



## Tansley review

# Integrating the evidence for a terrestrial carbon sink caused by increasing atmospheric CO<sub>2</sub>

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## Summary

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**Key words:** beta factor, carbon dioxide, CO<sub>2</sub> fertilization, CO<sub>2</sub>-fertilization hypothesis, free-air CO<sub>2</sub> enrichment (FACE), global carbon cycle, land–atmosphere feedback, terrestrial ecosystems.

Atmospheric carbon dioxide concentration ([CO<sub>2</sub>]) is increasing, which increases leaf-scale photosynthesis and intrinsic water-use efficiency. These direct responses have the potential to increase plant growth, vegetation biomass, and soil organic matter; transferring carbon from the atmosphere into terrestrial ecosystems (a carbon sink). A substantial global terrestrial carbon sink would slow the rate of [CO<sub>2</sub>] increase and thus climate change. However, ecosystem CO<sub>2</sub> responses are complex or confounded by concurrent changes in multiple agents of global change and evidence for a [CO<sub>2</sub>]-driven terrestrial carbon sink can appear contradictory. Here we synthesize theory and broad, multidisciplinary evidence for the effects of increasing [CO<sub>2</sub>] (iCO<sub>2</sub>) on the global terrestrial carbon sink. Evidence suggests a substantial increase in global photosynthesis since pre-industrial times. Established theory, supported by experiments, indicates that iCO<sub>2</sub> is likely responsible for about half of the increase. Global carbon budgeting, atmospheric data, and forest inventories indicate a historical carbon sink, and these apparent iCO<sub>2</sub> responses are high in comparison to experiments and predictions from theory. Plant mortality and soil carbon iCO<sub>2</sub> responses are highly uncertain. In conclusion, a range of evidence supports a positive terrestrial carbon sink in response to iCO<sub>2</sub>, albeit with uncertain magnitude and strong suggestion of a role for additional agents of global change.

## I. Introduction

Photosynthesis uses the energy in sunlight to bind CO<sub>2</sub> to a five-carbon sugar, transferring CO<sub>2</sub> from the atmosphere to plants (Calvin & Benson, 1948; Farquhar *et al.*, 1980). Sugars produced by photosynthesis provide the building blocks and the primary fuel for much of life on Earth. Plant tissues, many microbes, animals, and dead organic matter are all composed of carbon-rich compounds formed from these photosynthetic sugars. In many environments, an increase in atmospheric CO<sub>2</sub> concentration [CO<sub>2</sub>] increases photosynthesis. Thus an increase in [CO<sub>2</sub>] leads to greater plant sugar availability with the potential to increase the total amount of carbon stored in the live and dead organic matter in an ecosystem. These observations have led to the CO<sub>2</sub>-fertilization hypothesis (Box 1): that plant responses to increasing atmospheric [CO<sub>2</sub>] drive increases in terrestrial-ecosystem carbon storage, creating negative feedback on atmospheric [CO<sub>2</sub>] growth.

Since the industrial revolution, human activities have increased [CO<sub>2</sub>] by 48% (1760–2019, 277–411 ppm), an increase in atmospheric CO<sub>2</sub>-carbon of 277 Pg C (Friedlingstein *et al.*, 2019). However, global-scale carbon accounting quantifies anthropogenic emissions to the atmosphere at 645 Pg C and suggests a substantial 'natural' terrestrial carbon sink (a net flux of carbon from the atmosphere to intact terrestrial ecosystems) which currently removes the equivalent of  $33 \pm 9\%$  of anthropogenic atmospheric CO<sub>2</sub> (2009–2018; Friedlingstein *et al.*, 2019). Along with the ocean carbon sink, this terrestrial carbon sink is mitigating the rate of climate change. Process-based carbon-cycle models attribute increasing [CO<sub>2</sub>] (iCO<sub>2</sub>; Table 1) as the primary driver of the terrestrial carbon sink, albeit with substantial uncertainty (Huntzinger *et al.*, 2017; Arora *et al.*, 2019). However, iCO<sub>2</sub> is not the only global-change factor that can influence terrestrial carbon stocks. Anthropogenic land-use and land-cover change (hereafter land-use change) and recovery (Pugh *et al.*, 2019), nitrogen cycle changes (Fowler *et al.*, 2013), and climate change all affect ecosystem carbon stocks (Keenan & Williams, 2018). A vast and overwhelming literature often disagrees about the size and duration of CO<sub>2</sub>-driven increases in terrestrial carbon storage and predictive understanding of this process is a long-standing and unresolved scientific goal.

