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Supplementary information

Contrasting responses of woody and grassland ecosystems to increased CO_2 as water supply varies

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Supplementary Information

Contrasting responses of woody and grassland ecosystems to increased CO_2 as water supply varies

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Supplementary Discussion

Different EAPP responses to iPPT by C_3 and C_4 plants

C_3 and C_4 plants have different carboxylation pathways[1]. C_3 plants use the rubisco (ribulose bisphosphate carboxylase/oxygenase) enzyme to produce a 3-carbon molecule in the first step of carbon fixation, which is also known as the Calvin Cycle. The oxygenase activity of rubisco causes ~25% of fixed carbon to be lost in a process of photorespiration. C_4 plants use an alternate enzyme, PEP (phosphoenolpyruvate carboxylase) to produce a 4-carbon intermediate molecule (malate) in the initial step of carbon fixation. As PEP does not have oxygenase activity, it is more efficient for attaching CO_2 than rubisco. The specialized leaf anatomy in C_4 plants includes two types of photosynthetic cells, which are mesophyll cells on the leaf exterior near stomata containing PEP, and bundle sheath cells in the leaf interior away from stomata containing rubisco. The malate is transported to internal bundle sheath cells and releases CO_2 after decarboxylation, which is then fixed by rubisco as part of the Calvin Cycle. As there is very low oxygen content inside bundle sheath cells, rubisco is less likely to react to O_2 and lose carbon.

With this photosynthetic advantage, C_4 plants have adapted better than C_3 plants to conditions of drought and hot climate as well as to nitrogen and CO_2 limitation. Therefore, C_3 and C_4 plants are expected to respond differently to eCO_2 treatments and water supply. Among 8 grassland sites of the experiments, tallgrass prairies of the Kansas site are dominated by C_4 grasses. Other sites are more or less dominated by C_3 species mixed with C_4 grasses. The experiments at Cedar Creek established separate C_3 and C_4 subplots each with one or more grass species. Only 4 sites (including the Kansas site) have available data identifying C_3 and C_4 species (Extended Data Fig. 1a), which can be used to examine respectively their EAPP responses to iPPT.

With these limited data, the results show that EAPP of C_3 plants are generally consistent in responses, decreasing with increasing iPPT (Extended Data Fig.1b). EAPP of C_3 plants is greater in drier sites (e.g. Wyoming PHACE, Colorado steppe) than a moderately moist site (Cedar Creek). The latter site EAPP became less than 1 under higher iPPT, which means lower production under eCO_2 than under ambient treatments. EAPP of C_4 grasses relating to iPPT appears to be diverse: in drier sites (Wyoming, Colorado), it was insensitive with most EAPP <1, indicating negative impacts of eCO_2 on ANPP; at the moister site of Cedar Creek, EAPP >1, indicating generally positive impacts of eCO_2; and in the tallgrass prairies (Kansas), EAPP decreased from positive impacts of eCO_2 to negative impacts from drier to wetter years (Extended Data Fig. 1a).

The Z-score analyses show that EAPP of C_3 grasses declined with annual precipitation, whereas that of C_4 grasses did not have a clear relationship with annual precipitation (Extended Data Fig. 1b, 1c). However, ANPP enhancement of C_4 grasses was relatively greater when iPPT was near average of annual precipitation at the site (Extended Data Fig. 1c). From those different responses by C_3 and C_4 plants, it seems that productivity of C_3 plants was more enhanced by increased WUE; in contrast, C_4 plants that adapt well to water limitation could promote productivity at higher CO_2 when experiencing conditions slightly away from average precipitation. Both C_3 and C_4 grasses show lower ANPP under eCO_2 than ambient treatments during very wet years, which could be interpreted as relatively more limited nitrogen due to the legacy effect of more consumed soil nitrogen and also possibly more N leaching loss in moister eCO_2 sites due to watersaving[2]. The experiments in the tallgrass prairies dominated by C_4 grasses suggested that the majority of eCO_2 response was due to increased WUE, and that N-limitation was the major constraint with wetter conditions as the N-fertilization experiments at the site enhanced the eCO_2 effect in wetter years[3].

Direct relationships of ANPP-iPPT in forests and grasslands

In the main text, we examined the relationship between ANPP enhancement ratio (EAPP) and iPPT (Fig. 1), which show contrasting response patterns between woody and grassland ecosystems. Here, we examine direct relationships between ANPP and iPPT. Among the 14 experimental sites used in this study that have EAPP data, only 12 sites have ANPP data available, 5 from forest and 7 from grassland sites (the other two sites only have EAPP data) (Supplementary Fig. 2). The ANPP data from those different sites were standardized to Z-scores for overall analyses. We anticipated that temporal autocorrelation at each site is likely to be minimal because analyses aggregated plots at each site and each ANPP is an average of several measurements from several plots. These plots are located separately and designed to avoid spatial pseudo-replication and a single replicate measurement over time (See Supplementary Tables 3-4 for experimental designs and sampling methods). Nevertheless, the Durbin-Watson test was performed for testing temporal autocorrelation. It shows there is no temporal autocorrelation in the ANPP data except a few inconclusive cases (Supplementary Table 9). This also ensures Z-scores of ANPP are independent data entries in the model. The results indicate that ANPP was more enhanced in wetter years with eCO_2 in woody ecosystems, although ANPP under both eCO_2 and ambient treatments was positively related to iPPT (Supplementary Fig. 2c). In grassland ecosystems, ANPP was positively related to iPPT only with ambient CO_2 while there was no significant relationship with iPPT under eCO_2, although eCO_2 enhanced ANPP (Supplementary Fig. 2d). These results further confirm the contrasting patterns of EAPP-iPPT between woody and grassland ecosystems resulted from the previous Z-score analyses (Fig. 1c and 1d).

Interactions affecting EAPP responses to precipitation

Puzzled by the observations (Fig. 1, Fig. 2) that show contrasting responses of EAPP to annual precipitation (iPPT) within woody and grass-dominated ecosystems but similar patterns of $EAPP_{AV}$ responses to MAP across sites, we examined interactive effects of eCO_2 with temporal variations of iPPT on EAPP and with spatial variations of MAP on $EAPP_{AV}$.

We consider that EAPP responses to iPPT at a given site over multiple years were affected by both enhanced WUE and enhanced LAI. As enhanced WUE under eCO_2 was decreased with higher iPPT, the enhanced LAI could increase with iPPT within woody ecosystems to supplement a diminished WUE effect on ANPP (Supplementary Fig. 2c). It is likely that the effect of enhanced LAI exceeded that of decreased WUE within woody ecosystems in order to maintain positive EAPP-iPPT relationships. In contrast, within grassland sites, ELAI did not appear to increase in wetter years enough to provide additional contributions to ANPP enhancement (Supplementary Fig. 2d), and the effect of decreasing WUE likely dominated the EAPP pattern, which declined with iPPT. Greater N limitation in wetter years could also contribute to the decline of EAPP[2].

