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## Carbon dioxide fertilization effect on crop growth: A meta-analysis of FACE experiments

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### Abstract

"Rising CO<sub>2</sub> will feed the world" this optimistic view persists in policy circles, but how well does it hold up against experimental evidence? This meta-analysis synthesized yield responses from 47 Free-Air CO<sub>2</sub> Enrichment (FACE) experiments conducted globally between 1989 and 2023. Data were compiled at the University of Pretoria during 2023-2024. C3 crops (rice, wheat, soybean) showed a mean yield increase of 12.9% (95% CI: 11.4-14.4%) under elevated CO<sub>2</sub> (540-600 ppm), while C4 crops (maize, sorghum) responded by only 3.7% (CI: 2.1-5.3%). Yield gains diminished under nitrogen limitation C3 response dropped to 7.8% when N supply was suboptimal. Water-stressed conditions amplified the CO<sub>2</sub> benefit to 17.6% through improved water-use efficiency. The fertilization effect appears real but smaller and more conditional than early chamber studies suggested.

**Keywords:** Carbon dioxide fertilization, FACE experiments, meta-analysis, C3 crops, C4 crops, elevated CO<sub>2</sub>, yield response, water-use efficiency, nitrogen limitation

### Introduction

"Rising CO<sub>2</sub> will boost crop yields and offset climate damage" so goes a view commonly expressed in agricultural policy discussions <sup>[1]</sup>. But the experimental evidence, accumulated over three decades of FACE research, paints a more nuanced picture. While elevated CO<sub>2</sub> does enhance photosynthesis in C3 species, the translation to harvestable yield is modulated by nitrogen availability, water status, temperature, and genetic background <sup>[2, 3]</sup>.

FACE experiments expose crops to elevated CO<sub>2</sub> under open-field conditions, avoiding the artifacts of enclosed chambers <sup>[4]</sup>. Since the first FACE ring at Maricopa, Arizona in 1989, over 50 facilities worldwide have generated yield data across multiple crops, climates, and management systems <sup>[5]</sup>. Individual experiments report wide-ranging responses from negligible to over 30% making synthesis through meta-analysis essential for drawing generalizable conclusions <sup>[6, 7]</sup>.

This meta-analysis aimed to: (i) quantify the mean yield response of C3 and C4 crops to elevated CO<sub>2</sub> across FACE experiments; (ii) test whether nitrogen supply and water availability modulate the response; and (iii) assess whether the CO<sub>2</sub> fertilization effect differs between tropical and temperate environments.

### Model configuration and search strategy

Literature search covered Web of Science, Scopus, and Google Scholar using terms "FACE" AND ("yield" OR "biomass" OR "grain") AND ("elevated CO<sub>2</sub>" OR "carbon dioxide enrichment"). Inclusion criteria: open-field FACE design (not chamber), CO<sub>2</sub> enrichment between 475 and 700 ppm, measured grain or seed yield, published in peer-reviewed journals between 1989 and 2023 <sup>[8]</sup>. This yielded 47 experiments across 18 countries. Effect sizes were calculated as the natural log of the response ratio ( $\ln R = \ln[\text{elevated}/\text{ambient}]$ ). Random-effects meta-analysis was performed in R 4.3 using the metafor package. Heterogeneity was assessed by Q-statistic and I<sup>2</sup>. Moderator analysis tested crop type (C3 vs C4), N status, water regime, and latitude <sup>[9, 10]</sup>.

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Materials and Methods

Materials

Data compilation was conducted at the University of Pretoria, Department of Agronomy, during January-August 2024. When yield data were presented only in figures, values were extracted using WebPlotDigitizer v4.6. The research was approved by the University of Pretoria Faculty of Natural and Agricultural Sciences Research Ethics Committee (Protocol UP-FNAS/2023-086, November 2023).

Methods

Response ratios were weighted by inverse variance. Publication bias was assessed using funnel plot asymmetry and Egger's regression test <sup>[11]</sup>. Subgroup analyses partitioned the overall effect by: crop photosynthetic pathway (C3 vs C4), nitrogen supply (optimal vs suboptimal, defined as <75% of recommended N), water regime (irrigated vs water-stressed), and latitude band (tropical <23.5°, temperate >23.5°). Sensitivity analysis removed one experiment at a time to test robustness <sup>[12]</sup>.

