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Supplemental Material

Estimated Effects of Future Atmospheric CO₂ Concentrations on Protein Intake and the Risk of Protein Deficiency by Country and Region

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1. Systematic review: Exclusions

Citations were excluded from further analysis if there were no eCO₂ treatments, no protein or nitrogen content suggested in the abstract, and no institutional access to journals from the libraries of Harvard, Australian National University or Technical University of Berlin. Otherwise, full-text articles were assessed for eligibility. Articles were then excluded, based on not citing nitrogen or protein content from the intact edible portions of food plants, plants not being exposed to CO₂ from seedling to maturity, CO₂ treatments not being independent of ozone or warming treatments, CO₂ treatments exceeding 1000 ppm, and when no estimates of experimental error were provided. Studies were also excluded when the same experimental data was published elsewhere. The remaining articles were used for quantitative analysis.

2. Search strings

Systematic review 2014

TOPIC: (elevated (CO₂ OR carbon dioxide) (protein OR nitrogen) (seed OR grain OR fruit OR tuber)(wheat OR rice OR barley OR Rye OR Maize OR oats OR millet OR sorghum OR buckwheat OR triticale OR fonio OR popcorn OR canary OR quinoa OR cassava OR taro OR potato OR yam OR cocoyam OR yautia OR lentil OR *bean OR *pea OR nuts OR chestnuts OR almond OR walnut OR pistachio OR kola* OR hazelnut OR peanut OR sunflower OR rapeseed OR mustard OR coconut OR cabbage OR brassica OR artichoke OR asparagus OR lettuce OR copra OR sesame OR tomato OR onion OR spinach OR cauliflower OR broccoli OR pumpkin OR gourd OR squash OR cucumber OR eggplant OR aubergine OR garlic OR leek OR carrot OR turnip OR okra OR *melon OR citrus OR banana OR plantain OR apple OR pineapple OR date OR grape OR pear OR quince OR apricot OR cherry OR peach OR nectarine OR plum OR sloe OR *berry OR currant OR ficus OR mango OR mangosteen OR guava OR avocado OR persimmon OR cashewapple OR kiwi OR papaya OR ginger))

TOPIC: (elevated (CO₂ OR carbon dioxide) (protein OR nitrogen) (cassava OR taro OR (sweet potato) OR yam OR cocoyam OR yautia OR nuts OR chestnuts OR almond OR walnut OR pistachio OR kola* OR hazelnut OR peanut OR coconut OR cabbage OR brassica OR artichoke OR asparagus OR lettuce OR copra OR onion OR spinach OR cauliflower OR broccoli OR garlic OR leek OR carrot OR turnip OR ginger))

Total citations: 802

Articles selected for further evaluation: 206

Excluded based on full text: 133 (for exclusion criteria, see methods above).

Duplicate data: 8

Citations used for quantitative analysis: 73

Systematic review 2015

Staples and fruit:

TOPIC: ((CO₂ or "carbon dioxide") and (protein OR nitrogen) and (seed OR grain OR fruit OR tuber)) AND TITLE: (("carbon dioxide" OR CO₂) AND (elevated OR enrich* OR high OR increas*))

Total citations: 401

Articles selected for further evaluation: 256

Articles already assessed in 2014: 97

Excluded based on full text: 116

Duplicate data: 7

Citations used for quantitative analysis: 38

Vegetables:

TOPIC: (CO2 OR "carbon dioxide") (protein OR nitrogen) (banana* OR yam* OR tomato* OR plantain OR onion OR groundnut OR cassava OR cocoa OR coconut OR cabbage* OR brassica OR artichoke OR asparagus OR lettuce OR chicory OR spinach OR cauliflower OR broccoli OR pumpkin OR squash OR gourd* OR cucumber OR gherkin OR eggplant OR aubergine OR chilli OR shallot* OR garlic OR leek OR alliac* OR carrot OR turnip OR okra OR carob OR watermelon OR melon) AND TITLE: (("carbon dioxide" OR CO2) AND (elevated OR enrich* OR high OR increas*))

Total citations: 261

Articles selected for further evaluation: 72

Articles already assessed in 2014: 22

Excluded based on full text: 42

Duplicate data: 0

Citations used for quantitative analysis: 12

Fruit:

TOPIC: ((CO2 or "carbon dioxide") and (protein OR nitrogen) and (Pear* or Quince OR Apricot OR Cherry OR peach OR nectarine OR Plum OR sloe OR pome OR *berry OR Currant OR *melon OR Ficus OR fig or Mango* OR guava OR Avocado OR Persimmon OR *apple OR Kiwi OR Papaya) AND TITLE: (("carbon dioxide" OR CO2) AND (elevated OR enrich* OR high OR increas*))

Total citations: 69

Articles selected for further evaluation: 11

Articles already assessed in 2014: 4

Excluded based on full text: 6

Duplicate data: 0

Citations used for quantitative analysis: 0 (fruit included in staple search)

3. List of references used for meta-analysis

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CHIP dataset, the summary of which is published in:

Fangmeier A, De Temmerman L, Black C, Persson K, Vorne V. 2002. Effects of elevated CO₂ and/or ozone on nutrient concentrations and nutrient uptake of potatoes. *Eur J Agron* 17:353-368.

