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

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Experiments show that elevated atmospheric CO_2 (eCO_2) often enhances plant photosynthesis and productivity, yet this effect varies substantially and may be climate-sensitive. Understanding if, where, and how water supply regulates CO_2 enhancement is critical for projecting terrestrial responses to increasing atmospheric CO_2 and climate change. Here, using data from 14 long-term ecosystem-scale CO_2 experiments, we show that the eCO_2 enhancement of annual aboveground net primary productivity (ANPP) is sensitive to annual precipitation and that this sensitivity differs between woody and grassland ecosystems. During wetter years, CO_2 enhancement increases in woody ecosystems but declines in grass-dominated systems. Consistent with this difference, woody ecosystems can increase leaf area index (LAI) in wetter years more effectively under eCO_2 than grassland ecosystems. Overall, and across different precipitation regimes, woody systems had markedly stronger CO_2 enhancement (25%) than grasslands (13%). We developed an empirical relationship to quantify ANPP enhancement based on changes in LAI, providing a new approach for evaluating eCO_2 impacts on the productivity of terrestrial ecosystems.

Knowing how elevated atmospheric carbon dioxide (eCO_2) affects the capacity of terrestrial ecosystems to fix and store carbon is critical to understanding the future of the global carbon (C) cycle, including terrestrial productivity and C-cycle feedbacks on the climate system. Evidence from observations and modeling indicates that eCO_2 typically increases net primary production (NPP) of terrestrial ecosystems, but the extent of the response among biomes remains uncertain and can be sensitive to climate and nutrient constraints[1-4]. Two primary physiological mechanisms seem particularly important for understanding the CO_2 fertilization effect: increased leaf-level photosynthesis and decreased stomatal conductance[5]. Consequences of these mechanisms under

eCO_2 include increased water use efficiency (WUE)[6-9] and reduced water-stress in drier ecosystems[6].

Carbon-flux research in temperate and boreal forests of the Northern Hemisphere has revealed significant increases in WUE over the past two decades, most consistent with the hypothesis of a strong CO_2 fertilization effect attributable to elevated atmospheric CO_2[10]. Meanwhile, studies combining remote sensing and modeling report increases in foliage cover and NPP in drier regions of the world, suggesting that CO_2 fertilization has made the land surface "greener"[11-13]. Fatichi *et al.*[2] used a mechanistic model and experimental data to partition the effects of eCO_2 on NPP into the direct effects associated with C assimilation and indirect effects associated with changes in water condition and leaf area index (LAI). They concluded that the indirect effects of eCO_2 account for 28% of the total enhanced plant productivity, with a tendency for greater relative enhancements in arid ecosystems.

Free-air CO_2 enrichment (FACE) experiments and open-top chamber (OTC) systems have been used for many years to investigate *in situ* responses of intact plant communities to eCO_2 at ecosystem scales[9,14,15]. Published results indicate that, for a ~50% increase in CO_2 concentration to ~560 ppm[15-17], aboveground net primary productivity (ANPP*)* and total NPP in forests increase on average by ≈25%[17]. In contrast, results from grassland experiments show that growth responses to eCO_2 (~650 ppm) are somewhat less than in forests, with increases in ANPP ranging from 11% to 17%[17]. Across all forest and grassland experiments, stomatal conductance consistently decreased and instantaneous WUE increased by 4% to 44%[18,19]. However, leaf-level changes did not always lead to ecosystem-scale reductions in total water use or increases in soil moisture because of additional transpiration from increased leaf areas[7,18,19].

Although CO_2 fertilization might be expected to have a greater effect in xeric ecosystems and in drier conditions where and when the benefits of increased WUE are potentially stronger[6], evidence from enrichment studies is conflicting, with some studies supporting this hypothesis[9,20] but others not[16,21]. Inconsistencies in eCO_2 responses of plants to water availability may reflect variation in other factors, such as soil nutrient availability[22-24], light limitation[5], or indirect effects of eCO_2 on LAI via changes of carbon allocation and soil water[2,19]. Leaf and root structures and mechanisms for acquiring CO_2, water, light, and nutrients vary for different plant life-forms, which may also contribute to differences in eCO_2 responses to water availability.

To investigate mechanisms underpinning such inconsistencies, we analyzed data from 14 multi-year, ecosystem-scale CO_2 enrichment experiments, covering xeric to wet climates, in ecosystems dominated by grasses, shrubs, or trees (Table S1, S2). These sites are located in temperate and subtropical zones between latitudes of 48°N and 43°S in the northern or southern hemisphere. The criteria for selected sites were based on availability of ANPP data or ANPP enhancement ratios and a minimum eCO_2 treatment duration of 4 years. We explored the responses of ecosystem types to interactions of eCO_2 and water supply. The enhancement ratio of ANPP under eCO_2 to ANPP under ambient CO_2 (EAPP) was used as a measure of the **relative** response of ecosystem productivity to eCO_2. We examined two types of relationships between EAPP and precipitation for woody and grassland ecosystems: (1) annual EAPP (EAPP) and annual precipitation (iPPT) (i.e. an annual sum of monthly precipitation) at a given site over multiple experimental years; and (2) mean ecosystem EAPP ($EAPP_{AV}$) and mean annual precipitation (MAP) across multiple sites of the same ecosystem type. We evaluated the following three hypotheses: (H1) at a given site and over years, EAPP is greater in drier years; (H2) across multiple sites of the same ecosystem type, $EAPP_{AV}$ is greater in drier locations; and (H3) relative enhancements (both EAPP and $EAPP_{AV}$) in response to water supply are equivalent for ecosystems dominated by grasses or by woody taxa.

To test H1, we focused on the interactive effect of eCO_2 and temporal variations of iPPT on EAPP. To test H2, we examined the interactive effect of eCO_2 and spatial variations of MAP on $EAPP_{AV}$. The mechanisms underlying these two interactions likely differ. Finally, we tested H3 by comparing separate ecosystem types with distinct plant growth forms (i.e., woody and grassland ecosystems) to assess the consistency of the eCO_2 responses in magnitude and trend—given differences in their functional and structural traits, including height, leaf area and orientation, and biomass allocation, which can affect light and nutrient acquisition and may mediate eCO_2 and precipitation interactions.

Relationships between EAPP and iPPT within individual ecosystems

Annual precipitation varied widely across years and sites and affected both ANPP and the responses of ANPP to eCO_2. Across all ecosystems, eCO_2 enhanced growth in most years (EAPP >1; Fig.1a,1b), but responses differed remarkably for woody and grassland ecosystems. Within woody-dominated ecosystems, EAPP was positively related to iPPT and greater in wetter years at a given site (Fig.1a). In contrast, EAPP within a given grassland ecosystem declined in wetter years (Fig.1b).

The individual site response patterns appear to depend on the dominant life-form, although a linear relationship between EAPP and iPPT was not statistically significant at every individual site (Fig. 1a, 1b, Table S3a). This is particularly true for grassland ecosystems and those located near transition zones such as from semi-arid to moist zones, where growth responses were sometimes confounded with changing species composition under eCO_2[20,24]. Different carboxylation pathways of C_3 and C_4 grasses could also complicate EAPP responses to iPPT in grassland sites with both physiological types. For instance, C_3 grasses were more responsive to eCO_2 in drier years, whereas C_4 grasses showed little relationship with moisture conditions, despite responding well over typically average precipitation years (Fig. S1; see Supplementary Information about C_3 and C_4 plants).

For comparing diverse ecosystems, iPPT is a relatively simple proxy for water supply because of its independence from other site factors. We recognized that growing season precipitation could be a better predictor for plant productivity and sensitivity to eCO_2 at a given site[22]. The length of a growing season varies annually dependent on local temperature and vegetation types. Lacking growing season data from most sites, we used months from spring to early autumn as a growing season to relate EAPP to growing season precipitation (mPPT). Surprisingly, almost all the relationships weakened compared to those using annual precipitation (Table S3b, Fig.S2). The results suggest that non-growing season precipitation contributes to hydrological conditions in many sites. In temperate sites, soil water recharged by winter precipitation (e.g., snow) might benefit early spring growth, while in evergreen and subtropical sites year-round precipitation has an impact on growth.

Acknowledging statistical uncertainties in linear regressions of individual sites, we standardized the site data and developed Z-scores to pool annual data of different sites to examine patterns of EAPP-iPPT in woody and grassland ecosystems. The Z-scores eliminate scale differences and facilitate comparisons among sites (see Methods for approaches). The fixed effect regressions confirm the patterns we observed from individual sites: the relative CO_2 enhancement of growth for woody ecosystems increased in wet years ($p < 0.0001$) while the enhancement decreased with annual precipitation for grassland ecosystems ($p < 0.0001$) (Fig.1c, 1d).

Although the eCO_2 effect on plants is more directly related to water availability because it changes stomatal conductance, WUE, and plant-water dynamics, temperature can also influence the process through interactions with water. We therefore analyzed the impacts of annual mean temperature (iTEM) on EAPP (using Z-scores), interactive effects, and covariances with other variables, and found no statistically significant relationships (p= 0.33, 0.71 and p= 0.77, 0.57 for woody and grassland ecosystems, respectively) (Table 1).

Relationships between $EAPP_{AV}$ and MAP across sites

Across ecosystems from drier to moister sites, $EAPP_{AV}$ responses to MAP appear to decline with greater MAP for both woody and grassland ecosystems (Fig.2). Thus, in grasslands, the enhancement responses to precipitation were consistent within and across sites: greater for both drier years within a site and drier sites along the precipitation gradient. In contrast, the relative enhancement in woody systems was greater in wetter years within a site but lower for wetter sites across the precipitation gradient (Figs. 1, 2). The inter-site MAP gradient shows that the relative CO_2 fertilization effect on ANPP was greater in drier climates, independent of responses to annual variation in precipitation (Fig. 2), which likely reflects in part the importance of higher WUE in drier regions for maximizing carboxylation while minimizing water cost[25]. The $EAPP_{AV}$ trends of woody and grassland ecosystems are roughly parallel along the MAP gradient, although the woody ecosystem trend is not statistically significant ($p = 0.18$) due to the low ANPP response in the mature *Eucalyptus* woodland[26]. Some grassland sites, such as Colorado shortgrass steppe and Swiss meadows, achieve $EAPP_{AV}$ as great as woody ecosystems under similar precipitation conditions (Fig. 2).

