More nitrogen may be required for future grain production systems: A meta-analysis on the effect of elevated [CO_2] on nitrogen dynamics

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Abstract

By 2070, atmospheric carbon dioxide concentration [CO_2] is expected to double that observed in 1950. In this higher [CO_2] world the sustainability of global crop production may be in jeopardy unless current nitrogen (N) management strategies are changed. There have been many studies that have quantified the effect of increased [CO_2] on plant production and N utilization, but the individual results have been generally inconclusive and contradictory. To interpret the information available and provide new insight on crop management in the near future, we examined the effects of elevated [CO_2] on N dynamics in grain crop and legume pasture systems using meta-analytic techniques (366 observations from 127 studies). This analysis revealed that elevated [CO_2] increases crop production, however, to achieve this increase an adequate supply of N, derived from the soil, fertilizer or biological N-fixation is required. Since N demand and removal in many grain cropping systems is predicted to increase under future CO_2-enriched environments, current N management practice needs to be revised. These practices may include higher rates of fertilizer N application, greater use of legume intercropping, or legume cover crops.

Key Words

Elevated [CO_2], meta-analysis, grain N removal, residue C:N ratio, symbiotic N_2 fixation, fertilizer N recovery, N_2O emission

Introduction

Understanding nitrogen (N) removal and replenishment in soil is crucial for sustained crop production under rising atmospheric carbon dioxide concentration ([CO_2]). It is unclear how elevated [CO_2] will shift the N balance of cropping systems where grain harvest is a significant source of N removal from the system. Previous quantitative reviews show that elevated [CO_2] generally stimulated grain yield by 11–54%(Kimball, 1983; Long *et al.* 2006), but reduced the grain protein concentration of C_3 non-legumes (10–15%) and had little effect on legumes (–1.4%)(Jablonski*et al.* 2002; Taub*et al.* 2008). However, a quantitative review on the [CO_2] effects on the amount of grain N removal (the product of grain yield and grain N concentration of the same crop in the same study) is lacking.

Soil N removed from agroecosystems can be replenished by both fertilizer application and N_2 fixation by legumes. Literature on the effect of elevated [CO_2] on fertilizer N recovery shows inconsistent results (e.g. Martín-Olmedo*et al.* 2002; Kim *et al.* 2011; Lam *et al.* 2012). While a number of measurements of N_2 fixation under elevated [CO_2] have been reported (e.g. Edwards *et al.* 2006; Cheng *et al.* 2011), there has been no systematic synthesis of the effects of [CO_2] on the amount of N fixed by crop and pasture legumes.

Nitrous oxide (N_2O) emissions from soil in agroecosystems play a significant role in accelerating climate change (Forster *et al.* 2007). A recent meta-analysis concluded that elevated [CO_2] increases the emission of N_2O in terrestrial ecosystems by 1.2 Tg N_2O-N yr^{-1} (van Groenigen *et al.* 2011). However, the interaction of changing N dynamics with increased N_2O emissions from grain crops and legume pasture systems under elevated [CO_2] is not well understood.

In this meta-analytic review, we used 300 observations reporting the effects of elevated [CO_2] on N dynamics in grain crop and legume pasture systems. The objective of this review was to examine the effect of elevated [CO_2] on the demand and supply of N in grain crop andlegume pasture systems.

Methods

This meta-analysis is based on studies of the effects of elevated [CO_2] on N dynamics (grain N removal, N_2O emissions, fertilizer-N recovery, nodule growth, nitrogenase activity and N_2 fixation) in cropping systems (cereals, oilseeds, pulses and ley legume pastures) that were conducted in growth chambers, open-top chambers or free-air CO_2 enrichment (FACE) facility. The potential patterns of variation in [CO_2] effects were also assessed by including categorical variables in the meta-analysis models. These variables include plant functional group (C_3 non-legume, legume or C_4) and legume type (grain legume or ley pasture legume).The [CO_2] effects were averaged across other experimental treatments e.g. water regime (rainfed or irrigated), and fertilizer N input (low and high) where applicable.

We used the natural log of the response ratio (r = response at elevated [CO_2]/response at ambient [CO_2]) as a metric for analyses (Rosenberg *et al*. 2000). Theseresults were reported as the percentage change under elevated [CO_2] ((r – 1) ´100). The [CO_2] effects on the amount of grain N removal, N_2O emissions and N fixed were also expressed as U = amount at elevated [CO_2] – amount at ambient [CO_2] (van Groenigen*et al*. 2011).

