Supplementary Material

Low and contrasting impacts of vegetation CO2 fertilization on terrestrial runoff over the past three decades: Accounting for above- and below-ground vegetation-CO2 effects

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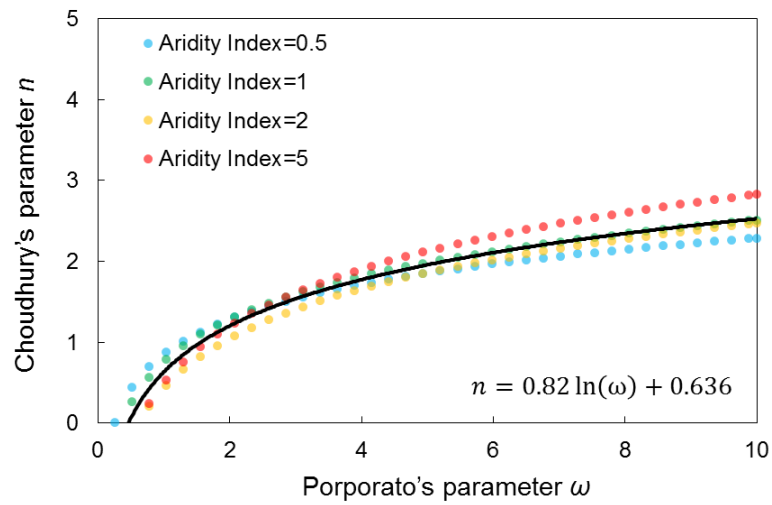
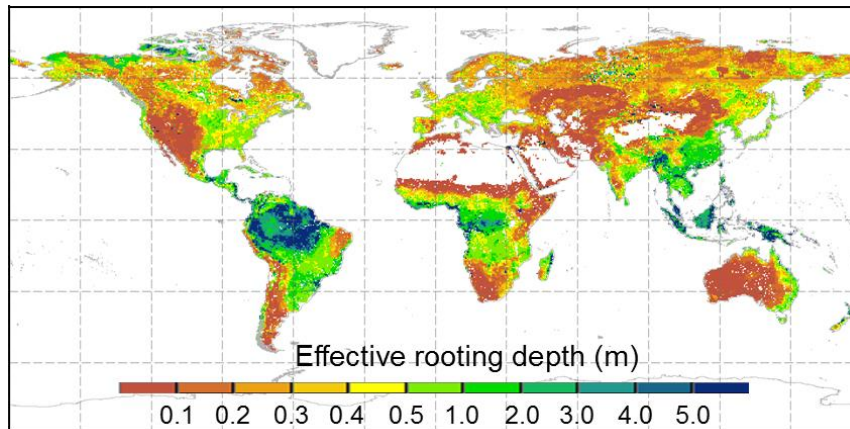
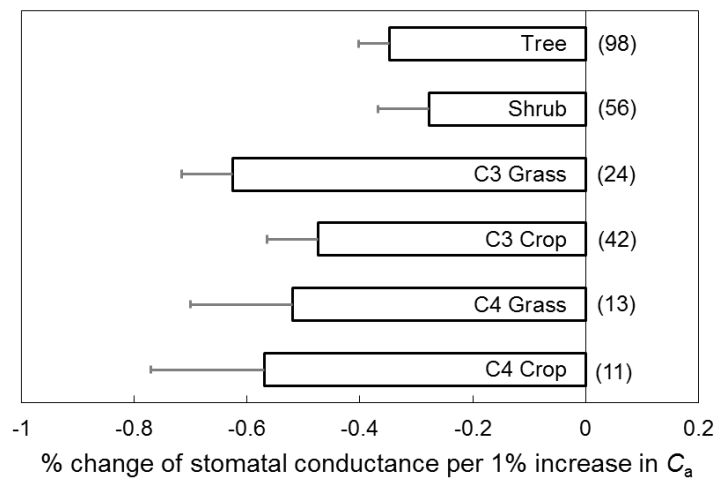
I. Relationship between Porporato's parameter ω and Chourhury's parameter n

Supplementary Figure S1 Relationship between Porporato's parameter ω and Chourhury's parameter n. The black solid curve represents the best fit relationship (R^2=0.96, p<0.001) provided by the equation given on the figure.

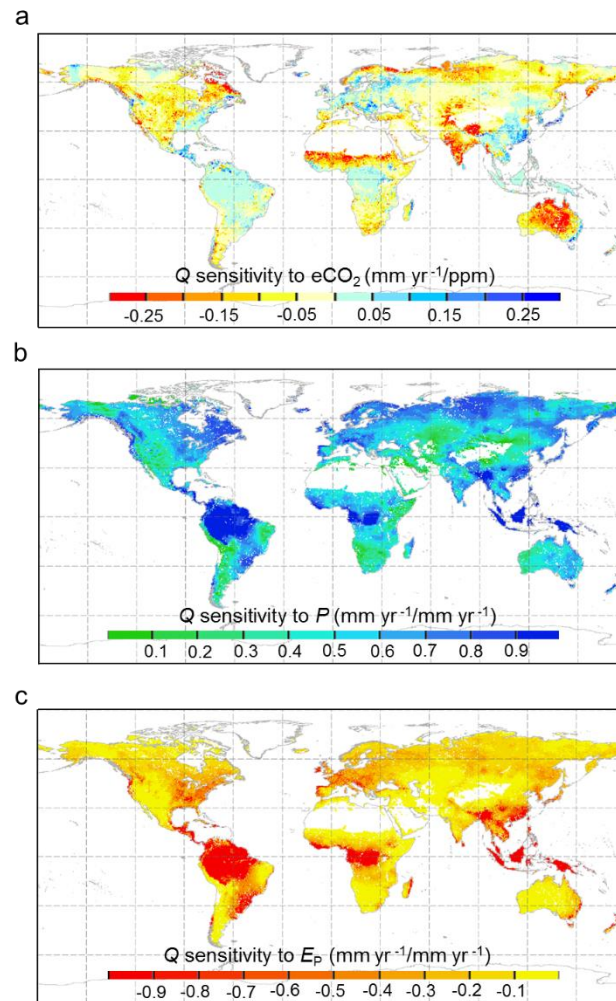
II. Global pattern of effective rooting depth

We estimated the effective rooting depth (Z_e) using an analytical carbon cost-benefit model based on ecosystem optimality theory (4). The climatological mean Z_e during 1982-2010 is shown in Supplementary Figure S2.