The sensitivity of EAPP to iPPT within an ecosystem approaches zero (i.e., the slopes of linear functions in Figure 1a, 1b) in wetter ecosystems for both woody and grassland habitats (Fig. S3). Whereas the sensitivity (i.e. the absolute CO_2-induced enhancement per iPPT) declines with annual precipitation, it appears to approach zero at higher MAP for woody systems (ca. 1200 mm) than grasslands (ca. 800 mm) and remains notable even for the wettest woody ecosystems in our dataset. This suggests that some eCO_2 enhancement may be sustained for ecosystems with more abundant precipitation such as tropical rainforests. We observed that considerable eCO_2 enhancement of ANPP (~5-15%) is still realized experimentally in relatively mesic ecosystems (Fig. 2) because of the direct eCO_2 fertilization effect and possibly periodic enhancements of WUE due to recurring (short-term) drought in sites even with high MAP[1,10]. Wetter terrestrial systems often experience some seasonal water stress[27]; for instance, seasonal water deficits for the loblolly pine in the Duke FACE site frequently led to stomatal closure during part of the growing seasons in drier years[28]. Elevated CO_2 could alleviate some or all impacts of these dry periods on ANPP.

The effect of eCO_2 on LAI mediates the EAPP-iPPT relationship within ecosystems

Our results raise two questions: (1) Why does eCO_2 induce contrasting responses of EAPP to iPPT within woody and grass-dominated ecosystems (Fig 1), despite similar declines of $EAPP_{AV}$ to MAP across sites (Fig 2)?; and (2) Why does EAPP respond differently to annual variations of iPPT than $EAPP_{AV}$ to geographic variations of MAP in woody systems, while the relationships are consistent in grassland ecosystems?

Mechanisms that could contribute to the divergent response of the eCO_2 to moisture in woody and grassland ecosystems include: (1) grassland ecosystems allocating additional production belowground in wet years[29], potentially limiting ANPP eCO_2 enhancement at these times; (2) differing seasonal sensitivities to moisture limitations, with grass-dominated systems most sensitive early in growing seasons when leaf biomass reaches the maximum[20,30], but woody systems affected throughout the growing season[31]; and (3) differences in plant architecture (such as stem height, arrangement of leaves and roots) which influence light interception and limitation aboveground, and access and storage of nutrients belowground. Although these and other potential mechanisms may influence our observations (Fig. 1), no single one is likely to explain all the observed patterns.

Because the eCO_2 effects on carbon assimilation efficiency and WUE should be functionally similar in woody vegetation and grasses, we considered indirect eCO_2 effects mediated by enhanced LAI[2]. Such an enhancement may result from increasing carbohydrate and water availability, and relevant changes in plant structures, and could have a compounding impact[7,32]. Across studies, we found a significant positive relationship ($p < 0.0001$) between EAPP and enhanced LAI (ELAI) over all data from woody and grassland ecosystems, despite mixed spatial and temporal scales (Fig. 3). The contrasting trends of EAPP responses to iPPT (Fig. 1) but similar enhancements of EAPP with greater LAI (ELAI, Fig. 3), lead logically to the conclusion that ELAI responses to iPPT must differ between woody and grassland ecosystems. Therefore, we propose that diverging ELAI responses to iPPT is one possible mechanism causing the contrasting EAPP responses to iPPT within woody and grassland ecosystems.

Other evidence from the eCO_2 experimental sites support this LAI-mediated interpretation. FACE experiments in forests indicate that under eCO_2 ANPP and LAI both increase consistently with increasing iPPT, particularly in sites with relatively low LAI[5,33,34]. LAI increases with eCO_2 in most forest and woodland experimental sites, although the magnitude varies with tree species, leaf traits, and stand structure[19,33]. In the Mojave Desert, a site dominated by shrubs, EAPP only shows great stimulation in wetter years, though EAPP and ELAI indicated enhancements for all treatment years[34,35]. Leaf-level stomatal conductance in woody ecosystems decreases on average by 21% under eCO_2 at a level of ~550 ppm. However, canopy transpiration does not always decline because increased LAI consumes the water-savings induced by eCO_2[36], resulting in similar total soil water use[33]. Thus, woody ecosystems effectively support new foliage[37] in wetter years, helping to maintain a positive within-site EAPP-iPPT relationship (Fig. S4c) (see Supplementary Information about interactive effects).

Grassland ecosystems differ structurally and morphologically from woody systems. Aboveground production (i.e., mostly leaf biomass) and LAI are more closely related in grasslands than in woody ecosystems, as are EAPP and ELAI. The EAPP and ELAI responses in grasslands are very much water-related responses, with water stress reduced by enhanced WUE under eCO_2 in drier years[9,20]. In wetter years when water is less limiting, the relative eCO_2 enhancement for ANPP and LAI is often minimal[9,30] (Fig. S4d). This result holds for multiple sites including semi-arid shortgrass steppe dominated by C_3 species, mixed grass prairie[9,38], and mesic but frequently water-stressed C_4 tallgrass prairie[30]. In these experimental CO_2 enrichment sites, instead of LAI increasing in wetter years, there was evidence of community shifts to greater abundance of invasive grass species that are usually adapted to moister conditions as well as substantial biomass enhancement of subshrub species[20,39].

Given the importance of increased LAI for enhancing ANPP, any site complexity affecting LAI dynamics could up- or down-regulate EAPP and affect observed EAPP-iPPT relationships. For example, the aspen forest in the Aspen-FACE study in Wisconsin[14], had a substantially greater increase in LAI under eCO_2 compared to other forest FACE sites (Fig. 3), likely because of the lower starting LAI in the young and expanding forest stand[5]. Together with a greater daily interception of light during the growing season, enhanced LAI resulted in a much greater EAPP at this site compared to the other forests (Fig. 2).

Woody ecosystems have greater ANPP enhancement

Across experimental sites with annual precipitation regimes from ~100 to 1700 mm, average EAPP weighted by all experimental years ($EAPP_{AVE}$) in woody ecosystems was about ~26% (n=44) compared to ~16% (n=62) in grassland ecosystems (i.e. significantly different at $p = 0.044$; t-test) (Fig. S5a). Experimental eCO_2 levels used in woody ecosystems were fairly consistent (~550 ppm) except the scrub-oak site (~700 ppm) (Table S1a), while grassland sites had various eCO_2 levels (~550-720 ppm), with 6 of 8 grassland sites exposing plants to higher eCO_2 (600-720 ppm) (Table S1b). Using the Farquhar model[40], we estimated these higher eCO_2 treatments induce 2-7% greater impact on photosynthetic rates compared to those for the standard 550 ppm site treatment (Fig. S6). Similarly, a published meta-analysis[41] shows that higher eCO_2 used in grassland experiments (vs. ~550 ppm) could on average cause 3-7% greater responses of plant growth. Therefore, after adjusting eCO_2 treatment levels to 550 ppm by the Farquhar model, the average ANPP enhancement of all experimental years in woody ecosystems is ~25%, while grassland ecosystems is reduced from 16% to 13%, approximately half that for woody ecosystems (Fig. S5b).

Forest sites used in this study are mostly young forests in relatively early developmental stages. One exception is a mature forest of *Eucalyptus* (EucFACE). EucFACE shows little eCO_2 enhancement in tree ANPP after 3 years'eCO_2 treatments despite a persistent 19% increase in leaf photosynthesis[26]. The slight enhancement in ANPP (~5%) presented in this study (Fig. 1, 2) is attributable to abundant understory aboveground vegetation in this open dry woodland[42]. Another mature forest study (WEB-FACE) in the fully-stocked European Beech-oak forest shows that tree-ring increments were small under eCO_2 (Fig. S7)[43], on average (4%) lower than the average ANPP enhancement ($EAPP_{AV}$) in the full-canopy sweetgum site in Oak Ridge (8%). Interestingly, several eCO_2 enrichment studies in mature forests reported remarkable eCO_2 enhancements in photosynthetic capacity or gross primary productivity, but not in carbon pools such as stem wood or woody necromass[42,44], which may suggest that mature forests may also respond via increased carbon losses or by transferring photosynthates to unmeasured carbon pools including those belowground.

We note that our analysis focusses on enhancement of ANPP rather than NPP because data relating belowground production (BP, i.e. fine root) responses to eCO_2 are sparse and typically less certain. This gap may constrain full understanding of eCO_2 impacts on plant productivity because C allocation to above- and belowground organs differ between woody and grassland ecosystems, and likely shift with changes in carbon and water resources[45,46]. It is also notable that the forest FACE sites (except Oak Ridge) have much lower fine root allocation ratios than the median value (0.26) of many FluxNet sites[47]. From limited data (Table S5), we found that BP was higher in drier grasslands and moister forests, and BP enhancement was greater in moister sites for both ecosystem types and could be 2-3 times BP under ambient CO_2. Allocation of enhanced production to ANPP and BP was dynamic, which could be affected by seasonal variations of precipitation[48] (see Supplementary Information regarding belowground production).

Remarks and perspectives on terrestrial ecosystems under eCO_2

Returning to our hypotheses, we conclude: H1 (EAPP being greater in drier years) is supported for grassland but not for woody ecosystems; H2 ($EAPP_{AV}$ being greater in drier ecosystems) holds across all ecosystems; and H3 (EAPP responses to water supply being equivalent for woody- and grass-dominated ecosystems) is unlikely.

Collectively, the eCO_2 experiments suggest that greater eCO_2 enhancement in productivity will occur in drier years within grass-dominated ecosystems, whereas within woody ecosystems, eCO_2 enhancement is expected greater in wetter years despite the fact that woody ecosystems with drier baseline climates have greater average eCO_2 enhancement of ANPP. The CO_2-induced increase in plant productivity is likely achieved through direct enhancement of photosynthetic efficiency and indirect enhancement by increased WUE, and further augmented by a greater photosynthetic surface (LAI) resulting from more available carbohydrate and water[2,32]. Our study showed that woody ecosystems can effectively increase production under eCO_2, likely by using all of these mechanisms and particularly by enhancing LAI in years when water is abundant. In contrast, grassland ecosystems, due perhaps to differences in plant architecture and growth form, are less able to increase LAI in wetter years. The relatively more restricted LAI responses in grasslands would reduce the indirect effect enhancing carbon assimilation through enhanced LAI. Instead, excessive soil water in some grassland sites may increase N leaching losses and N limitation[22,30], and in others may trigger changes in species composition[20,39].