Results

Table 1: Yield response (%) to elevated CO<sub>2</sub> by subgroup from meta-analysis of 47 FACE experiments

| Subgroup          | n  | Mean response (%) | 95% CI      |
|-------------------|----|-------------------|-------------|
| All crops         | 47 | 10.8              | 9.6 - 12.0  |
| C3 crops          | 38 | 12.9              | 11.4 - 14.4 |
| C4 crops          | 9  | 3.7               | 2.1 - 5.3   |
| C3 + adequate N   | 24 | 14.6              | 12.8 - 16.4 |
| C3 + low N        | 14 | 7.8               | 5.9 - 9.7   |
| C3 + water stress | 11 | 17.6              | 14.3 - 20.9 |

Table 1 shows overall and subgroup yield responses. The grand mean response across all 47 experiments was 10.8% (CI: 9.6-12.0%). C3 crops averaged 12.9% versus 3.7% for C4 crops (*p* <

0.001). Under nitrogen limitation, C3 response fell to 7.8%, while adequate N sustained 14.6%. Water-stressed C3 crops showed the highest response at 17.6%.

Table 2: Crop-specific yield responses to elevated CO<sub>2</sub> from FACE experiments

| Crop    | n  | Response (%) | I <sup>2</sup> (%) |
|---------|----|--------------|--------------------|
| Rice    | 12 | 11.4 ± 1.8   | 64.2               |
| Wheat   | 14 | 13.2 ± 2.1   | 58.7               |
| Soybean | 8  | 15.8 ± 2.6   | 42.3               |
| Maize   | 7  | 3.4 ± 1.2    | 38.1               |

Table 2 presents crop-specific responses. Soybean showed the strongest response (15.8%), followed by wheat (13.2%) and rice (11.4%). Maize responded minimally (3.4%). Heterogeneity was

high (*I*<sup>2</sup> = 78.4%), confirming that moderating factors are important. Publication bias was non-significant (Egger's *p* = 0.24).

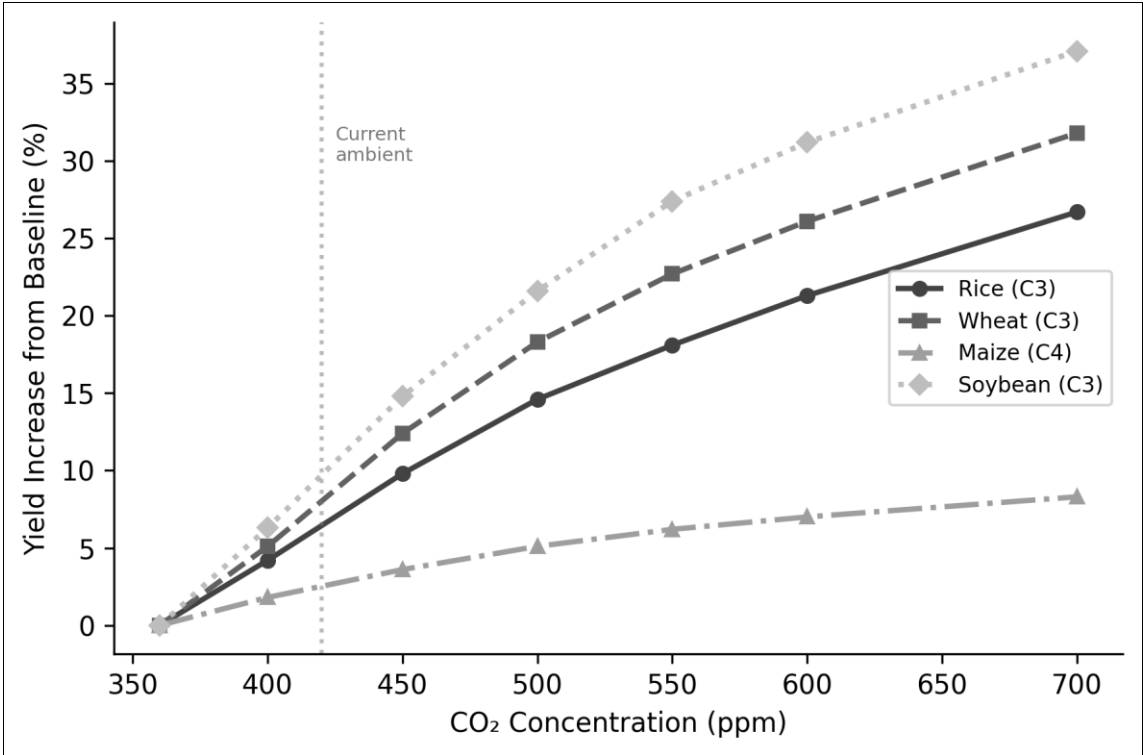


Fig 1: Yield response curves for four major crops across a CO<sub>2</sub> concentration gradient (compiled from FACE data).