Predictive understanding of how terrestrial ecosystems respond to iCO<sub>2</sub> requires knowledge of a range of processes, their interactions, and how these processes scale. For example, terrestrial ecosystem responses begin with photosynthesis inside the leaf, yet scale to have long-term global impacts. All the relevant processes must be understood across scales, and ultimately at the global scale because iCO<sub>2</sub> and climate change are global-scale phenomena with decadal to centennial dynamics.

Given that *c.* 50% of plant biomass is carbon-acquired via photosynthesis, it is reasonable to assume that increased photosynthesis increases plant biomass production (BP) and experimentally elevated [CO<sub>2</sub>] (eCO<sub>2</sub>) commonly increases BP (e.g. Baig *et al.*, 2015). However, in natural ecosystems iCO<sub>2</sub> may not always increase BP, primarily because plant tissues require nutrients, and BP responses to iCO<sub>2</sub> will interact with soil nutrient availability and other limiting factors (Strain & Bazzaz, 1983; Rastetter *et al.*,

**Table 1** Acronyms and abbreviations.

A <sub>net</sub>	Net photosynthetic carbon assimilation
fAPAR	Fraction absorbed photosynthetically active radiation
BAI	Basal area increment
BP	Biomass production, the sum of all tissue production over a given time, typically 1 yr
C <sub>x</sub>	Carbon in pool x, where x is either vegetation ('veg'), soil, ecosystem ('eco')
CO <sub>2</sub>	Carbon dioxide
[CO <sub>2</sub> ]	Atmospheric CO <sub>2</sub> concentration
eCO <sub>2</sub>	Elevated CO <sub>2</sub> from experiments and CO <sub>2</sub> springs
FACE	Free-air CO <sub>2</sub> enrichment
GPP	Gross primary production
g <sub>s</sub>	Stomatal conductance
iCO <sub>2</sub>	Increasing CO <sub>2</sub> from fossil fuel emissions and land-use change
iWUE	Intrinsic WUE (A <sub>net</sub> /g <sub>s</sub> )
k <sub>x</sub>	Turnover rate of carbon in pool x (see C <sub>x</sub> )
LAI	Leaf area index
NBP	Net biome production, net land atmosphere exchange
NEP	Net ecosystem production
OCS	Carbonyl sulphide
UE	Use efficiency
VPD	Vapour pressure deficit
WUE	Water-use efficiency (transpiration/BP)

1997). A related argument is that present-day [CO<sub>2</sub>] is likely to supply plants with unprecedented carbon availability that may be surplus to BP requirements (Körner, 2003a). This is because for at least one million years before the industrial revolution [CO<sub>2</sub>] was much lower (170–300 ppm) (Bereiter *et al.*, 2015).

Ecosystem carbon stocks are the result of both inputs (BP for plants or litter production for soils) and outputs. Thus for the CO<sub>2</sub>-fertilization hypothesis to hold true, the residence time of carbon in an ecosystem must not be reduced by an amount that would negate effects of increased BP on terrestrial carbon pools. However, it has been suggested that both vegetation and soil carbon residence times may be reduced by iCO<sub>2</sub> (van Groenigen *et al.*, 2014; Körner, 2017).

Drawing from multiple disciplines, vast quantities of diverse data have been collected on the [CO<sub>2</sub>] responses of many processes. Often this evidence can appear conflicting. For example, many free-air CO<sub>2</sub> enrichment (FACE) experiments show BP gains (Walker *et al.*, 2019), while others show none (Bader *et al.*, 2013; Ellsworth *et al.*, 2017). Many tree-ring studies indicate historical increases in intrinsic water-use efficiency (iWUE) but no detectable change in BP (Peñuelas *et al.*, 2011; van der Sleen *et al.*, 2015), while the majority of forest-inventory analyses suggest biomass gains (Brienen *et al.*, 2015; Hubau *et al.*, 2020). Flux-tower data, global CO<sub>2</sub>-flask networks, and remote-sensing data are now of sufficient timescales (decades) to study CO<sub>2</sub> responses against background variability, but have led to different inferences (Kolby Smith *et al.*, 2016; Fernández-Martínez *et al.*, 2017).

