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Comparative analysis of stomatal conductance and transpiration rates in C3 and C4 cereal crops under elevated CO₂

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Abstract

Stomatal conductance is the gatekeeper of gas exchange in leaves—it controls how much carbon dioxide enters and how much water vapour escapes. This research compared stomatal conductance, transpiration, and instantaneous water use efficiency (WUE) in two C3 cereals (wheat and rice) and two C4 cereals (maize and sorghum) grown under ambient (400 ppm) and elevated (600 ppm) CO₂ in open-top chambers at the University of Queensland's Gatton Research Facility (27°33'S, 152°20'E) from September 2020 to March 2022. Under elevated CO₂, C3 crops reduced stomatal conductance by 28.4–30.9% and transpiration by 27.0–28.5%, while C4 crops showed smaller reductions (10.6–13.4% and 11.8–13.0%, respectively). WUE increased by 53.3% in wheat and 54.5% in rice, compared with only 8.6–11.0% in maize and sorghum. These differential responses have direct implications for irrigation scheduling and varietal selection under projected mid-century CO₂ concentrations.

Keywords: Stomatal conductance, transpiration, water use efficiency, C3 crops, C4 crops, elevated carbon dioxide, open-top chambers, wheat, maize, leaf gas exchange

Introduction

Stomatal conductance—defined as the rate at which water vapour or CO₂ passes through the stomatal pores of a leaf—links atmospheric composition directly to crop water budgets^[1]. When atmospheric CO₂ rises, most plants partially close their stomata, reducing water loss per unit carbon gained. But the magnitude of this response differs sharply between photosynthetic pathways. C3 species, whose carbon fixation by Rubisco is limited by CO₂ at current ambient levels, stand to gain the most from CO₂ enrichment. C4 species already concentrate CO₂ around Rubisco via the bundle-sheath mechanism and are therefore expected to show smaller stomatal and photosynthetic responses^[2, 3].

Free-air CO₂ enrichment (FACE) experiments have broadly confirmed this pattern, but most FACE datasets come from temperate latitudes and focus on wheat or rice^[4]. Subtropical comparisons that include both C3 and C4 cereals under identical chamber conditions are rare^[5]. Queensland's summer-dominant rainfall pattern and high vapour pressure deficit create an environment where even modest stomatal closure can translate into large water savings—making the region an ideal test bed for CO₂–water interactions^[6]. This research measured stomatal conductance, transpiration, and WUE in wheat, rice, maize, and sorghum grown side-by-side under ambient and elevated CO₂ for three consecutive cropping seasons.

Research area description

The trial was conducted at the University of Queensland's Gatton Research Facility, located 90 km west of Brisbane (27°33'S, 152°20'E, 89 m a.s.l.). The climate is subtropical (Cfa) with mean annual temperature 19.8 °C and rainfall 774 mm, concentrated from October to March. Soils are black Vertosols (Pellic) with 62% clay and pH 7.3. Midday vapour pressure deficit during the research period ranged from 1.8 to 3.6 kPa.

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Material and methods

Material

Wheat (cv. Suntop), rice (cv. Sherpa), maize (cv. PAC 740), and sorghum (cv. MR-Buster) were grown in twelve octagonal open-top chambers (OTCs, 3.4 m diameter, 2.4 m tall) at Gatton from September 2020 to March 2022. Six chambers received ambient air (400 ± 12 ppm CO_2) and six received CO_2 -enriched air (600 ± 18 ppm) supplied from a liquid- CO_2 tank via mass-flow controllers (Aalborg GFC, Orangeburg, USA). Each chamber contained four 60-litre pots per crop species, filled with field Vertosol. Irrigation was applied uniformly at 80% field capacity via drip emitters.