Supplementary Figure S2 Global pattern of mean annual effective rooting depth over 1982-2010.

V. Response of stomatal conductance to eCO₂

The response of stomatal conductance (C_s) to eCO$_2$ was determined using meta-analysis based on observations collected from 244 field experiments as summarized in *Ainsworth and Rogers* (5). As the magnitude of eCO$_2$ varies in these 244 experiments, we obtained the sensitivity of C_s to eCO$_2$ (percentage change in C_s per 1% increase in C_a) using linear interpolation. We then classified the 244 observations based on their biome type to construct a biome type-based look-up table of C_s sensitivity to eCO$_2$ (Supplementary Figure S3).

Supplementary Figure S3 Sensitivity of leaf-level stomatal conductance to eCO$_2$. Numbers in the brackets indicate the number of observations in each biome type. Error bars represent one standard deviation among individual observations.

VIII. Sensitivity of *Q* to eCO₂, *P* and *E*ₚ

In addition to showing the relative sensitivity of Q to eCO_2, P and E_P in the main text (Figure 7), here we also show the absolute sensitivity of Q to eCO_2, P and E_P (Supplementary Figure S4). Similar to the relative values, the absolute sensitivity of Q to eCO_2 is higher in dry regions and lower in wet areas (Supplementary Figure S8a). Regarding the absolute sensitivity of Q to P and E_P, both show a higher value in wet regions and smaller value in dry areas (Supplementary Figure S4b and c).

Supplementary Figure S4 Spatial distribution of the absolute sensitivity of Q to (a) eCO_2, (b) P and (c) E_P.

IX. Literature review of observed plant root characteristics in response to eCO$_2$

In the current study, we modeled the response of effective rooting depth (Z_e) to eCO$_2$ and found that Z_e increases with eCO$_2$ across the majority of global terrestrial ecosystems. However, it is impossible to directly validate our modeling result with field observations, as it is impossible to measure rooting depth across large regions. Here, we collected measured response of plant rooting characteristics (i.e., rooting depth and root biomass) to eCO$_2$ from 97 published observations (Supplementary Tables S1 and S2). Among these 97 observations, 86 (88.7%) reported an increased root length and/or root biomass as C_a rises. This is in consistent with our modeling results that eCO$_2$ generally increases the effective rooting depth (i.e., more roots, either in length or biomass). Since there is currently no large scale observations of rooting depth in response to eCO$_2$, the Supplementary Tables S1 and S2 provide an indirect, yet best available observational support for our modeling results.

Supplementary Table S1 Observed percentage changes (mean ± 1 standard deviation) in root characteristics (Δ root) in response to eCO$_2$. n is the number of observations and numbers in the brackets under column n indicates the number of observations showing increased root characteristics in response to eCO$_2$.

Root characteristics	Free-Air CO2 Enrichment			Open Top Chamber / Glasshouse		
	N	eCO$_2$ (%)	Δ root (%)	n	eCO$_2$ (%)	Δ root (%)
Total root Biomass	28 (26)	+52.6 ± 7.0	+34.6 ± 32.7	36 (32)	+91.3 ± 18.3	+38.0 ± 48.6
Total root length	1 (1)	+76.5	+38.8	3 (3)	+90.7 ± 6.9	+33.3 ± 12.5
Fine root biomass	24 (22)	+52.6 ± 8.6	+52.6 ± 35.4	15 (14)	+80.0 ± 25.8	+57.5 ± 52.1
Fine root length	4 (3)	+44.0 ± 7.6	+14.7 ± 11.3	3 (3)	+98.4 ± 1.5	+96.8 ± 74.4

Supplementary Table S2 Summary of observed root characteristics in response to elevation in atmospheric CO_2 concentration. aCO$_2$ in the ambient CO_2 concentration (ppm) and eCO$_2$ in the elevated CO_2 concentration (ppm). DRB is the dry root biomass; TRL is the total root length; DFRB is the dry fine root biomass; FRL is the fine root length. In the Method column, FACE represents Free-Air CO_2 Enrichment, OTC stands for open-top chamber and GH indicates glasshouse. Superscript 1 indicates root biomass in g m^{-2}, superscript 2 indicates root biomass in g per experimental unit, superscript 3 indicates root biomass in g per plant, superscript 4 indicates root length in mm cm^{-2}, superscript 5 indicates root length in m per plant. NR means not reported.

No.	Species	Location		CO_2 concentration (ppm)			DRB [a] or TRL [b]			DFRB [c] or FRL[d]			Method	Reference
		Latitude	*Longitude*	*a*CO$_2$	*e*CO$_2$	Increase	*a*CO$_2$	*e*CO$_2$	Change	*a*CO$_2$	*e*CO$_2$	Change		
1	*Pinus taeda L.*	35.97° N	79.08° W	363	563	200 (55%)	NR	NR	NR	238 [c,1]	325	+87 (36.5%)	FACE	Allen et al. (8)
2	*Calluna vulgaris, Deschampsia flexuosa*	55.88° N	8.68° E	380	510	130 (34.2%)	NR	NR	NR	47 [c,1]	71	+24 (51%)	FACE	Andresen et al. (9)
3	*Mixed forest*	47.47° N	7.5° E	380	550	170 (44.7%)	NR	NR	NR	290 [c,1]	256	-34 (-13.2%)	FACE	Bader et al. (10)
4	*A. capillaris*	53.22° N	4.13° W	340	680	340 (100%)	0.05 [a,3]	0.11	+0.06 (120%)	NR	NR	NR	OTC	Baxter et al. (11)
5	*P. alpine*	53.22° N	4.13° W	340	680	340 (100%)	0.45 [a,3]	0.55	+0.10 (22.2%)	NR	NR	NR	OTC	Baxter et al. (11)
6	*F. vivipara*	53.22° N	4.13° W	340	680	340 (100%)	5.2 [a,3]	2.80	-2.4 (-46.1%)	NR	NR	NR	OTC	Baxter et al. (11)
7	*Lolium perenne*	47.45° N	8.68° E	350	600	250 (71.4%)	1.125 [a,3]	1.25	+0.125 (11.1%)	NR	NR	NR	FACE	Bazot et al. (12)
8	*Sweet potato*	35.78° N	78.68° W	364	666	302 (83%)	59.28 [a,3]	83.18	+23.9 (40.3%)	NR	NR	NR	OTC	Bhattacharya et al. (13)
9	*Scrub-Oak*	28.63° N	80.7° W	363	726	363 (100%)	737 [a,1]	498	-239 (32.4%)	NR	NR	NR	OTC	Brown et al. (14)
10	*P.alba*	42.37° N	11.8° E	370	550	180 (48.6%)	758 [a,1]	1046	+288 (38%)	265 [c,1]	478	+2.13 (80.4%)	FACE	Calfapietra et al. (15)
11	*P.nigra*	42.37° N	11.8° E	370	550	180 (48.6%)	844 [a,1]	1030	+186 (22%)	273 [c,1]	387	+1.14 (41.8%)	FACE	Calfapietra et al. (15)

