Climate Impacts Assessment On Global Agriculture

Disentangling the role of rising CO₂ concentrations on crop yield and water use

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Potential Impacts of Climate Change on Crops

“...doubling of the atmospheric carbon dioxide concentrations of crops will lead to only a small decrease in global crop productions. But developing countries are likely to bear the brunt of the problem...”

Rosenzweig & Parry, 1994

Global hunger index, von Grebmer et al., 2012
Synthesis for the last IPCC report

Maize, temperate regions

- No adaptation ($n = 120$)
- With adaptation ($n = 69$)

Maize, tropical regions

- No adaptation ($n = 122$)
- With adaptation ($n = 92$)

Wheat, tropical regions

- No adaptation ($n = 45$)
- With adaptation ($n = 42$)

Wheat, temperate regions

- No adaptation ($n = 198$)
- With adaptation ($n = 127$)

Rice, temperate regions

- No adaptation ($n = 30$)
- With adaptation ($n = 20$)

Rice, tropical regions

- No adaptation ($n = 116$)
- With adaptation ($n = 77$)

The impact of adaptation is also evident in Fig. 2, which plots yield change against local mean temperature change ($°C$). Shaded bands indicate the 95% confidence interval of regressions consistent with the data. The linear model should be $Y_s = \beta_1 T_s + \beta_2 T_s^2 + \epsilon$, where $T_s$ is the local mean temperature change ($°C$), $Y_s$ is the yield change ($%$), and $\epsilon$ is the error term. The model also inferred $\beta_2 < 0.0031$ and $\beta_1 > 0.022$, with adapted crops yielding on average 7.16% greater than non-adapted (Table 1). The global mean sensitivity derived from statistical analyses of historical crop yields is $4.90\%$ per $°C$ of local warming, with an average yield loss of $3.92\%$ ($t = 5.00, P < 0.0001$) negative impacts, which has large uncertainties.

IPCC AR5 WG2, Chap7 (2014) & Challinor et al., 2014
Review: climate change and food security

Rosenzweig & Parry, 1994
World Development report, World Bank 2010
Wheeler, 2013
With and without CO₂?

Rosenzweig & Parry, 1994

Climate Change with CO₂ effects

World Development Report, World Bank 2010

Climate Change without CO₂ effects

Wheeler, 2013
With or without CO$_2$?

Rosenzweig & Parry, 1994

Climate Change with CO$_2$ effects

World Development report, 2010

Wheeler, 2013

CO$_2$

no CO$_2$
What do we know about these CO$_2$ effects on crops?

A doubling of atm. CO$_2$ concentrations:

- Increases yield of:
  - C$_3$ crops by ~10-45% (mainly due to photosynthesis enhancement)
  - C$_4$ crops by ~10% (due to water stress reduction)

- Reduces crop water use (transpiration) by ~10%

- Reduces crop quality (lower nutrients content (zinc, aluminium); unbalance C-N ratio leads to lower protein content)
Crop Responses to elevated [CO$_2$]

- Evapotranspiration of both C$_3$ and C$_4$ plants decrease by about 10% on average
- Corresponding yields of most C$_3$ grain crops increase on average by about 19%
- Yields of C$_4$ crops increase only when water is limiting, as in this case [CO$_2$] stimulate crop growth via improved water conservation

**Table:**

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Relative Changes Due to Elevated CO$_2$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat (C$_3$ grass)</td>
<td>-20</td>
</tr>
<tr>
<td>Rice (C$_3$ grass)</td>
<td>-20</td>
</tr>
<tr>
<td>Sorghum (C$_4$ grass)</td>
<td>0</td>
</tr>
<tr>
<td>Maize (C$_4$ grass)</td>
<td>20</td>
</tr>
<tr>
<td>Poplar (woody)</td>
<td>-20</td>
</tr>
<tr>
<td>Cotton (woody)</td>
<td>-20</td>
</tr>
<tr>
<td>Sweetgum (woody)</td>
<td>-20</td>
</tr>
<tr>
<td>Soybean (C$_3$ legume)</td>
<td>-20</td>
</tr>
<tr>
<td>Potato (C$_3$ forb)</td>
<td>-20</td>
</tr>
<tr>
<td>All C$_3$ &amp; C$_4$</td>
<td>-20</td>
</tr>
</tbody>
</table>

