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 $\omega$ and Chourhury’s parameter $n$

Supplementary Figure S1 Relationship between Porporato’s parameter $\omega$ 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 eCO$_2$

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 eCO$_2$, $P$ 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 ($\Delta$ 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$_2$ (%) | $\Delta$ root (%) | $n$ | eCO$_2$ (%) | $\Delta$ 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. $a$CO$_2$ in the ambient CO$_2$ concentration (ppm) and $e$CO$_2$ 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 | 353 | 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. alpina* | 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. × euramerica*ca | 42.37° N | 11.8° E | 370 | 550 | 180 (48.6%) | 787 | 1011 | +224 (28.5%) | 295 | 446 | +1.51 (51.2%) | FACE | Calfapietra et al. (15) |
| 13 | Mixed grasses | 41.18° N | 104.9° W | 383 | 600 | 217 (56.7%) | NR | NR | NR | 303.4 | 319 | +15.6 (5.1%) | FACE | Carrillo et al. (16) |
| 14 | *Prunus persica* | 55.87° N | 3.2° W | 350 | 700 | 350 (100%) | 15.8 | 19.8 | +4 (25.3%) | NR | NR | NR | OTC | Centritto et al. (17) |
| 15 | Scots Pine | 51.12° N | 0.83° W | 350 | 700 | 350 (100%) | NR | NR | +50% a | NR | NR | NR | OTC | Crookshanks et al. (18) |
| 16 | Ash | 51.12° N | 0.83° W | 350 | 700 | 350 (100%) | 131.3 | 133.3 | +2.0 (1.5%) | 30.75 | 39.25 | +8.5 (27.6%) | OTC | Crookshanks et al. (18) |
| 17 | Oak | 51.12° N | 0.83° W | 350 | 700 | 350 (100%) | 106.9 | 133.7 | +26.8 (25.1%) | 8.75 | 20.12 | +11.37 (130%) | OTC | Crookshanks et al. (18) |
| 18 | Mixed grasses | 45.4° N | 93.18° W | 378 | 560 | 182 (48.1%) | 580 | 715 | +135 (23.3%) | 410 | 520 | +110 (26.8%) | FACE | Crouse et al. (19) |
| 19 | Mixed forbs | 45.4° N | 93.18° W | 378 | 560 | 182 (48.1%) | 145 | 170 | +25 (17.2%) | 80 | 125 | +45 (56.3%) | FACE | Crouse et al. (19) |
| 20 | Oak-palmetto | 28.63° N | 80.7° W | 350 | 700 | 350 (100%) | NR | NR | NR | NR | NR | +63.2% d | OTC | Day et al. (20) |
| 21 | Sorghum | 33.07° N | 111.97° W | 373 | 566 | 193 (51.7%) | 134 | 161 | +27 (20.1%) | NR | NR | NR | FACE | Derner et al. (21) |
| 22 | Cotton | 33.07° N | 111.97° W | 373 | 566 | 193 (51.7%) | 41 | 74.5 | +33.5 (81.7%) | NR | NR | NR | FACE | Derner et al. (21) |
| 23 | *Quercus* | 28.63° N | 80.7° W | 363 | 713 | 350 (96.4%) | NR | NR | NR | 7 | 21 | +14 (200%) | OTC | Dilustro et al. (22) |