12	*P. × euramericana*	42.37º N	11.8º E	370	550	180 (48.6%)	787 [a,1]	1011	+224 (28.5%)	295 [c,1]	446	+1.51 (51.2%)	FACE	Calfapietra et al. (15)
13	*Mixed grasses*	41.18º N	104.9º W	383	600	217 (56.7%)	NR	NR	NR	303.4 [c,1]	319	+15.6 (5.1%)	FACE	Carrillo et al. (16)
14	*Prunus persica*	55.87º N	3.2º W	350	700	350 (100%)	15.8 [a,3]	19.8	+4 (25.3%)	NR	NR	NR	OTC	Centritto et al. (17)
15	*Scots Pine*	51.12º N	0.83º W	350	700	350 (100%)	NR	NR	+50% [a,3]	NR	NR	NR	OTC	Crookshanks et al. (18)
16	*Ash*	51.12º N	0.83º W	350	700	350 (100%)	131.3 [a,3]	133.3	+2.0 (1.5%)	30.75 [c,3]	39.25	+8.5 (27.6%)	OTC	Crookshanks et al. (18)
17	*Oak*	51.12º N	0.83º W	350	700	350 (100%)	106.9 [a,3]	133.7	+26.8 (25.1%)	8.75 [c,3]	20.12	+11.37 (130%)	OTC	Crookshanks et al. (18)
18	*Mixed grasses*	45.4º N	93.18º W	378	560	182 (48.1%)	580 [a,1]	715	+135 (23.3%)	410 [c,1]	520	+110 (26.8%)	FACE	Crous et al. (19)
19	*Mixed forbs*	45.4º N	93.18º W	378	560	182 (48.1%)	145 [a,1]	170	+25 (17.2%)	80 [c,1]	125	+45 (56.3%)	FACE	Crous et al. (19)
20	*Oak-palmetto*	28.63º N	80.7º W	350	700	350 (100%)	NR	NR	NR	NR	NR	+63.2% [d,4]	OTC	Day et al. (20)
21	*Sorghum*	33.07º N	111.97º W	373	566	193 (51.7%)	134 [a,1]	161	+27 (20.1%)	NR	NR	NR	FACE	Derner et al. (21)
22	*Cotton*	33.07º N	111.97º W	373	566	193 (51.7%)	41 [a,1]	74.5	+33.5 (81.7%)	NR	NR	NR	FACE	Derner et al. (21)
23	*Quercus myrtifolia* Wasd.	28.63º N	80.7º W	363	713	350 (96.4%)	NR	NR	NR	7 [d,4]	21	+14 (200%)	OTC	Dilustro et al. (22)
24	*Ambrosia*	36.82º N	115.75º W	374	511	137 (36.6%)	NR	NR	NR	14.9 [d,4]	14.6	-0.3 (-0.2%)	FACE	Ferguson et al. (23)
25	*Larrea*	36.82º N	115.75º W	374	511	137 (36.6%)	NR	NR	NR	20.6 [d,4]	22.3	+1.7 (8.3%)	FACE	Ferguson et al. (23)
26	*Mixed grasses*	54.17º N	2.78º W	350	600	250 (71.4%)	2970 [a,1]	4390	+1420 (48%)	NR	NR	NR	OTC	Fitter et al. (24)
27	*Pinus taeda L.*	35.97º N	79.15º W	334	534	200 (59.9%)	NR	NR	NR	363.5 [c,1]	385.4	+21.9 (6%)	FACE	George et al. (25)
28	*Sweetgum*	35.97º N	79.15º W	345	545	200 (58%)	NR	NR	NR	112.6 [c,1]	194.8	+82.8 (73%)	FACE	George et al. (25)
29	*Larix decidua*	46.77º N	9.87º E	370	576	206 (55.7%)	NR	NR	NR	240.5 [c,1]	221.5	-19 (-7.9%)	FACE	Handa et al. (26)
30	*Pinus uncinata*	46.77º N	9.87º E	370	576	206 (55.7%)	NR	NR	NR	261.5 [c,1]	463	+201.5 (77.1%)	FACE	Handa et al. (26)
31	*Mixed grasses*	37.67º N	122.37º W	370	680	310 (83.8%)	NR	NR	NR	185 [c,1]	405	+220 (118.9%)	FACE	Henry et al. (27)
32	*Mixed grasses*	37.4º N	122.22º W	360	720	360 (100%)	36 [a,1]	48	+12 (33.3%)	NR	NR	NR	OTC	Higgins et al. (28)
33	*Lolium perenne*	47.45º N	8.68º E	350	600	250 (71.4%)	6 [a,3]	10.5	+4.5 (75%)	NR	NR	NR	FACE	Hill et al. (29)