**Graph:**

- Ample N, Ample H$_2$O
- Low N, Ample H$_2$O
- Ample N, Low H$_2$O

Synthesis open-top chamber (OTC) and free air CO$_2$ enrichment (FACE) experiments

Kimball, 2016
Carbon Assimilation 101

Photosynthesis

$\text{CO}_2$

Transpiration

$\text{H}_2\text{O}$
Both experimental studies and modeling analyses of temperate ecosystems suggest that responses to multi-factor environmental change are predominantly controlled by additive or two-way interactions among elevated $[\text{CO}_2]$ and temperature, precipitation or nutrient availability [7,21–24]. However, the statistical power to detect higher order interactions in current experiments may be a limitation, and there are examples of higher order interactions controlling ecosystem performance [13,16,25]. Higher order interactions may also become more apparent as experimental and modeling analyses expand to include a larger climate envelope and new ecological contexts.

For example, while greater temperatures increase the stimulation of productivity by elevated $[\text{CO}_2]$ in mesic conditions, the increase in water use at high temperature may combine with low water availability under semi-arid and arid conditions to cause significant stress that cannot be ameliorated by elevated $[\text{CO}_2]$. In the case of C$_4$ species, photosynthesis is saturated by current $[\text{CO}_2]$, but growth at elevated $[\text{CO}_2]$ can ameliorate stress in times or places of drought [15]. It has also been proposed that the $\text{CO}_2$ required to saturate C$_4$ photosynthesis will increase with rising temperature [26]. This opens the possibility of a three-way interaction in which elevated $[\text{CO}_2]$ stimulates C$_4$ photosynthesis to a much greater extent when temperatures surpass a certain threshold.

Investigating interactive effects of climate change factors

A number of experimental approaches have been used to assess the interactive effects of elevated $[\text{CO}_2]$ and other factors.
Free-Air CO$_2$ enrichment (FACE)

Rice-FACE, Japan

Soy-FACE, Illinois

AgFACE, Australia
Regional disparities in the beneficial effects of rising CO$_2$ concentrations on crop water productivity

Delphine Deryng$^{1,2,3*}$, Joshua Elliott$^{1,2}$, Christian Folberth$^{4,5}$, Christoph Müller$^6$, Thomas A. M. Pugh$^{7,8}$, Kenneth J. Boote$^9$, Declan Conway$^{10}$, Alex C. Ruane$^{11,2}$, Dieter Gerten$^{6,12}$, James W. Jones$^9$, Nikolay Khabarov$^5$, Stefan Olin$^{13}$, Sibyll Schaphoff$^6$, Erwin Schmid$^{14}$, Hong Yang$^4$ and Cynthia Rosenzweig$^{11,2}$

1. Multi-model assessment of the impacts of climate change on crop yield and ET
2. Comprehensive model.observation comparison in respects to CO$_2$ effects
3. Global analysis of the spatial variations in the CO$_2$ effects on crops
4. Attribution of model uncertainties
Multi-model Assessment

• 6 Global Gridded Crop Models (GGCMs):
  
<table>
<thead>
<tr>
<th>Site-based</th>
<th>Ecosystem</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPIC</td>
<td>pDSSAT</td>
</tr>
<tr>
<td>GEPLIC</td>
<td>PEGASUS</td>
</tr>
</tbody>
</table>

• Driven by 5 Global Climate Models (GCMs)
  HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2-M, NorESM1-M

• under RCP 8.5 (Climate+CO$_2$ effects)

• Simulated crop yield, evapotranspiration, and more...

<table>
<thead>
<tr>
<th>Crop</th>
<th>Photosynthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>$C_4$ photosynthesis</td>
</tr>
<tr>
<td>Wheat</td>
<td>$C_3$ photosynthesis</td>
</tr>
<tr>
<td>Rice</td>
<td>$C_3$ photosynthesis</td>
</tr>
<tr>
<td>Soybean</td>
<td>$C_3$ photosynthesis, N-fixing legume</td>
</tr>
</tbody>
</table>
Projected Impacts on Crop Yields

Simulated change in crop yields in 2080 relative to 2000 under RCP 8.5 CO₂ concentrations double relative to present-day

Rosenzweig et al., 2014

Median across 30 combinations of 6 global crop models and 5 global climate models
Global water use

Total water withdrawal: 3700 km³/yr
Agriculture water withdrawal: 2590 km³/yr

Agriculture sector uses 70% of global freshwater use!
Water availability and scarcity

IWMI, 2007
Can elevated atmospheric [CO$_2$] contribute to produce more food with less water?

