Does nitrogen-induced forest carbon sequestration offset agricultural N_2O emissions? – A meta-analysis of nitrogen addition effects on carbon sequestration in tree woody biomass

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Abstract
Agricultural nitrogen (N) use accounts for 66% of global nitrous oxide (N_2O) emissions and is thus an important driver of climate change (UNEP 2013). However, elevated N deposition may also increase net primary productivity in N-limited terrestrial ecosystems and thus enhance the terrestrial carbon sink. This indirect effect can lead to a considerable reduction of the net climatic impact of agricultural N use.

We performed a meta-analysis on data from 63 forest fertilization experiments to estimate N-induced carbon (C) sequestration in above-ground tree woody biomass (AGWB), a relatively stable C pool with long turnover times. Results show that boreal and temperate forests respond strongly to N deposition and store on average an additional 23 and 12 kg C per kg N in AGWB, respectively. Sub-tropical and tropical forests show much weaker response to N addition (6 and 2 kg C per kg N, respectively).

We estimated global C storage in tree AGWB resulting from agricultural N use by multiplying the C–N responses obtained from the meta-analysis with ammonia (NH_3) deposition estimates per forest biome. We thus derive a global C sink of about 84 (47–120) Tg C yr^{-1} in AGWB, which compensates on average 16 (9–23) % of N_2O emissions from agriculture (6.4 Tg N_2O yr^{-1} or 520 Tg CO_2-C_{eq} yr^{-1}). Adding estimates for N-induced C sequestration in soils and below-ground woody biomass obtained by stoichiometric scaling, we estimate total forest C sequestration resulting from agricultural N use at 236 (147–341) Tg C yr^{-1}, or 40 (28–54) % of agricultural N_2O emissions.

Key Words
Forest carbon sequestration, nitrogen deposition, woody biomass, meta-analysis, climate impact of agricultural N use

Introduction

Nitrogen (N) use in agriculture benefits crop production, but also leads to nitrous oxide (N_2O) emissions, which contribute to climate change (Reay et al. 2012). N_2O is emitted directly from agricultural soils, as well as indirectly from water bodies and terrestrial systems due to elevated N deposition and N runoff to water. However, elevated N deposition may also increase net primary productivity (NPP) in N-limited terrestrial ecosystems and thus carbon dioxide (CO_2) uptake from the atmosphere (De Vries et al. 2014). This indirect effect can lead to a considerable reduction of the overall climate impact of N use in agriculture.

The magnitude of the stimulation of the global terrestrial C sink by N deposition has previously been estimated by stoichiometric scaling (e.g. Peterson and Melillo 1985; De Vries et al. 2014), dynamic global vegetation models (e.g. Townsend et al. 1996; Fleischer et al. 2015), and based on empirical relationships between N deposition and forest growth observed in forest inventories (e.g. Thomas et al. 2010). The stimulating effect of N deposition on forest C sequestration can be derived by multiplying total anthropogenic N deposition on forests with the C–N response ratio (defined as the additional mass unit of C sequestered per additional mass unit of N deposition) of each forest ecosystem compartment. The most important compartments are those with both a large C storage potential and long turnover time: the woody biomass (or tree) C pool and the soil C pool.

Fertilization experiments provide a direct observation of the effect of N on forest productivity and are therefore suitable to derive C–N responses. Previous meta-analyses that summarized results from forest fertilization experiments have found that N addition generally increases forest productivity (Janssens et al. 2010; LeBauer and Treseder 2008; Liu and Greaver 2009). However, previous meta-analyses only reported relative changes in productivity in response to N addition (% increase in NPP following N addition instead of kg C per kg N). Other limitations to use results from previous meta-analyses to estimate the global N-induced C sink are that they include C pools with both long and short turnover times (e.g. litter and fine roots), and/or are based on studies from only one country. Our aim was to use results from forest fertilization experiments to derive a quantitative estimate of the N-induced C sink in above-ground tree woody biomass. We did this by performing a meta-analysis of forest fertilization experiments conducted in boreal, temperate, and (sub-)tropical forests. In addition, we derived an estimate of the net climatic impact of N use in agricultural by comparing the size of the N-induced forest C sink to agricultural N_2O emissions.

Methods

Meta-analysis

As forests currently account for about 90% of the terrestrial C sink (Pan et al. 2011), the size of the N-induced C sink is largely determined by forests' response to N deposition, in interaction with other environmental drivers, such as CO_2 concentration, temperature, and availability of water and other nutrients (e.g. phosphorus). In order to assess additional C sequestration per unit N deposition (C–N response) in forests, as well as factors influencing this response, we performed a meta-analysis on data from forest fertilization experiments around the globe. We focused on studies reporting changes in above-ground woody biomass (AGWB), a relatively stable C pool with long turnover times, in response to N addition. We hypothesize that the C–N response differs among forest biomes (boreal, temperate and (sub-)tropical forests).