**myrtifolia** Wasd.
|   | Species                      | L LAT | N LAT | E LAT | Elev (m) | % Site | lat A | lat B | lat C | lat D | OTC | FACE | Reference                       |
|---|------------------------------|-------|-------|-------|----------|--------|-------|-------|-------|-------|-----|------|---------------------------------|
| 34 | *Luzula*                     | 46.57°| N     | 8.42° | E       | 385    | 580   | 195   | 50.6% | 4.2 a,2 | 4.4 | +0.2 (4.8%) | 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%) | 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%) | 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%) | Inauen et al. (30) |
| 38 | *Sweetgum*                   | 35.9° | N     | 84.3° | W      | 380    | 560   | 180   | 50%   | NR       | NR   | NR   | Iverson et al. (31)          |
| 39 | *Pinus sylvestris*           | 51.22°| N     | 4.41° | E       | 350    | 750   | 400   | 114%  | 130.2 a,2 | 328.5 | +198.3 (126%) | Jach et al. (32)   |
| 40 | Loblolly pine forest         | 35.97°| N     | 79.083°| W     | 370    | 570   | 200   | 54%   | NR       | NR   | NR   | Jackson et al. (33)         |
| 41 | *Loblolly pine forest*       | 51.17°| N     | 4.40° | E       | 350    | 700   | 350   | 100%  | 81.7 a,3 | 184.6 | +102.9 (126%) | Janssens et al. (34) |
| 42 | *Mixed grasses*              | 39.2° | N     | 96.58°| W      | 353    | 706   | 353   | 100%  | 1038 a,1 | 1430 | +392 (37.7%) | 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%) | Jongen et al. (36) |
| 44 | *Pinus sylvestris*           | 35.97°| N     | 79.083°| W     | 360    | 720   | 360   | 100%  | NR       | NR   | NR   | Kasurinen et al. (37)       |
| 45 | *Citrus aurantium*           | 33.42°| N     | 112.1°| W      | 360    | 760   | 300   | 83.3% | 65 b,4 | 82.3 | +17.3 (26.6%) | Kimball et al. (38) |
| 46 | *Wheat*                      | 33.07°| N     | 111.98°| W     | 358    | 550   | 192   | 53.6% | NR       | NR   | +17% a,1 | Kimball et al. (39)       |
| 47 | *Trembling aspen*            | 45.55°| N     | 84.78°| W      | 360    | 560   | 200   | 55.6% | NR       | NR   | 72 c,1 | King et al. (40)             |
| 48 | *Sugar maple*                | 45.55°| N     | 84.78°| W      | 360    | 560   | 200   | 55.6% | NR       | NR   | 142 c,1 | King et al. (40)             |
| 49 | *Aspen*                      | 45.68°| N     | 89.63°| W      | 346    | 547   | 201   | 58.1% | NR       | NR   | 261 c,1 | King et al. (41)             |
| 50 | *Aspen--birth*               | 45.68°| N     | 89.63°| W      | 346    | 547   | 201   | 58.1% | NR       | NR   | 173 c,1 | King et al. (41)             |
|   | Species                  | Longitude | Latitude | Biomass (kg/ha) | Carbon (kg/ha) | Soil Loss (kg/ha) | Study Location |
|---|--------------------------|-----------|-----------|-----------------|----------------|------------------|----------------|
| 51| Mixed grasses            | 40.85° N  | 104.72° W| 360 (100%)      | 920 a,1        | 1030              | King et al. (42) |
| 52| Wheat                    | 32.6° N   | 119.7° E | 378 (52.9%)     | 90.7 a,1       | 96.7              | Kou et al. (43)  |
| 53| Acacia floribunda        | 33.77° S  | 151.11° E| 390 (41%)       | 89.5 a,1       | 95.6              | Lawson et al. (44) |
| 54| Casuarina cunninghamiana | 33.77° S  | 151.11° E| 390 (41%)       | 91.9 a,1       | 172.7             | Lawson et al. (44) |
| 55| Eucalyptus camaldulensis | 33.77° S  | 151.11° E| 390 (41%)       | 235.7 a,1      | 227.3             | Lawson et al. (44) |
| 56| P. alba                  | 42.37° N  | 11.8° E  | 370 (48.6%)     | NR             | NR                | Liberloo et al. (45) |