34	*Luzula*	46.57° N	8.42° E	385	580	195 (50.6%)	4.2 [a,2]	4.4	+0.2 (4.8%)	NR	NR	NR	FACE	Inauen et al. (30)
35	*Poa*	46.57° N	8.42° E	385	580	195 (50.6%)	0.72 [a,2]	0.73	+0.01 (1.4%)	NR	NR	NR	FACE	Inauen et al. (30)
36	*Ranunculus*	46.57° N	8.42° E	385	580	195 (50.6%)	1.1 [a,2]	0.98	-0.12 (-10.9%)	NR	NR	NR	FACE	Inauen et al. (30)
37	*Veronica*	46.57° N	8.42° E	385	580	195 (50.6%)	0.8 [a,2]	0.82	+0.02 (2.5%)	NR	NR	NR	FACE	Inauen et al. (30)
38	*Sweetgum*	35.9° N	84.33° W	380	560	180 (50%)	NR	NR	NR	209 [c,1]	437	+228 (109%)	FACE	Iverson et al. (31)
39	*Pinus sylvestris L.*	51.22° N	4.41° E	350	750	400 (114%)	130.2 [a,2]	328.5	+198.3 (152%)	13.0 [c,2]	29.6	+16.6 (128%)	OTC	Jach et al. (32)
40	*Loblolly pine forest*	35.97° N	79.083° W	370	570	200 (54%)	NR	NR	NR	248 [c,1]	307	+59 (23.8%)	FACE	Jackson et al. (33)
41	*Pinus sylvestris L.*	51.17° N	4.4° E	350	700	350 (100%)	81.7 [a,3]	184.6	+102.9 (126%)	22 [c,3]	50	+28 (127%)	OTC	Janssens et al. (34)
42	*Mixed grasses*	39.2° N	96.58° W	353	706	353 (100%)	1038 [a,1]	1430	+392 (37.7%)	327 [a,1]	489	+162 (49.5%)	OTC	Jastrow et al. (35)
43	*Lolium perenne, Trifolium repens*	35.97° N	79.08° W	340	600	260 (76.5%)	1020 [b,5]	1410	+390 (38.8%)	NR	NR	NR	FACE	Jongen et al. (36)
44	*Pinus sylvestris L.*	35.97° N	79.083° W	360	720	360 (100%)	NR	NR	NR	NR	NR	+39.9% [c,1]	OTC	Kasurinen et al. (37)
45	*Citrus aurantium L.*	33.42° N	112.1° W	360	760	300 (83.3%)	65 [b,4]	82.3	+17.3 (26.6%)	NR	NR	NR	OTC	Kimball et al. (38)
46	*Wheat*	33.07° N	111.98° W	358	550	192 (53.6%)	NR	NR	+17% [a,1]	NR	NR	NR	FACE	Kimball et al. (39)
47	*Trembling aspen*	45.55° N	84.78° W	360	560	200 (55.6%)	NR	NR	NR	72 [c,1]	124	+52 (72.2%)	OTC	King et al. (40)
48	*Sugar maple*	45.55° N	84.78° W	360	560	200 (55.6%)	NR	NR	NR	142 [c,1]	143	+1 (0.7%)	OTC	King et al. (40)
49	*Aspen*	45.68° N	89.63° W	346	547	201 (58.1%)	NR	NR	NR	261 [c,1]	555	+294 (113%)	FACE	King et al. (41)
50	*Aspen--birth*	45.68° N	89.63° W	346	547	201 (58.1%)	NR	NR	NR	173 [c,1]	317	+144 (83%)	FACE	King et al. (41)

51	*Mixed grasses*	40.85º N	104.72º W	360	720	360 (100%)	920 [a,1]	1030	+110 (12%)	NR	NR	NR	OTC	King et al. (42)
52	*Wheat*	32.6º N	119.7º E	378	578	200 (52.9%)	90.7 [a,1]	96.7	+6 (6.6%)	NR	NR	NR	FACE	Kou et al. (43)
53	*Acacia floribunda*	33.77º S	151.11º E	390	550	160 (41%)	89.5 [a,1]	95.6	+6.1 (6.8%)	33.7 [c,1]	36.0	+2.3 (7.1%)	GH	Lawson et al. (44)
54	*Casuarina cunninghamiana*	33.77º S	151.11º E	390	550	160 (41%)	91.9 [a,1]	172.7	+80.8 (87.9%)	26.3 [c,1]	65.2	+38.9 (147.5%)	GH	Lawson et al. (44)
55	*Eucalyptus camaldulensis*	33.77º S	151.11º E	390	550	160 (41%)	235.7 [a,1]	227.3	-8.4 (0.36%)	41.9 [c,1]	27.5	-14.4 (-34.5%)	GH	Lawson et al. (44)
56	*P. alba*	42.37º N	11.8º E	370	550	180 (48.6%)	NR	NR	+19% [a,1]	NR	NR	NR	FACE	Liberloo et al. (45)
57	*P. nigra*	42.37º N	11.8º E	370	550	180 (48.6%)	NR	NR	+28% [a,1]	NR	NR	NR	FACE	Liberloo et al. (45)
58	*P. ×euramericana*	42.37º N	11.8º E	370	550	180 (48.6%)	NR	NR	+48% [a,1]	NR	NR	NR	FACE	Liberloo et al. (45)
59	*P. alba*	42.62º N	11.81º E	370	550	180 (48.6%)	NR	NR	+47% [a,1]	NR	NR	+35% [c,1]	FACE	Lukac et al. (46)
60	*P. nigra*	42.62º N	11.81º E	370	550	180 (48.6%)	NR	NR	+76% [a,1]	NR	NR	+84% [c,1]	FACE	Lukac et al. (46)
61	*P. × euramericana*	42.62º N	11.81º E	370	550	180 (48.6%)	NR	NR	+71% [a,1]	NR	NR	+53% [c,1]	FACE	Lukac et al. (46)
62	*Pine tree*	35.97º N	70.09º W	365	565	200 (54.8%)	NR	NR	NR	79.8 [c,1]	134.2	+54.4 (68.2%)	FACE	Matamala et al. (47)
63	*Mixed grass and shrub*	40.82º N	104.77º W	360	720	360 (100%)	1.31 [b,4]	1.98	+0.67 (50.8%)	NR	NR	NR	OTC	Milchunas et al. (48)
64	*Pinus echinata seedlings*	35.93º N	84.31º W	368	695	327 (88.9%)	1.92 [a,3]	2.71	+0.79 (41%)	1.00 [c,3]	1.52	+0.52 (52%)	OTC	Norby et al. (49)
65	*Sweetgum*	35.9º N	84.33º W	368	537	169 (45.9%)	254 [a,1]	491	+237 (93.3%)	240 [c,1]	375	+135 (56.3%)	FACE	Norby et al. (50)
66	*Mixed grasses*	39.2º N	96.58º W	357	714	357 (100%)	181 [a,1]	249	+68 (37.6%)	NR	NR	NR	OTC	Owensby et al. (51)
67	*Rice*	31.62º N	120.47º E	375	575	200 (53.3%)	NR	NR	+66% [a,2]	NR	NR	NR	FACE	Pang et al. (52)
68	*Mixed grasses*	40.67º N	104.75º W	360	720	360 (100%)	842 [a,1]	972	+130 (15.4%)	NR	NR	NR	OTC	Pendall et al. (53)