We performed an extensive literature search to identify relevant studies and selected articles based on pre-defined criteria. In total, we identified 20 relevant studies with 63 observations (of which about one third in natural forests and two thirds in plantation forests). Effect sizes (kg C sequestered in AGWB per kg N added) were extracted from individual studies. Summary effect sizes were calculated as the weighted average of individual effect sizes using a random-effects meta-analytical model (Borenstein et al. 2009), with 'climate zone' as a grouping variable.

Scaling C-N response

To calculate global C sequestration in forests' AGWB resulting from agriculture-related N deposition, we multiplied average C–N responses of tropical, sub-tropical, temperate and boreal forests with the amount of ammonia (NH_3) deposited on these forest types. We assume here that NH_3 deposition presents a reasonable estimate of total N deposition caused by N use in agriculture – in fact, a small part of NH_3 emissions stems from other sources, however, this is compensated by neglecting agricultural nitrogen oxide (NO_x) emissions, which are in the same order of magnitude. NH_3 deposition per forest biome was estimated by overlaying a land cover map (GLC 2000) and spatially explicit TM5 model estimates of total NH_3 deposition for the year 2000 (Dentener et al. 2006). After calculating global C sequestration in forests' AGWB, we compared the climatic effect of agricultural N-induced forest C sequestration with the climatic effect of agricultural N_2O emissions by converting both fluxes to CO_2-C equivalents (CO_2-C_{eq}).

Results and Discussion

C–N responses obtained from the meta-analysis are shown in Table 1. We found that the C–N response of AGWB increases with latitude, from a very weak response of 1.9 kg C per kg N in tropical forests to a strong response of 22.5 kg C per kg N in boreal forests. The observed weak response of tropical forests confirms the hypothesis that tropical forests do not respond strongly to N as their weathered soils are mainly P limited (Cleveland et al. 2011). Temperate forest might show a lower C–N response than boreal forests as these forests historically experienced much higher levels of N deposition (ca. 6.6 kg ha^{-1} compared to 1.4 kg ha^{-1}), which might have lowered the efficiency with which these forests absorb the additional N (Tian et al. 2016).

The estimated C–N responses from the meta-analysis agree well with results from stoichiometric scaling (De Vries et al. 2014; see Table 2). In this approach, N-induced C sequestration is estimated by multiplying N deposition with the fraction of N retained in ecosystems, N allocation to ecosystem compartments, and C:N ratios of these compartments. Results thus obtained for AGWB are 5.0, 14.4 and 21.3 kg C per kg N for tropical, temperate and boreal forests, respectively (Table 2, for more details see De Vries et al. 2014). C–N responses for below-ground woody biomass (BGWB) are 1.1, 3.1 and 5.0 kg C per kg N for tropical, temperate and boreal forests, respectively (on average 22% of the AGWB response).

We also compared our estimates of C–N responses in AGWB with estimates from a global process-based dynamic vegetation model (DGVM) for C–N response of total plant biomass (AGWB+BGWB) (Fleischer et al. 2015, see Table 2). Results from the model are slightly lower for boreal forests (17.5 kg C per kg N), but twice as high for temperate forests (24.0 kg C per kg N). For tropical forests, the model estimates a much higher response (25.9 kg C per kg N). However, the authors acknowledge that this estimate is highly uncertain due to (among others) the lack of P cycle representation in the model.

Table 1. Summary effect sizes for C–N responses per forest biome obtained from the meta-analysis (1), estimates of NH_3 emissions per forest biome (2), and the calculated N-induced C sink expressed in Tg C yr^{-1} (3). Values shown are means; values in brackets are confidence intervals (± 1 standard error).

	(1) C–N response [kg C kg N^{-1}]	(2) NH_3 deposition[1] [Tg NH_3-N yr^{-1}]	(3) N-induced C sink [Tg C yr^{-1}] (= (1) * (2))
Tropical forests (n=10)	1.9 (-1.0–4.7)	5.5	11 (-5–26)
Sub-tropical forests (n=9)	6.2 (1.5–10.9)	2.7	17 (4–29)
Temperate forests (n=32)	12.4 (10.4–14.3)	3.5	43 (36–50)
Boreal forests (n=12)	22.5 (19.9–25.2)	0.6	13.5 (12–15)
All (n=63)	***12.1 (10.8–13.5)***	12.3	***84 (47–120)***

[1] NH_3 deposition estimates are based on an overlay of the GLC 2000 and the total deposition of NH_3 at 1 x 1 degree calculated with the TM5 model for the year 2000 (Dentener et al. 2006)