| 57| P. nigra                 | 42.37° N  | 11.8° E  | 370 (48.6%)     | NR             | NR                | Liberloo et al. (45) |
| 58| P. × euramericana        | 42.37° N  | 11.8° E  | 370 (48.6%)     | NR             | NR                | Liberloo et al. (45) |
| 59| P. alba                  | 42.62° N  | 11.81° E | 370 (48.6%)     | NR             | NR                | Lukac et al. (46) |
| 60| P. nigra                 | 42.62° N  | 11.81° E | 370 (48.6%)     | NR             | NR                | Lukac et al. (46) |
| 61| P. × euramericana        | 42.62° N  | 11.81° E | 370 (48.6%)     | NR             | NR                | Lukac et al. (46) |
| 62| Pine tree                | 35.97° N  | 70.09° W | 365 (54.8%)     | NR             | NR                | Matamala et al. (47) |
| 63| Mixed grass and shrub    | 40.82° N  | 104.77° W| 360 (100%)      | 1.31 b,4       | 1.98              | Milchunas et al. (48) |
| 64| Pinus echinata seedlings | 35.93° N  | 84.31° W | 368 (88.9%)     | 1.92 a,3       | 2.71              | Norby et al. (49) |
| 65| Sweetgum                 | 35.9° N   | 84.33° W | 368 (45.9%)     | 254 a,1        | 491               | Norby et al. (50) |
| 66| Mixed grasses            | 39.2° N   | 96.58° W | 357 (100%)      | 181 a,1        | 249               | Owensby et al. (51) |
| 67| Rice                     | 31.62° N  | 120.47° E| 375 (53.3%)     | NR             | NR                | Pang et al. (52) |
| 68| Mixed grasses            | 40.67° N  | 104.75° W| 360 (100%)      | 842 a,1        | 972               | Pendall et al. (53) |
| Site | Plant Species                  | GPS Latitude | GPS Longitude | Mean Biomass | Standard Deviation | Treatment Target | Treatment Method | Reference |
|------|--------------------------------|--------------|---------------|--------------|-------------------|------------------|-----------------|-----------|
| 69   | Mixed grasses                 | 42.7° N      | 147.27° E     | 372          | 549               | 177 (47.6%)      | NR              | 429       | -224 (-34.3%) | NR       | NR       | NR       | FACE     | Pendall et al. (54) |
| 70   | *Pinus ponderosa* (Dougl. Ex Laws.) | 35.97° N      | 79.08° W      | 420          | 690               | 270 (64%)        | NR              | 429       | -224 (-34.3%) | NR       | NR       | NR       | OTC      | Phillips et al. (55) |
| 71   | Aspen                         | 45.67° N      | 89.63° E      | 356          | 534               | 178 (50%)        | NR              | 270       | +76.7 (39.7%)  | 171 c,1   | 230      | +59 (35.4%) | FACE     | Pregitzer et al. (56) |
| 72   | *Populus*                     | 45.57° N      | 84.67° 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*                     | 45.58° N      | 84.7° W       | 357          | 707               | 350 (98%)        | NR              | 79.8 c,1   | 121       | +41.2 (51.6%)  | NR       | NR       | NR       | OTC      | Pregitzer et al. (58) |
| 74   | Cotton                        | 33.07° N      | 111.98° W     | 370          | 550               | 180 (48.6%)      | NR              | 115.6      | +9.1 (8.5%)    | 1.73 d,5  | 2.11     | +0.38 (22%) | FACE     | Prior et al. (59)    |
| 75   | *Longleaf pine* savannahs     | 32.1° N       | 85.08° 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 | 36.15° N      | 79.97° 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.              | 35.97° N      | 79.08° W      | 368          | 567               | 199 (54%)        | NR              | 270       | +76.7 (39.7%)  | 1210 d,4  | 1540     | +330 (27.3%) | OTC      | Qiao et al. (63)     |