69	*Mixed grasses*	42.7º S	147.27º E	372	549	177 (47.6%)	653 [a,1]	429	-224 (-34.3%)	NR	NR	NR	FACE	Pendall et al. (54)
70	*Pinus ponderosa Dougl. Ex Laws.*	35.97º N	79.08º W	420	690	270 (64%)	NR	NR	NR	485.6 [c,1]	563.5	+77.9 (16%)	OTC	Phillips et al. (55)
71	*Aspen*	45.67º N	89.63º E	356	534	178 (50%)	NR	NR	NR	171 [c,1]	230	+59 (34.5%)	FACE	Pregitzer et al. (56)
72	*Populus*	45.57º N	84.67º W	345	693	348 (101%)	193.3 [a,3]	270	+76.7 (39.7%)	18.3 [c,3]	27.2	+8.9 (48.6%)	OTC	Pregitzer et al. (57)
73	*Populus termuloides*	45.58º N	84.7º W	357	707	350 (98%)	NR	NR	NR	79.8 [c,1]	121	+41.2 (51.6%)	OTC	Pregitzer et al. (58)
74	*Cotton*	33.07º N	111.98º W	370	550	180 (48.6%)	NR	NR	NR	1.73 [d,5]	2.11	+0.38 (22%)	FACE	Prior et al. (59)
75	*Longleaf pine savannahs*	32.1º N	85.08º W	365	720	355 (97.3%)	106.5 [a,1]	115.6	+9.1 (8.5%)	NR	NR	NR	OTC	Pritchard et al. (60)
76	*Red maple, winged elm, sweetgum*	36.15º N	79.97º W	365	565	200 (54.8%)	181.1 [a,1]	228.6	+47.5 (26.2%)	NR	NR	NR	FACE	Pritchard et al. (61)
77	*Pinus taeda L.*	35.97º N	79.08º W	368	567	199 (54%)	NR	NR	NR	NR	NR	+28.6% [d,4]	FACE	Pritchard et al. (62)
78	*Winter wheat*	37.88º N	114.68 º E	358	712	354 (98.9%)	NR	NR	NR	1210 [d,4]	1540	+330 (27.3%)	OTC	Qiao et al. (63)
79	*Phaseolus vulgaris*	55.52º N	3.2º W	350	700	350 (100%)	4.02 [a,3]	4.75	+0.73 (18.2%)	NR	NR	NR	OTC	Radoglou & Jarvis (64)
80	*Birch tree*	55.52º N	3.2º W	350	700	350 (100%)	470 [a,1]	1040	+570 (121%)	200 [c,1]	480	+280 (140%)	OTC	Rey & Jarvis (65)
81	*Wheat*	55.68º N	12.2º E	360	680	320 (88.9%)	17.8 [b,4]	21.8	+4 (22.5%)	NR	NR	NR	OTC	Ronn et al. (66)
82	*Pinus*	32.62º N	85.48º W	365	720	355 (97.3)	1000 [a,1]	1800	+800 (80%)	NR	NR	NR	OTC	Runion et al. (67)
83	*Quercus*	32.62º N	85.48º W	365	720	355 (97.3)	145 [a,1]	165	+20 (13.8%)	NR	NR	NR	OTC	Runion et al. (67)
84	*Aristida*	32.62º N	85.48º W	365	720	355 (97.3)	190 [a,1]	130	-60 (-31.6%)	NR	NR	NR	OTC	Runion et al. (67)
85	*Asclepias*	32.62º N	85.48º W	365	720	355 (97.3)	6.4 [a,1]	3.2	-3.2 (-50%)	NR	NR	NR	OTC	Runion et al. (67)

86	*Crotalaria*	32.62° N	85.48° W	365	720	355 (97.3)	1.9 [a,1]	1.2	-0.7 (-36.8%)	NR	NR	NR	OTC	Runion et al. (67)
87	*Pigeon pea*	28.58° N	77.2° E	387	580	193 (49.9%)	450 [a,1]	600	+150 (33.3%)	NR	NR	NR	OTC	Saha et al. (68)
88	*Mixed grasses*	46.58° N	8.38° E	355	680	325 (91.5%)	80 [a,1]	84.4	+4.4 (5.5%)	NR	NR	NR	OTC	Schappi & Korner (69)
89	*Lolium perenne*	47.45° N	8.68° E	360	600	240 (66.7%)	184 [a,1]	384	+200 (109%)	NR	NR	NR	FACE	Suter et al. (70)
90	*Pinus radiata D. Don*	43.53° S	172.7° E	350	650	300 (85.7%)	NR	NR	NR	NR	NR	+36% [c,1]	OTC	Thomas et al. (71)
91	*Phalaris swards*	35.37° S	149.22° E	375	750	375 (100%)	NR	NR	NR	400 [c,1]	465	+65 (16.3%)	OTC	Volder et al. (72)
92	*Acer rubrum L., Acer saccharum Marsh.*	35.9° N	84.33° W	364	664	300 (82.4%)	NR	NR	NR	NR	NR	+122% [c,1]	OTC	Wan et al. (73)
93	*Birch tree*	55.95° N	3.22° W	350	700	350 (100%)	315.5 [a,3]	511	+195.5 (62%)	110 [c,3]	251	+141 (128%)	OTC	Wang et al. (74)
94	*Mixed grasses*	47.45° N	8.68° E	358	598	240 (67%)	0.48 [a,2]	0.78	+0.3 (62.5%)	NR	NR	NR	FACE	Warwick et al. (75)
95	*Red spring wheat*	33.12° N	111.15° W	370	550	180 (48.6%)	88.8 [a,1]	104.2	+15.4 (17.3%)	NR	NR	NR	FACE	Wechsung et al. (76)
96	*P. tremuloides*	45.57° N	84.67° W	357	707	350 (98%)	3110 [a,2]	4245	+1135 (36.5%)	555 [c,2]	750	+195 (35.1%)	OTC	Zak et al. (77)
97	*Cirsium arvense*	39.03° N	76.9° W	419	762	343 (81.9%)	0.335 [a,2]	0.825	+0.49 (146%)	NR	NR	NR	OTC	Ziska et al. (78)

References in Supporting Information

1. Nemani, R. R. *et al*. Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999. *Science* **300**, 1560-1563 (2003).

2. Budyko, M. I. Climate and life. (Academic, New York, 1974).

3. Yang, Y., Randall, R. J., McVicar, T. R. & Roderick, M. L. An analytical model for relating global terrestrial carbon assimilation with climate and surface conditions using a rate limitation framework. *Geophys. Res. Lett*. **42**, 9825-9835.

