Is elevated CO_2 a driver of global dryland greening?

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Supplementary Appendix S1. List of references used to collect database for this study

1. Adair, E.C., Reich, P.B., Trost, J.J. & Hobbie, S.E. Elevated CO_2 stimulates grassland soil respiration by increasing carbon inputs rather than by enhancing soil moisture. Global Change Biology 17, 3546-3563 (2011).

2. Allard, V. et al. Increased quantity and quality of coarse soil organic matter fraction at elevated CO_2 in a grazed grassland are a consequence of enhanced root growth rate and turnover. Plant and Soil 276, 49-60 (2005).

3. Ambus, P. & Robertson, G.P. Fluxes of CH_4 and N_2O in aspen stands grown under ambient and twice-ambient CO_2. Plant and Soil 209, 1-8 (1999).

4. Arnone, J.A. & Bohlen, P.J. Stimulated N_2O flux from intact grassland monoliths after two growing seasons under elevated atmospheric CO_2. Oecologia 116, 331-335 (1998).

5. Bader, M., Hiltbrunner, E. & Korner, C. Fine root responses of mature deciduous forest trees to free air carbon dioxide enrichment (FACE). Functional Ecology 23, 913-921 (2009).

6. Baggs, E.M., Richter, M., Hartwig, U.A. & Cadisch, G. Nitrous oxide emissions from grass swards during the eighth year of elevated atmospheric pCO(2) (Swiss FACE). Global Change Biology 9, 1214-1222 (2003).

7. Baggs, E.M. & Blum, H. CH_4 oxidation and emissions of CH_4 and N_2O from Lolium perenne swards under elevated atmospheric CO_2. Soil Biology & Biochemistry 36, 713-723 (2004).

8. Burkart, S., Manderscheid, R. & Weigel, H.J. Interactive effects of elevated atmospheric CO_2 concentrations and plant available soil water content on canopy evapotranspiration and conductance of spring wheat. European Journal of Agronomy 21, 401-417 (2004).

9. Catovsky, S. & Bazzaz, F.A. Elevated CO_2 influences the responses of two birch species to soil moisture: implications for forest community structure. Global Change Biology 5, 507-518 (1999).

10. Carrillo, Y., Pendall, E., Dijkstra, F.A., Morgan, J.A. & Newcomb, J.M. Response of soil organic matter pools to elevated CO_2 and warming in a semi-arid grassland. Plant and Soil 347, 339-350 (2011).

11. Conley, M.M. et al. CO_2 enrichment increases water-use efficiency in sorghum. New Phytologist 151, 407-412 (2001).

12. Craine, J.M., Wedin, D.A. & Reich, P.B. The response of soil CO_2 flux to changes in atmospheric $CO_{2,}$ nitrogen supply and plant diversity. Global Change Biology 7, 947-953 (2001).

13. Decock, C. et al. Elevated CO_2 and O_3 modify N turnover rates, but not N_2O emissions in a soybean agroecosystem. Soil Biology & Biochemistry 51, 104-114 (2012).

14. Deng, Q. et al. Responses of soil respiration to elevated carbon dioxide and nitrogen addition in young subtropical forest ecosystems in China. Biogeosciences 7, 315-328 (2010).

15. Dijkstra, F.A. et al. Contrasting effects of elevated CO_2 and warming on nitrogen cycling in a semiarid grassland. New Phytologist 187, 426-437 (2010).

16. Dijkstra, F.A., Morgan, J.A., Follett, R.F. & Lecain, D.R. Climate change reduces the net sink of CH_4 and N_2O in a semiarid grassland. Global Change Biology 19, 1816-1826 (2013).

17. Dubbs, L.L. & Whalen, S.C. Reduced net atmospheric CH_4 consumption is a sustained response to elevated CO_2 in a temperate forest. Biology and Fertility of Soils 46, 597-606 (2010).

18. Edwards, G.R., Clark, H. & Newton, P.C.D. The effects of elevated CO_2 on seed production and seedling recruitment in a sheep-grazed pasture. Oecologia 127, 383-394 (2001).