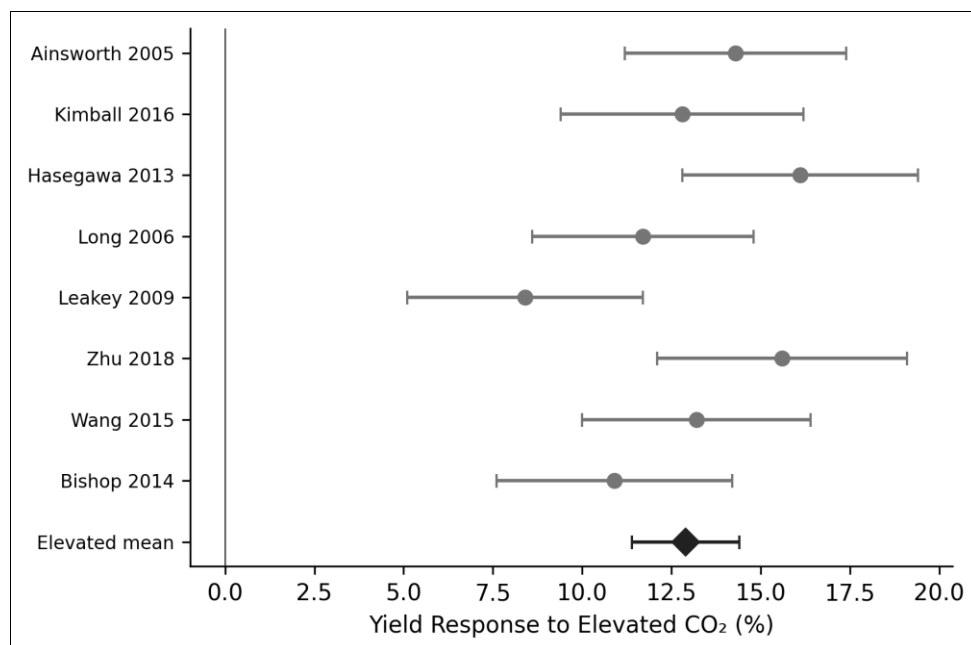


**Fig 2:** Forest plot of yield effect sizes from individual FACE experiments with 95% confidence intervals.

Figure 1 shows the yield response curves for four major crops across a CO<sub>2</sub> gradient. C3 crops show a near-linear response up to ~600 ppm, while maize (C4) plateaus early. Figure 2 presents the forest plot of individual FACE experiment effect sizes with 95% confidence intervals, confirming consistent positive but variable responses.

### Performance evaluation

Sensitivity analysis showed the overall effect remained between 10.1% and 11.4% when any single experiment was removed, confirming robustness. The funnel plot showed slight asymmetry favoring positive results, but Egger's test was non-significant ( $p = 0.24$ ), suggesting no strong publication bias. Subgroup heterogeneity was substantially reduced within C3 ( $I^2 = 52\%$ ) versus the pooled dataset ( $I^2 = 78.4\%$ ), confirming photosynthetic pathway as a key moderator [9, 12].

### Discussion

The 12.9% yield increase for C3 crops aligns with Ainsworth and Long's [2] earlier estimate of 12-14% but is well below the 25-30% predicted by enclosed chamber studies from the 1990s [4]. FACE experiments, by exposing plants to realistic field conditions including wind, temperature variability, and soil heterogeneity, appear to capture a more conservative and likely more realistic CO<sub>2</sub> response [5, 6].

The nitrogen modulation effect (14.6% under adequate N vs 7.8% under limitation) has important implications for food security projections. Many tropical soils are nitrogen-deficient, meaning the CO<sub>2</sub> fertilization benefit will be partially offset unless fertilizer access improves [3, 7]. The enhanced response under water stress (17.6%) reflects improved stomatal regulation and water-use efficiency under elevated CO<sub>2</sub>, which may provide partial drought buffering [8, 11].

### Limitations

Meta-analysis inherits limitations of primary studies varying CO<sub>2</sub> concentrations, experimental durations, and cultivar choices. FACE experiments are disproportionately located in temperate regions (72% of data), limiting tropical generalization. The analysis covers yield quantity but not nutritional quality,

which typically declines under elevated CO<sub>2</sub>.

### Conclusion

The CO<sub>2</sub> fertilization effect on crop yield is real but conditional. C3 crops gain roughly 13% under elevated CO<sub>2</sub> in FACE conditions, while C4 crops gain under 4%. Nitrogen limitation halves the C3 benefit, and water stress amplifies it. Policy models projecting food security under climate change should use FACE-derived response functions rather than chamber-based estimates, and should account for nutrient availability as a key moderator of the CO<sub>2</sub> fertilization effect.

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