Given that woody ecosystems have a markedly stronger ANPP enhancement than grasslands (25% vs.13%, for eCO_2 level at ~550 ppm), occupy ~30% of the Earth's land, and generally have a greater ANPP, our results suggest that eCO_2-enhanced terrestrial ANPP is likely to become increasingly dominated by woody plants under rising atmospheric CO_2, independent of other disturbance- and climate-related effects. However, we caution that as most forest FACE experiments to date have treated relatively young trees, with ecosystem LAI less than six[5], mature forests are generally underrepresented in our analysis. Our analyses also only focused on ANPP rather than NPP because of limited data regarding the impacts of eCO_2 on BP. Available data show that responses of BP to eCO_2 are complex. Additional belowground research is needed to understand terrestrial responses to eCO_2 and mechanisms controlling carbon allocation.

Our finding that LAI plays a pivotal role in plant eCO_2 enhancement is consistent with a number of other recent observations, including: (i) forests with sparse canopies, such as relatively young systems or boreal forests[49], have a greater potential for eCO_2 enhancement; (ii) drier ecosystems appear to be subject to greater greening, and a greater relative increase in LAI[11-13]; and (iii) plants with greater flexibility for increasing LAI, such as lianas in tropical forests[50], climbing vines in some temperate forests[51], and invasive species capable of strongly competing for photosynthetic space[52], preferentially benefit from eCO_2. Together, these results, along with the effects of local disturbances, provide mechanistic support for elevated atmospheric CO_2 being a potentially key driver in facilitating increased woody encroachment in arid grasslands and savannas in recent decades[53].

The eCO_2 experiments in our study ranged from arid to moist ecosystems but only covered temperate to subtropical regions. There remains a lack of eCO_2 experiments in boreal and tropical zones with ecosystems which are particularly vulnerable to climate change. For forest biomes, other studies have reported widespread growth enhancements, likely due to globally elevated atmospheric CO_2[54,55]. For grassland ecosystems, C_3 grasses appear to enhance productivity through altered WUE with eCO_2. Although C_4 grasses are less sensitive to water supply than C_3 grasses, we have limited knowledge about how eCO_2 affects the productivity of C_4 plants, the main component of tropical savannas covering ~20% of Earth's surface. The manipulated CO_2 concentrations from the experimental sites used in our analysis vary between 540 to 730 ppm. These values represent the mid-range that would be attained by the end of the century under the

IPCC RCP 4.5 and 6.0 scenarios[56]. Atmospheric CO_2 concentration at these levels would cause global temperatures to rise and make the climate system less stable. Our future climate will be partly determined by plant responses to eCO_2, which will modulate ecosystem feedbacks on the climate system. The insights into CO_2 responses from the ecosystem experiments analyzed here can help constrain and validate Earth System Model representations of terrestrial ecosystem responses and their feedbacks to atmospheric CO_2, including critical sensitivity to and interactions with the climate system.

Overall, our findings provide new understanding of ecosystem responses to eCO_2 and water availability. The observation that ANPP enhancement is mediated via increased LAI suggests that long-term and inter-annual changes in foliage cover can be used as key indicators of eCO_2 impacts on terrestrial ecosystems. In particular, the empirical, general equation linking increased LAI with enhanced ANPP across different terrestrial ecosystems will be useful for detecting eCO_2 fertilization effects and quantifying large-area changes in terrestrial productivity through satellite-observed changes in LAI. The relationships uncovered among ecosystem types, eCO_2 and water supply can help validate Dynamic Global Vegetation Models and assist with better projecting the future impacts of elevated atmospheric CO_2 and climate change on terrestrial ecosystems.

Methods

Study sites, experimental designs and data

To study the interactive response of productivity to elevated CO_2 and precipitation variability in different ecosystem types, data from eCO_2 experiments of 14 ecosystems were collated from published studies (Table S1a, S1b) or project websites (http://www.lter.umn.edu/research/data/dataset?ple141, http://www.ars.usda.gov/Main/docs.htm?docid=11120) and the Oak-Ridge National Laboratory websites (http://cdiac.ornl.gov/ftp/FACE/ndffdata/, http://facedata.ornl.gov/npp-cdiac.html, http://facedata.ornl.gov/ndff/ndff_data_co2weather.html) (Table S1). Studies included six woody ecosystem and eight grassland ecosystem sites. The sites are located in temperate and subtropical zones between latitudes of 48°N and 43°S in the northern or southern hemisphere. The criteria for selected sites were based on availability of ANPP data or ANPP enhancement ratios (EAPP) (either from publications or websites) and having eCO_2 treatments longer than four years at a site. Although we separated the experimental sites into woody and grassland groups based on their lifeforms, both groups have diverse floras. This is particularly true for woody ecosystems which are a mixture of different types including desert shrubs, scrub-oaks, coniferous, and deciduous forests.

Free-air CO_2 enrichment (FACE) and open-top chamber (OTC) CO_2 enrichment systems are manipulative ecosystem-scale experiments. There was also an advanced OTC system established in the site of a Swiss calcareous grassland, which used the Screen-Aided CO_2 Control (SACC) technology. Site locations, conditions, experimental designs, data sources, and the methods of measurements and estimations for the variables used in this study are outlined and described in Table S1 and Table S2. The designs of FACE and OTC in different experimental sites have been widely reported in different publications (see Table S1). Overall, fewer CO_2 enrichment experiments have been established for woody ecosystems than grassland ecosystems. Most woody eCO_2 experiments are based on FACE technology (without the chamber effect) except the scrub-oak ecosystem which used OTCs[57] (Table S1a, S2a). Grassland experiments were established with either FACE, OTC, or SACC technologies (Table S1b, S2b). In most woody ecosystem experiments, the levels of eCO_2 varied between ~540 and 580 ppm with a mean of 555±15 ppm. An exception is the scrub-oak ecosystem using the OTCs, which applied higher eCO_2 levels (~700-730 ppm) in the treatments. The levels of elevated CO_2 concentration were generally higher in grassland experiments, varying between ~550 and 720 ppm with a mean of 623±62 ppm.

At several of the FACE and OTC sites, multiple factors in addition to elevated CO_2 were manipulated, including nitrogen fertilization, water supply, and temperature. For these sites, only the results from the eCO_2 experiments and CO_2 control sites were used. The one exception is for the experiment in Eschikon, Switzerland, where the FACE sites were all treated with low or high levels of N fertilization. Here, we used the average values for the low and high levels of N from the eCO_2 and controlled CO_2 sites. For the OTC and SACC studies, if the experiments included both ambient CO_2 and chamber (OTC) without eCO_2, only the results from the chamber experiments without eCO_2 were used as the control conditions for more suitable comparisons with consideration of chamber effects (Table S2b). Multiple year data were used from each site. The longest experiments were run for more than a decade, but most experiments ran for fewer years, which limits the statistical power for individual sites (Table S3a).

Data analyses and statistical modeling

The ANPP enhancement ratio (EAPP) is defined as ANPPe/ANPPa, i.e., aboveground annual net productivity (ANPP) under eCO_2 (ANPPe) divided by ANPP under ambient CO_2 concentration (ANPPa). ANPPe and ANPPa were respectively the averages of replicates (plots or subplots) for a given year at a given site (Table S1, S2). EAPP represents the relative enhancement in ANPP by eCO_2, and there is no enhancement if EAPP equals 1. Note that EAPP is distinct from a percentage, although their values are interchangeable. For instance, EAPP =1.2 is equivalent to 20% enhancement in ANPP; and EAPP =2.0 means 100% enhancement.

EAPP of each site all passed the Shapiro–Wilk normality test except for the Tasmania site. For each experimental site, a linear regression was fit to the data points representing EAPP against annual precipitation (iPPT) across different years (Fig. 1a, 1b, Table S3a). The slopes of these linear functions, which represent precipitation sensitivity of ANPP enhancement ratios, were extracted for examination (Fig. S3). The site average of EAPP ($EAPP_{AV}$) and the average of iPPT (MAP) of multiple experimental years were estimated for each of the experimental sites. Linear regressions were used to fit $EAPP_{AV}$ and MAP across all ecosystems, and multiple woody and grass dominated ecosystems (Fig. 2. Table S4).

In addition, we estimated LAI enhancement ratios (ELAI = LAIe/LAIa), which is LAI under eCO_2 (LAIe) divided by LAI under an ambient CO_2 concentration (LAIa), using data from the few available sites (Table S2). Among 14 sites in this study, only five have LAI data available, including three forests and two grasslands. A logistic equation for the EAPP-ELAI relationship was developed using all available data points (across vegetation types, spatial and temporal scales) by a non-linear regression (Fig. 3, Table S4). SigmaPlot11 was used for statistics and curve fitting.

Z-score analysis and statistics

For each experimental site, a linear regression was fit to data representing EAPP against inter-annual precipitation (iPPT) over experimental years (Fig. 1a, 1b, Table S3a). Although EAPP response patterns obviously differed between woody and grassland ecosystems (Fig. 1a, 1b), some regressions for individual sites were not statistically significant due to small sample sizes of experimental years. To examine the response patterns, we standardized site data to generate Z-scores based on the mean value and standard deviations of the data at each site, and then pooled together all site data for analysis:

$$Z_{ik} = \frac{X_{ik-}\mu_k}{\sigma_k} \qquad \text{(Eq. 1)}$$

Here, *i =1,2…n* for the sample size of site *k*, while *k =1, 2…6* for woody ecosystems and *k =1, 2…*8 for grassland systems. The Z-scores eliminate scale differences in data from different sites and make them comparable, while retaining statistical properties. The variations in Z-scores represent interactions between eCO_2 enhancement ratios (EAPP) and annual precipitation (iPPT). Z-scores of EAPP and iPPT are, respectively:

$$EAPPz_{ik} = \frac{EAPP_{ik}-\mu\,[EAPP_{ik}]}{\sigma[EAPP_{ik}]} \qquad \text{(Eq. 2)}$$

$$Pz_{ik} = \frac{iPPT_{ik}-\mu[iPPT_{ik}]}{\sigma[iPPT_{ik}]} \qquad \text{(Eq. 3)}$$

The Z-scores vary below or above zero, showing annual variations of EAPP and indicating relatively drier or wetter years in the sites (Fig 1c, 1d).