19. Ellsworth, D.S. CO_2 enrichment in a maturing pine forest: are CO_2 exchange and water status in the canopy affected? Plant Cell and Environment 22, 461-472 (1999).

20. Erbs, M., Franzaring, J., Hogy, P. & Fangmeier, A. Free-air CO_2 enrichment in a wheat-weed assembly - effects on water relations. Basic and Applied Ecology 10, 358-367 (2009).

21. Fatichi, S. & Leuzinger, S. Reconciling observations with modeling: The fate of water and carbon allocation in a mature deciduous forest exposed to elevated CO_2. Agricultural and Forest Meteorology 174, 144-157 (2013).

22. Field, C.B., Lund, C.P., Chiariello, N.R. & Mortimer, B.E. CO_2 effects on the water budget of grassland microcosm communities. Global Change Biology 3, 197-206 (1997).

23. Grunzweig, J.M. & Korner, C. Growth, water and nitrogen relations in grassland model ecosystems of the semi-arid Negev of Israel exposed to elevated CO_2. Oecologia 128, 251-262 (2001).

24. Kettunen, R., Saarnio, S., Martikainen, P. & Silvola, J. Elevated CO_2 concentration and nitrogen fertilisation effects on N_2O and CH_4 fluxes and biomass production of Phleum pratense on farmed peat soil. Soil Biology & Biochemistry 37, 739-750 (2005).

25. Leakey, A.D.B. et al. Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought. Plant Physiology 140, 779-790 (2006).

26. Lecain, D.R., Morgan, J.A., Mosier, A.R. & Nelson, J.A. Soil and plant water relations determine photosynthetic responses of C_3 and C_4 grasses in a semi-arid ecosystem under elevated CO_2. Annals of Botany 92, 41-52 (2003).

27. LeCain, D.R., Morgan, J.A., Hutchinson, G.L., Reeder, J.D. & Dijkstra, F.A. Interactions between elevated atmospheric CO_2 and defoliation on North American rangeland plant species at low and high N availability. Grass and Forage Science 67, 350-360 (2012).

28. Leuzinger, S. & Korner, C. Water savings in mature deciduous forest trees under elevated CO_2. Global Change Biology 13, 2498-2508 (2007).

29. Liu, J.X. et al. CO_2 enrichment increases nutrient leaching from model forest ecosystems in subtropical China. Biogeosciences 5, 1783-1795 (2008).

30. Marhan, S., Kandeler, E., Rein, S., Fangmeier, A. & Niklaus, P.A. Indirect effects of soil moisture reverse soil C sequestration responses of a spring wheat agroecosystem to elevated CO_2. Global Change Biology 16, 469-483 (2010).

31. Matamala, R. & Schlesinger, W.H. Effects of elevated atmospheric CO_2 on fine root production and activity in an intact temperate forest ecosystem. Global Change Biology 6, 967-979 (2000).

32. McCarthy, H.R. et al. Re-assessment of plant carbon dynamics at the Duke free-air CO_2 enrichment site: interactions of atmospheric CO_2 with nitrogen and water availability over stand development. New Phytologist 185, 514-528 (2010).

33. McLain, J.E.T. & Ahmann, D.M. Increased moisture and methanogenesis contribute to reduced methane oxidation in elevated CO_2 soils. Biology and Fertility of Soils 44, 623-631 (2008).

34. Morgan, J.A., LeCain, D.R., Mosier, A.R. & Milchunas, D.G. Elevated CO_2 enhances water relations and productivity and affects gas exchange in C_3 and C_4 grasses of the Colorado shortgrass steppe. Global Change Biology 7, 451-466 (2001).

35. Mosier, A.R., Morgan, J.A., King, J.Y., LeCain, D. & Milchunas, D.G. Soil-atmosphere exchange of CH_4, CO_2, NO_x, and N_2O in the Colorado shortgrass steppe under elevated CO_2. Plant and Soil 240, 201-211 (2002).

