How Will Climate Change Affect Wheat Nutrition in Australian Cropping Systems?

By Shu-kee Lam, Deli Chen, Roger Armstrong, and Rob Norton

Understanding N dynamics is crucial to crop sustainability under rising atmospheric CO_2 concentration. Field and glasshouse trials were conducted to investigate the effect of elevated CO_2 on N dynamics in Australian cropping systems, with specific focuses on fertilizer N recovery by wheat, symbiotic N_2 fixation by legumes, and N_2O emission. Our results indicate that grain N removal will be higher in a carbon-rich world, and that current N management practice will need to be revised. However, because of the positive relationship between CO_2 elevation and N_2O emissions, global warming may be higher than current estimates.

Atmospheric [CO_2] has been rising since the industrial revolution and has increased at a much greater rate since 1950. If CO_2 emissions continue at their present rate the atmospheric [CO_2] is estimated to reach about 550 ppm by 2050 and 700 ppm by the end of this century (Houghton et al., 2001; IPCC, 2007). When grown under elevated [CO_2], C_3 crops generally produce more biomass and grain yield, and demand more N (Kimball et al., 2002). This increase in N demand would be expected to gradually reduce soil N reserves unless replenished. So in order to secure future crop yields, this increased demand must be met with a combination of fertilizer and biological N fixed by legumes.

Another consequence of the "fertilizer effect" of elevated [CO_2] is the likely increase in the amount of root growth. These roots then provide more C substrate that are available to denitrifying soil microbes, so that N_2O production may be stimulated under elevated [CO_2] (Baggs et al., 2003).

Common abbreviations and notes: N = nitrogen; P = phosphorus; C = carbon; CO_2 = carbon dioxide; [CO_2] = carbon dioxide concentration; N_2O = nitrous oxide; NO_3^- = nitrate.

Even though there is general understanding, the effects of elevated [CO_2] on fertilizer N recovery by cereals, symbiotic N_2 fixation by legumes, and soil N_2O emission in Australian cropping systems have not been studied for rainfed wheat production systems. To investigate the implications of these various processes on soil fertility we conducted outdoor (Australian Grains Free-air CO_2 enrichment; AGFACE) and indoor (glasshouse chamber) experiments at Horsham, Victoria, Australia.

AGFACE Study Site

Field experiments were conducted on a Vertisol from early June to mid December in 2008 and 2009 at Horsham (36°45'S, 142°07'E), Victoria. This area has a temperate climate with a long-term average rainfall and maximum temperature of 316 mm and 17.5°C during the wheat-growing season. Elevation of atmospheric [CO_2] was achieved using a FACE system, consisting of sixteen 12 m diameter (expanded to 16 m in 2009) experimental areas, eight ambient and eight elevated (**Figure 1**). The experimental areas were sown with wheat at 60 kg/ha seed and 23 kg P_2O_5/ha. The two target CO_2 concentrations were 390 (ambient) and 550 ppm (elevated). Seasonal rainfall

Figure 1. One of the eight FACE rings in Horsham, Victoria.

Table 1. The effect of elevated $[CO_2]$ and supplementary irrigation on fertilizer ^{15}N recovery in wheat and in soil.

	Fertilizer N recovery, %					
	Plant	Soil	Plant	Soil	Plant	Soil
	2008NS †		*2008LS*		*2009NS*	
Rainfed						
Ambient $[CO_2]$	43	29	4	82	39	31
Elevated $[CO_2]$	49	27	4	78	42	27
Irrigated						
Ambient $[CO_2]$	49	27	25	61	48	23
Elevated $[CO_2]$	46	24	32	54	44	26
$[CO_2]$ (C)	ns	ns	ns	ns	ns	ns
Irrigation regime (I)	ns	ns	***	***	ns	*
C × I	ns	ns	ns	ns	ns	*

Values are means of the four replicates for each treatment.

† *2008NS* = 2008 normal sowing; *2008LS* = 2008 late sowing; and *2009NS* = 2009 normal sowing.

Significant effects for main effects and interactions are indicated as $^{*}p < 0.05$ and $^{***}p < 0.001$. ns = not significant.

Table 2. Effect of elevated $[CO_2]$ and P application on the proportion of N derived from the atmosphere (%Ndfa) and the amount of N fixed by chickpea, field pea, and barrel medic.

