loss (Bobbink et al., 2010; Bowman et al., 2008).

Despite these well-known negative effects, there has been much debate among researchers regarding a potential "silver lining" of atmospheric N deposition, in that it might alleviate N limitation in ecosystems, and thereby promote global terrestrial C uptake which mitigates a significant share of global CO_2 emissions. But in which environments is C uptake stimulated the most? And does this C sequestration impact outweigh the negative effects of reactive N emissions and deposition? The study by Schulte-Uebbing et al. (2021) provides answers to these questions, as well as many additional insights into the global impact of atmospheric N deposition on Earth's forested landscapes.

The degree to which atmospheric N deposition stimulates terrestrial productivity and C sequestration has been hotly debated (Nadelhoffer et al., 1999; de Vries et al., 2008). Numerous approaches have been used to arrive at a C–N response (unit of C uptake per unit of N deposition), including dynamic global vegetation modelling, stoichiometric scaling, observational studies along deposition gradients, and meta-analysis of forest fertilization experiments. These contrasting approaches have led to highly variable estimates of forest C–N responses; however, as an increasing number of empirical studies have been published (e.g. Gundale et al., 2014; Figure 1), estimates have become narrower, with nitrogen deposition recently proposed to explain somewhere between 130 and 345 Tg C $year^{-1}$ in forest biomass globally (Du & de Vries, 2018). However, as Schulte-Uebbing et al. point out, these estimates have lacked explicit consideration of site factors that can vary substantially from one forest to another, even within a particular biome, which can greatly impact forest C–N responses.

To reduce uncertainty in these estimates, Schulte-Uebbing et al. used a multi-step approach that explicitly evaluates the importance of site factors that vary across published empirical studies. First, they applied a meta-regression approach to select a model that best explained how C–N responses across different forest fertilization experiments are sensitive to variation in site factors, including biome, latitude, tree species and stand characteristics (e.g. age, mycorrhizal type), nutrient and water availability, and N saturation. This analysis showed that the forest C–N increased with absolute latitude (i.e. boreal forests had higher C–N responses than tropical forests) and soil N content, and decreased with temperature, potential evapotranspiration (PET), forest age, and N addition rate. A model consisting of a combination of soil N content, PET, and tree age provided the best predictive power of the C–N response across published N fertilization studies, explaining an impressive 68% of the C–N response variation among those studies.

After honing in on this regression model, Schulte-Uebbing et al. estimated the global carbon impact of atmospheric N deposition in the world's forests by applying their model to a global grid (0.5° × 0.5°) of relevant site factors. Their modelling revealed average C–N responses for tropical, temperate, and boreal forests of 0, 4, and 11 kg C kg^{-1} N, respectively, with a global forest average of 2 kg C kg^{-1} N. Once modelled C–N responses were projected onto global grid space, the authors then used established models of atmospheric N deposition rates to quantify the annual C uptake rate attributed to atmospheric N deposition. From this, they arrived at a global estimate of forest C uptake of 41 Tg C $year^{-1}$ as a result of N

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FIGURE 1 On the left-hand side, nitrogen fertilizers are applied to an experimental *Abies balsamea* forest in the Laflamme Watershed, Quebec, Canada (photo provided by Daniel Houle, Ministry of Forest, Parks, and Wildlife, Quebec, and Ministry of Environment and Climate Change Canada). On the right-hand side, Dr. Benjamin Forskmark applies nitrogen fertilizers to an experimental *Picea abies* forest near Vindeln, Sweden (photo by Viktor Boström). Experimental studies such as these provide a tool to estimate carbon to nitrogen (C–N) response rates at specific sites, which were the focus of across site meta-analysis and modelling in Schulte-Uebbing et al. (2021)

deposition, with hotspots of uptake occurring mainly in mid-latitude forests of Central Europe, Southern China, Southern Korea, Japan, New Zealand, and Northeastern North America. High C uptake as a result of N deposition occurred in these areas because they all receive moderate to high N deposition rates, as well as exhibited above average uptake responses per unit N deposition (i.e. the C–N response). Nitrogen deposition caused relatively little C uptake in tropical and boreal forests, but for different reasons. In the tropics, this occurred because of very low C–N response rates, whereas for boreal forest this occurred because N deposition rates are too low to illicit substantial C uptake.

While it is well accepted that forests globally serve as a major terrestrial CO_2 sink, it has been hotly debated what portion of this sink strength is influenced by atmospheric N deposition (Sutton et al., 2008; de Vries et al., 2008). It is notable that the estimate by Schulte-Uebbing et al. of 41 Tg C $year^{-1}$ sequestration in forest biomass as a result of N deposition is much lower compared to some rates previously discussed and debated (e.g. 460 Tg C $year^{-1}$ N; Fleischer et al., 2015), including previous estimates from some of the same authors (e.g. 144 Tg C $year^{-1}$; Du & De Vries, 2018). The current study by Schulte-Uebbing stands out by providing an estimate that is both robust and more conservative than previous estimates. Their analysis suggests N-induced C sequestration only accounts for 2% of the total net forest C sink (i.e. 41 of 1900 Tg C $year^{-1}$), which suggests that other global change drivers of forest C sink strength are likely to be relatively more important, such as CO_2 fertilization, increasing temperatures, longer growing seasons in northern latitudes, forest regrowth, or specific forest management activities.

So, how does the stimulation of forest C uptake of 41 Tg $year^{-1}$ contribute towards climate mitigation relative to the climate warming impacts of N_2O emissions? Schulte-Uebbing et al. suggest an answer to this question as well. Their analysis shows that in most regions, the warming effects of N_2O emissions strongly outweighs the cooling effects of forest C uptake, including in regions where C uptake was highest (the specific mid-latitude areas mentioned above) or where the C–N responses are the highest (in boreal forests). One notable exception was a large area in northern Russia, where relatively low N_2O emissions occur, and where the cooling effect of C uptake appears to balance out the warming effect of N_2O emissions. However, their analysis showed that globally only 5% of the warming effect of N_2O emissions was offset by forest C uptake due to anthropogenic N deposition, while these shares were only 1%, 5%, and 23% in tropical, temperate, and boreal forests, respectively. This indicates that there really is no significant silver lining when considering the impacts of atmospheric N emissions and deposition on greenhouse gas balances across forests globally.

While the modelling approach taken by Schulte-Uebbing et al. sheds new light on the climate impacts of atmospheric N emissions and deposition in forests globally, there are clearly some uncertainties that remain to be addressed with future research. As the authors themselves note, their estimates are sensitive to definitions of forest area, inputs from atmospheric N deposition models, and background rates of N deposition that may influence measured C–N responses. Furthermore, their analysis does not include changes in soil C stocks, which have been shown in some cases to be of a similar magnitude to N-induced changes in aboveground biomass C stocks (Forsmark et al., 2020; Maaroufi et al., 2019). Another important dimension that needs to be addressed is the lifespan of C stocks that are enhanced by anthropogenic N inputs. Finally, similar analyses are needed for non-forested terrestrial environments. The research community will surely address these additional uncertainties in the near future.

CONFLICT OF INTEREST

The author declares no conflicts of interest.

DATA AVAILABILITY STATEMENT

The manuscript is a commentary and does not include any data.

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