For the site average of EAPP ($EAPP_{AV}$), annual variability of EAPP influenced by WUE and LAI was averaged, and $EAPP_{AV}$ declined with increasing MAP, mainly reflecting the effect of decreased WUE from drier to moister locations. The seemingly contrary responses to precipitation within compared to across woody ecosystems, as well as between woody and grassland ecosystems, are different manifestations of the combined effects of enhanced WUE and LAI annually at a given site versus averaged across multiple sites along a precipitation gradient.

Impact of eCO_2 on belowground production

Forest enrichment studies indicated that the contribution of BP to total NPP was normally low, ranging from 3 to 16%, depending on nutrient and soil conditions, plant species, and land-use history[4,5]. As mentioned earlier, grasslands have high root:shoot ratios with approximately 56 to 96 % of total plant production in natural grassland systems belowground[6]. Thus, eCO_2 enhancement on BP could be different between grassland and forest ecosystems.

Based on limited data (Supplementary Table 8), we found that BP enhancement ratios (EBP= BPe/BPa) generally are more variable than EAPP in response to iPPT. In the forest sites, EBP could range between 2 and 254%, although overall this contributed little to total NPP at the aspen and loblolly pine sites (both ~2% of NPP) because BP was low to start with. However, the sweetgum site was quite different. In this experiment, enhanced BP could account for 9% of total NPP because of much higher BP and contributed 59% of total enhanced production (compared to 6% in the aspen forest and 9% in the loblolly pine forest).

In the grassland sites, EBP under eCO_2 was not consistent and ranged from changes of -37% to +137% (Supplementary Table 8). At the Jasper Ridge annual grassland, BP was mostly not enhanced (EBP < 1), which could reflect a strategy of reducing C allocation to BP in short-lived annual species with improved soil water conditions. On average, BP was generally higher in the drier Wyoming site compared to the Jasper Ridge annual grassland and Kansas tallgrass prairie under eCO_2 (322, 260, 246 g m^{-2}, respectively), although the relative enhancement ratio (EBP) is higher in the moister Kansas tallgrass site (+26%, -11%, +56%, respectively). The enhanced BP in the Wyoming site contributed more to NPP (37%) and total enhanced production (86%), compared to the moist Kansas tallgrass site for NPP (8%) and total enhanced production (58%).

Higher BP (fine roots) in drier grasslands but moister forests may reflect C allocation strategies for differing resource needs– likely water for drier grasslands but nutrients for moister forests. However, the enhancement ratio, EBP, was higher in moister sites for both forests and grasslands, suggesting similar increased needs for acquiring nutrients with less water stress in both types of ecosystems (Supplementary Table 8). In addition, the relative enhancement ratios in ANPP and BP in the same year were often opposite (i.e. higher EAPP often accompanied a lower EBP, and vice versa)[7], indicating dynamic allocation of enhanced C production to ANPP and BP. This suggests that total NPP enhancement under eCO_2 could not only be greater than ANPP enhancement, but also less sensitive to iPPT than ANPP due to this compensating effect of above-and belowground enhancement ratios. However, ANPP and BP data from more experiments clearly are needed to make robust conclusions.

Supplementary Table 1. CO_2 enrichment sites of woody ecosystems, data sources, and key references

Woody Ecosystem	Location	Long-term climate*	Experiment design**	Data source		Additional References
				ANPP	Annual *PPT* of sites	
Nevada desert shrub	Mojave Desert, NV, USA (36° 46' 30", 115° 57' 45" & 36° 45' 20",115°59' 15")	MAP: 130 mm MAT: 16.9 ºC	FACE, ~550 ppm CO_2; 1998-2002	Nowak *et al.*[8] (Fig. 7); http://cdiac.ornl.gov/ftp/FACE/ndffdata/	Housman *et al.*[9] (Table 1); http://facedata.ornl.gov/ndff/ndff_data_co2weather.html	Naumburg *et al.*[10] Evans *et al.*[11]
Wisconsin aspen-poplar forest	Rhinelander, WI, USA (45.6°N, 89.5°W)	MAP: 800 mm MAT: 5.3 ºC	FACE, ~560 ppm CO_2; 1998-2003	Nowak *et al.*[8] (Fig. 7); Isbrands *et al.*[12] (Table 4); http://facedata.ornl.gov/npp-cdiac.html	NCDC Rhinelander (477113)***	Percy *et al.*[13] Norby *et al.*[4] Karnosky *et al.*[14] Norby & Zak[15]
Florida scrub oak	Merritt Island, FL, USA (28º38'N, 80º42'W)	MAP: 1310 mm MAT: 22.4 ºC	OTC ~700 ppm CO_2; 1996-2007	Seiler *et al.*[16] (Fig. 1c, Fig. 2)	Seiler *et al.*[16] (Fig. 2); NCDC Merritt island (0000FMER); NCDC Titusville (00088942)	Hymus *et al.*[17] Day *et al.*[18] Dijkstra *et al.*[19]
Duke loblolly pines	Duke Forest Chapel Hill, NC, USA (35° 58' N, 79° 05' W)	MAP: 1203 mm MAT: 15.0 ºC	FACE I & FACE II ~550 ppm CO_2; 1994-2004	Oren *et al.*[20] (Fig. 1); McCarthy *et al.*[21] (Table 2, Fig. 5) ; http://facedata.ornl.gov/npp-cdiac.html	NCDC Chapel Hill (311677) http://facedata.ornl.gov/ndff/ndff_data_co2weather.html	Oren *et al.*[22] Delucia *et al.*[23,24] Finzi *et al.*[25] McCarthy *et al.*[26,27] Norby & Zak[14]
Oak Ridge sweetgum plantation	Oak Ridge National Laboratory, Oak Ridge, TN, USA (35º54'N, 84º20'W)	MAP: 1410 mm MAT: 14.7 ºC	FACE ~537 ppm CO_2; 1998-2008	Norby *et al.*[28] (Table 1); http://facedata.ornl.gov/npp-cdiac.html;	NCDC Oak Ridge (406750) http://facedata.ornl.gov/ndff/ndff_data_co2weather.html	Norby *et al.*[4,29,30] Norby & Zak[15]
EucFACE Mature evergreen *Eucalyptus* woodland	Western Sydney, Australia (33°36′S, 150°44′E)	MAP: 809 mm MAT: 17.5ºC	FACE ~550 ppm CO^2; 2013-2016	Jiang *et al.* [31] https://researchdata.edu.au/aboveground-net-primary-2013-2015/754374	Jiang *et al*, [31] Australia BM Hawkesbury (67021) Springwood (63077)	Ellsworth *et al.*[32]

*MAP: Long-term annual precipitation; MAT: long-term mean annual average temperature. The long-term MAP may not be same as the MAP of experimental years in an experimental site, which mostly lasted less than a decade.

** The designed eCO_2 levels are described in the table, and the control CO_2 was the ambient CO_2 for those experimental years.