36. Nelson, J.A. et al. Elevated CO_2 increases soil moisture and enhances plant water relations in a long-term field study in semi-arid shortgrass steppe of Colorado. Plant and Soil 259, 169-179 (2004).

37. Nendel, C. et al. Testing different CO_2 response algorithms against a FACE crop rotation experiment. Njas-Wageningen Journal of Life Sciences 57, 17-25 (2009).

38. Newton, P.C.D., Carran, R.A. & Lawrence, E.J. Reduced water repellency of a grassland soil under elevated atmospheric CO_2. Global Change Biology 10, 1-4 (2004).

39. Niklaus, P.A., Spinnler, D. & Korner, C. Soil moisture dynamics of calcareous grassland under elevated CO_2. Oecologia 117, 201-208 (1998).

40. Pataki, D.E. et al. Water use of two Mojave Desert shrubs under elevated CO_2. Global Change Biology 6, 889-897 (2000).

41. Pendall, E. et al. Elevated atmospheric CO_2 effects and soil water feedbacks on soil respiration components in a Colorado grassland. Global Biogeochemical Cycles 17 (2003).

42. Pregitzer, K., Loya, W., Kubiske, M. & Zak, D. Soil respiration in northern forests exposed to elevated atmospheric carbon dioxide and ozone. Oecologia 148, 503-516 (2006).

43. Sindhoj, E. et al. Root dynamics in a semi-natural grassland in relation to atmospheric carbon dioxide enrichment, soil water and shoot biomass. Plant and Soil 223, 253-263 (2000).

44. Volk, M., Niklaus, P.A. & Korner, C. Soil moisture effects determine CO_2 responses of grassland species. Oecologia 125, 380-388 (2000).

45. Wall, G.W. et al. Elevated atmospheric CO_2 improved Sorghum plant water status by ameliorating the adverse effects of drought. New Phytologist 152, 231-248 (2001).