To assess the impact of mean annual temperature (iTEM) on EAPP and the interactive effects between iPPT and iTEM, we also generated Z-scores of mean annual temperature:

$$Tz_{ik} = \frac{iTEM_{ik}-\mu[iTEM_{ik}]}{\sigma[iTEM_{ik}]} \qquad \text{(Eq. 4)}$$

Because our interest lies in identifying response patterns of EAPP to iPPT rather than to model parameters, we examined combined data using general regression analysis. Our approach is analogous to the one-stage IPD (individual participant data) fixed effects meta-regression model. The one-stage IPD meta-regression approach allows analysis of all individual data values from across studies simultaneously and has been suggested to have several advantages over traditional AD (aggregated data) meta-analysis[58]. The meta-regression model is expressed as:

$$EAPPz_{ik} = \beta_0 + \beta_1 Pz_{ik} + \epsilon_{ik} + \zeta_k \qquad \text{(Eq. 5)}$$

Here, $i = 1, 2, \ldots n_k$, and n_k is the sum of sample sizes of all sites.

The variable EAPP is an enhancement ratio of aboveground NPP (EAPP=APPe/APPa) under ambient CO_2 and eCO_2 treatments. Because CO_2 treatments under ambient CO_2 and eCO_2 were independent experimental units, each EAPP value can be considered as a random sample from year to year because within-pair differences in measurements are random[58]. In addition, the data from different sites are also independent among them because the experiments were independently conducted in different years and under different plot designs (Table S2). These conditions ensure that EAPP and Z-scores of EAPP from all sites were independent data entries in the model. In Eq. 5, two terms, ϵ_{ik} and ζ_k denote two types of independent errors for the subgroup k: the first one, ϵ_{ik}, represents sampling error for sample i, whereas ζ_k denotes between-study heterogeneity. However, ζ_k can be ignored in the equation for our analysis because we applied a fixed effect model with z-scores (as the mean Z-score of each site all equals zero and the effect sizes between-studies are not the concern in the analysis). The heterogeneity variance between-sites is encapsulated in the intercept of the regression model. Therefore, the one-step IPD fixed effect meta-regression analysis can be carried out virtually as a regular linear model applied to pooled data from all sites[60].

$$\widehat{EAPP}z_{ik} = \hat{\beta}_0 + \hat{\beta}_1 Pz_{ik} \qquad \text{(Eq. 6)}$$

The sampling error ϵ_{ik} (Eq. 5) was estimated by the root mean square error (MSE) and used to estimate 95% confidence intervals of the model (Fig. 1c, 1d).

The statistical analyses were performed with SPSS v.28.0 (SPSS Inc, Chicago, IL) supplemented with the plug-in macros MetaReg.sps. Using Z-scores, we were able to unify the data from different sites for analyses. The results show that fitted linear curves are statistically significant for both ecosystem types ($p < 0.0001$), which confirm the patterns we observed from individual sites. To further investigate the impact of annual mean temperature on eCO_2 enhancement ratios of ANPP and interactions with annual precipitation, we added Z-scores of iTEM as an additive predictor and an interaction term to Eq. 5 and reported the ANOVA in Table 1. The multi-variable regression results verify that annual precipitation has opposite impacts on EAPP in woody and grassland ecosystems, and annual mean temperature has no significant effect on EAPP.

Uncertainty in data application

Synthesizing growth and productivity responses from CO_2 enrichment experiments present challenges about how to properly collate needed data and assemble them from different sites and sources. There are relatively few CO_2 enrichment experiments, and each is unique in terms of vegetation, site conditions, experimental design, and the number of experimental years. Although many forest FACE experiments used a protocol designed to improve experimental consistency, there were still great disparities in plot layouts, sampling, and data processing methods (Table S2a). The experiments of grassland ecosystems were even more diverse. Different grassland sites applied different CO_2 enrichment technologies and equipment (FACE, OTC, or SACC), different enriched CO_2 levels, different plot sizes and sampling repetitions, and different harvest methods and turnover (Table S2b). All those internally inherited variations affect statistical results when drawing conclusions with across-site comparisons.

Here we chose to compare ANPP enhancement ratios (EAPP) against the single variable annual precipitation (iPPT), a key reason being to simplify comparisons among sites and reduce inconsistency. Annual precipitation is a variable independent from temperature and other site factors and reflects site water conditions experienced by plants *in situ*. It is suitable for comparing the effect of eCO_2 on ANPP across different sites. In addition, we found growing season precipitation (mPPT) does not relate better to EAPP than annual precipitation (iPPT) (Fig. S2, Table S3b). Even when using a simple variable such as iPPT, i.e., the sum of monthly precipitation over one year, the actual value of iPPT varies depending on whether the operator chooses to use hydrological year, calendar year, different first month in northern and southern hemisphere, and whether to include snow or only rainfall, etc. Wherever possible, we used iPPT data provided by site researchers (Table S1) because we assume that they know best how to represent iPPT. Although temperature is also an important variable affecting plant growth and hydrological dynamics, our analyses show that it has little effect on eCO_2 enhancement.

For ANPP data used in this study, we found uncertainty could result from different analyses, which might result in different values even when starting from the same raw data (e.g., this study vs. Hovenden[48]). Various factors could contribute to different conclusions. For instance, vegetation in grassland ecosystems may have C_3 and C_4 grasses and forbs, and whether one includes forbs (as we did) in the data processes impacts results. Some grassland OTC experiments set up control plots with or without chambers; using chambered or un-chambered ambient plots as reference could result in different ANPP enhancement ratios.

Grassland experiments also need to deal with biomass harvest and some experiments may alter harvest protocols over experimental years, for instance changing from two harvests in early and late summers to one in mid-summer. Changes in harvest protocols may affect estimated eCO_2 effects on ANPP in grassland ecosystems because growth responses to eCO_2 during earlier and later growing seasons are often different.

Finally, researchers at some experimental sites may adjust their site data based on their knowledge of the sites, requiring sound judgement and understanding to do appropriately. All these issues increase the uncertainty associated with data-processing in addition to sampling and measurement uncertainties.

Data availability

All data needed to reach conclusions in the paper are presented in the paper and/or the Supplementary Materials with figures or tables. Additional data related to this paper may be requested from the authors.

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Figure Legends

Figure 1. Relationships between eCO_2 enhancement of ANPP and annual precipitation. EAPP is an enhancement ratio of ANPP under eCO_2 (ANPPe) and ambient CO_2 (ANPPa) treatments. (a) EAPP responses to annual precipitation (iPPT) over multiple experimental years within woody ecosystems, and (b) within grassland ecosystems; at $^*p = 0.1$, solid lines represent the regression statistically significant, dashed lines not significant (Table S3a); the horizontal line EAPP =1 denotes no enhancement, while above or below it enhancement or reduction under eCO_2. The fixed effect regressions between Z-scores of EAPP and iPPT (thick solid lines with confidence intervals of gray areas) in (c) woody and (d) grassland ecosystems; the thin lines are linear regressions of Z-scores of individual sites.

Figure 2. Mean responses of eCO_2 enhancement ($EAPP_{AV}$) to mean annual precipitation (MAP) across multiple ecosystems. $EAPP_{AV}$ is the mean EAPP of experimental years, while MAP the mean annual precipitation (iPPT) of experimental years at a given site. The solid line represents the regression for all sites; the dashed lines are those for woody and grassland ecosystems. The regression for woody ecosystems is not statistically significant at $^*p = 0.1$, largely due to a low

$EAPP_{AV}$ at the EucFACE site. Solid symbols are for woody ecosystems and open symbols for grassland ecosystems. Error bars represent the standard errors (SEs) at each site.

Figure 3. The relationship between EAPP and ELAI. EAPP and ELAI are respectively the enhancement ratios of ANPP and LAI under eCO_2 vs. ambient treatments. Solid symbols are woody ecosystems, open symbols grassland ecosystems. A logistic function was used for data fitting (Table S4). The excluded outlier was from the C_4 tallgrass prairies, which occurred in the driest year of the site with abnormal low LAI at the ambient CO_2 plots, causing exceptionally high relative LAI enhancement.

Table 1. ANOVA of fixed effect multi-variable regression and covariance of variables. Annual precipitation (iPPT), annual mean temperature (iTEM), and ANPP enhancement ratios (EAPP) of woody and grassland ecosystems, were standardized as z-scores (P_Z, T_Z and $EAPP_Z$), respectively (see Methods).

Woody ecosystem	*df*	*SE*	*MS*	*F*	*P-value*	R^2
Model	43	0.7527	5.0657	8.9409	0.0001	0.4014

$EAPP_Z$[&]	*B*	*SE*	*z-test*	*P-value*	$CV_{(Pz,Tz)}$[*]	CV_{EAPPz}[†]
Intercept	0.0106	0.1144	0.0926	0.9268		
P_Z	0.6372	0.1233	5.1679	< 0.0001	0.8636	0.5343
T_Z	0.1209	0.1235	0.9789	0.3336	0.8133	0.0317
P_Z x T_Z	0.0473	0.1243	0.3805	0.7053	-0.1186	0.0244