***For precipitation data, station names and numbers from the U.S. NOAA National Climate Data Center (NCDC) are given when off-site climate data were used.

Supplementary Table 2. CO_2 enrichment sites of grassland ecosystems, data sources, and key references

Grass Ecosystem	Location	Long-term climate	Experiment design	Data source		Other References
				ANPP	Annual PPT of sites	
Wyoming mixed grass prairie (C_3/C_4)	PHACE, High Plains Grasslands Research Station, Cheyenne, WY, USA (41°11'N, 104°54'W)	MAP: 397 mm MAT: 7.2 °C	FACE ~600 ppm CO_2; 2006-2013	Kevin Mueller (personal communication)	Kevin Mueller (personal communication)	Morgan *et al.*[33] Muller *et al.*[7]
Tasmania mixed native grassland (C_3/C_4)	TasFACE Experiment, the Southeastern Tasmania, Australia (42°42'S, 147°16'E)	MAP: 560 mm MAT: 11.6 °C	FACE ~550 ppm CO_2; 2002-2010 (data in this work)	Hovenden *et al.*[2,34] (Fig. 1a).	Hovenden et al.[34] (Fig 1c). Australia BM Melton Mowbray (94201)	Hovenden *et al.*[35,36]
Colorado shortgrass steppe (C_3/C_4)	Center Plains Exp. Range, Nunn, CO, USA (40°50'N, 104°43'W)	MAP: 320 mm MAT: 9.0 °C	OTC ~720 ppm CO_2; 1997-2001	Morgan *et al.*[37] (Fig. 3).	Nowak et al.[8] (Fig. 8) Site data: http://www.ars.usda.gov/Main/docs.htm?docid=11120	Morgan *et al.*[38,39]
Jasper Ridge annual grassland	Jasper Ridge Biological Preserve, CA, USA (37°40'N, 122°23'W)	MAP: 582 mm MAT: 15 °C	FACE ~655 ppm CO_2; 1999-2003	Dukes *et al.*[40] (Fig. 4)	Site data (requested from R Jackson) NCDC Woodside (00049792)	Shaw *et al.*[41]
Cedar Creek perennial prairie (C_3/C_4)	BioCON Experiment, Cedar, MN, USA (45°24'N, 93°12'W)	MAP: 679 mm MAT: 6.4 °C	FACE ~560 ppm CO_2; 1998-2008	Study site: https://www.cedarcreek.umn.edu/research/experiments/e141	Site data http://www.lter.umn.edu/research/data/ NCDC Cedar (211390)	Reich *et al.*[42]
Kansas tallgrass prairie (C_4)	North of Manhattan, KS, USA (39.12°N, 96.35°W)	MAP: 840 mm MAT: 12.7 °C	OTC ~700 ppm CO_2; 1989-1996	Owensby *et al.*[43] (Fig. 3)	NCDC Manhattan (144972)	Owensby *et al.*[3] Knapp *et al.*[44] Jastrow *et al.*[45]
Swiss calcareous grassland*	Nenzlingen, Switzerland (47°33'N, 7°34'E)	MAP: 883 mm MAT: 9.2 °C	SACC ~600 ppm CO_2; 1994-1999	Niklaus & Körner[46] (Fig. 1)	Niklaus & Körner[46] (Table 1)	Körner *et al.*[47]
Swiss meadows**	ETH station, Eschikon, Switzerland (47°27'N, 8°41'E)	MAP: 1108 mm MAT: 8.6 °C	FACE ~600 ppm CO_2; 1993-2002	Hebeisen *et al.*[48] (Fig. 1b); Däpp *et al.*[49] (Fig. 1b); Schneider *et al.*[50] (Fig. 1b)	Hebeisen et al.[48](Table 1); NCDC Zurich (SZ000003700)	Lüscher *et al.*[51, 52] Soussana & Lüscher[53] Schneider *et al.*[54]

* The site used Screen-Aided CO_2 Control (SACC) technology for eCO2 exposure system, which is a middle ground between FACE and traditional OTC.
** Response of *Lolium perenne* using the average data of low and high N fertilization under ambient and elevated CO_2.

Supplementary Table 3. Descriptions of experimental sites of woody ecosystems, experimental designs, data collections and estimation methods

Site	**Plot designs, data, and methods estimating ANPP and annual precipitation**
Nevada desert shrubs	Three plots set for both ambient and eCO2 treatments. Each plot is 25 m in diameter. Growth of shoots (diameter & length) was converted to biomass growth via regressions derived from harvested shoot data. ANPP was estimated as annual biomass growth for eCO_2 and ambient plots. Precipitation was measured at the study site based on precipitation events. Annual PPT (iPPT) was the sum of hydro-year from October to September.
Wisconsin aspen-poplar forest	Three replicates for each control and elevated CO_2 block in treatment rings. Tree stem (D &H) and litterfall were measured. Empirical equations converted stem volume growth to biomass growth. ANPP was stem biomass growth plus leaf biomass and averaged for eCO_2 and ambient plots, which are only available for 2001-2003. For 1998-2000, biomass growth was estimated from volume growth and indices of wood density. Precipitation data were derived from the NCDC Rhinelander station (477113). Annual PPT was the sum of measurement at daily base for a calendar year. LAI estimates refer to the methods applied in the Oak-Ridge deciduous sweetgum sites (the protocols).
Florida scrub-oak woodland	For 16 octagonal OTC chambers (at 2.5m H × 3.45m D_1 × 3.66m D_2), 8 plots with eCO_2 treatment were randomly assigned*[1]. Shoots were counted and stem basal diameters measured at 2–5 cm height. Biomass allometric equations were developed using data from three destructive harvests to calculate aboveground biomass. ANPP was estimated as average biomass increment for eCO2 and control plots, respectively. Precipitation data were derived from the weather station located at the John F. Kennedy Space Center (the location of the study site). Annual PPT was the sum of daily-based measurements for a calendar year.
Duke loblolly pine plantation	For the FACE prototype (plots 7-8 since 1994) and the replicated experiment (plots 1–6 since 1996) of 30m diameter rings, 4 plots received eCO_2 treatment. Empirical allometric equations and wood density were used to calculate wood biomass (stems, branches, coarse roots) based on tree diameters and heights. Tree diameter was measured annually using dendrobands, and height measured in every 5 years and averaged for each year. Leaf litterfall was collected using masses. For 1996-2004, ANPP was estimated as annual increment of wood plus litterfall biomass, averaged for eCO_2 and control plots, respectively. For 1994-1995, only wood NPP are available[22], which was converted to aboveground NPP based on the average fraction of woody NPP to ANPP (0.55) of following years (1997-1999). Precipitation data were from site measurements and a nearby NCDC (311677) station (when site data were not available). Annual PPT was the sum of daily based measurements for a calendar year. LAI estimates of pines[26] depend on measurements and modeling. The optical gap fraction measurements were taken using a LAI-2000 canopy analyzer (Li-Cor, Lincoln, NE, USA). Fresh leaf litter samples were collected and measured optically for leaf area (DIAS, Decagon Devices Inc., Pullman, WA, USA) and oven dried for dry mass. The leaf area and dry mass of the samples were used to determine Specific Leaf Area (SLA, $cm^2\ g^{-1}$), which was also scaled by the ratio of canopy LAI of pines. The dry mass of leaf litter collected through a year and SLA were used to estimate annual leaf area production (L_{prod}). The leaf area loss (L_{loss}) was calculated using litter mass at the time of collection and SLA. A continuous leaf area gain (L_{gain}) was estimated by L_{prod} multiplying the relative leaf area expansion (L_{exp}). L_{exp} was calculated based on relative new needle elongation monitored continuously at lower, middle and upper canopy and the proportional LAI for the position, scaled for the canopy. The dynamic LAI was the previous LAI plus the balance between L_{gain} and L_{loss}. The LAI before the experimental years was estimated using empirical allometric equations.