This literature represents a wealth of information and inference that can appear fragmented, posing an opportunity for integration. Thus our overall goal is to provide a synthetic review of key lines of evidence related to the CO<sub>2</sub>-fertilization hypothesis, specifically: (1) overview of theory and potential mechanisms within the CO<sub>2</sub>-fertilization hypothesis;

**Box 1** The CO<sub>2</sub>-fertilization hypothesis.

The stimulation of photosynthesis by CO<sub>2</sub> has been called 'CO<sub>2</sub> fertilization' (Ciais *et al.*, 2014), a term that goes back to global carbon cycle modelling in the 1970s (Bacastow & Keeling, 1973). However, 'CO<sub>2</sub> fertilization' or the 'CO<sub>2</sub>-fertilization effect' have been used to refer to the [CO<sub>2</sub>] response of any number of variables across scales. This broad usage has been a source of confusion and, more commonly, 'fertilization' is a value-laden, agricultural term that means the addition of nutrients to increase crop yield. Acknowledging the precedence of the term, its multiple uses, and the fact that CO<sub>2</sub> responses of some processes may be neutral or negative, we opt to refer to 'CO<sub>2</sub> responses' of explicitly defined variables and scales.

We reserve the term 'CO<sub>2</sub> fertilization' solely to label the hypothesis that: plant responses to increasing atmospheric [CO<sub>2</sub>] lead to increasing terrestrial-ecosystem carbon storage, causing negative feedback on atmospheric [CO<sub>2</sub>] growth. This definition of the CO<sub>2</sub>-fertilization hypothesis is explicit about the feedback on atmospheric [CO<sub>2</sub>] growth, implying the potential of this process to slow climate change. The hypothesis is therefore defined at climate-change relevant scales, that is, global in space and decadal to centennial in time.

For the CO<sub>2</sub>-fertilization hypothesis to be true, Eqn B1 must be positive at the global scale and over a specified time period:

$$\Delta\text{NEP} = \Delta C_{\text{eco}} = \Delta C_{\text{veg}} + \Delta C_{\text{soil}} \quad \text{Eqn B1}$$

where NEP is net ecosystem production,  $C_{\text{veg}}$  and  $C_{\text{soil}}$  are plant and soil (including litter and coarse woody debris) terrestrial carbon that sum to give total ecosystem carbon ( $C_{\text{eco}}$ ), and  $\Delta$  represents change as a result of increasing [CO<sub>2</sub>]. A change in carbon storage is the net result of inputs and outputs (Olson, 1963):

$$dC/dt = I - kC \quad \text{Eqn B2}$$

where  $C$  is stored carbon,  $I$  is the input, and  $k$  is the turnover rate of the pool (the inverse of mean residence time).

Net primary production (NPP) represents the net input of carbon to  $C_{\text{veg}}$  and is calculated as gross primary production (GPP), which responds directly to  $i\text{CO}_2$ , minus autotrophic respiration ( $R_a$ ). In practice, NPP is often estimated from total biomass production (BP), the sum of leaf, wood, root, and reproductive tissue production over a given time period (Vicca *et al.*, 2012). In addition to BP, NPP includes carbon used for the production of volatiles, root exudation, supply to symbionts, and changes in nonstructural carbohydrates (NSCs). However, these carbon fluxes are difficult to measure and often have very short residence times, somewhat akin to respiratory carbon. Therefore, to align with measurements and residence time we use BP to decompose changes in  $C_{\text{veg}}$ :

$$dC_{\text{veg}}/dt = \text{BP} - k_{\text{veg}}C_{\text{veg}} \quad \text{Eqn B3}$$

where  $k_{\text{veg}}$  is the turnover (litterfall and mortality) rate of vegetation biomass. For soils, the inputs to  $C_{\text{soil}}$  are vegetation litter production and mortality, as well as nonbiomass NPP fluxes ( $S$ ) that include exudation and carbon supply to symbionts:

$$dC_{\text{soil}}/dt = k_{\text{veg}}C_{\text{veg}} + S - k_{\text{soil}}C_{\text{soil}} \quad \text{Eqn B4}$$

where  $k_{\text{soil}}$  represents the turnover rate of soil carbon caused by microbial decomposition.