- Crop Water Productivity
- CWP is the ratio of crop yield to total water use throughout the crop development period (AET)
- CWP = Yield/AET
Both experimental studies and modeling analyses of temperate ecosystems suggest that responses to multi-factor environmental change are predominantly controlled by additive or two-way interactions among elevated \( [\text{CO}_2] \) and temperature, precipitation or nutrient availability \([7,21–24]\). However, the statistical power to detect higher order interactions in current experiments may be a limitation, and there are examples of higher order interactions controlling ecosystem performance \([13,16]\). Higher order interactions may also become more apparent as experimental and modeling analyses expand to include a larger climate envelope and new ecological contexts. For example, while greater temperatures increase the stimulation of productivity by elevated \( [\text{CO}_2] \) in mesic conditions, the increase in water use at high temperature may combine with low water availability under semi-arid and arid conditions to cause significant stress that cannot be ameliorated by elevated \( [\text{CO}_2] \) \([7]\). In the case of \( \text{C}_4 \) species, photosynthesis is saturated by current \( [\text{CO}_2] \), but growth at elevated \( [\text{CO}_2] \) can ameliorate stress in times or places of drought \([15]\). It has also been proposed that the \( \text{CO}_2 \) required to saturate \( \text{C}_4 \) photosynthesis will increase with rising temperature \([26]\). This opens the possibility of a three-way interaction in which elevated \( [\text{CO}_2] \) stimulates \( \text{C}_4 \) photosynthesis to a much greater extent when temperatures surpass a certain threshold.

Investigating interactive effects of climate change factors

A number of experimental approaches have been used to assess the interactive effects of elevated \( [\text{CO}_2] \) and other factors. A multi-biome gap in understanding of crop and ecosystem responses

Table 1

<table>
<thead>
<tr>
<th>Biome</th>
<th>Primary functional groups</th>
<th>% change in: N</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperate forest</td>
<td>( \text{C}_3 ) trees</td>
<td>23%</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>( \text{C}_4 ) grasses</td>
<td>37%</td>
<td>36%</td>
</tr>
<tr>
<td>Temperate grassland</td>
<td>Community</td>
<td>13%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{C}_3 ) grasses</td>
<td>37%</td>
<td></td>
</tr>
<tr>
<td>Temperate cropland</td>
<td>( \text{C}_3 ) crops</td>
<td>17%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{C}_4 ) crops</td>
<td>6%</td>
<td></td>
</tr>
</tbody>
</table>

- Estimates from Ainsworth and Rogers \([1]\).
- Estimate based on four FACE experiments from Norby et al. \([29]\).
- Estimate based on updated meta-analysis of FACE data following methods of Ainsworth and Long \([11]\).

Location of FACE where data on both yield and AET are available

→ Wheat in two sites (Arizona, USA & SE Australia)
→ Maize in Germany
→ Rice in two sites (Japan & China)
→ Soybean in Illinois, USA
Model/Observation Comparison

![Graph comparing Model/Observation for different crops (Maize, Wheat, Rice, Soybean). The graph shows the comparison of 
median FACE wet, median FACE dry, GGCMs irrigated, and GGCMs rainfed. The x-axis represents the change in CWP (%) ranging from -20 to 100. Each crop has a separate section showing the variation in CWP.](image-url)
## Global Impacts

<table>
<thead>
<tr>
<th>Wheat (C&lt;sub&gt;3&lt;/sub&gt; crop)</th>
<th>Climate change with CO&lt;sub&gt;2&lt;/sub&gt; effects</th>
<th>Climate change without CO&lt;sub&gt;2&lt;/sub&gt; effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>+3 [-1;+14] %</td>
<td>-23 [-28;-15] %</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>-11 [-21;-6] %</td>
<td>-7 [-12;-5] %</td>
</tr>
<tr>
<td>Crop water productivity</td>
<td>+27 [7;37] %</td>
<td>-17 [-24;-1] %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Maize (C&lt;sub&gt;4&lt;/sub&gt; crop)</th>
<th>Climate change with CO&lt;sub&gt;2&lt;/sub&gt; effects</th>
<th>Climate change without CO&lt;sub&gt;2&lt;/sub&gt; effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>-9 [-16;+1] %</td>
<td>-21 [-28;-13] %</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>-17 [-24;-5] %</td>
<td>-8 [-13;-2] %</td>
</tr>
<tr>
<td>Crop water productivity</td>
<td>+13 [3;22] %</td>
<td>-13 [-22;-2] %</td>
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</table>
Spatial variations: CO$_2$ effects on yield (rainfed)