Oak Ridge sweetgum plantation	Five 25-m diameter plots were laid out in 1997, comprised 2 plots with eCO_2 and 3 plots with ambient CO_2. Dendrobands were set for measuring tree diameters at 1.3m height. Tree basal area (BA) was calculated from the diameter and summed for a plot. Using data from destructive harvests and other measurements, allometric equations were developed to estimate biomass of wood (stem & branches) and coarse roots with BA, tree height, taper index and wood density. Leaf biomass was collected every 2 weeks using 5 baskets in each plot. ANPP*[2] was estimated as mean annual increment of biomass (wood, coarse roots, leaf) for eCO_2 and control plots. ANPP data of 1998-1999 were from the publication[7], while 2000-2008 from the Oak-Ridge website. Precipitation data of 1998-1999 were from the NCDC Oak Ridge station (406750) and other years from the site measurements. Annual precipitation was the sum of daily based measurements for a calendar year. The LAI estimates involved the following process[55]: PAR sensors (LI-190SB, LI-COR, Lincoln, Neb., USA) were mounted to measure PAR above canopy and near the center of each plot at 2 m above the ground. For the period of leaf production, the fractional transmission of PAR (ζ) was calculated and used to estimate LAI based on the relationship between LAI and ζ. Leaf litter was collected in litter traps continuously through growing season until all leaves fell. The data was used to estimate lost leaf mass over time. The fresh leaves were collected at each meter of canopy depth to measure their leaf area (LI-3100 area meter, LI-COR, Lincoln, Neb., USA) and dry mass, then the leaf mass per unit area (LMA) of each layer was estimated. A canopy-averaged LMA was calculated by weighting the LMA of each 1-m layer by the proportion of total leaf area (LAI) in that layer. The lost leaf area was calculated using the litter mass data and LMA. The LAI through the year was estimated as the difference of the transmittance-based LAI and the lost leaf area.
Australia mature evergreen eucalypt woodland	Six circular plots (490 m^2 each) were established in 2010, comprised 3 plots subjected to free-air CO_2 enrichment treatment receiving extra 150 ppm CO_2 input using a computer-controlled pre-dilution method and maintaining CO_2 level at ~550 ppm, while other 3 plots under ambient CO_2 (~ 400 ppm). *Eucalyptus tereticornis* Sm. is the dominant tree species and counts for 98% of the overstory basal area of the sites. Understory vegetation is a diverse mixture of forbs, graminoids and shrubs. The diameters of all trees in the plots were measured at 1.3m height at approximately monthly intervals using manual band dendrometers to monitor stem diameter changes. A species-specific allometric equation for *Eucalyptus tereticornis* was applied to convert diameter increments to aboveground biomass increment. Of a total of 146 trees measured across the ambient and elevated plots, measurements of 87 trees were used by excluding those of suppressed and deformed trees. Eight circular fine-mesh traps each at ~0.2 m^2 were randomly placed in each plot and litterfall was collected monthly to estimate foliage and twig production. Litter was sorted into leaf, twigs, bark, and other materials. In addition, consumption of overstory leaf by insect herbivores was estimated based on insect frass data collected from the circular fine-mesh traps, and a relationship between frass mass and insect-consumed leaf mass[31]. Understory aboveground production was estimated based on biomass harvest, taken between 2015 and 2017*[3]. In this study, ANPP was estimated as the sum of production in stem, foliage, twigs, bark, seeds, insect consumption, and understory plants.

Note: All harvested live biomass materials were taken to laboratories, separated (often for different purposes), dried and weighted for values of dry organic matter.

*1. There were 8 additional plots established as unchambered controls, but the data were not used in this analysis.

*2. To be consistent with the Duke FACE data, coarse root (woody root) biomass was included in calculating aboveground biomass increment.

*3. In this study, understory aboveground production for 2013 and 2014 was estimated using average ratios of understory NPP plus respiration to understory GPP based on understory NPP of 2015 and 2016 with available understory GPP and respiration data for all years[29].

Supplementary 4. Descriptions of experimental sites of grassland ecosystems, experimental designs, data collections and estimation methods