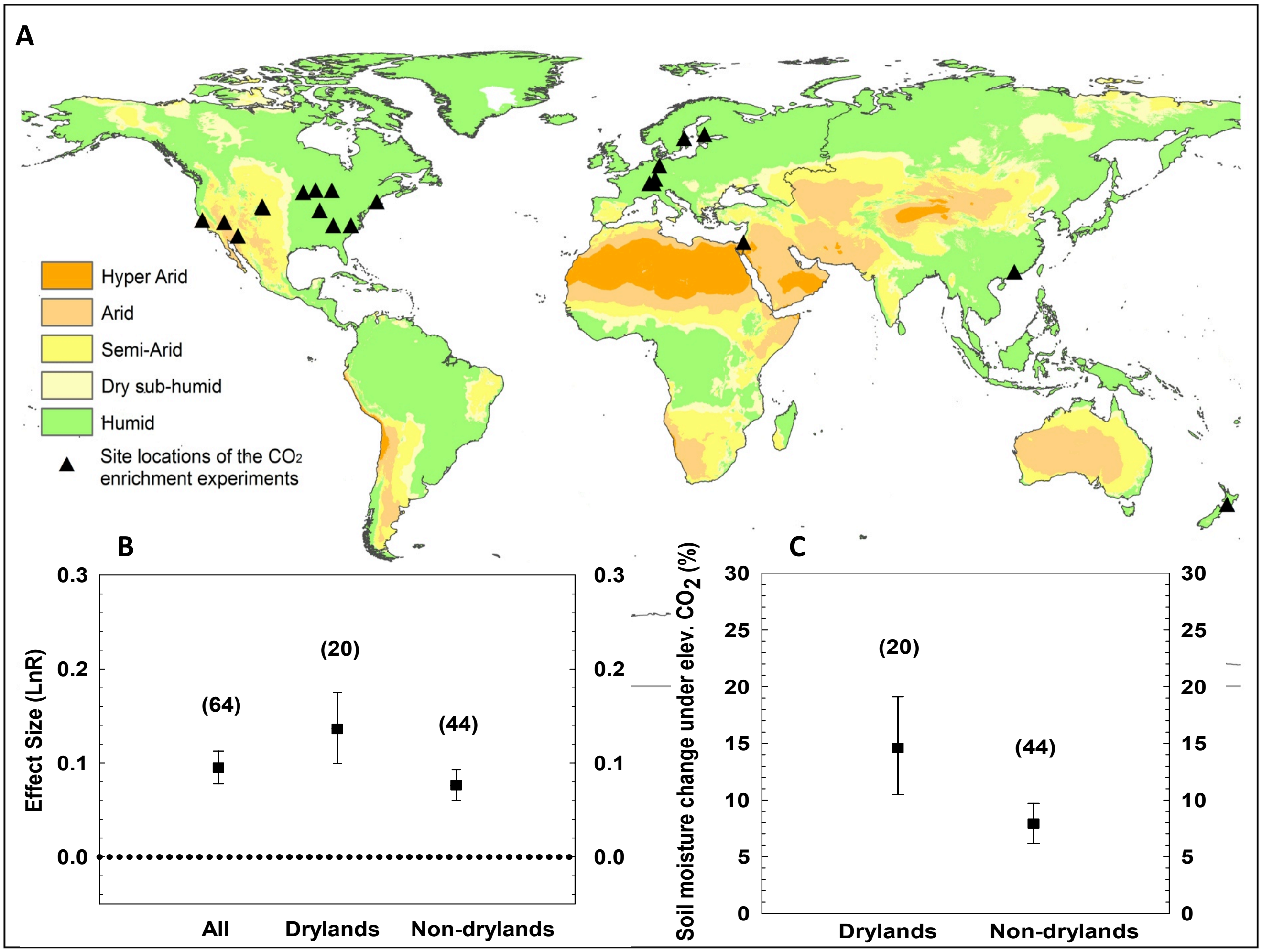

Figure S1. Comparisons of mean effect size and soil moisture response under elevated CO_2 for overall data (including both growing season data and non-growing season data). A. Site locations of the CO_2 enrichment experiments together with globally distributed climate zones based on a standard aridity index formulation (precipitation/potential evapotranspiration); B. Mean effect size of soil water content under elevated CO_2 for the entire data set, under dryland and non-dryland regimes. The effect size was calculated as the natural log of the magnitude of an experimental treatment mean (the soil water under elevated CO_2) relative to the control treatment mean (the soil water under ambient CO_2); C. Enhancement of soil water content under elevated CO_2 for dryland versus non-dryland regimes. The number of cases is shown in brackets. Error bars are bootstrapped confidence intervals (CI). All the statistics are significant at $P < 0.05$. The map was generated using ArcGIS for Desktop 10.3.1 (http://www.arcgis.com).

Table 1 A list of all the individual studies that were included in the meta-analysis. Only growing season data were used for the statistical analysis.
Soil Water Content Method: GSWC: Gravimetric Soil Water Content, VSWC: Volumetric Soil Water Content, PAW: Plant Available Water, WFPS: Water Filled Pore Space.
Vegetation Type: G: Grassland, F: Forest, C: Cropland. Soil Texture: S: Sand, LS: Loamy Sand, SL: Silt Loam, SCL: Silt/Sand Clay Loam, CL: Clay Loam, SDL: Sandy Loam, L: Loam, LC:Loamy Clay.