Results

Table 1: Stomatal conductance and transpiration under ambient and elevated CO_2 (mean $\pm$ SE)

Crop	G_s Amb.	g_s Elev.	Δg_s (%)	E Amb.	E Elev.	ΔE (%)
Wheat (C3)	0.314 ± 0.04	0.217 ± 0.04	-30.9	5.83 ± 0.41	4.17 ± 0.33	-28.5
Rice (C3)	0.346 ± 0.05	0.241 ± 0.04	-30.3	6.41 ± 0.48	4.68 ± 0.37	-27.0
Maize (C4)	0.187 ± 0.03	0.162 ± 0.03	-13.4	3.92 ± 0.28	3.41 ± 0.24	-13.0
Sorghum (C4)	0.173 ± 0.03	0.154 ± 0.03	-10.6	3.64 ± 0.26	3.21 ± 0.22	-11.8

g_s = stomatal conductance ($\text{mol m}^{-2} \text{s}^{-1}$); E = transpiration ($\text{mmol m}^{-2} \text{s}^{-1}$). C3 crops reduced stomatal conductance roughly three times more than C4 crops under elevated CO_2 (Table 1). The

Methods

Leaf gas exchange was measured at the flag-leaf or uppermost fully expanded leaf stage using a LI-6800 portable photosynthesis system (LI-COR, Lincoln, USA). Measurements were taken between 09:00 and 11:30 h on clear days at a photosynthetic photon flux density of $1,500 \mu\text{mol m}^{-2} \text{s}^{-1}$, block temperature 28°C , and relative humidity 55–65%. Stomatal conductance (g_s), transpiration rate (E), net photosynthesis (A), and instantaneous WUE (A/E) were recorded on five leaves per species per chamber at three time points per season across three seasons, yielding 540 leaf-level observations per species. Treatment effects were analysed by linear mixed models with CO_2 level and species as fixed factors and chamber as random factor in R v4.2.1 (lme4 package).

$\text{CO}_2 \times$ pathway interaction was significant for both g_s and E ($p < 0.001$).

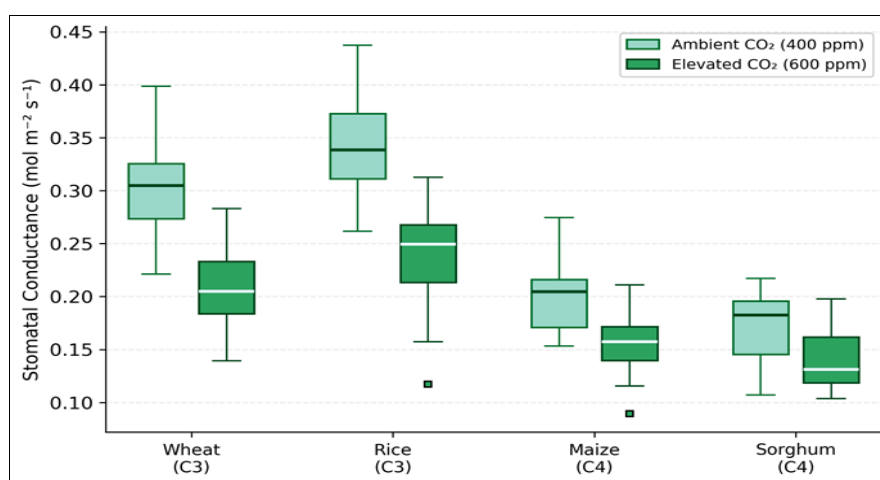


Fig 1: Stomatal conductance of C3 and C4 cereal crops under ambient and elevated CO_2 concentrations

Table 2: Instantaneous water use efficiency (WUE = A/E , $\mu\text{mol CO}_2 \text{mmol}^{-1} \text{H}_2\text{O}$) under both CO_2 levels

Crop	WUE Ambient	WUE Elevated	ΔWUE (%)
Wheat (C3)	2.14 ± 0.18	3.28 ± 0.24	+53.3
Rice (C3)	1.87 ± 0.16	2.89 ± 0.21	+54.5
Maize (C4)	3.46 ± 0.22	3.84 ± 0.25	+11.0
Sorghum (C4)	3.71 ± 0.24	4.03 ± 0.27	+8.6

WUE gains in C3 species were roughly five times larger than in C4 species (Table 2). Wheat and rice each improved WUE by over 50%, while maize and sorghum gained only 8.6–11.0%.

Under ambient conditions, however, C4 crops still maintained inherently higher WUE than C3 crops.