| 78   | Winter wheat                  | 37.88° N      | 114.68° E     | 358          | 712               | 354 (98.9%)      | NR              | 1210 d,4   | 1540     | +330 (27.3%)  | NR       | NR       | NR       | OTC      | Runion et al. (66)   |
| 79   | *Phaseolus vulgaris*           | 55.52° N      | 3.2° W        | 350          | 700               | 350 (100%)       | 4.02 a,3        | 4.75       | +0.73 (18.2%)  | NR       | NR       | NR       | OTC      | Rey & Jarvis (65)    |
| 80   | Birch tree                    | 55.52° N      | 3.2° W        | 350          | 700               | 350 (100%)       | 470 a,1         | 1040       | +570 (121%)    | 200 c,1   | 480      | +280 (140%) | OTC      | Runion et al. (67)   |
| 81   | Wheat                         | 55.68° N      | 12.2° 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*                       | 32.62° N      | 85.48° W      | 365          | 720               | 355 (97.3%)      | 1000 a,1        | 1800       | +800 (80%)     | NR       | NR       | NR       | OTC      | Runion et al. (67)   |
| 83   | *Quercus*                     | 32.62° N      | 85.48° W      | 365          | 720               | 355 (97.3%)      | 145 a,1         | 165        | +20 (13.8%)    | NR       | NR       | NR       | OTC      | Runion et al. (67)   |
| 84   | *Aristida*                    | 32.62° N      | 85.48° W      | 365          | 720               | 355 (97.3%)      | 190 a,1         | 130        | -60 (-31.6%)   | NR       | NR       | NR       | OTC      | Runion et al. (67)   |
| 85   | *Asclepias*                   | 32.62° N      | 85.48° W      | 365          | 720               | 355 (97.3%)      | 6.4 a,1         | 3.2        | -3.2 (-50%)    | NR       | NR       | NR       | OTC      | Runion et al. (67)   |
| Plant Species       | Latitude  | Longitude | Treatment | Temperature | CO2 | Nitrogen | Control | OTC |
|---------------------|-----------|-----------|-----------|-------------|-----|----------|---------|-----|
| Crotalaria          | 32.62° N  | 85.48° W  | 365       | 355 (97.3)  | 1.9 a,1 | 1.2      | -0.7 (-36.8%) | NR | NR | NR | OTC Runion et al. (67) |
| Pigeon pea          | 28.58° N  | 77.2° E   | 387       | 193 (49.9%)  | 450 a,1 | 600      | +150 (33.3%) | NR | NR | NR | OTC Saha et al. (68) |
| Mixed grasses       | 46.58° N  | 8.38° E   | 355       | 325 (91.5%)  | 80 a,1 | 84.4     | +4.4 (5.5%) | NR | NR | NR | OTC Schappi & Korner (69) |
| Lolium perenne      | 47.45° N  | 8.68° E   | 360       | 240 (66.7%)  | 184 a,1 | 384      | +200 (109%) | NR | NR | NR | FACE Suter et al. (70) |
| Pinus radiata D.    | 43.53° S  | 172.7° E  | 350       | 300 (85.7%)  | NR     | NR       | NR      | NR | NR | +36% c,1 | OTC Thomas et al. (71) |
| P. tremuloides      | 45.57° N  | 84.67° W  | 357       | 350 (98%)    | 3110 a,2 | 4245     | +1135 (36.5%) | 555 c,2 | 750 | +195 (35.1%) | OTC Zak et al. (77) |
| Acer rubrum L.      | 35.9° N   | 84.33° W  | 364       | 300 (82.4%)  | NR     | NR       | NR      | NR | NR | +122% c,1 | OTC Wan et al. (73) |
| Mixed grasses       | 47.45° N  | 8.68° E   | 358       | 240 (67%)    | 0.48 a,2 | 0.78     | +0.3 (62.5%) | NR | NR | NR | FACE Warwick et al. (75) |
| Red spring wheat    | 33.12° N  | 111.15° W | 370       | 180 (48.6%)  | 88.8 a,1 | 104.2    | +15.4 (17.3%) | NR | NR | NR | FACE Wechsung et al. (76) |
| P. tremuloides      | 45.57° N  | 84.67° W  | 357       | 350 (98%)    | 3110 a,2 | 4245     | +1135 (36.5%) | 555 c,2 | 750 | +195 (35.1%) | OTC Zak et al. (77) |
| Cirsium arvense     | 39.03° N  | 76.9° W   | 419       | 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 (2016).