(2) quantitative evaluation of the evidence, identifying agreement and major conflicts;

(3) resolution of apparent conflicts and, where this is not possible, identification of key knowledge gaps to guide future studies.

We structure this multidisciplinary review within the mechanistic theory of the five broad processes that are key to the CO<sub>2</sub>-fertilization hypothesis (Box 1; Fig. 1a): gross primary production (GPP), plant BP, vegetation mortality rate ( $k_{\text{veg}}$ ), soil organic matter (SOM) decomposition rate ( $k_{\text{soil}}$ ), and terrestrial carbon storage ( $C_{\text{eco}}$ ). Within each of these high-level processes, numerous interrelated mechanisms and subprocesses shape terrestrial ecosystem CO<sub>2</sub> responses (Fig. 1b; Section II).

Within these processes we integrate four primary evidence themes (Box 2). eCO<sub>2</sub> studies in Evidence theme 1 provide the only direct evidence for CO<sub>2</sub> responses but are restricted in space and time. Observation studies (Evidence themes 2–4) span a broader range of evidence types covering larger spatial scales and

longer temporal scales but provide only indirect evidence for the effect of  $i\text{CO}_2$  on terrestrial ecosystems.

To quantify and standardize CO<sub>2</sub> effects across variables and varying ranges of [CO<sub>2</sub>] we report data as a relativized  $\beta$ -factor:

$$\beta = \log_e(y_e/y_a) / \log_e(\text{CO}_{2,e}/\text{CO}_{2,a}) \quad \text{Eqn 1}$$

where  $y_a$  and  $y_e$  are the values of any response variable at lower [CO<sub>2</sub>] ( $\text{CO}_{2,a}$ ) and higher [CO<sub>2</sub>] ( $\text{CO}_{2,e}$ ), respectively. Other methods to calculate the  $\beta$ -factor have been proposed (e.g. Friedlingstein *et al.*, 1995) but we use Eqn 1 for the ease of interpretation that results from scale independence (Supporting Information Notes S1; Fig. S1). A value of  $\beta = 1$  represents direct proportionality between a variable's CO<sub>2</sub> response and the change in CO<sub>2</sub>. Where possible (i.e. when reported at source) we report uncertainties as 95% confidence intervals.

As described earlier, attributing  $i\text{CO}_2$  as the cause of trends is confounded by covarying factors which also drive variability in the terrestrial carbon sink. We discuss these other global-change factors in the context of attribution, but do not cover them in depth. The difference between direct evidence from  $e\text{CO}_2$  experiments and indirect evidence from historical data (concurrent with a suite of global-change factors) motivates our use of two abbreviations:  $e\text{CO}_2$  and  $i\text{CO}_2$ . As with  $e\text{CO}_2$  and  $i\text{CO}_2$ , we distinguish direct  $\text{CO}_2$  responses ( $\beta_{\text{dir}}$ ) from indirect apparent  $\text{CO}_2$  'responses' ( $\beta_{\text{app}}$ ).

## II. Theory – a hierarchy of mechanism

### 1. Direct plant physiological responses to $\text{CO}_2$

Photosynthesis is limited by  $\text{CO}_2$  or light (Farquhar *et al.*, 1980). When  $\text{CO}_2$  is limiting, theory predicts that  $e\text{CO}_2$  increases leaf-scale net carbon assimilation ( $A_{\text{net}}$ ) ( $\beta_{\text{dir,hist}} = 0.86$ , *c.* 280–400 ppm; Table S1). The enzyme that fixes  $\text{CO}_2$  (RuBisCO) also catalyses an oxygenation reaction, which results in  $\text{CO}_2$  loss (photorespiration; Farquhar *et al.*, 1980).  $e\text{CO}_2$  also suppresses photorespiration (Fig. 2a). Given that photorespiration always occurs during  $\text{C}_3$  photosynthesis, the suppression of photorespiration by  $e\text{CO}_2$  increases  $A_{\text{net}}$  also when light is limiting, but with a lower response ( $\beta_{\text{dir,hist}} = 0.31$ ). Canopy-scale  $A_{\text{net}}$  results from a mixture of  $\text{CO}_2$  and light-limited photosynthesis, and thus has an intermediate  $e\text{CO}_2$  response that depends on the fraction of light-saturated leaves in the canopy ( $\beta_{\text{dir,hist}} = 0.60 \pm 0.3$ ; Fig. 2c). As  $[\text{CO}_2]$  increases, the fraction of light-saturated leaves in the canopy is expected to decrease, and therefore the historical  $e\text{CO}_2$  response of GPP is expected to be higher than the future response ( $\beta_{\text{dir,fut}} = 0.46 \pm 0.2$ , *c.* 400–550 ppm; Fig. 2c).