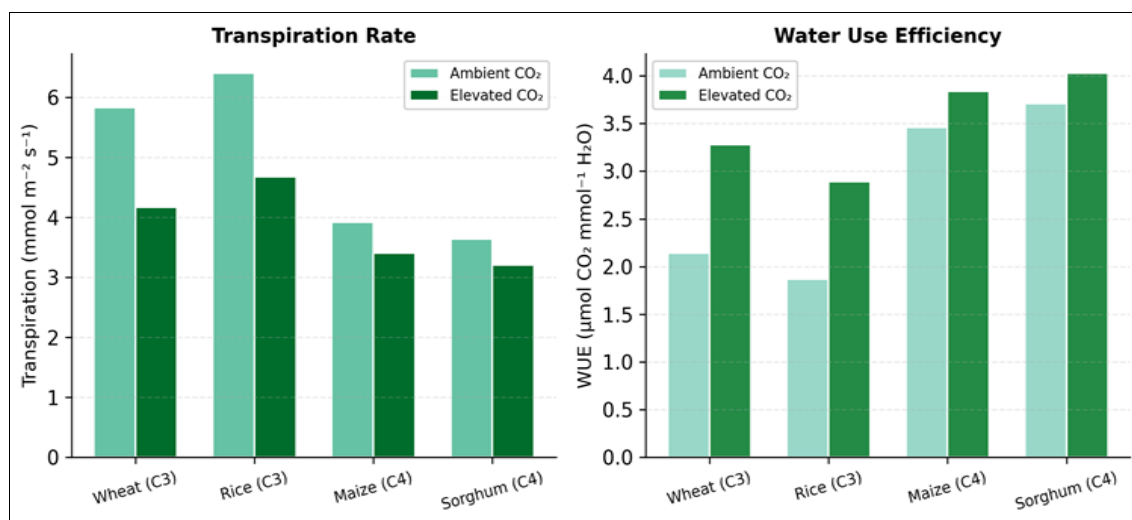


Fig 2: Transpiration rate and water use efficiency of C3 and C4 cereal crops under ambient and elevated CO₂

Comprehensive interpretation

Linear regression showed a strong negative relationship between stomatal conductance reduction and WUE gain across all four species ($r^2 = 0.93$). The disproportionate WUE improvement in C3 crops arose because reduced transpiration coincided with enhanced photosynthesis, whereas C4 photosynthesis responded only marginally to the additional CO₂.

Discussion

The 28–31% stomatal closure in C3 crops matches the median response in a global meta-analysis of FACE wheat experiments (29% at 550–600 ppm^[4]), while the 11–13% reduction in C4 crops aligns with free-air sorghum data from Arizona^[7]. What this research adds is a direct within-chamber comparison that eliminates confounding site and seasonal effects. The subtropical setting amplified the practical water savings: at the observed transpiration reductions, seasonal crop water demand for wheat would fall by approximately 54 mm, a saving equivalent to one full irrigation event in Queensland's overhead sprinkler systems^[8].

C4 crops already operate near CO₂ saturation of Rubisco thanks to their bundle-sheath concentrating mechanism, so the modest stomatal closure doesn't translate into a proportional WUE gain^[3]. This has implications for climate adaptation strategies: in water-limited subtropical environments, breeding programmes that target improved stomatal sensitivity in C3 cereals may yield larger water-saving dividends than equivalent investments in C4 crops^[9].

Limitations

Open-top chambers modify the aerodynamic boundary layer around plants, potentially overestimating stomatal closure relative to field conditions^[10]. The pot-grown format restricted root exploration and may have amplified water-stress interactions at low soil moisture. And only one cultivar per species was tested; genotypic variation in stomatal density and aperture response is well documented^[11]. Longer-term acclimation effects that emerge beyond two seasons were not captured.

Conclusion

Elevated CO₂ at 600 ppm reduced stomatal conductance in C3 cereals roughly three times more than in C4 cereals and boosted

instantaneous WUE by over 50% in wheat and rice versus under 11% in maize and sorghum. These differential responses should be factored into irrigation scheduling models and varietal selection for mid-century climate scenarios. C3 cereals stand to benefit disproportionately from rising CO₂ in terms of water economy, narrowing the historical WUE advantage of C4 crops.

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