	%Ndfa		Amount Ndfa, mg N/pot	
Soil P status	–P	+P	–P	+P
		Chickpea		
Ambient $[CO_2]$	34	30	17	17
Elevated $[CO_2]$	26	36	18	27
		Field pea		
Ambient $[CO_2]$	46	48	23	35
Elevated $[CO_2]$	39	44	28	42
		Barrel medic		
Ambient $[CO_2]$	30	43	11	26
Elevated $[CO_2]$	57	51	30	49
$[CO_2]$ (C)	ns		**	
P	ns		**	
Species (Spp)	*		*	
C × P	ns		ns	
C × Spp	ns		ns	
P × Spp	ns		ns	
C × P × Spp	ns		ns	

Values are means of the four replicates for each treatment. Significant effects for main effects and interactions are indicated as $^{*}p < 0.05$ and $^{**}p < 0.01$. ns = not significant.

and temperature scenarios were simulated by supplementary irrigation and delayed sowing. The fertilizer N recovery experiment was conducted over three experimental periods [2008 normal sowing (2008NS), 2008 late sowing (2008LS) and 2009 normal sowing (2009NS)], while N_2O flux measurements were made on the 2009NS treatment.

Application of ^{15}N-labeled Fertilizer

In each treatment area, a micro-plot was established by enclosing part of a wheat row with a PVC cylinder (0.24 m diameter, 0.25 m deep) inserted to 0.20 m depth. At the start of tillering, ^{15}N-enriched (10.22 atom%) granular urea was surface broadcast onto the micro-plot at the same rate (50 kg N/ha) and at the same time as non-labeled granular urea was applied to the remainder of the plot. Plants were harvested ten days after physiological maturity. Samples of dried plant (grain, shoot, and root) and soil (0 to 0.10 m, 0.10 to 0.20 m, and 0.20 to 0.40 m depths) were weighed, finely ground to ~100 µm, and analyzed for total N and ^{15}N enrichment by isotope ratio mass spectrometry (IRMS).

N_2O Flux Measurement

Gas samples for N_2O analysis were taken from closed static chambers (0.24 m diameter, 0.25 m deep) between 1200 and 1500 h at stem elongation, booting, anthesis, dough development, and ripening of wheat, respectively. One day before each sampling event, two chambers were inserted to a soil depth of 50 mm at random locations on each treatment area. On each sampling day, gas samples (30 mL) were collected at 0, 30, and 60 minutes after chamber closure using a gas-tight syringe, transferred into vacutainers and analyzed by gas chromatography.

Symbiotic N_2 Fixation

The interaction of $[CO_2]$ and P availability on symbiotic N_2 fixation by chickpea, field pea, and barrel medic was examined under controlled environment conditions. These legumes were grown on pots (0.14 m diameter, 0.15 m deep) with addition of either 0 or 46 kg P_2O_5/ha in either ambient (390 ppm) or elevated $[CO_2]$ (700 ppm) glasshouse chambers. Plants were harvested at flowering stage, and the dried plant samples (legume and wheat as a reference plant) were finely ground to ~100 µm and analyzed for total N and ^{15}N enrichment by IRMS. The proportion of shoot N derived from the atmosphere was assessed using ^{15}N natural abundance technique.

Results

Depending on treatment and year, the total N removed in grain was between 75 to 118 kg N/ha under elevated $[CO_2]$ compared to 63 to 101 kg N/ha under ambient $[CO_2]$. This increase in grain N removal was not apparent in rainfed plots at 2008LS, which was equivalent to severe drought conditions. Regardless of $[CO_2]$ the recovery of fertilizer N in the wheat parts followed the order grain > shoot > root, and the recovery from the soil decreased with soil depth. The recovery in the whole plant ranged from 43 to 49%, 4 to 32%, and 39 to 48% for 2008NS, 2008LS, and 2009NS, respectively (**Table 1**). Elevated $[CO_2]$ had no significant effect on the recovery of fertilizer N in the whole wheat plant or in any plant parts for any experimental periods. The $[CO_2]$-induced increase in plant N uptake (18 to 44%) was satisfied mostly by increased uptake of indigenous N (20 to 50%), probably because the proportion of applied fertilizer N in soil mineral N pool was small. Irrespective of [CO$_2$], the recovery of fertilizer N in wheat grown under supplementary irrigated plots was higher than that in rainfed counterparts in 2008LS (hot and dry period). Elevated [CO$_2$] generally did not affect the total recovery of fertilizer N in these systems (**Table 1**), so nutrient recovery from fertilizer is not expected to be any higher.