4. Guswa, A. J. The influence of climate on root depth: A carbon cost-benefit analysis. *Water Resour. Res*. **44**, WR006384 (2008).

5. Ainsworth, E. A. & Rogers, A. The response of photosynthesis and stomatal conductance to rising [CO_2]: mechanisms and environmental interactions. *Plant, Cell Environ*. **30**, 258-270 (2007).

6. Zhang, Y. *et al*. Multi-decadal trends in global terrestrial evapotranspiration and its components. *Sci. Rep.* **6**, 19124 (2006).

7. Jung, M. *et al*. Global patterns of land-atmosphere fluxes of carbon dioxide, latent heat, and sensible heat derived from eddy covariance, satellite, and meteorological observations. *J. Geophys. Res. Biogeosci.* **116**, JG001566 (2011).

8. Allen, A.S., Andrews, J.A., Finzi, A.C., Matamala, R., Richter, D.D. & Schlesinger, W.H. Effects of free-air CO_2 enrichment (FACE) on belowground processes in a *Pinus taeda* forest. *Ecol. Appl.* **10**, 437-448 (2000).

9. Andresen, L.C., Michelsen, A., Ambus, P. & Beier, C. Belowground heathland responses after 2 years of combined warming, elevated CO_2 and summer drought. *Biogeochemistry* **101**, 27-42 (2010).

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

11. Baxter, R., Ashenden, T.W., Sparks, T.H. & Farrar, J.F. Effects of elevated carbon dioxide on three montane grass species. I. Growth and dry matter partitioning. *J. Exp. Bot.* **45**, 305-315 (1994).

37 12. Bazot, S., Ulff, L., Blum, H., Nguyen, C. & Robin, C. Effects of elevated CO_2

38   concentration on rhizodeposition from *Lolium perenne* grown on soil exposed to

39   9 years of CO_2 enrichment. *Soil Biol. Biochem.* **38**, 729-736 (2006).

40 13. Bhattacharya N.C., *et al*. Interaction of enriched CO_2 and water stress on the

41   physiology of and biomass production in sweet potato grown in open-top

42   chambers. *Plant Cell Environ.* **13**, 933-940 (1990).

43 14. Brown, A.L.P., Day, F.P. & Stover, D.B. Fine root biomass estimates from

44   minirhizotron imagery in a shrub ecosystem exposed to elevated CO_2. *Plant and*

45   *Soil* **317**, 145-153 (2009).

46 15. Calfapietra, C. *et al.* (2003) Free-air CO_2 enrichment (FACE) enhances biomass

47   production in a short-rotation poplar plantation. *Tree Physiol.* **23**, 805-814

48   (2003).

49 16. Carrillo, Y., Pendall, E., Dijkstra, F.A., Morgan, J.A. & Newcomb, J.M.

50   Response of soil organic matter pools to elevated CO_2 and warming in a semi-

51   arid grassland. *Plant and Soil* **347**, 339-350 (2011).

52 17. Centritto, M. The effects of elevated CO_2 and water availability on growth and

53   physiology of peach (*Prunus persica*) plants. *Plant Biosyst.* **136**, 177-188 (2002).

54 18. Crookshanks, M., Taylor, G. & Broadmeadow, M. Elevated CO_2 and tree root

55   growth: contrasting responses in *Fraxinus excelsior*, *Quercus petraea* and *Pinus*

56   *sylvestris*. *New Phytol.* **138**, 241-250 (1998).

57 19. Crous, K.Y., Reich, P.B., Hunter, M.D. & Ellsworth, D.S. Maintenance of leaf N

58   controls the photosynthetic CO_2 response of grassland species exposed to 9 years

59   of free-air CO_2 enrichment. *Global Change Biol.* **16**, 2076-2088 (2010).

60 20. Day, F.P., Weber, E.P., Hinkle, C.R. & Drake, B.G. Effects of elevated

61   atmospheric CO_2 on fine root length and distribution in an oak-palmetto scrub

62   ecosystem in central Florida. *Global Change Biol.* **2**, 143-148 (1996).

63 21. Derner, J.D. *et al.* (2003) Above- and below-ground responses of C_3-C_4 species

64   mixtures to elevated CO_2 and soil water availability. *Global Change Biol.* **9**, 452-

65   460 (2003).

22. Dilustro, J.J., Day, F.P., Drake, B.G. & Hinkle, C.R. Abundance, production and mortality of fine roots under elevated atmospheric CO_2 in an oak-scrub ecosystem. *Environ. Exper. Bot.* **48**, 149-159 (2002).

23. Ferguson, S.D. & Nowak, R.S. Transitory effects of elevated atmospheric CO_2 on fine root dynamics in an arid ecosystem do not increase long-term soil carbon input from fine root litter. *New Phytol.* **190**, 953-967 (2011).

24. Fitter, A.H. *et al*. Root production and turnover and carbon budgets of two contrasting grasslands under ambient and elevated atmospheric carbon dioxide concentrations. *New Phytol.* **137**, 247-255 (1997).

25. George, K., Norby, R.J., Hamilton, J.G. & Delucia, E.H. Fine-root respiration in a loblolly pine and sweetgum forest growing in elevated CO_2. *New Phytol.* **160**, 511-522 (2003).

26. Handa, I.T., Hagedorn, F. & Hattenschwiler, S. No stimulation in root production in response to 4 years of *in situ* CO_2 enrichment at the Swiss treeline. *Funct. Ecol.* **22**, 348-358 (2008).

27. Henry, H., Chiariello, N.R., Vitousek, P.M., Mooney, H.A. & Field, C.B. Interactive effects of fire, elevated carbon dioxide, nitrogen deposition, and precipitation on a California annual grassland. *Ecosystems* **9**, 1066-1075 (2006).

28. Higgins, P., Jackson, R.B., Des Rosiers, J.M. & Field, C.B. Root production and demography in a california annual grassland under elevated atmospheric carbon dioxide. *Global Change Biol.* **8**, 841-850 (2002).

29. Hill, P.W. *et al*. The fate of photosynthetically-fixed carbon in *Lolium perenne* grassland as modified by elevated CO_2 and sward management. *New Phytol.* **173**, 766-777 (2007).

30. Inauen, N., Körner, C. & Hiltbrunner, E. No growth stimulation by CO_2 enrichment in alpine glacier forefield plants. *Global Change Biol.* **18**, 985-999 (2012).