N°	Source	Location	SWC Method	Vegetation Type	Soil Texture	Soil Depth (cm)	CO_2 Enrich Factor	Sampling Time	Number of Data Points
1	Adair 2011	USA (45°00'N, 93°00'W)	VSWC	G	S	0-17	1.5	Jun - Oct 2006 (Continuous)	1
2	Allard 2005	New Zealand (40°14'S, 175°16'E)	VSWC	G	S	0-15	1.3	Dec 2000 - May 2001, Sept-Dec 2001 (Continuous)	1
3	Ambus 1999	USA (45°34'N, 84°40'W)	WFPS	F	LS	0-15	2	May 1, 28 & July 6	2[1]
4	Arnone 1998	Switzerland (47°28'N, 7°30'E)	GSWC	G	SCL	0-15	1.7	Springtime/Summer	2[2]
5	Bader 2009	Switzerland (47°28'N, 7°30'E)	VSWC	F	SCL	0-10	1.5	Apr - Oct 2007 (Continuous)	1
6	Baggs 2003	Switzerland (47°27'N, 8°41'E)	GSWC	G	CL	0-25	1.7	Jun-Oct 2000, Apr-Jun 2001 (Sampled twice per re-growth period)	1
7	Baggs 2004	Switzerland (47°27'N, 8°41'E)	GSWC	G	CL	0-25	1.7	Jun-Jul 2002 (Sampled periodically after fertilization)	1
8	Burkart 2004	Germany (52°18'N, 10°26'E)	PAW	C	LS	0-50	1.7	Apr – Aug 1998, 1999 (Continuous)	2[3]
9	Catovsky 1999	USA (42°30'N, 71°35'W)	GSWC	F	n/a	n/a	1.9	August 20-28 (Sampled every morning over 8-day watering cycle)	1
10	Carrillo 2011	USA (41°11'N, 104°54'W)	VSWC	G	L	0-20	1.7	Growing season in 2007, 2008 (Continuous)	1
11	Conley 2001	USA (33°06'N, 112°W)	VSWC	C	CL	0-180	1.5	Growing season in 1998, 1999 (Continuous)	2[4]
12	Craine 2001	USA (45°00'N, 93°00'W)	GSWC	G	S	0-20	1.5	Growing season in 1998, 1999	1
13	Decock 2012	USA (40°03'N, 88°12'W)	WFPS	C	SL	5-25	1.5	Growing season in 2005, 2006 (During each phenological stage)	1
14	Deng 2010	China (23°20'N, 113°30'E)	VSWC	F	SDL	0-5	1.9	Apr-Sept 2006, 2007, 2008 (Continuous)	1
15	Dijkstra 2010	USA (40°50'N, 104°42'W)	VSWC	G	L	0-20	1.5	Growing season in 2006 (Continuous)	1
16	Dijkstra 2013	USA (41°11′ N, 104°54′W)	WFPS	G	L	0-10	1.5	Growing season in 2007-2011 (Continuous)	1
17	Dubbs 2010	USA (35°58'N, 79°05'W)	VSWC	F	CL	0-30	1.5	Apr-Oct 2004, 2005, 2006 (Continuous)	1
18	Edwards 2001	New Zealand (40°14'S, 175°16'E)	VSWC	G	S	0-15	1.3	Nov 1998-May 1999, Sept-Dec 1999 (Continuous)	1
19	Ellsworth 1999	USA (35°58'N, 79°05'W)	VSWC	F	CL	0-30	1.5	June - Oct 2007 (Continuous)	1
20	Erbs 2009	Germany (48°42'N, 9°11'E)	VSWC	C	SL	0-30	1.4	May-Aug 2003, Mar-Aug 2004, 2005 (Continuous)	3[5]
21	Fatichi 2013	Switzerland (47°28' N, 7°30' E)	VSWC	F	LC	15-20	1.6	Summer 2004, 2005 (Continuous)	1
22	Field 1997	USA (37°24'N, 122°13'W)	VSWC	G	S	0-15	2	Apr-Jun 1995 (Continuous)	2[6]
23	Grunzweig 2001	Israel (31°21'N, 34°51'E)	GSWC	G	Bedrock	0-35	1.4/1.6	Mar-May 1997 (Measured weekly)	2[7]
24	Kettunen 2005	Finland (60°49′N, 23°30′E)	VSWC	C	Peat	n/a	2	2nd, 5th, 6th Period in May (Continuous)	1