The proportion of shoot N derived from the atmosphere (%Ndfa) of the chickpea, field pea, and barrel medic was not affected by elevated [CO$_2$] regardless of soil P supply. However, because the legumes responded well to the higher P supply, the total amount of shoot N fixed by these legumes was increased by elevated [CO$_2$] (chickpea: 34%; field pea: 21%; barrel medic: 118%) and P fertilization (chickpea: 26%; field pea: 52%; barrel medic: 84%) (**Table 2**). In a similar experiment, we found the amount of N removed in grain from these legume crops also increased under elevated [CO$_2$] for chickpea (31%) and field pea (26%). As a result, the increased N fixation was mostly exported in grain that resulted in a negative N contribution by the legumes to the whole system.

Elevated [CO$_2$] increased the overall N$_2$O emission by 108%, with changes being greater during the wheat vegetative stage than during either dough development and ripening stages (**Figure 2**). This is possibly because N uptake by plant and N loss during the vegetative growth stage of wheat resulted in lower availability of NO$_3^-$ at those later growth stages. Moreover, later in crop growth, wheat root activity and N uptake declined, which reduced the difference in C and N dynamics between [CO$_2$] treatments. The supplementary irrigation reduced N$_2$O emission by 36% when averaged across [CO$_2$] treatments (**Figure 2**), suggesting that N$_2$O was reduced to N$_2$ in the denitrification process.

The results of the present study have several implications. First, grain N removal will be higher under elevated [CO$_2$], and extra N will need to be added to the systems to maintain soil N availability and sustain grain yield. Second, higher rates of fertilizer N application and greater use of pasture legume intercropping rather than grain legumes will be able to rectify the negative N balance due to grain N removal. The contribution of N by the legumes to the overall N economy of these mixed cropping systems will be contingent on adequate P supply. Finally, the extent of the stimulation of N$_2$O emission by elevated [CO$_2$] will be lower if water supply is sufficient to facilitate the reduction of N$_2$O to N$_2$, or if the vegetative stage of crop growth is shortened (e.g. by future warmer and drier climates).

This research has identified that fertilizer N and P strategies will need review as the impact of climate change and elevated [CO$_2$] become more evident. Changing patterns of growth and therefore nutrient demand mean that research will need to consider new combinations of the right source at the right rate, right time, and right place for nutrient best management practices.

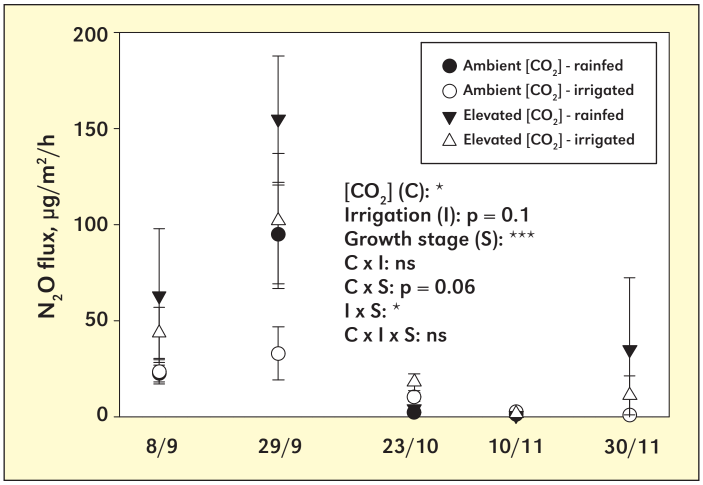

Figure 2. Effect of elevated [CO$_2$] and supplementary irrigation on N$_2$O flux at various key growth stages of wheat (stem elongation on 8/9/09; booting on 29/9/09; anthesis on 23/10/09; dough development on 10/11/09 and ripening on 30/11/09). Values are the means of four replicates for each treatment. Vertical bars indicate standard errors. Significant effects for main effects and interactions are indicated as *p < 0.05 and ***p < 0.001. ns = not significant.

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Acknowledgements

This work was supported by the Grains Research and Development Corporation, the Australian Research Council, the Victorian Department of Primary Industries and The University of Melbourne. The authors wish to thank Mr. Peter Howie, Mr. Russel Argall, Mr. Roger Perris for field assistance, and Dr. Xing Chen, Dr. Helen Suter, Mr. Jianlei Sun, Dr. Brett Kuskopf and Mr. Ron Teo for chemical analyzes.

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