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).
12. Bazot, S., Ulff, L., Blum, H., Nguyen, C. & Robin, C. Effects of elevated CO₂ concentration on rhizodeposition from *Lolium perenne* grown on soil exposed to 9 years of CO₂ enrichment. *Soil Biol. Biochem.* **38**, 729-736 (2006).

13. Bhattacharya N.C., *et al.* Interaction of enriched CO₂ and water stress on the physiology of and biomass production in sweet potato grown in open-top chambers. *Plant Cell Environ.* **13**, 933-940 (1990).

14. Brown, A.L.P., Day, F.P. & Stover, D.B. Fine root biomass estimates from minirhizotron imagery in a shrub ecosystem exposed to elevated CO₂. *Plant and Soil* **317**, 145-153 (2009).

15. Calfapietra, C. *et al.* (2003) Free-air CO₂ enrichment (FACE) enhances biomass production in a short-rotation poplar plantation. *Tree Physiol.* **23**, 805-814 (2003).

16. Carrillo, Y., Pendall, E., Dijkstra, F.A., Morgan, J.A. & Newcomb, J.M. Response of soil organic matter pools to elevated CO₂ and warming in a semi-arid grassland. *Plant and Soil* **347**, 339-350 (2011).

17. Centritto, M. The effects of elevated CO₂ and water availability on growth and physiology of peach (*Prunus persica*) plants. *Plant Biosyst.* **136**, 177-188 (2002).

18. Crookshanks, M., Taylor, G. & Broadmeadow, M. Elevated CO₂ and tree root growth: contrasting responses in *Fraxinus excelsior*, *Quercus petraea* and *Pinus sylvestris*. *New Phytol.* **138**, 241-250 (1998).

19. Crous, K.Y., Reich, P.B., Hunter, M.D. & Ellsworth, D.S. Maintenance of leaf N controls the photosynthetic CO₂ response of grassland species exposed to 9 years of free-air CO₂ enrichment. *Global Change Biol.* **16**, 2076-2088 (2010).

20. Day, F.P., Weber, E.P., Hinkle, C.R. & Drake, B.G. Effects of elevated atmospheric CO₂ on fine root length and distribution in an oak-palmetto scrub ecosystem in central Florida. *Global Change Biol.* **2**, 143-148 (1996).

21. Derner, J.D. *et al.* (2003) Above- and below-ground responses of C₃-C₄ species mixtures to elevated CO₂ and soil water availability. *Global Change Biol.* **9**, 452-460 (2003).
22. Dilustro, J.J., Day, F.P., Drake, B.G. & Hinkle, C.R. Abundance, production and mortality of fine roots under elevated atmospheric CO₂ in an oak-escrub system. *Environ. Exper. Bot.* **48**, 149-159 (2002).

23. Ferguson, S.D. & Nowak, R.S. Transitory effects of elevated atmospheric CO₂ 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 CO₂. *New Phytol.* **160**, 511-522 (2003).

26. Handa, I.T., Hagedorn, F. & Hättenschwiler, S. No stimulation in root production in response to 4 years of *in situ* CO₂ 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 CO₂ and sward management. *New Phytol.* **173**, 766-777 (2007).

30. Inauen, N., Körner, C. & Hiltbrunner, E. No growth stimulation by CO₂ enrichment in alpine glacier forefield plants. *Global Change Biol.* **18**, 985-999 (2012).

31. Iversen, C.M., Ledford, J., Norby, R.J. CO₂ enrichment increases carbon and nitrogen input from fine roots in a deciduous forest. *New Phytol.* **179**, 837-847
32. Jach, M.E., Laureysens, I., Ceulemans, R. Above- and below-ground production of young Scots pine (Pinus sylvestris L.) trees after three years of growth in the field under elevated CO$_2$. *Ann. Bot.* 85, 789-798 (2000).

33. Jackson, R.B., Cook, C.W., Pippen, J.S. & Palmer, S.M. Increased belowground biomass and soil CO$_2$ fluxes after a decade of carbon dioxide enrichment in a warm-temperate forest. *Ecology* 90, 3352-3366 (2009).

34. Janssens, I.A., Crookshanks, M., Taylor, G. & Ceulemans, R. Elevated atmospheric CO$_2$ increases fine root production, respiration, rhizosphere respiration and soil CO$_2$ efflux in Scots pine seedlings. *Global Change Biol.* 4, 871-878 (1998).

35. Jastrow, J.D., Miller, R.M. & Owensby, C.E. Long-term effects of elevated atmospheric CO$_2$ on below-ground biomass and transformations to soil organic matter in grassland. *Plant and Soil* 224, 85-97 (2000).

36. Jongen, M., Jones, M.B., Hebeisen, T., Blum, H. & Hendrey, G. The effects of elevated CO$_2$ concentrations on the root growth of Lolium perenne and Trifolium repens grown in a FACE system. *Global Change Biol.* 1, 361-371 (1995).

37. Kasurinen, A., Keinanen, M.M., Kaipainen, S., Nilsson, L.O., Vapaavuori, E., Kontro, M.H. & Holopainen, T. Below-ground responses of silver birch trees exposed to elevated CO$_2$ and O$_3$ levels during three growing seasons. *Global Change Biol.* 11, 1167-1179 (2005).

38. Kimball, B.A., Idso, S.B., Johnson, S. & Rillig, M.C. Seventeen years of carbon dioxide enrichment of sour orange trees: final results. *Global Change Biol.* 13, 2171-2183 (2007).