Site	**Plot designs, data, and methods estimating ANPP and annual precipitation**
Wyoming mixed grass prairie (C_3/C_4)	Plots were circular with a 3.3 m diameter. Each treatment (control and eCO_2)*[1] was applied to 5 plots. Plant aboveground biomass was measured annually in mid-July when near its maximum, which was sampled by clipping half the quadrats in a harvest area (1.5 m^2 per plot). Vegetation include C_3 and C_4 grasses and C_3 forbs. ANPP was estimated as aboveground biomass per square meters, averaged for eCO_2 and control plots, respectively. Precipitation data were from PHACE site measurements. Annual precipitation was the sum of daily measurements for a calendar year.
Tasmania mixed native grassland (C_3/C_4)	1.5 m FACE rings, 3 replicate plots were designed for ambient CO_2 and eCO_2 only treatments*[2]. Vegetation includes perennial C_3, C_4 grasses and forbs. Above-ground biomass was sampled annually by clipping to 2mm above the ground surface at the end of summer in one quadrat (20 x20 cm^2) randomly located in each plot. ANPP was estimated as aboveground biomass per square meters, averaged for eCO_2 and control plots, respectively. Precipitation for each year started from March 1st (autumn). Annual precipitation was the sum of seasonal precipitation totals of autumn, winter, spring and summer (data were derived from the publication).
Colorado shortgrass steppe (C_3/C_4)	Six open-top chambers (4.5 m D x 3.8 m H) were set in 6 plots*[3], 3 with eCO_2 and 3 controls. Aboveground biomass was sampled by clipping half the quadrats in a harvest area (1.73m^2) of each chamber in late July. ANPP was estimated as above-ground biomass per m^2 for eCO_2 and control plots, respectively. Precipitation data were from the site measurements. Annual precipitation was the sum of daily-based measurements for a calendar year.
Jasper Ridge annual grassland	Of 32 plots*[4] at 2 m in diameter, each was divided into 4 equal quadrants for multifactorial treatments. The control and eCO_2 only treatments were replicated at 8 plots, respectively. Aboveground biomass was harvested at the time of peak biomass in an area (141 cm^2) in a quadrant, averaged for estimating ANPP for the treatment. Annual precipitation was summed from daily site measurements for a calendar year.
Cedar Creek perennial prairie (C_3/C_4)	Among 296 individual plots (2 x 2 m^2) in six 20-m diameter rings*[5], 90 plots exposed to eCO_2 only and 90 control to ambient CO_2. A strip (10x100cm) was clipped at just above the soil surface. Two harvests occurred in early June and August in the first 11 experimental years, then the harvest routine changed to once a year in August. For consistency, only the first 11 years' data were used because growth responses to eCO_2 in June and August were different (based on the data) and different harvest rotations affect estimates of biomass responses to eCO_2. The mean value of two harvests was used for each plot. In most years, all plots were sampled, while in some years, only 80% or 50% plots were sampled. ANPP was estimated as harvested aboveground biomass per m^2, averaged for all plots with eCO_2 and ambient CO_2 treatments respectively. C_3 and C_4 data were derived from subplots that were planted with only C_3 or C_4 species for a comparison analysis (Extended Data Fig. 1). Precipitation data were derived from nearby weather station NCDC Cedar (211390). Annual precipitation was the sum of daily-based measurements for a calendar year.
Kansas tallgrass prairie (dominated by C_4)	Open-top chambers (4.5m D x 4.0m H) with three replicates for eCO_2 and three for ambient CO_2 treatment*[6]. For 1989-1990, sampling was made in late May and mid-September by clipping to ground level from two subplots (0.2 x 0.5m) in each plot. For 1991-1996, peak live biomass was sampled in early August by clipping two subplots (50 x 100cm). ANPP was estimated as harvested aboveground biomass per m^2, averaged for all plots with eCO_2 and ambient CO_2, respectively. Precipitation data were derived from nearby weather station NCDC Manhattan (144972). Annual precipitation was the sum of daily-based measurements for a

	calendar year. Leaf area was estimated for each species or species group using a leaf area meter (LI-COR, Model LI-3100) immediately after separation of the samples.
Swiss calcareous grassland	Among 24 plots (each 1.27 m^2), 8 plots selected randomly for eCO_2 treatments with SACC*[7], and 8 for screened ambient CO_2. Samples were collected in the center area (0.82 cm^2) of each plot by clipping at a height of 5 cm aboveground in June and the end of October. ANPP was estimated only using the data of June (peak aboveground biomass) for eCO_2 and ambient treatments. Annual precipitation was from the data table of the publication (see Supplementary Table 2), which was the sum of monthly totals for a calendar year.
Swiss meadows	An eCO_2 and a control plot (18m diameter) were set in each of 3 experimental blocks. Fixed plots (10m^2) of monoculture and bi-species swards (sub-subplots) were fertilized with low or high N level*[8]. Aboveground biomass from the central sample area (1m^2) was harvested at 0.05m height. There were two cutting frequencies (6-8 times & 4 times) for 1993-95, but one (5 times) for 1996-02. ANPP was the mean biomass of the cutting frequencies and sums through growing seasons. ANPP of low and high N levels was also averaged, resulting in 3 replicates for eCO_2 and control treatment. Precipitation data were from a publication (1993-1995) and weather station of WMO Zurich (646066600) (1996-2002) as both datasets were matched. Annual precipitation was the sum of monthly data for a calendar year.

Note: All harvested live biomass materials were taken to laboratories, separated (often based on different purposes), dried and weighted for values of dry organic matter.

*1. Treatments also replicated three times for ambient CO_2-no chamber sites, although that data were not used in this analysis.

*2. The experimental site had established 12 FACE rings, including eCO_2 and warming experiments. Only the replicates from the plots of eCO_2 and ambient CO_2 (without warming) were used in the analysis.

*3. The pasture for the experiment was divided into three blocks, and three 15.5 m^2 circular plots per block were randomly selected for the experimental treatments, including an ambient chamber CO_2 treatment, an elevated chamber CO_2 treatment, and an unchambered control plot of equal ground area. Only the data from chambered eCO_2 and chambered ambient CO_2 were used in this analysis.

*5. The BioCON experiment was designed to manipulate multifactorial experiments including elevated CO_2, N addition, soil warming, and species diversity. A factorial 232 design with three replicate rings and 296 individual split-split plots (subplots) for replicated experiments with combined factors. For this analysis, only the data from control and eCO_2 only plots (~89-94 plots) were used.

*6. The experiment had treatments replicated three times consisted of ambient CO_2-no chamber (A), ambient CO_2 with chamber (CA), and eCO_2 with chamber (CE). The data from CA and CE were used in this analysis.

*7. The site used Screen-Aided CO_2 Control (SACC) technology for eCO_2 exposure system, which is a middle ground between FACE and traditional OTC and superior to OTCs for minimizing microclimate impacts. There were 24 plots in the experiment, and 8 plots were randomly and assigned for unscreened ambient control plots (C), screened ambient plots (A), and eCO2 plots (E), respectively. Only data from A and E plots were used in this analysis.

*8. The experiment was designed as split-split plot for testing growth responses to multifactorial treatments, including eCO_2, N addition, cutting frequency and species. All sub-subplots were fertilized with N either at a low (10-14 g N m^2) or high (40-56 g N m^2) level and had monoculture species (*Trifolium repens* L or *Lolium* perenne L) or mixed bi-species. In this analysis, only the data from monoculture subplots of *Lolium perenne* L were used, which were averaged for cutting frequencies and N additions for comparing growth responses under eCO_2 and ambient CO_2 conditions.

Supplementary Table 5. Linear regression equations between ANPP enhancement ratios (EAPP) and annual precipitation (iPPT, mm) over multiple experimental years within individual experimental sites, represented by regression lines in Fig. 1a and 1b. Bold values represent statistically significant at *p= 0.1.