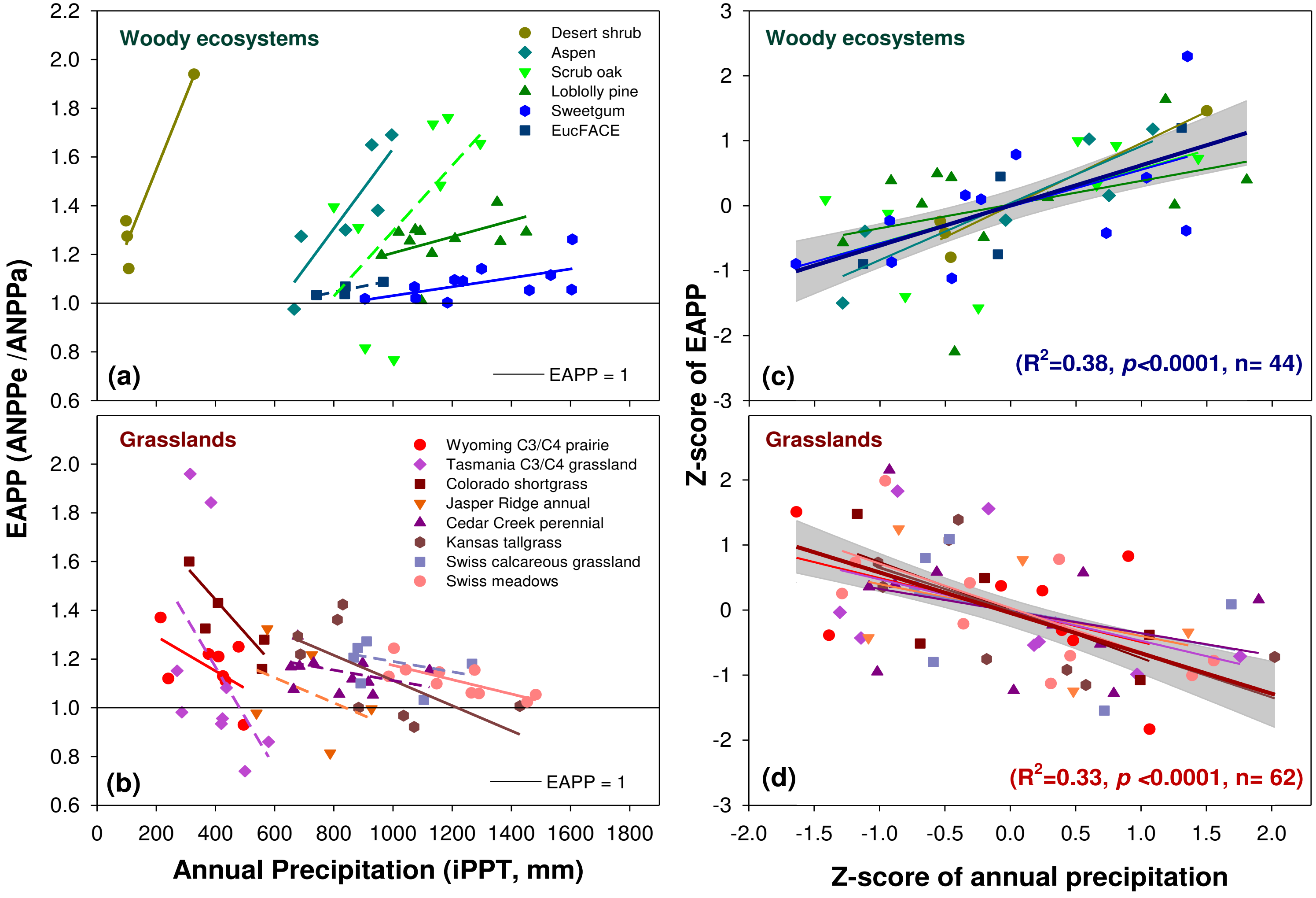
Grassland ecosystem	*df*	*SE*	*MS*	*F*	*P-value*	R^2
Model	61	0.8151	8.2825	8.2825	0.0001	0.3073

$EAPP_Z$[&]	*B*	SE	*z-test*	*P-value*	$CV_{(Pz,Tz)}$	CV_{EAPPz}
Intercept	0.0027	0.1064	0.0254	0.9800		
P_Z	-0.6053	0.1217	-4.9737	< 0.0001	0.8684	-0.4549
T_Z	-0.0319	0.1107	-0.2882	0.7743	0.9090	0.0318
P_Z x T_Z	0.0686	0.1215	0.5646	0.5743	-0.0964	0.0126

[&] Dependent variable

[*] Covariances of independent variables P_Z and T_Z

[†] Covariances of predictive variables and dependent variable $EAPP_Z$



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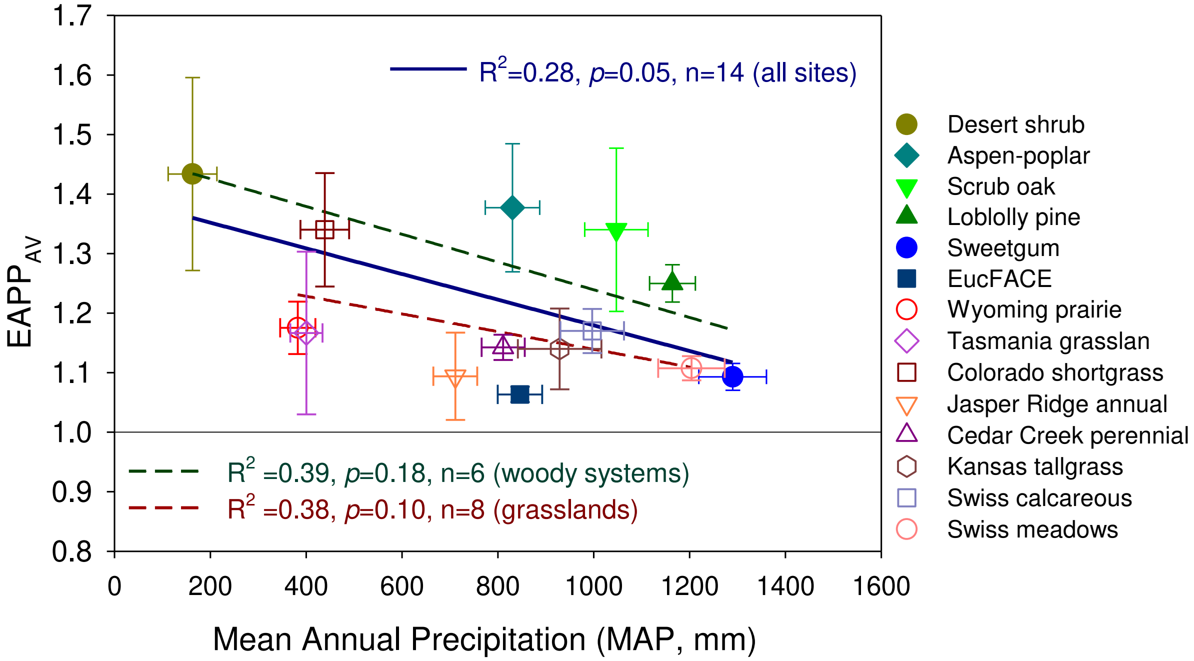

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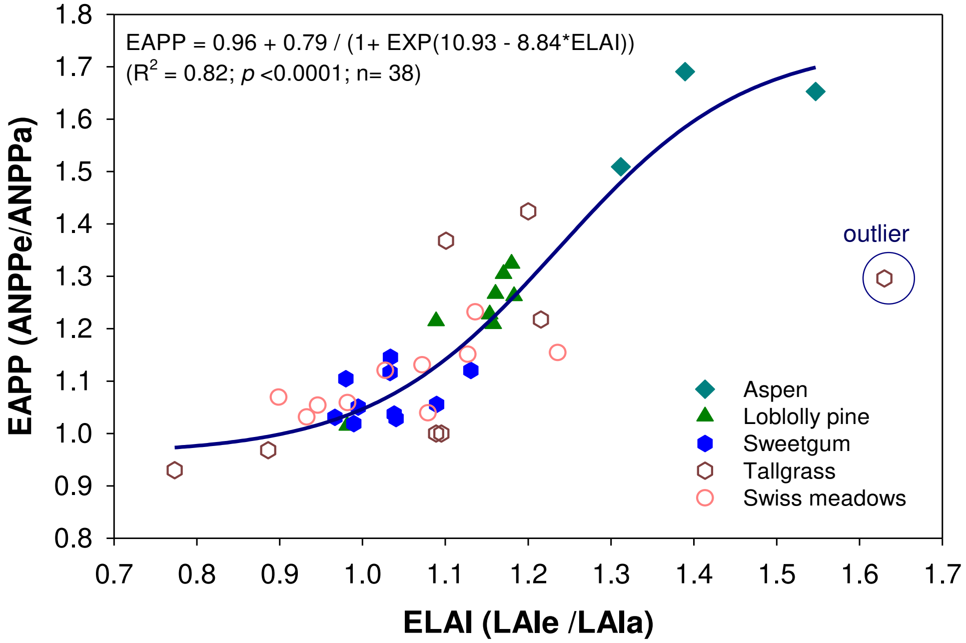

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Supplementary Information

Supplementary Text
Table S1-S5
Figure S1-S6

Supplementary Text

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 (Fig. S1a), 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 (Fig. S1b). 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 (Fig. S1a).

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 (Fig. S1b, 1c). However, ANPP enhancement of C_4 grasses was relatively greater when iPPT was near average (or slightly wetter than average) of annual precipitation at the site (Fig. S1c). 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 average or slightly wetter conditions. 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 water-saving[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). 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 Table S2 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 (Table S6). 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 (Fig. S4c). 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 (Fig. S4d). 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 (Fig. S4c). 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 (Fig. S4d), 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 ($\mathrm{EAPP_{AV}}$), annual variability of EAPP influenced by WUE and LAI was averaged, and $\mathrm{EAPP_{AV}}$ 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 eCO₂ 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 (Table S5), 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% (Table S5), 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% (Table S5). 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 (Table S5). 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.

Table S1a. 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 °C	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 °C	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 (28°38'N, 80°42'W)	MAP: 1310 mm MAT: 22.4 °C	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 °C	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 (35°54'N, 84°20'W)	MAP: 1410 mm MAT: 14.7 °C	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: 17.5°C	FACE ~550 ppm CO^2; 2013-	Jiang *et al.* [31] https://researchdata.edu.au/aboveground-net-primary-2013-2015/754374	Jiang *et al*, [31] Australia BM Richmond - UWS Hawkesbury (67021)	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.

Table S1b. 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).	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: http://www.lter.umn.edu/research/data/dataset?ple141	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.

Table S2a. 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 (Ꙁ) was calculated and used to estimate LAI based on the relationship between LAI and Ꙁ. 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].

Table S2b. 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 (Fig. S2). 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 Table S1b), 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.