39. Kimball, B.A. *et al.* Productivity and water use of wheat under free-air CO$_2$ enrichment. *Global Change Biol.* 1, 429-442 (1995).

40. King, J.S., Pregitzer, K.S., Zak, D.R., Holmes, W.E. & Schmidt, K. Fine root chemistry and decomposition in model communities of north-temperate tree species show little response to elevated atmospheric CO$_2$ and varying soil
resource availability. *Oecologia* **146**, 318-328 (2005).

41. King, J.S. *et al.* Fine-root biomass and fluxes of soil carbon in young stands of paper birch and trembling aspen as affected by elevated atmospheric CO$_2$ and tropospheric O$_3$. *Oecologia* **128**, 237-250 (2001).

42. King, J.Y., Mosier, A.R., Morgan, J.A., Lecain, D.R., Milchunas, D.G. & Parton, W.J. Plant nitrogen dynamics in shortgrass steppe under elevated atmospheric carbon dioxide. *Ecosystems* **7**, 147-160 (2004).

43. Kou, T.J., Zhu, J.G., Xie, Z.B., Hasegawa, T. & Heiduk, K. Effect of elevated atmospheric CO$_2$ concentration on soil and root respiration in winter wheat by using a respiration partitioning chamber. *Plant and Soil* **299**, 237-249 (2007).

44. Lawson, J.R., Fryirs, K.A. & Leishman, M.R. Interactive effects of waterlogging and atmospheric CO2 concentration on gas exchange, growth and functional traits of Australian riparian tree seedlings. *Ecohydrology* **10**, e1803 (2017).

45. Liberloo, M. *et al.* Woody biomass production during the second rotation of a bio-energy Populus plantation increases in a future high CO$_2$ world. *Global Change Biol.* **12**, 1094-1106 (2006).

46. Lukac, M., Calfapietra, C. & Godbold, D.L. Production, turnover and mycorrhizal colonization of root systems of three *Populus* species grown under elevated CO$_2$ (POPFACE). *Global Change Biol.* **9**, 838-848 (2003).

47. 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 Biol.* **6**, 967-979 (2000).

48. Milchunas, D.G., Morgan, J.A., Mosier, A.R. & Lecain, D.R. Root dynamics and demography in shortgrass steppe under elevated CO$_2$, and comments on minirhizotron methodology. *Global Change Biol.* **11**, 1837-1855 (2005).

49. Norby, R.J., O’Neill, E.G., Hood, W.G. & Luxmoore, R.J. Carbon allocation, root exudation and mycorrhizal colonization of Pinus echinata seedlings grown under CO2 enrichment. *Tree Physiol.* **3**, 302-210 (1987).

50. Norby, R.J. *et al.* Net primary productivity of a CO$_2$-enriched deciduous forest
and the implications for carbon storage. *Ecol. Appl.* **12**, 1261-1266 (2002).

51. Owensby, C.E., Ham, J.M., Knapp, A.K. & Auen, L.M. Biomass production and species composition change in a tallgrass prairie ecosystem after long-term exposure to elevated atmospheric CO$_2$. *Global Change Biol.* **5**, 497-506 (1999).

52. Pang, J. *et al.* A new explanation of the N concentration decrease in tissues of rice (*Oryza sativa* L.) exposed to elevated atmospheric pCO$_2$. *Environ. Exper. Bot.* **57**, 98-105 (2006).

53. Pendall, E., Mosier, A.R. & Morgan, J.A. Rhizodeposition stimulated by elevated CO$_2$ in a semiarid grassland. *New Phytol.* **162**, 447-458 (2004).

54. Pendall, E., Osanai, Y., Williams, A.L. & Hovenden, M.J. Soil carbon storage under simulated climate change is mediated by plant functional type. *Global Change Biol.* **17**, 505-514 (2011).

55. Phillips, D.L., Johnson, M.G., Tingey, D.T., Catricala, C.E., Hoyman, T.L. & Nowak, R.S. Effects of elevated CO$_2$ on fine root dynamics in a Mojave Desert community: a FACE study. *Global Change Biol.* **12**, 61-73 (2006).

56. Pregitzer, K.S., Burton, A.J., King, J.S. & Zak, D.R. Soil respiration, root biomass, and root turnover following long-term exposure of northern forests to elevated atmospheric CO$_2$ and tropospheric O$_3$. *New Phytol.* **180**, 153-161 (2008).