The effect sizes in our analysis were weighted by replication (Adams *et al*. 1997; van Groenigen *et al*. 2011). Mean effect sizes and 95% confidence intervals were generated by bootstrapping (4,999 iterations) (Adams *et al*. 1997) using MetaWin 2.1 (Rosenberg *et al*. 2000). The effects of elevated [CO_2] were considered significant if the confidence intervals did not overlap with zero. Means of different categorical variables were considered significantly different from one another if their 95% confidence intervals did not overlap.

Results and Discussion

Effect of elevated [CO_2] on grain N removal

Overall, elevated [CO_2] significantly increased grain N removal by 16.6% (Fig. 1a). This increase suggests that future grain cropping systems will require more N to maintain soil N availability and sustain grain yields. The increased grain N removal under elevated [CO_2] resulted from a 26.8% increase in grain yield but an 8.1% reduction in grain N concentration (Fig. 1). The increase in grain N removal of legumes (35.8%) was significantly higher than that of C_3 non-legumes (10.7%) and C_4 crops (13.9%) (Fig. 1a). This was associated with a significantly greater increase in grain yield of legumes (38.7%) under elevated [CO_2] compared to that of C_3 non-legumes (23.0%) and C_4 crops (23.7%) (Fig. 1b). In contrast, elevated [CO_2] resulted in a small and non-significant reduction in grain N concentration of legumes (2.1%), but a greater and significant reduction in grain N concentration of C_3 non-legumes (10.0%) and C_4 crops (7.9%) (Fig. 1c).

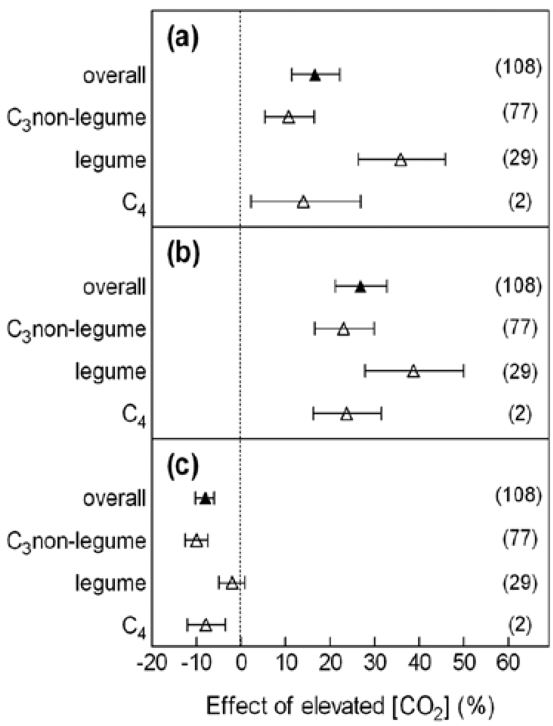

Figure 1. Effect of elevated [CO_2] on (a) grain N yield, (b) grain yield and (c) grain %N. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses.

Effect of elevated [CO_2] on N_2 fixation

Our analysis shows that elevated [CO_2] significantly increases whole plant nodule number (32.7%), nodule mass (39.1%), and total nitrogenase activity (36.7%), but resulted in a non-significant increase in the proportion of plant N derived from the atmosphere (Ndfa)(9.6%). Nonetheless, the amount of Ndfa was significantly increased by 38.2% under elevated [CO_2] (Fig. 2). This stimulation is associated with greater availability of photoassimilate for nodules and the host plant under elevated[CO_2] (Rogers *et al.* 2009). The amount of N fixed by legumes might be underestimated in our synthesis because fixed N in nodulated roots was not examined in some studies included in our database.

Effect of elevated [CO_2] on fertilizer N recovery

Our meta-analysis indicates that elevated [CO_2] increases fertilizer N recovery in the plant by 16.8% (Fig. 3a). Five out of 11 observations in the database of fertilizer N recovery examined the recovery of fertilizer N in the soil-plant system. These five observations show that the recovery of fertilizer N in the soil-plant system was generally not affected by elevated [CO_2]. The effect of elevated [CO_2] on the distribution of assimilated fertilizer N in different plant parts has rarely been examined, but one study (using ^{15}N tracer technique) indicated that elevated [CO_2] increased the remobilization of fertilizer derived N into grain by 46% under ambient temperature and 14% under elevated temperature (ambient +2°C) (Kim *et al.* 2011), suggesting that more fertilizer N will be removed in grain and a higher fertilizer application rate will be required to replenish the soil N pool under future elevated CO_2 atmospheres.