ESPACE dataset, the summary of which is published in:

Fangmeier A, De Temmerman L, Mortensen L, Kemp K, Burke J, Mitchell R, et al. 1999. Effects on nutrients and on grain quality in spring wheat crops grown under elevated CO₂ concentrations and stress conditions in the European, multiple-site experiment 'ESPACE-wheat'. *Eur J Agron* 10:215-229.

Table S1. Results of systematic review and raw data:

Commodity		Number of experimental sites	Cultivars/ varieties	Field sites	Sites with Fertiliser experiments	Sites with Watering experiments	Sites with field experiments replicated over multiple years	Experiments intentionally over multiple elevated CO ₂ concentrations	Experiments undertaken elsewhere than Europe or USA
Wheat	Literature	24	39	14	10	2	9	2	7
	Raw data	7	9	7	4	1	5	4	2
Rice	Literatur	9	13	7	3	0	6	1	8
	Raw data	2	18	2	0	0	1	0	2
Barley	Literature	6	13	2	4	0	1	0	0
Maize	Literature	1	1	1	0	1	1	0	0
	Raw data	1	2	1	1	0	0	0	0
Sorghum	Literature	2	2	1	0	0	1	0	1
	Raw Data	1	1	1	0	1	1	0	0
Potato	Literature	1	1	0	0	0	0	0	0
	Raw data	6	1	6	0	0	3	3	0
Peas	Literature	2	4	1	1	0	0	0	2
	Raw data	1	5	1	0	1	0	0	1
Beans	Literature	5	7	2	1	0	0	0	3
Soy	Literature	11	11	6	1	2	4	2	4
	Raw data	1	7	1	0	0	1	0	0
Rapeseed/ mustardseed	Literature	3	5	2	1	0	1	0	1
C ₃ Veg.	Literature	16	26	3	6	0	1	2	6
C ₃ Fruit	Literature	3	3	0	2	1	0	1	2
Other	Literature	4	7	2	0	0	1	0	2
Total*		99	168	54	34	9	35	14	37

*Some sites were sources of both raw data and literature data

Table S2: Meta-regression results and meta-analysis fertiliser effects. Meta-regression :dose-response of protein content to degree of CO₂ elevation (elevated minus ambient); Meta-analysis: effect of fertiliser application on protein response to CO₂.

Commodity	Slope	Intercept	P value of slope	For meta analysis, p value for N fertiliser modifier
C₃ grains	-2*10 ⁻⁴	0.96	0.82	0.84
Wheat	-2*10 ⁻⁴	0.96	0.59	0.70
Rice	-3*10 ⁻⁴	0.99	0.39	0.39
Barley	-1*10 ⁻⁴	0.87	0.84	0.73
C₄ grains	0.00	1.01	1.00	0.90
Maize	-0.02	4.83	<0.001*	0.99
Sorghum	3*10 ⁻⁴	0.94	0.94	NA
Root vegetable	2*10 ⁻⁴	0.91	0.41	0.17
Potato	3*10 ⁻⁴	0.88	0.33	NA
Pulses, legumes	-1*10 ⁻⁴	0.98	0.84	0.60
Peas	-7*10 ⁻⁴	0.86	0.008*	0.69
Beans	2*10 ⁻⁴	1.01	0.84	0.74
Oilcrops	-1*10 ⁻⁴	1.01	0.70	0.39
Soy	1*10 ⁻⁴	1.00	0.36	0.01**
Rapeseed/ mustard seed	-1.4*10 ⁻³	1.22	0.003*	0.002**
Fruit	0.005	-0.47	0.06*	0.42
C₃ Vegetables	0.00	0.84	1.00	0.97

* For maize, there were two studies with considerable variability in results between these. We considered use of the meta-analysis-derived mean as a more reliable estimate of maize response to CO₂. The response of maize and peas has been discussed in the main text. As fruit and rapeseed are not substantial contributors to daily protein intake, further analysis was not sensitive to these results being significant.