25	Leakey 2006	USA (40°03′N, 88°12′W)	VSWC	C	SCL	5-25	1.5	May-Sept 2004 (Continuous)	1
26	Lecain 2003	USA (40°50'N, 104°42'W)	VSWC	G	SDL	0-100	2	Growing season in 1998, 2000 (Continuous)	1
27	Lecain 2012	USA (41°11'N, 104°54'W)	VSWC	G	SDL	n/a	1.9	Growing season (Continuous)	3[8]
28	Leuzinger 2007	Switzerland (47°28'N, 7°30'E)	VSWC	F	LC	0-90	1.5	Jun-Jul 2004, Jul-Aug 2005	2[9]
29	Liu 2008	China (23°20'N, 113°30'E)	VSWC	F	SDL	0-70	1.9	Jun-Sept 2006, Jan-Mar 2007 (Continuous)	2[10]
30	Marhan 2010	Germany (48°42'N, 9°11'E)	VSWC	C	SL	0-15	1.4	Mar-Oct 2003-2006 (Continuous)	1
31	Matamala 2000	USA (35°58'N, 79°05'W)	VSWC	F	CL	0-30	1.5	May-Oct 1997, Apr-Oct 1998 (Continuous)	1
32	McCarthy 2010	USA (35°58'N, 79°05'W)	VSWC	F	CL	0-30	1.5	May-Oct 1997, Apr-Oct 1998-2004 (Continuous)	1
33	McLain 2008	USA (35°58'N, 79°05'W)	VSWC	F	CL	0-30	1.5	Apr-Oct 2000 (Continuous)	1
34	Morgan 2001	USA (40°40'N, 104°45'W)	VSWC	G	SDL	n/a	2	Growing season in 1997, 1998 (Continuous)	1
35	Mosier 2002	USA (40°50'N, 104°42'W)	VSWC	G	SDL	0-15	1.9	Apr-Oct 1997-2000 (Continuous)	2[11]
36	Nelson 2004	USA (40°49' N, 107°47' W)	VSWC	G	SDL	0-105	2	Apr-Oct 1997-2001 (Continuous)	1
37	Nendel 2009	Germany (52°18'N 10°26'E)	VSWC	C	LS	0-30	1.5	Growing season (Continuous)	1
38	Newton 2003	New Zealand (40°14'S, 175°16'E)	VSWC	G	S	0-15	1.3	Sept-May 1998-2003 (Continuous)	1
39	Niklaus 1998	Switzerland (47°33'N 7°34'E)	VSWC	G	L	0-10	1.7	Mar, Jun, Oct 1995, 1996 (Continuous)	1
40	Pataki 2000	USA (36°49′N, 115°55′W)	VSWC	G	LS	0-20	1.9	Oct-Nov 1998 (Continuous)	1
41	Pendall 2003	USA (40°40′N, 104°45′W)	VSWC	G	SDL	0-15	2	Apr-Oct 1999, 2000 (Continuous)	1
42	Pregitzer 2006	USA (49°40′N, 89°37′E)	VSWC	F	SDL	0-10	1.5	Growing seasons in 2002-2004 (Continuous)	1
43	Sindhoj 2000	Sweden (59°48′N, 17°38′E)	VSWC	G	CL	0-25	1.9	Growing season in 1997, 1998 (Continuous)	1
44	Volk 2000	Switzerland (47°33′N, 7°34′E)	GSWC	G	SCL	0-25	1.7	June - July 2007	1
45	Wall 2001	USA (33.1°N, 112.0°W)	VSWC	C	CL	0-180	1.5	Growing season (Continuous)	1
								Total Studies	**45**
								Total Data Points	**58**

[1] The soil was incubated with low nitrogen and 'high' nitrogen treatment
[3] [4] Crops were treated with two irrigation regimes - well watered vs. drought stress
[7] The experiment was conducted at two different soil texture – rocks vs. sand
[6] FACE experiment was taken at two CO_2 enrichment factors: 1.4 and 1.6
[2] [5] [8] [10] [11] Plants are subject to different climatic regimes
[9] Grassland is treated with nitrogen addition and defoliation or none