Within woody ecosystems	**Regression equations**	R^2	*n*	*p*
Nevada desert shrub	EAPP = 0.9645 + 3.0263e^{-3} * iPPT	0.93	4	**0.0349**
Wisconsin aspen-poplar forests	EAPP = -0.0095 + 1.6432e^{-3} * iPPT	0.74	6	**0.0271**
Florida scrub oak	EAPP = -0.1282 + 1.4097e^{-3} * iPPT	0.37	8	**0.1013**
Duke loblolly pine planation	EAPP = 0.9811 + 2.3320e^{-4} * iPPT	0.14	11	0.2538
Oak Ridge sweetgum plantation	EAPP = 0.8475 + 1.8295e^{-4} * iPPT	0.34	11	**0.0578**
EucFACE eucalyptus woodland	EAPP = 0.8837 + 2.1109e^{-4} * iPPT	0.78	4	0.1197
Within grassland ecosystems				
Wyoming mixed grass prairie	EAPP = 1.4882 - 7.9671e^{-4} * iPPT	0.39	8	**0.1008**
Tasmania mixed native grassland	EAPP = 2.2218 - 2.3449e^{-3} * iPPT	0.30	9	0.1298
Colorado shortgrass steppe	EAPP = 2.0027 - 1.5718e^{-3} * iPPT	0.87	5	**0.0219**
Jasper Ridge annual grassland	EAPP = 1.3404 - 3.4948e^{-4} * iPPT	0.06	5	0.6861
Cedar Creek perennial prairie	EAPP = 1.2711 - 1.5435e^{-4} * iPPT	0.11	10	0.3204
Kansas tallgrass prairie	EAPP = 1.6292 - 5.0930e^{-4} * iPPT	0.42	8	**0.0832**
Swiss calcareous grassland	EAPP = 1.3696 - 1.9932e^{-4} * iPPT	0.13	6	0.4881
Swiss meadows	EAPP = 1.3354 - 2.0503e^{-4} * iPPT	0.47	10	**0.0282**

Supplementary Table 6. Linear regression equations between ANPP enhancement ratios (EAPP) and growing season precipitation (mPPT, mm) aggregated for months over multiple experimental years within individual experimental sites (Supplementary Fig. 1.). The growing season is set from March to September in the Northern Hemisphere and September to March in the Southern Hemisphere (†), or uses site data if available. Bold values represent statistically significant at **p*= 0.1.

Within woody ecosystems	**Regression equations**	R^2	*n*	*p*	mPPT
Nevada desert shrub	EAPP = 1.0860 + 7.3998e^{-3} * mPPT	0.74	4	0.1398	Site data[9]
Wisconsin aspen-poplar forests	EAPP = 0.2519 + 1.7369e^{-3} * mPPT	0.70	6	**0.0370**	3 - 9
Florida scrub oak	EAPP = 0.9137 + 5.7035e^{-4} * mPPT	0.03	8	0.6686	3 - 9
Duke loblolly pine planation	EAPP = 1.1601 + 1.3991e^{-4} * mPPT	0.04	11	0.5464	3 - 9
Oak Ridge sweetgum plantation	EAPP = 0.9263 + 1.9774e^{-4} * mPPT	0.23	11	0.1380	3 - 9
†EucFACE eucalyptus woodland	EAPP = 0.8195 + 4.7344e^{-4} * mPPT	0.59	4	0.2303	9 - 3
Within grassland ecosystems					
Wyoming mixed grass prairie	EAPP = 1.3711 - 6.0496e^{-4} * mPPT	0.19	8	0.2745	3 - 9
†Tasmania mixed native grassland	EAPP = 1.8849 - 2.6811e^{-3} * mPPT	0.16	9	0.2823	9 - 3
Colorado shortgrass steppe	EAPP = 1.7899 - 9.6752e^{-4} * mPPT	0.57	5	0.1407	3 - 9
Jasper Ridge annual grassland	EAPP = 1.3996 - 2.0664e^{-3} * mPPT	0.13	5	0.5679	3 - 9
Cedar Creek perennial prairie	EAPP = 1.3798 - 4.0008e^{-4} * mPPT	0.10	11	0.3473	3 - 9
Kansas tallgrass prairie	EAPP = 1.5193 - 4.8957e^{-4} * mPPT	0.43	8	**0.0758**	3 - 9
Swiss calcareous grassland	EAPP = 1.3359 - 2.5437e^{-4} * mPPT	0.14	6	0.4608	3 - 9
Swiss meadows	EAPP = 1.3386 - 3.1745e^{-4} * mPPT	0.55	10	**0.0134**	3 - 9

Note: † is for sites located in Southern Hemisphere.

Supplementary Table 7. Linear regression equations between mean site EAPP ($EAPP_{AV}$) and mean annual precipitation (MAP) across multiple woody and grassland ecosystems, represented by regression lines in Fig. 2. The logistic equation between LAI enhancement ratios (ELAI) and ANPP enhancement ratios (EAPP), represented by the logistic curve in Fig. 3; data from different experimental sites and years were used for curve fitting.

Across-ecosystems	**Regression equations**	R^2	*n*	*p*
Woody & Grassland ecosystems	$EAPP_{AV}$ = 1.3776 - 2.0316e^{-4}*MAP	0.28	14	**0.0515**
Woody ecosystems	$EAPP_{AV}$ = 1.4981 - 2.6226e^{-4}*MAP	0.45	6	0.1463
Grassland ecosystems	$EAPP_{AV}$ = 1.3464 - 2.2883e^{-4}*MAP	0.43	8	**0.0787**
ELAI-EAPP relationships				
Logistic function	EAPP = 0.93 +0.79/(1+EXP(10.98 - 9.07*ELAI))	0.82	38	**<0.0001**

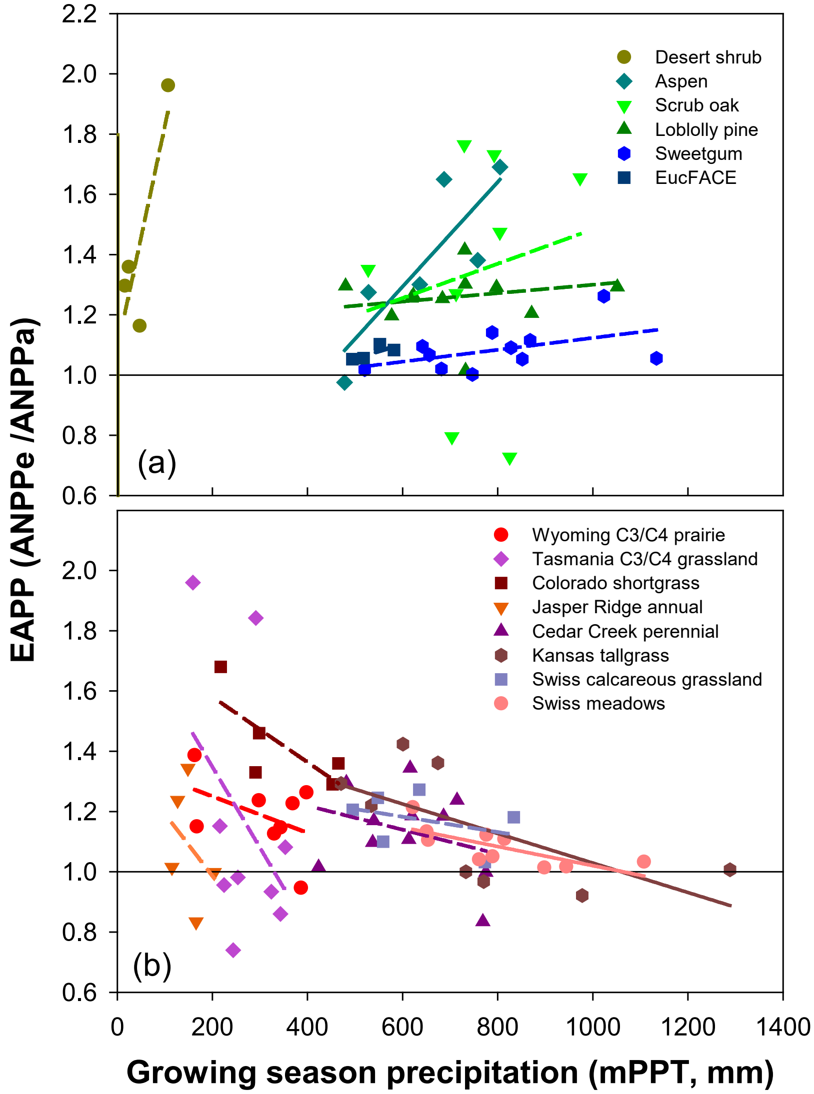
Supplementary Table 8. Fine root productivity of forest and grassland ecosystems under ambient and elevated CO_2 concentration, and enhancement ratios