Table S3a. 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 = 0.9428 + 3.0264e^{-3} * iPPT	0.93	4	**0.03**
Wisconsin aspen-poplar forests	EAPP = -0.0196+ 1.6628e^{-3} * iPPT	0.77	6	**0.02**
Florida scrub oak	EAPP = -0.0455 + 1.3414e^{-3} * iPPT	0.34	8	0.13
Duke loblolly pine planation	EAPP = 0.8736 + 3.3229e^{-4} * iPPT	0.26	11	**0.10**
Oak Ridge sweetgum plantation	EAPP = 0.8475 + 1.8295e^{-4} * iPPT	0.34	11	**0.06**
EucFACE eucalyptus woodland	EAPP = 0.8499 + 2.4420e^{-4} * iPPT	0.76	4	0.12
Within grassland ecosystems				
Wyoming mixed grass prairie	EAPP = 1.4361 – 7.1258e^{-4} * iPPT	0.35	8	**0.10**
Tasmania mixed native grassland	EAPP = 1.9923 – 2.0597e^{-3} * iPPT	0.23	9	0.19
Colorado shortgrass steppe	EAPP = 1.9903 – 1.3653e^{-3} * iPPT	0.67	5	**0.09**
Jasper Ridge annual grassland	EAPP = 1.4329 – 5.1607e^{-4} * iPPT	0.16	5	0.50
Cedar Creek perennial prairie	EAPP = 1.3270 – 2.1515e^{-4} * iPPT	0.20	10	0.20
Kansas tallgrass prairie	EAPP = 1.6261 – 5.0930e^{-4} * iPPT	0.42	8	**0.08**
Swiss calcareous grassland	EAPP = 1.4021 – 2.1220e^{-4} * iPPT	0.13	6	0.49
Swiss meadows	EAPP = 1.4318 – 2.7922e^{-4} * iPPT	0.69	10	**< 0.01**

Table S3b. 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 (Fig. S3.). 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 = 1.0644 + $7.3998e^{-3}$ * mPPT	0.74	4	0.14	Site data[9]
Wisconsin aspen-poplar forests	EAPP = 0.2519 + $1.7369e^{-3}$ * mPPT	0.77	6	**0.04**	3 - 9
Florida scrub oak	EAPP = 0.9874 + $4.9857e^{-4}$ * mPPT	0.03	8	0.69	3 - 9
Duke loblolly pine planation	EAPP = 1.1601 + $1.3991e^{-4}$ * mPPT	0.04	11	0.55	3 - 9
Oak Ridge sweetgum plantation	EAPP = 0.9262 + $1.9776e^{-4}$ * mPPT	0.23	11	0.14	3 - 9
†EucFACE eucalyptus woodland	EAPP = 0.7698 + $5.3430e^{-4}$ * mPPT	0.62	4	0.21	9 - 3
Within grassland ecosystems					
Wyoming mixed grass prairie	EAPP = 1.3418 – $5.6902e^{-4}$ * mPPT	0.17	8	0.31	3 - 9
†Tasmania mixed native grassland	EAPP = 1.8849 – $2.6811e^{-3}$ * mPPT	0.16	9	0.28	9 - 3
Colorado shortgrass steppe	EAPP = 1.8927 – $1.3653e^{-3}$ * mPPT	0.74	5	**0.06**	Site data[37]
Jasper Ridge annual grassland	EAPP = 1.3799 – $2.0665e^{-3}$ * mPPT	0.13	5	0.56	3 - 9
Cedar Creek perennial prairie	EAPP = 1.2838 – $2.3054e^{-4}$ * mPPT	0.14	11	0.26	3 - 9
Kansas tallgrass prairie	EAPP = 1.5193 – $4.8957e^{-4}$ * mPPT	0.43	8	**0.07**	3 - 9
Swiss calcareous grassland	EAPP = 1.3359 – $2.5438e^{-4}$ * mPPT	0.14	6	0.46	3 - 9
Swiss meadows	EAPP = 1.3647 – $3.1483e^{-4}$ * mPPT	0.51	10	**0.02**	3 - 9

Note: † is for sites located in Southern Hemisphere.

Table S4. 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	$EAPP_{AV} = 1.3952 – 2.1564e^{-4}*MAP$	0.28	14	**0.0523**
Woody ecosystems	$EAPP_{AV} = 1.4721 – 2.3307e^{-4}*MAP$	0.39	6	0.1824
Grassland ecosystems	$EAPP_{AV} = 1.2751 – 1.4642e^{-4}*MAP$	0.38	8	**0.1031**
ELAI-EAPP relationships				
Logistic function	EAPP = 0.96+0.79/(1+EXP(10.93 – 9.84*ELAI))	0.82	38	**<0.0001**

Table S5. 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 Table S1a
	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 Table Sa1
	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 Table S1a
	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 Table S1b
	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 Table S1
	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 Table S1
	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	

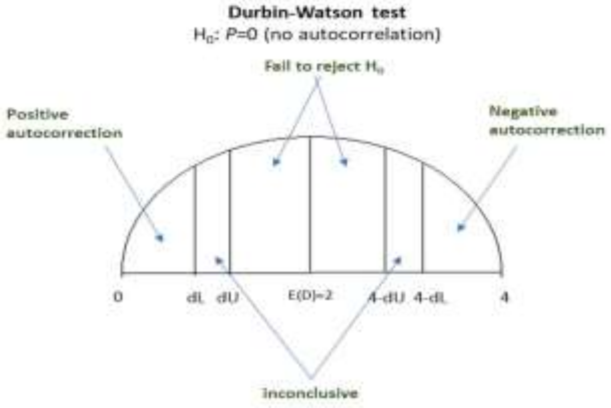
Table S6. The Durbin-Watson test for temporal autocorrelation in ANPP data.

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 (see below illustration). 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.

$$D = \frac{\sum_{t=2}^{n}(e_t - e_{t-1})^2}{\sum_{t=1}^{n} e_t^2}$$

Where $e_t = y_t - \hat{y}_t$ are the residuals from the ordinary least squares fit, and y_t is the time sequence of data measured over experimental years.



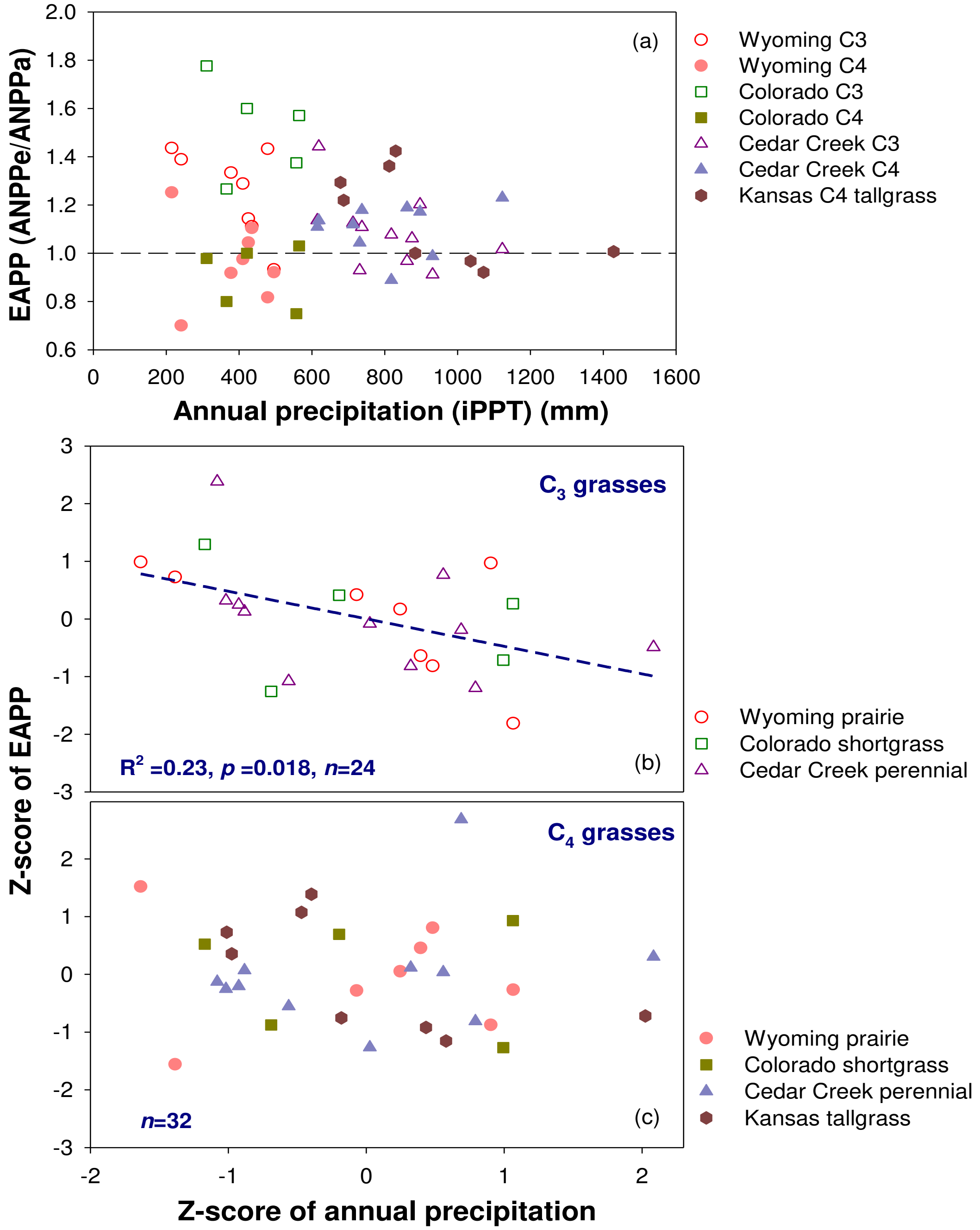


Fig. S1. Responses of C_3 and C_4 grasses to eCO_2. (a) EAPP responses of C_3 and C_4 grasses to annual precipitation (iPPT); (b) the Z-score analysis for C_3 grasses, and a linear regression; and (c) the Z-scores analysis for C_4 grasses; there is not an obvious relationship between EAPP and iPPT.