57. Pregitzer, K.S., Zak, D.R., Curtis, P.S., Kubiske, M.E., Teeri, J.A. & Vogel, C.S. Atmospheric CO$_2$, soil nitrogen and turnover of fine roots. *New Phytol.* **129**, 579-585 (1995).

58. Pregitzer, K.S., Zak, D.R., Maziasz, J., Deforest, J., Curtis, P.S. & Lussenhop, J. Interactive effects of atmospheric CO$_2$ and soil-N availability on fine roots of *Populus tremuloides*. *Ecol. Appl.* **10**, 18-33 (2000).

59. Prior, S.A., Rogers, H.H., Runion, G.B. & Mauney, J.R. Effects of free-air CO$_2$ enrichment on cotton root growth. *Agr. Forest Meteorol.* **70**, 69-86 (1994).

60. Pritchard, S.G. *et al.* Root dynamics in an artificially constructed regenerating longleaf pine ecosystem are affected by atmospheric CO$_2$ enrichment. *Environ. Exper. Bot.* **46**, 55-69 (2001a).
61. Pritchard, S.G. et al. The influence of elevated atmospheric CO\(_2\) on fine root dynamics in an intact temperate forest. *Global Change Biol.* 7, 829-837 (2001b).

62. Pritchard, S.G. et al. Fine root dynamics in a loblolly pine forest are influenced by free-air-CO\(_2\)-enrichment: a six-year-minirhizotron study. *Global Change Biol.* 14, 588-602 (2008).

63. Qiao, Y.Z. et al. Effects of elevated CO\(_2\) concentration on growth and water use efficiency of winter wheat under two soil water regimes. *Agr. Water Manag.* 97, 1742-1748 (2010).

64. Radoglou, K.M. & Jarvis, P.G. The effects of CO\(_2\) enrichment and nutrient supply on growth, morphology and anatomy of *Phaseolus vulgaris* seedlings. *Ann. Bot.* 70, 245-256 (1992).

65. Rey, A. & Jarvis, P.G. Growth response of young birch trees (*Betula pendula* Roth.) after four and a half years of CO\(_2\) exposure. *Ann. Bot.* 80, 809-816 (1997).

66. Ronn, R., Ekelund, F. & Christensen, S. Effects of elevated atmospheric CO\(_2\) on protozoan abundance in soil planted with wheat and on decomposition of wheat roots. *Plant and Soil* 251, 13-21 (2003).

67. Runion, G.B. et al. Effects of elevated atmospheric carbon dioxide on biomass and carbon accumulation in a model regenerating longleaf pine community. *J. Environ. Qual.* 35, 1478-1486 (2006).

68. Saha, S., Chakraborty, D., Lata., P. & Nagarajan, S. Impact of elevated CO\(_2\) on utilization of soil moisture and associated soil biophysical parameters in pigeon pea (*Cajanus cajan* L.). *Agric. Ecosyst. Environ.* 142, 213-221 (2011).

69. Schappi, B. & Korner, C. Growth responses of an alpine grassland to elevated CO\(_2\). *Oecologia* 105, 43-52 (1996).

70. Suter, D., Frehner, M., Fischer, B.U., Nosberger, J. & Luscher, A. Elevated CO\(_2\) increases carbon allocation to the roots of *Lolium perenne* under free-air CO\(_2\) enrichment but not in a controlled environment. *New Phytol.* 154, 65-75 (2002).

71. Thomas, S.M., Whitehead, D., Reid, J.B., Cook, F.J., Adams, J.A. & Leckie, A.C. Growth, loss, and vertical distribution of *Pinus radiata* fine roots growing at
ambient and elevated CO₂ concentration. *Global Change Biol.* **5**, 107-121 (1999).

72. Volder, A., Gifford, R.M. & Evans, J.R. Effects of elevated atmospheric CO₂, 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. CO₂ 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 CO₂ 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 CO₂ for two seasons in FACE. *Global Change Biol.* **4**, 375-385 (1998).

76. Wechsung, G. *et al.* The effects of free-air CO₂ 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 CO₂, 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 CO₂: implications for control with glyphosate. *Weed Science* **52**, 584-588 (2004).