Site	Year	Fine root productivity (g/m2)		Enhancement ratio	Data Reference
		aCO2	eCO2		
Wisconsin aspen-poplar forest	2001	25	43	1.73	http://facedata.ornl.gov/npp-cdiac.html. More site information refers to Supplementary Table 1
	2002	29	51	1.77	
	2003	45	58	1.28	
Duke loblolly pine forest	1996	52	94	1.81	http://facedata.ornl.gov/npp-cdiac.html. More site information refers to Supplementary Table 1
	1997	31	73	2.35	
	1998	31	73	2.35	
	1999	32	37	1.17	
	2000	33	48	1.45	
	2001	33	48	1.45	
	2002	33	48	1.45	
Oak Ridge sweetgum plantation	1998	157	172	1.09	http://facedata.ornl.gov/npp-cdiac.html. More site information refers to Supplementary Table 1
	1999	239	286	1.20	
	2000	270	536	1.98	
	2001	414	853	2.06	
	2002	245	802	3.27	
	2003	149	317	2.12	
	2004	209	372	1.78	
	2005	96	342	3.54	
	2006	102	254	2.49	
	2007	137	237	1.72	
	2008	105	107	1.02	
Wyoming mixed grass prairie (C_3/C_4)	2007	125	175	1.39	Mueller *et al.*[7]. More site information refers to Supplementary Table 2
	2008	239	238	1.00	
	2009	228	296	1.30	
	2010	287	425	1.48	
	2011	418	450	1.08	
	2012	258	348	1.35	
Jasper Ridge annual grassland	1999	192	231	1.20	Dukes *et al.*[40]. More site information refers to Supplementary Table 1
	2000	343	322	0.94	
	2001	376	276	0.73	
	2002	339	215	0.63	
	2003	276	256	0.93	
Kansas tallgrass prairie (C_4)	1990	115	272	2.37	Owensby *et al.*[43]. More site information refers to Supplementary Table 2
	1991	178	209	1.18	
	1992	281	330	1.18	
	1993	244	216	0.89	
	1994	102	196	1.92	
	1995	138	252	1.83	

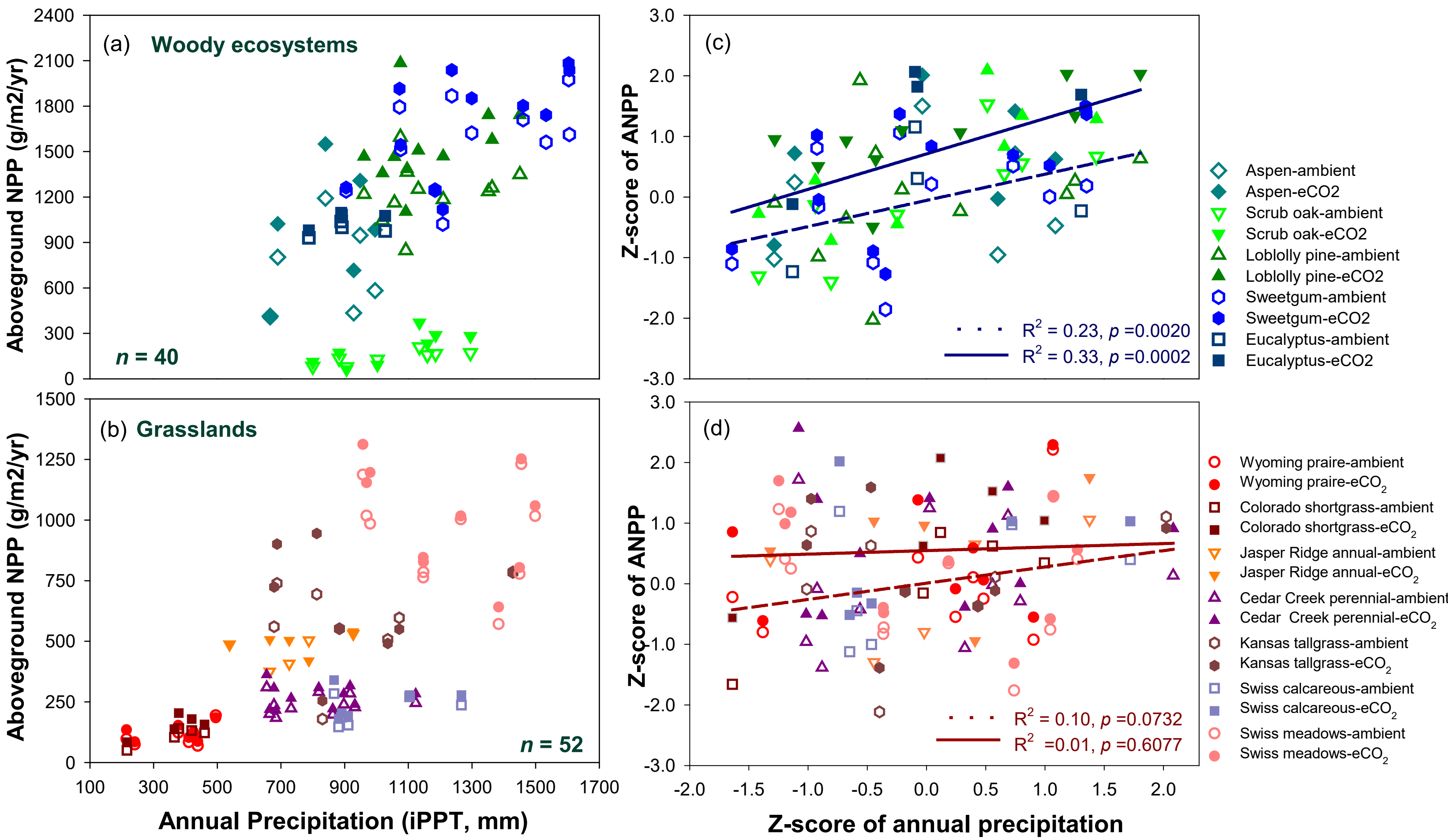
Supplementary Table 9. The Durbin-Watson test for temporal autocorrelation in ANPP data.