Effect of elevated [CO_2] on nitrous oxide emission

Our analysis indicates that overall, elevated [CO_2] increases N_2O emission by 27.0% (Fig. 3b). The increase was associated with a 24.0 and 33.4% increase in above-ground and below-ground biomass, respectively, at the experimental location where N_2O fluxes were measured. This finding suggests an association between N_2O emission and soil C substrate availability. While N_2O emission has little effect on the N balance of a cropping system, the [CO_2]-induced increase in N_2O emission suggests that denitrification is likely to be stimulated under elevated [CO_2]. This was observed in a study where denitrification increased under elevated [CO_2] (Baggs and Blum, 2004). This increase was attributed to greater C substrate input (Baggs *et al.* 2003) and/or improved soil moisture (Leakey*et al.* 2009) under increased [CO_2].

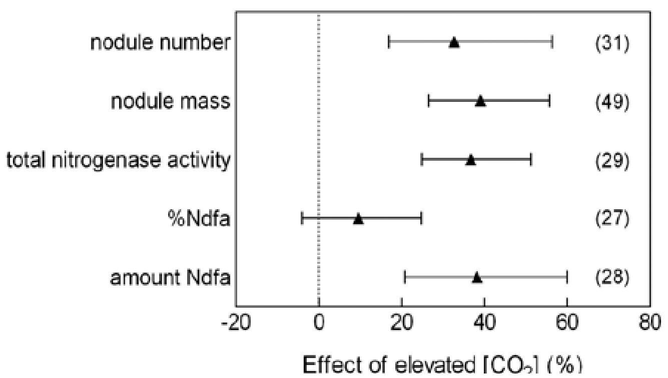

Figure 2: Effect of elevated [CO2] on nodule number, nodule mass, total nitrogenase activity, %N derived from the atmosphere (Ndfa) and amount of Ndfa. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses.

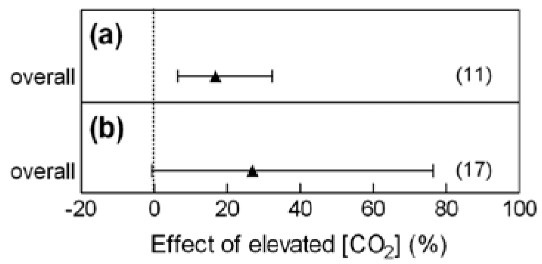

Figure 3: Effect of elevated [CO2] on (a) fertilizer N recovery in plant and (b) N2O emission from soil. Means and 95% confidence intervals are depicted. Numbers of experimental observations are in parentheses.

[CO2]-induced changes in N balance

We evaluated the effect of elevated [CO_2] on N balance in various cropping systems by the [CO_2]-induced changes in N input and N output of the systems (Table 1). Growing pasture legumes under elevated [CO_2] (without altering fertilizer inputs) resulted in a net N gain of 53.0 kg N ha^{-1}season^{-1}, while a net N loss occurred for grain legumes (–35.2 kg N ha^{-1}season^{-1}), C_3 non-legumes (–12.6 kg N ha^{-1}season^{-1}) and C_4 crops (–12.0 kg N ha^{-1}season^{-1}) (Table 1). The results suggest that N demand and removal in grain cropping systems will increase under elevated [CO_2]. The extra amount of N fixed under elevated [CO_2] by grain legumes can partly compensate for the additional N removal of grain crops in grain legume rotation. Incorporating pasture legumes into a crop rotation will increase N input to cropping systems under future higher [CO_2] atmospheres (Table 1).

Table 1: [CO2]-induced changes in N balance in various cropping systems.

	$[CO_2]$-induced changes in						
	Grain N removal (I)		N_2O emission (II)		Amount of N fixed (III)		N balance (III – I – II)
Plant system	mean	95% CI	mean	95% CI	mean	95% CI	
	kg N ha^{-1} season^{-1}						
C_3 non-legume	12.4	4.6 to 20.4	0.22	–0.06 to 0.50	0	NA	–12.6
Grain legume	59.6	35.8 to 86.7	0.60	0.13 to 1.06	25.0	5.3 to 53.0	–35.2
Pasture legume	0	NA	–0.04	–0.12 to 0.05	53.0	28.3 to 81.1	53.0
C_4	11.8	1.5 to 22.1	0.16	–0.04 to 0.36	0	NA	–12.0

In summary, our analysis suggests that N demand and removal in grain cropping systems will increase under elevated $[CO_2]$. Extra N input will be necessary to maintain soil N availability and sustain crop yields. This additional N may be obtained via applying higher rates of fertilizer N, greater use of legume intercropping, or legume cover crops under future elevated CO_2 atmospheres.

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