31. Iversen, C.M., Ledford, J., Norby, R.J. CO_2 enrichment increases carbon and nitrogen input from fine roots in a deciduous forest. *New Phytol.* **179**, 837-847

95   (2008).

96   32. Jach, M.E., Laureysens, I., Ceulemans, R. Above- and below-ground production

97   of young Scots pine (*Pinus sylvestris* L.) trees after three years of growth in the

98   field under elevated CO_2. *Ann. Bot.* **85**, 789-798 (2000).

99   33. Jackson, R.B., Cook, C.W., Pippen, J.S. & Palmer, S.M. Increased belowground

100   biomass and soil CO_2 fluxes after a decade of carbon dioxide enrichment in a

101   warm-temperate forest. *Ecology* **90**, 3352-3366 (2009).

102 34. Janssens, I.A., Crookshanks, M., Taylor, G. & Ceulemans, R. Elevated

103   atmospheric CO_2 increases fine root production, respiration, rhizosphere

104   respiration and soil CO_2 efflux in Scots pine seedlings. *Global Change Biol.* **4**,

105   871-878 (1998).

106 35. Jastrow, J.D., Miller, R.M. & Owensby, C.E. Long-term effects of elevated

107   atmospheric CO_2 on below-ground biomass and transformations to soil organic

108   matter in grassland. *Plant and Soil* **224**, 85-97 (2000).

109 36. Jongen, M., Jones, M.B., Hebeisen, T., Blum, H. & Hendrey, G. The effects of

110   elevated CO_2 concentrations on the root growth of *Lolium perenne* and *Trifolium*

111   *repens* grown in a FACE system. *Global Change Biol.* **1**, 361-371 (1995).

112 37. Kasurinen, A., Keinanen, M.M., Kaipainen, S., Nilsson, L.O., Vapaavuori, E.,

113   Kontro, M.H. & Holopainen, T. Below-ground responses of silver birch trees

114   exposed to elevated CO_2 and O_3 levels during three growing seasons. *Global*

115   *Change Biol.* **11**, 1167-1179 (2005).

116 38. Kimball, B.A., Idso, S.B., Johnson, S. & Rillig, M.C. Seventeen years of carbon

117   dioxide enrichment of sour orange trees: final results. *Global Change Biol.* **13**,

118   2171-2183 (2007).

119 39. Kimball, B.A. *et al.* Productivity and water use of wheat under free-air CO_2

120   enrichment. *Global Change Biol.* **1**, 429-442 (1995).

121 40. King, J.S., Pregitzer, K.S., Zak, D.R., Holmes, W.E. & Schmidt, K. Fine root

122   chemistry and decomposition in model communities of north-temperate tree

123   species show little response to elevated atmospheric CO_2 and varying soil

124   resource availability. *Oecologia* **146**, 318-328 (2005).

125   41. King, J.S. *et al.* Fine-root biomass and fluxes of soil carbon in young stands of

126   paper birch and trembling aspen as affected by elevated atmospheric CO_2 and

127   tropospheric O_3. *Oecologia* **128**, 237-250 (2001).

128   42. King, J.Y., Mosier, A.R., Morgan, J.A., Lecain, D.R., Milchunas, D.G. & Parton,

129   W.J. Plant nitrogen dynamics in shortgrass steppe under elevated atmospheric

130   carbon dioxide. *Ecosystems* **7**, 147-160 (2004).

131   43. Kou, T.J., Zhu, J.G., Xie, Z.B., Hasegawa, T. & Heiduk, K. Effect of elevated

132   atmospheric CO_2 concentration on soil and root respiration in winter wheat by

133   using a respiration partitioning chamber. *Plant and Soil* **299**, 237-249 (2007).

134   44. Lawson, J.R., Fryirs, K.A. & Leishman, M.R. Interactive effects of waterlogging

135   and atmospheric CO2 concentration on gas exchange, growth and functional traits

136   of Australian riparian tree seedlings. *Ecohydrology* **10**, e1803 (2017).

137   45. Liberloo, M. *et al.* Woody biomass production during the second rotation of a

138   bio-energy Populus plantation increases in a future high CO_2 world. *Global*

139   *Change Biol.* **12**, 1094-1106 (2006).

140   46. Lukac, M., Calfapietra, C. & Godbold, D.L. Production, turnover and

141   mycorrhizal colonization of root systems of three *Populus* species grown under

142   elevated CO_2 (POPFACE). *Global Change Biol.* **9**, 838-848 (2003).

143   47. Matamala, R. & Schlesinger, W.H. Effects of elevated atmospheric CO_2 on fine

144   root production and activity in an intact temperate forest ecosystem. *Global*

145   *Change Biol.* **6**, 967-979 (2000).

146   48. Milchunas, D.G., Morgan, J.A., Mosier, A.R. & Lecain, D.R. Root dynamics and

147   demography in shortgrass steppe under elevated CO_2, and comments on

148   minirhizotron methodology. *Global Change Biol.* **11**, 1837-1855 (2005).

149   49. Norby, R.J., O'Neill, E.G., Hood, W.G. & Luxmoore, R.J. Carbon allocation,

150   root exudation and mycorrhizal colonization of Pinus echinata seedlings grown

151   under CO2 enrichment. *Tree Physiol.* **3**, 302-210 (1987).

152   50. Norby, R.J. *et al.* Net primary productivity of a CO2-enriched deciduous forest

153   and the implications for carbon storage. *Ecol. Appl.* **12**, 1261-1266 (2002).

154   51. Owensby, C.E., Ham, J.M., Knapp, A.K. & Auen, L.M. Biomass production and

155   species composition change in a tallgrass prairie ecosystem after long-term

156   exposure to elevated atmospheric CO_2. *Global Change Biol.* **5**, 497-506 (1999).

157   52. Pang, J. *et al.* A new explanation of the N concentration decrease in tissues of

158   rice (*Oryza sativa* L.) exposed to elevated atmospheric pCO_2. *Environ. Exper.*

159   *Bot.* **57**, 98-105 (2006).

160   53. Pendall, E., Mosier, A.R. & Morgan, J.A. Rhizodeposition stimulated by elevated

161   CO_2 in a semiarid grassland. *New Phytol.* **162**, 447-458 (2004).

162   54. Pendall, E., Osanai, Y., Williams, A.L. & Hovenden, M.J. Soil carbon storage

163   under simulated climate change is mediated by plant functional type. *Global*

164   *Change Biol.* **17**, 505-514 (2011).