Experimental sites	Sampled years *n*	Durbin-Watson Test (D)		Critical values (at 1% significant level)		APPa			APPe		
Woody ecosystem		D (APPa)	D (APPe)	dL	dU	4-D	*Evaluation*	*Result*	4-D	*Evaluation*	*Result*
Wisconsin aspen forest	6	3.395	2.926	0.390	1.142	0.605	dL < 4-D < dU	inconclusive	1.074	dL < 4-D < dU	inconclusive
Florida scrub-oak woodland	8	2.547	2.515	0.497	1.003	1.453	4-D > dU	no autocorrelation	1.485	4-D > dU	no autocorrelation
Duke loblolly pine forest	11	1.271	1.350	0.653	1.010		D > dU	no autocorrelation		D > dU	no autocorrelation
Oak Ridge sweetgum forest	11	1.024	1.263	0.653	1.010		D > dU	no autocorrelation		D > dU	no autocorrelation
Australia Eucalyptus woodland	4	2.357	2.786	0.286	1.264	1.643	4-D > dU	no autocorrelation	1.214	dL <4-D < dU	inconclusive
Grassland ecosystem											
Wyoming mixed grass prairie	8	1.733	1.447	0.497	1.003		D > dU	no autocorrelation		D > dU	no autocorrelation
Colorado shortgrass steppe	5	2.923	2.621	0.343	1.186	1.077	dL < 4-D < dU	inconclusive	1.379	4-D > dU	no autocorrelation
Jasper Ridge annual grassland	5	2.385	3.285	0.343	1.186	1.615	4-D > dU	no autocorrelation	0.715	dL < 4-D < dU	inconclusive
Cedar Creek perennial prairie	11	1.867	1.886	0.653	1.010		D > dU	no autocorrelation		D > dU	no autocorrelation
Kansas tallgrass prairie	8	1.804	2.646	0.497	1.003		D > dU	no autocorrelation	1.354	4-D > dU	no autocorrelation
Swiss calcareous grassland	6	2.689	2.625	0.390	1.142	1.311	4-D > dU	no autocorrelation	1.375	4-D > dU	no autocorrelation
Swiss meadows	10	1.172	0.978	0.604	1.001		D > dU	no autocorrelation		d_L < D < dU	inconclusive

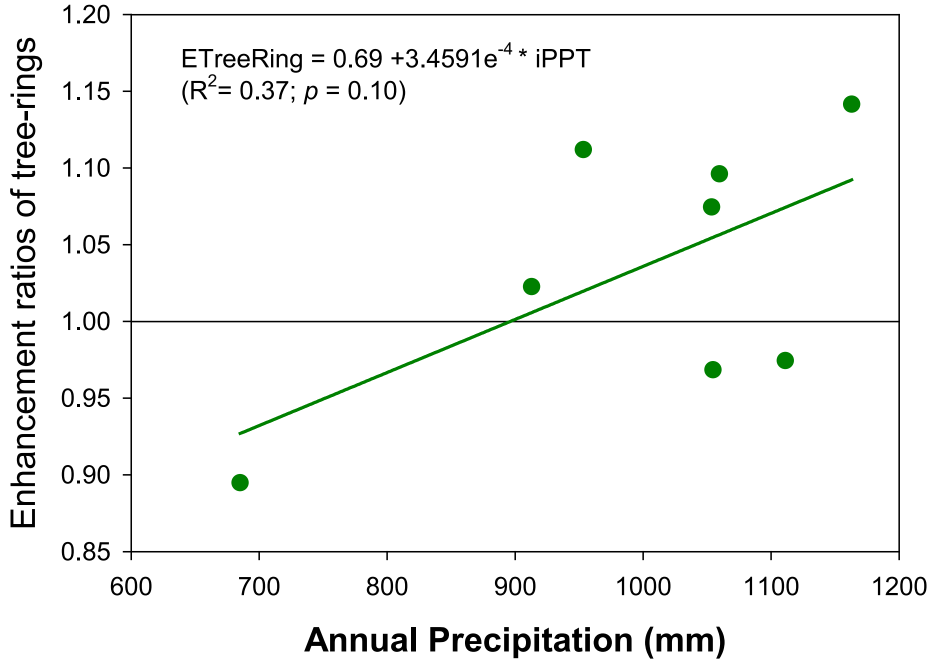
Note: D is the Durbin-Watson test for autocorrelation. The value of D always lies between 0 and 4. If D is close to 2 there is no autocorrelation. The critical value dL and dU is the Lower critical value and the Upper critical value at a given significant level, respectively. When the test value D <2, D is evaluated by dL and dU; while when D > 2. 4-D is evaluated by dL and dU. When D< dL a positive autocorrelation is present, while 4-D <dL a negative autocorrelation is present. When D falls into the range of dL and dU, or 4-dU and 4-dL, the result is inconclusive.



Supplementary Figure 1. Relationships between eCO_2 enhancement of ANPP and growing season precipitation (Supplementary Table 5). EAPP is enhancement ratio of ANPP under eCO_2 (ANPPe) and ambient CO_2 (ANPPa) treatments. (a) EAPP responses to growing season precipitation (mPPT) over multiple experimental years within woody ecosystems, and (b) within grassland ecosystems. At *p= 0.1, solid lines represent statistically significant regressions, dashed lines not significant (Supplementary Table 6).



Supplementary Figure 2. Direct responses of ANPP to iPPT under ambient CO_2 (open symbols) and eCO_2 (solid symbols) in (a) woody and (b) grassland ecosystems (n= 40 and n=53, respectively). Not all sites have ANPP values as some only reported ANPP response ratios (EAPP). Z-score analyses of ANPP responses to iPPT and regression lines under ambient CO_2 (thin line) and eCO_2 (thick line) in (c) woody and (d) grassland ecosystems. The regressions of Z-scores are statistically significant for both treatments in woody ecosystems; in grassland ecosystems, a positive relationship between ANPP and iPPT occurs under ambient CO_2 but not under eCO_2 treatments, although eCO_2 enhances ANPP.



Supplementary Figure 3. The eCO_2 enhancements in tree-ring increments at a mature European beech forest located in the Swiss Canopy Crane (SCC) FACE site (operated from 2001 to 2008). ETreeRing is enhancement ratios of standardized tree rings under eCO_2 vs. ambient CO_2 treatments, and the mean of enhancement ratios of two dominant canopy tree species, *Fagus sylvatica* and *Quercus petraea*. The crowns of study trees with eCO_2 treatments were exposed to eCO_2 at ~550 ppm during daylight hours throughout the growing season. The annual precipitation data were from the weather station located in Basel, Switzerland.

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