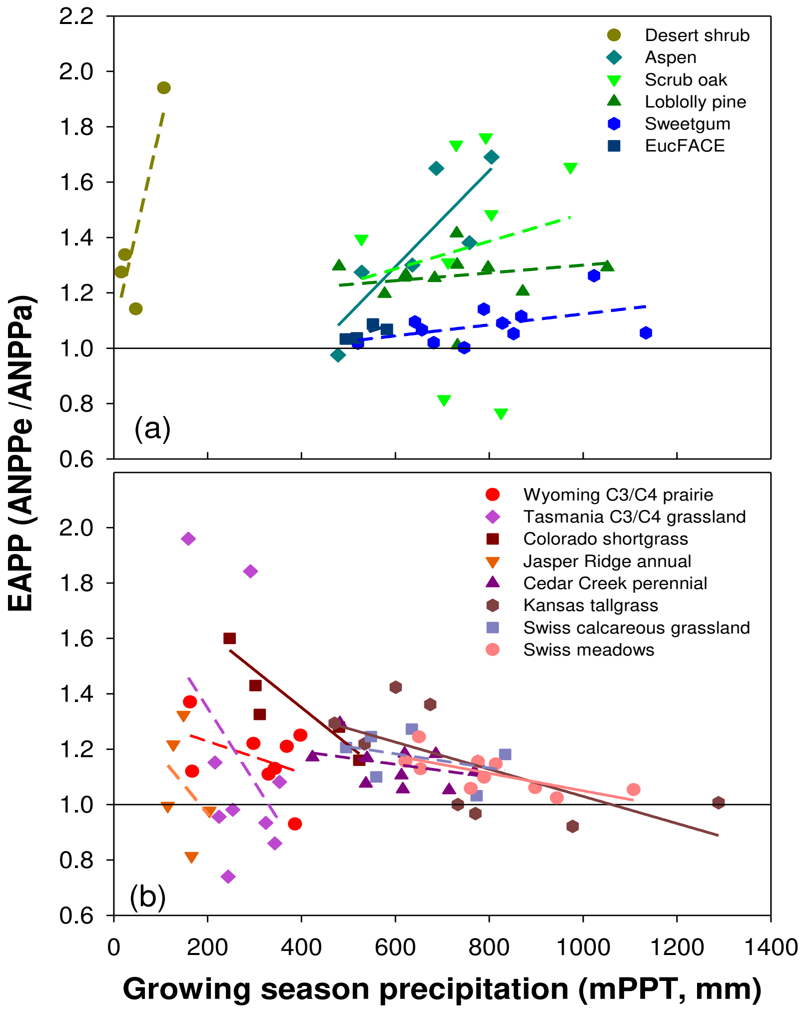


Fig. S2. Relationships between eCO_2 enhancement of ANPP and growing season precipitation (Table S3b). EAPP is enhancement ratio of ANPP under eCO_2 (ANPPe) and ambient CO_2 (ANPPa) treatments. (a) EAPP responses to growing season precipitation (mPPT) over multiple experimental years within woody ecosystems, and (b) within grassland ecosystems. At *p= 0.1, solid lines represent statistically significant regressions, dashed lines not significant (Table S3a).

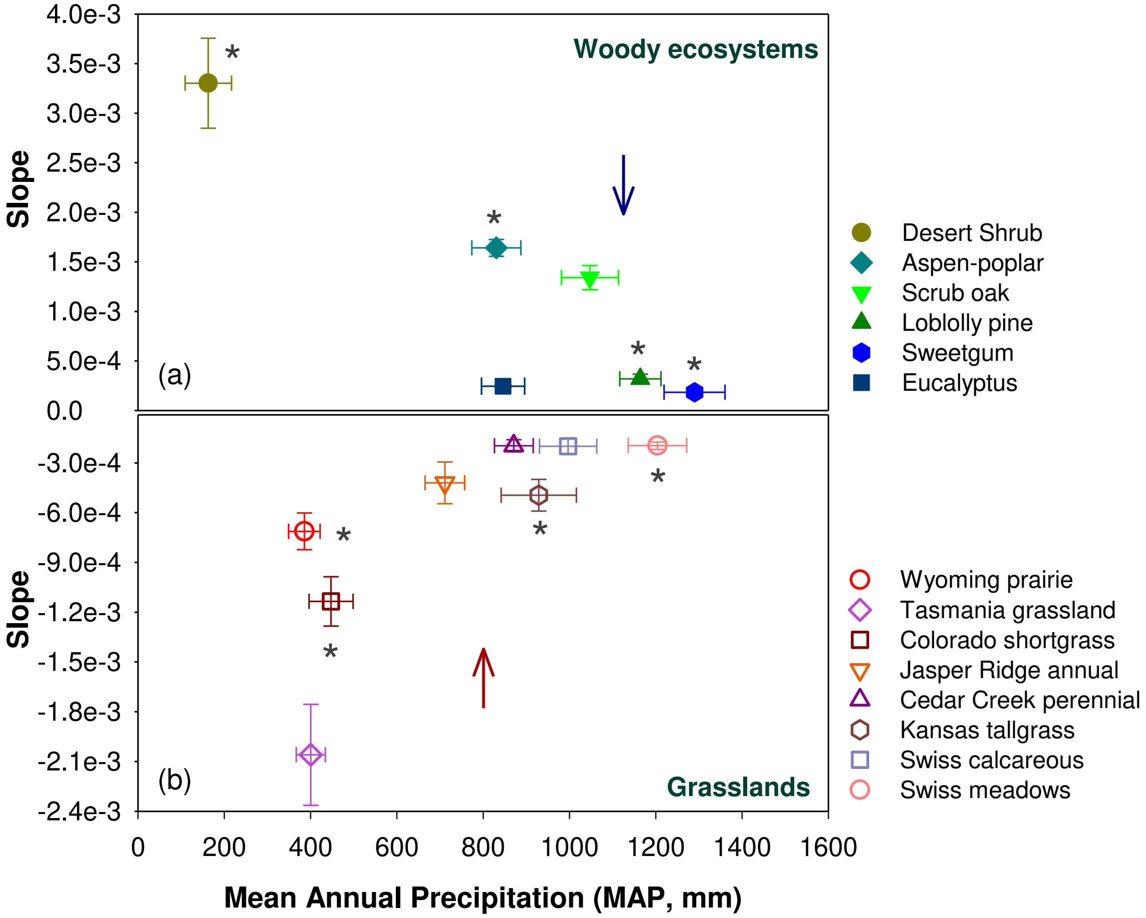


Fig. S3. Sensitivity of ANPP enhancement to annual precipitation (slope). Slopes (ΔEAPP/ΔiPPT mm^{-1}) of linear functions of EAPP-iPPT (Fig. 1a and 1b and Table S3a) across (a) woody and (b) grassland ecosystems. A positive slope means EAPP increasing with increasing iPPT at a given site; a negative slope EAPP decreasing with increasing iPPT. Error bars are the standard errors (SEs) for slopes and MAP, respectively. The symbol "*" is used for sites with a linear regression at *p=0.1. Arrows show MAP levels when slopes approach zero in woody and grassland ecosystems.

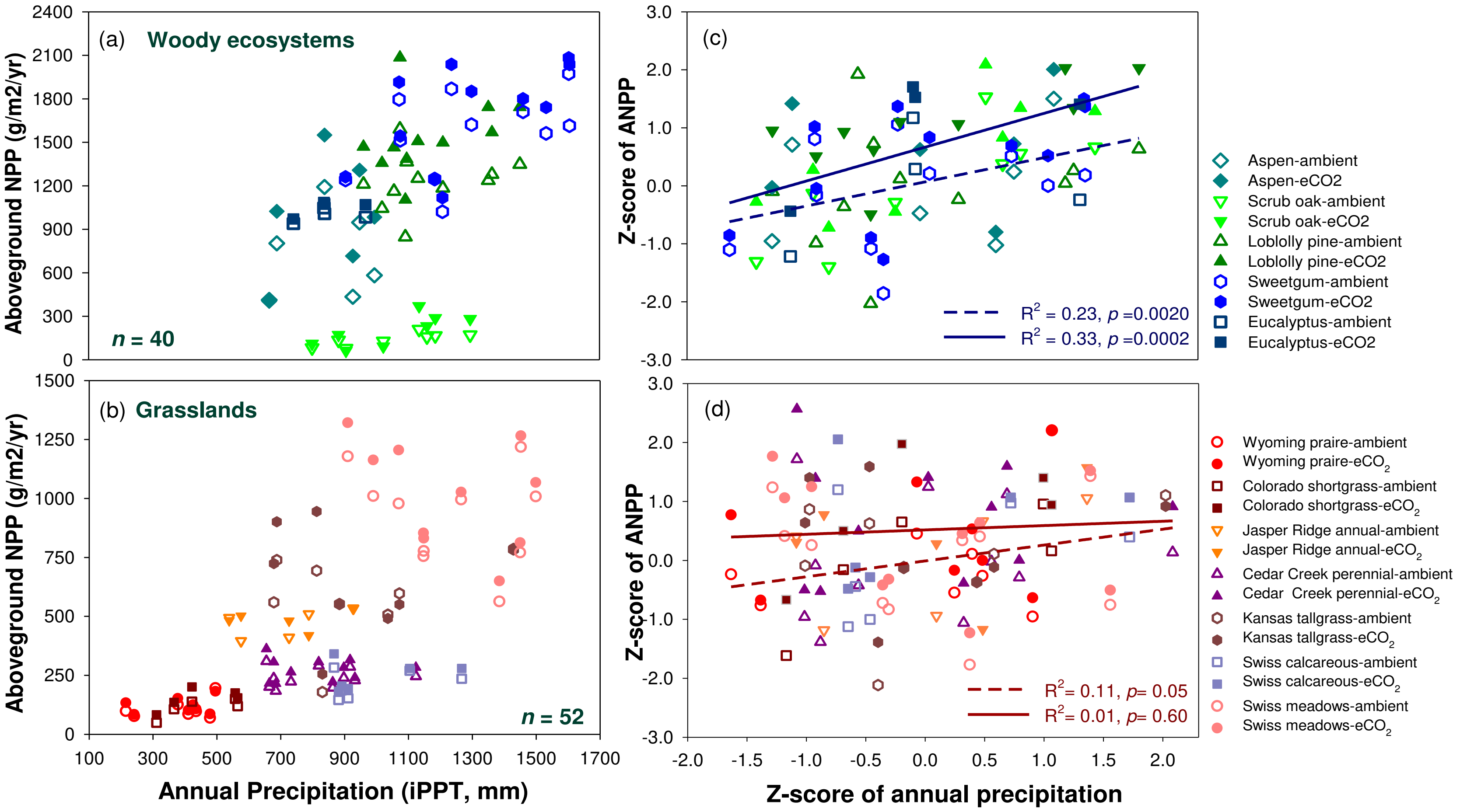


Figure S4. Direct responses of ANPP to iPPT under ambient CO_2 (open symbols) and eCO_2 (solid symbols) in (a) woody and (b) grassland ecosystems (n= 40 and n=53, respectively). Not all sites have ANPP values as some only reported ANPP response ratios (EAPP). Z-score analyses of ANPP responses to iPPT and regression lines under ambient CO_2 (dashed line) and eCO_2 (solid 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.