Table 2. Comparison of C–N responses for tree woody biomass obtained by our meta-analysis and other approaches. Values shown are means ± 1 standard error. AGWB = above-ground woody biomass, BGWB= below-ground woody biomass, DGVM = Dynamic global vegetation model

	Meta-analysis (*this study*)	Stoichiometric scaling (De Vries et al. 2014)			DGVM (Fleischer et al. 2015)
Compartment	*AGWB*	*AGWB*	*BGWB*	*AGWB+BGWB*	*AGWB+BGWB*
Tropical forests	2.1 ± 1.2[1]	5.0 ± 1.7	1.1 ± 0.3	6.1 ± 2.0	25.9 ± 10.8
Temperate forests	12.4 ± 2.0	14.4 ± 2.8	3.1 ± 0.6	17.5 ± 3.5	24.0 ± 2.4
Boreal forests	22.5 ± 2.6	21.3 ± 4.3	5.0 ± 1.0	26.3 ± 5.3	17.5 ± 5.2
All	***12.1 ± 1.3***				***23.0 ± 7.5***

[1] Results for Tropical and Sub-tropical forests from the meta-analysis were grouped because the other studies do not distinguish between those biomes.

We multiplied C–N responses obtained by our meta-analysis with estimates of agriculture-induced N deposition per forest biome and thus derived a global C sink in forest AGWB of about 84 (47–120) Tg C yr^{-1}. Temperate forests accounted for about 50% of the global N-induced C sink in AGWB, due to a combination of high N deposition and an intermediate C–N response. Despite their strong response to N addition, boreal forests only account for 16% of the N-induced C sink in AGWB as N deposition in this region is low.

Recent estimates for global N_2O emissions from agriculture vary mostly between 6.0 and 10.7 Tg N_2O yr^{-1} (Davidson and Kanter 2014), with a recent UNEP report presenting a 'best estimate' of 6.4 Tg N_2O yr^{-1} (UNEP 2013), or 520 Tg CO2-C_{eq} yr^{-1} (N_2O was converted to CO_2-C equivalent by multiplying with the 100-year global warming potential of 298 and dividing by 44/12 to convert from CO_2 to C). Using our range for N-induced C sequestration, we estimate that 16 (9–23) % of agricultural N_2O emissions are compensated by N-induced C sequestration in above-ground tree woody biomass following agricultural N use.

To put these estimates in perspective, we compared the potential C sequestration in AGWB to estimates of C–N responses in other forest ecosystem compartment. Using the C–N responses derived by De Vries et al. (2014) using stoichiometric scaling, we estimate an additional global annual C sequestration of 100 (80–133) Tg C in soils and 23 (18–29) Tg C in BGWB resulting from agricultural N use. Total ecosystem C sequestration caused by agricultural N use thus amounts to ca. 207 (145–282) Tg C yr^{-1}, or 40 (28–54) % of agricultural N_2O emission.

Future analysis of the fertilization experiment dataset will allow a refinement of this estimate by determining variables that influence C–N responses, such as nutrient availability (either in terms of foliar N concentration or soil N content), climate characteristics and/or dominant mycorrhizal associations. Another factor to examine more closely is the influence of N addition level on C–N responses: in our current analysis we assumed constant C–N responses, while there is evidence that C–N responses decrease with increasing levels of N deposition (De Vries et al. 2014; Tian et al. 2016). In addition, there is evidence that at sustained N deposition the N deposition effect on C sequestration might decrease over time as ecosystems are becoming progressively P-limited (Li et al. 2016; Peñuelas et al. 2013). Furthermore, climate change may affect forests' response to N deposition, for example by increasing N availability through warming-induced increases in soil organic matter decomposition (Hyvönen et al. 2007).

Conclusion

This study is the first to obtain an estimate of global C sequestration in forest above-ground woody biomass caused by agricultural N use using results from a meta-analysis. Based on a meta-analysis of data from 63 fertilization experiments in boreal, temperate, sub-tropical and tropical forests, we estimate that these forests store an additional 22.5, 12.4, 6.2 and 1.9 kg C per kg N deposition, respectively. Total global C sequestration in aboveground tree woody biomass caused by agricultural N use was estimated at 113 (49–178) Tg C yr^{-1} by multiplying NH_3 deposition on boreal, temperate, sub-tropical and tropical forests with C–N responses obtained from the meta-analysis. Adding results for N-induced C sequestration for below-ground woody biomass and soils from stoichiometric scaling leads to a total estimate of 207 (145–282) Tg C yr^{-1} sequestered in forests due to agricultural N use. This N-induced C storage only offsets about 40 (28–54) % of the climatic effect of N_2O emissions caused by agricultural N use (estimated at 520 Tg CO_2-C_{eq} yr^{-1}).

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