** N fertiliser had a negative effect on soy response to CO₂ but this was driven by two data points only.

Table S3. Addressing publication bias: Number of additional experiments with no CO₂ effect (i.e. CO₂ response ratio 1, with variance 0.5, that would be required to raise upper CI above 1

Commodity	Number of additional experiments required for no effect
C₃ grains	1250
Wheat	350
Rice	1
Barley	1
C₄ grains	0
Maize	0
Sorghum	0
Root vegetable	0
Potato	2
Pulses, legumes	0t
Peas	0
Beans	0
Oilcrops	0
Soy	0
Rapeseed/ mustard seed	0
C₃ Vegetables	2

Table S4. Classification of country groups

Region	Countries
High-Income (HIGHIN)	Australia, Austria, Belgium, Brunei Darussalam, Canada, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Malta, Netherlands, New Zealand, Norway, Portugal, Republic of Korea, Spain, Sweden, Switzerland, United Kingdom, United States of America
Southern and Tropical Latin America (SOTRLA)	Argentina, Brazil, Chile, Paraguay, Uruguay
Greater China (CHINAR)	Mainland China, Hong Kong SAR (China), Macau SAR (China), Taiwan
Central and Eastern Europe (CEEAEU)	Albania, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Macedonia (Former Yugoslav Republic of), Moldova, Montenegro, Poland, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Ukraine
Central and Andean Latin America and the Caribbean (CALACA)	Antigua and Barbuda, Bahamas, Barbados, Belize, Bolivia, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Peru, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Venezuela (Bolivarian Republic of)
Central Asia, North Africa and Middle East (CANAME)	Algeria, Armenia, Azerbaijan, Egypt, Georgia, Iran (Islamic Republic of), Iraq, Jordan, Kazakhstan, Kuwait, Kyrgyzstan, Lebanon, Libyan Arab Jamahiriya, Mongolia, Morocco, Occupied Palestinian Territory, Saudi Arabia, Syrian Arab Republic, Tajikistan, Tunisia, Turkey, Turkmenistan, United Arab Emirates, Uzbekistan, Yemen
East and Southeast Asia and Pacific (ESEASP)	Cambodia, Democratic People's Republic of Korea, Fiji, French Polynesia, Indonesia, Kiribati, Lao People's Democratic Republic, Malaysia, Maldives, Micronesia (Federated States of), Myanmar, New Caledonia, Philippines, Samoa, Solomon Islands, Sri Lanka, Thailand, Timor-Leste, Vanuatu, Viet Nam
Sub-Saharan Africa (SUSAAF)	Angola, Benin, Botswana, Burkina Faso, Burundi, Cape Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, São Tomé and Príncipe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Sudan (former), Swaziland, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
South Asia (SOASIA)	Afghanistan, Bangladesh, Nepal, Pakistan Included separately: India

Table S5. Summary of inputs for EAR calculations

Region	Population 2011 (million) ¹	Population 2050 (million) ¹	Birth Rate 2011 (per 1000 people) ²	Birth Rate 2050 (per 1000 people) ¹	Median Breast feeding duration ³	Percent of infants ever breastfed ³	Average height, female (cm) ⁴	Average height, male (cm) ⁴	Stillbirth rate (per 1000 births) ¹
HIGHIN	980	1100	11.1	10.2	1	87.1	162	175	3.1
SOTRLA	265	317	15.7	10.4	1	93.5	157	169	9.4
CHINAR	1376	1394	11.9	8.8	1	95.9	158	169	10
India	1221	1620	21.0	12.7	2	96.4	152	165	22
CEEAEU	328	273	11.3	10.7	1	96.2	164	176	8.2
CALACA	337	464	20.4	12.1	2	69.9	154	167	8.6
CANAME	772	1165	22.4	14.8	1	93.8	157	171	11.9
ESEASP	654	848	18.8	13.4	2	86.0	151	162	14.1
SUSAAF	889	2150	38.3	26.2	2	93.8	158	169	27.0
SOASIA	386	567	24.5	15.5	3	96.1	153	165	39.7
(Total countries available)	(200)	(200)	(207)	(196)	(79)	(78)	(127)	(71)	(194)

For abbreviations, see preceding table.

¹Source: UN (United Nations). 2013. World Population Prospects: The 2012 revision. United Nations. Available: <http://esa.un.org/unpd/wpp/index.htm> [accessed Feb 15, 2015].

²Used to calculate number of women pregnant. Source: World Bank. 2014. World Bank Open Data. World Bank. Available: <http://data.worldbank.org/> [accessed Sep 5, 2014].

³Used to calculate number of women breastfeeding. Source: USAID (United States Agency for International Development). 2012. Demographic and Health Surveys via Stat Compiler. ICF international. Available: <http://www.statcompiler.com> [accessed Aug 28, 2014], and other references (see methods).

⁴Used to calculate lowest safe body weight. Sources:

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