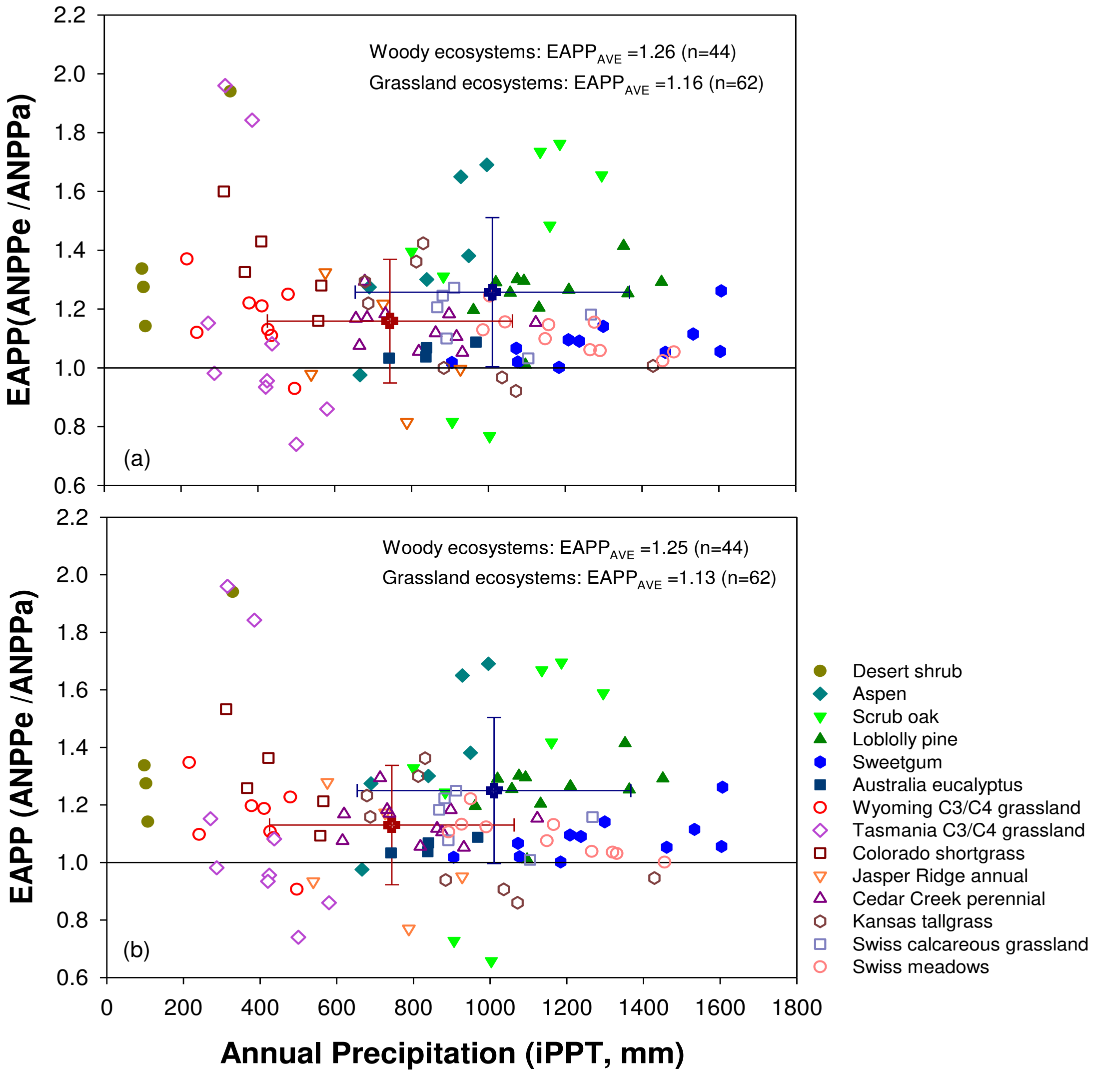


Fig. S5. Mean ANPP enhancements affected by eCO$_2$ levels. (a) Mean values of EAPP for all sampling years and all sites (EAPP$_{AVE}$) of woody (solid symbols) and grassland (open symbols) ecosystems; EAPP responses to iPPT are significantly different between woody and grassland ecosystems (t-test: p =0.044); (b) EAPP$_{AVE}$ of woody and grassland ecosystems after adjusting higher eCO$_2$ concentrations used in grassland experiments and the scrub-oak site to 550 ppm based on the Farquhar model (Fig. S6); EAPP responses to iPPT are significantly different between woody and grassland ecosystems (t-test: p =0.015). Error bars represent standard deviations (SDs).

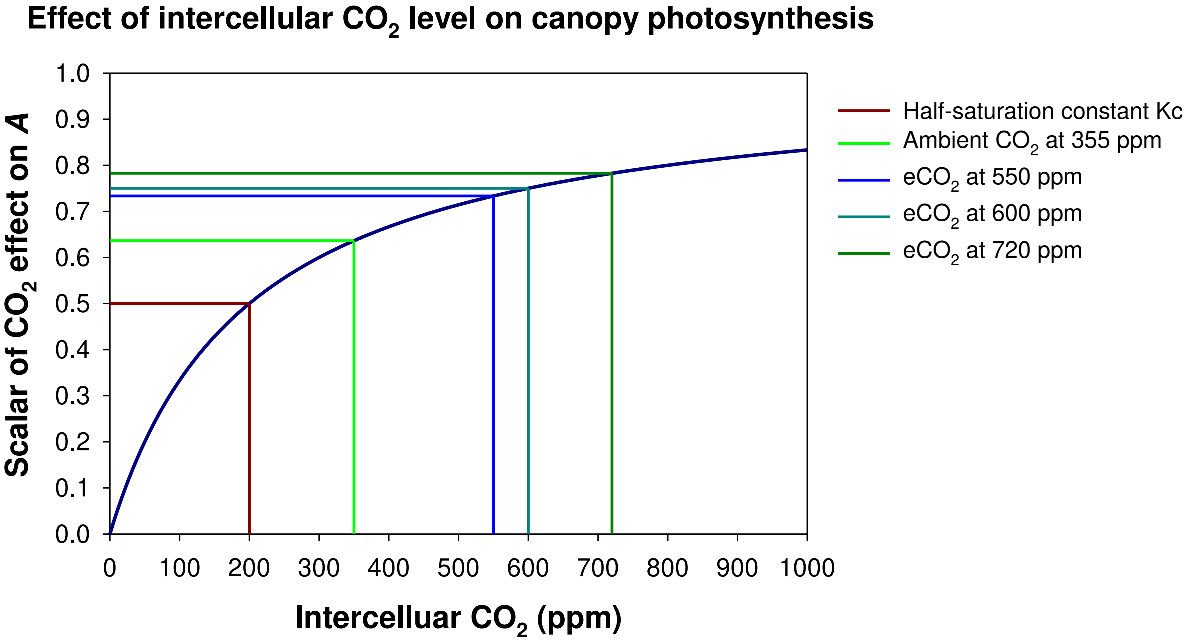


Fig. S6. Effects of CO_2 levels on canopy photosynthetic rates illustrated by the Farquhar model. Y-axis shows the impact (scalar) of intercellular CO_2 levels on canopy photosynthesis rates, given an assumption of optimal intercellular CO_2 level being close to the atmospheric level. Relatively higher CO_2 concentrations were used in 6 enrichment experiments of grassland ecosystems (600-720 ppm) compared to the CO_2 concentration (~550 ppm) used in woody ecosystems.

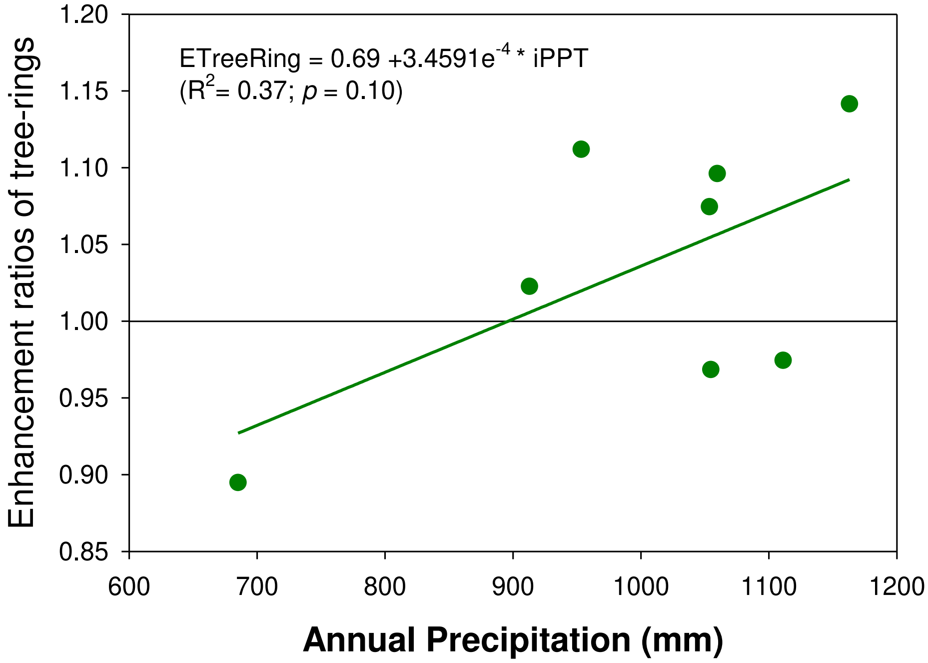


Fig. S7. The eCO_2 enhancements in tree-ring increments at a mature European beech forest located in the Swiss Canopy Crane (SCC) FACE site (operated from 2001 to 2008). ETreeRing is enhancement ratios of standardized tree rings under eCO_2 vs. ambient CO_2 treatments, and the mean of enhancement ratios 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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