[CO$_2$] levels correspond to year 2050 under a business as usual greenhouse gases emission scenario

Median across 30 combinations of 6 global crop models and 5 global climate models
Spatial variations: CO$_2$ effects on CWP (rainfed)

% difference in simulated CWP with and without CO$_2$

[CO$_2$] levels correspond to year 2050 under RCP 8.5 - median across the GGCM-GCM ensemble
Summary across climatic regions

Large benefits in arid regions (CWP increases by 48% for rainfed wheat)

% difference in simulated CWP with and without CO₂

[CO₂] levels correspond to year 2050 under RCP 8.5 - median across the GGCM-GCM ensemble
Wheat CO₂ effects on CWP
[CO₂] levels correspond to year 2050 under RCP 8.5 - median across 5 GCMs
Large uncertainties in impact model projections

6 different crop models driven by climate data from 5 different climate models:

<table>
<thead>
<tr>
<th>Crop</th>
<th>Climate change with CO$_2$</th>
<th>Climate change without CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>13 [-13; 22] %</td>
<td>-13 [-22; -2] %</td>
</tr>
<tr>
<td>Rice</td>
<td>10 [0; 47] %</td>
<td>-23 [-27; -17] %</td>
</tr>
<tr>
<td>Soybean</td>
<td>18 [-9; 42] %</td>
<td>-26 [-40; -19] %</td>
</tr>
<tr>
<td>Wheat</td>
<td>27 [7; 37] %</td>
<td>-17 [-24; -1] %</td>
</tr>
</tbody>
</table>

Uncertainties double when including CO$_2$ effects.
Source of Uncertainties in Impacts Projections

- Climate signal (climate change projections from GCMs)
- Crop simulation methodology (parameterization, ET equation, nitrogen stress, extreme heat sensitivity, phenology & planting date decision/cultivar choice...)
- CO₂ sensitivity methodology (Radiation Use Efficiency vs Photosynthesis-Respiration)
Climate Adaptation Strategies

- Increase fertilizer application – CO$_2$ effects are stronger for well-fertilizer crops
- Elevated CO$_2$ could reduce irrigation demand (in some cases)
- Elevated CO$_2$ could help rainfed crops to cope with water stress
  → Choice of crop type (switch to a less water demanding crop)
- Crop genetics (develop cultivars adapted to high CO$_2$ levels)
Increases in CO$_2$ and temperature have opposite effects on the carbon sink: increases in atmospheric carbon dioxide stimulate photosynthetic uptake of CO$_2$ in a "CO$_2$ fertilization" effect that dampens anthropogenic-induced increases in atmospheric CO$_2$, and increases terrestrial carbon storage by 1.35 Gt-C/ppm increase in atmospheric CO$_2$ (Bonan, 2008)
Feedback processes contributing to radiative forcings

Total positive radiative forcings resulting from feedbacks between the terrestrial biosphere and the atmosphere are estimated to reach up to 0.9 or 1.5 W m⁻² K⁻¹ towards the end of the twenty-first century, depending on the extent to which interactions with the nitrogen cycle stimulate or limit carbon sequestration. This substantially reduces and potentially even eliminates the cooling effect owing to carbon dioxide fertilization of the terrestrial biota. (Arneth et al., 2010)
Next steps

• Expand FACE experience and develop collaboration between agronomists and crop modelers

• CTWN modeling sensitivity (Global Gridded Crop Modeling Initiative phase 2)

• Communication, science/policy interaction
  → understand challenges for adaptation by practitioners, farmers...etc.

e.g. Adaptation Futures conference in Rotterdam, May 10-13
Thank you!

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Ref. Deryng et al., (2016) doi:10.1038/nclimate2995

Regional disparities in the beneficial effects of rising CO₂ concentrations on crop water productivity

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