165   55. Phillips, D.L., Johnson, M.G., Tingey, D.T., Catricala, C.E., Hoyman, T.L. &

166   Nowak, R.S. Effects of elevated CO_2 on fine root dynamics in a Mojave Desert

167   community: a FACE study. *Global Change Biol.* **12**, 61-73 (2006).

168   56. Pregitzer, K.S., Burton, A.J., King, J.S. & Zak, D.R. Soil respiration, root

169   biomass, and root turnover following long-term exposure of northern forests to

170   elevated atmospheric CO_2 and tropospheric O_3. *New Phytol.* **180**, 153-161 (2008).

171   57. Pregitzer, K.S., Zak, D.R., Curtis, P.S., Kubiske, M.E., Teeri, J.A. & Vogel, C.S.

172   Atmospheric CO_2, soil nitrogen and turnover of fine roots. *New Phytol.* **129**, 579-

173   585 (1995).

174   58. Pregitzer, K.S., Zak, D.R., Maziasz, J., Deforest, J., Curtis, P.S. & Lussenhop, J.

175   Interactive effects of atmospheric CO_2 and soil-N availability on fine roots of

176   *Populus tremuloides*. *Ecol. Appl.* **10**, 18-33 (2000).

177   59. Prior, S.A., Rogers, H.H., Runion, G.B. & Mauney, J.R. Effects of free-air CO_2

178   enrichment on cotton root growth. *Agr. Forest Meteorol.* **70**, 69-86 (1994).

179   60. Pritchard, S.G. *et al.* Root dynamics in an artificially constructed regenerating

180   longleaf pine ecosystem are affected by atmospheric CO_2 enrichment. *Environ.*

181   *Exper. Bot.* **46**, 55-69 (2001a).

182   61. Pritchard, S.G. *et al.* The influence of elevated atmospheric CO_2 on fine root

183   dynamics in an intact temperate forest. *Global Change Biol.* **7**, 829-837 (2001b).

184   62. Pritchard, S.G. *et al.* Fine root dynamics in a loblolly pine forest are influenced

185   by free-air-CO_2-enrichment: a six-year-minirhizotron study. *Global Change Biol.*

186   **14**, 588-602 (2008).

187   63. Qiao, Y.Z. *et al.* Effects of elevated CO_2 concentration on growth and water use

188   efficiency of winter wheat under two soil water regimes. *Agr. Water Manag.* **97**,

189   1742-1748 (2010).

190   64. Radoglou, K.M. & Jarvis, P.G. The effects of CO_2 enrichment and nutrient

191   supply on growth, morphology and anatomy of *Phaseolus vulgaris* seedlings.

192   *Ann. Bot.* **70**, 245-256 (1992).

193   65. Rey, A. & Jarvis, P.G. Growth response of young birch trees (*Betula pendula*

194   Roth.) after four and a half years of CO_2 exposure. *Ann. Bot.* **80**, 809-816 (1997).

195   66. Ronn, R., Ekelund, F. & Christensen, S. Effects of elevated atmospheric CO_2 on

196   protozoan abundance in soil planted with wheat and on decomposition of wheat

197   roots. *Plant and Soil* **251**, 13-21 (2003).

198   67. Runion, G.B. *et al.* Effects of elevated atmospheric carbon dioxide on biomass

199   and carbon accumulation in a model regenerating longleaf pine community. *J.*

200   *Environ. Qual.* **35**, 1478-1486 (2006).

201   68. Saha, S., Chakraborty, D., Lata,, P. & Nagarajan, S. Impact of elevated CO_2 on

202   utilization of soil moisture and associated soil biophysical parameters in pigeon

203   pea (*Cajanus cajan* L.). *Agric. Ecosyst. Environ.* **142**, 213-221 (2011).

204   69. Schappi, B. & Korner, C. Growth responses of an alpine grassland to elevated

205   CO_2. *Oecologia* **105**, 43-52 (1996).

206   70. Suter, D., Frehner, M., Fischer, B.U., Nosberger, J. & Luscher, A. Elevated CO_2

207   increases carbon allocation to the roots of *Lolium perenne* under free-air CO_2

208   enrichment but not in a controlled environment. *New Phytol.* **154**, 65-75 (2002).

209   71. Thomas, S.M., Whitehead, D., Reid, J.B., Cook, F.J., Adams, J.A. & Leckie,

210   A.C. Growth, loss, and vertical distribution of *Pinus radiata* fine roots growing at

ambient and elevated CO_2 concentration. *Global Change Biol.* **5**, 107-121 (1999).

72. Volder, A., Gifford, R.M. & Evans, J.R. Effects of elevated atmospheric CO_2, cutting frequency, and differential day/night atmospheric warming on root growth and turnover of *Phalaris swards*. *Global Change Biol.* **13**, 1040-1052 (2007).

73. Wan, S.Q., Norby, R.J., Pregitzer, K.S., Ledford, J. & O'neill, E.G. CO_2 enrichment and warming of the atmosphere enhance both productivity and mortality of maple tree fine roots. *New Phytologist* **162**, 437-446 (2004).

74. Wang, Y.P., Rey, A. & Jarvis, P.G. Carbon balance of young birch trees grown in ambient and elevated atmospheric CO_2 concentrations. *Global Change Biol.* **4**, 797-807 (1998).

75. Warwick, K.R., Taylor, G. & Blum, H. Biomass and compositional changes occur in chalk grassland turves exposed to elevated CO_2 for two seasons in FACE. *Global Change Biol.* **4**, 375-385 (1998).

76. Wechsung, G. *et al.* The effects of free-air CO_2 enrichment and soil water availability on spatial and seasonal patterns of wheat root growth. *Global Change Biol.* **5**, 519-529 (1999).

77. Zak, D.R., Pregitzer, K.S., Curtis, P.S., Vogel, C.S., Holmes, W.E. & Lussenhop, J. Atmospheric CO_2, soil-N availability, and allocation of biomass and nitrogen by *Populus tremuloides*. *Ecol. Appl.* **10**, 34-46 (2000).

78. Ziska, L.H., Faulkner, S. & Lydon, J. Changes in biomass and root: shoot ratio of field-grown Canada thistle (*Cirsium arvense*), a noxious, invasive weed, with elevated CO_2: implications for control with glyphosate. *Weed Science* **52**, 584-588 (2004).