$\text{C}_4$  plants have evolved to concentrate carbon, thus saturating photosynthesis and suppressing photorespiration at low  $[\text{CO}_2]$  (Ehleringer & Björkman, 1977). Therefore  $A_{\text{net}}$  in  $\text{C}_4$  plants is not directly influenced by  $[\text{CO}_2]$  above *c.* 200 ppm (Fig. 2a), although water savings from reduced stomatal conductance ( $g_s$ ) may stimulate  $A_{\text{net}}$  indirectly (Leakey *et al.*, 2004).

Photosynthesis requires the acquisition of other resources and  $e\text{CO}_2$  stimulation of  $A_{\text{net}}$  increases  $A_{\text{net}}$  per unit resource consumption, that is, increases resource use-efficiencies of water (WUE), light (LUE), and leaf nitrogen (Cowan, 1982; Drake *et al.*, 1997). Increased use efficiencies imply a shift in a plant's resource-use economy (Bloom *et al.*, 1985) which is commonly studied using optimization theory.

Optimization theory predicts that a change in the ratio of  $A_{\text{net}} : g_s$  (iWUE) in proportion to the change in  $[\text{CO}_2]$  ( $\beta_{\text{dir}} \approx 1$ ; Fig. 2d) maximizes the benefit of carbon gain while minimizing the cost of water lost for  $\text{C}_3$  (Medlyn *et al.*, 2011) and  $\text{C}_4$  plants (Lin *et al.*, 2015). Canopy-scaling theory predicts that the increase in iWUE is preserved at the canopy scale (Fig. 2e). Where the response of  $A_{\text{net}}$  to  $e\text{CO}_2$  is less than proportional ( $\beta_{\text{dir}} < 1$ ) the increase in iWUE (i.e.  $A_{\text{net}}/g_s$ ) implies a reduction in  $g_s$  (canopy-scale iWUE  $\beta_{\text{dir,hist}} = 1.1 \pm 0.1$ ,  $A_{\text{net}} \beta_{\text{dir,hist}} = 0.60 \pm 0.3$ , thus  $g_s \beta_{\text{dir,hist}} = -0.53 \pm 0.2$ ; Fig. 2f,i). Owing to the lower predicted  $A_{\text{net}}$  in the future, the predicted decrease in  $g_s$  is greater ( $\beta_{\text{dir,fut}} = -0.62 \pm 0.1$ ).

Optimization theory also predicts reduction in photosynthetic carboxylation capacity ( $V_{\text{cmax}}$ ), reducing nitrogen demand (Bowes, 1991; Drake *et al.*, 1997). A reduction in leaf nitrogen may also occur as a result of limited plant-available soil nitrogen (Section II.2) or physiological competition for the products of electron transport (Bloom *et al.*, 2012).

### 2. Plant biomass production

Biomass production of leaf, wood, and root tissues is controlled by the interplay of source (resource acquisition), sink (metabolic tissue production) (Muller *et al.*, 2011; Fatichi *et al.*, 2019), and regulatory processes (phenology, hormones) (Schwartz, 2013; Bahuguna & Jagdish, 2015). Within this framework,  $e\text{CO}_2$  can increase BP when BP is either carbon source-limited or when  $e\text{CO}_2$  can alleviate other limitations. Plant BP is carbon source-limited when in competition with respiration for available carbon and when light limits BP (Lloyd & Farquhar, 2008). Sustained periods of high growth may also reduce carbon stores (Würth *et al.*, 2005), potentially leading to carbon-source limitation.

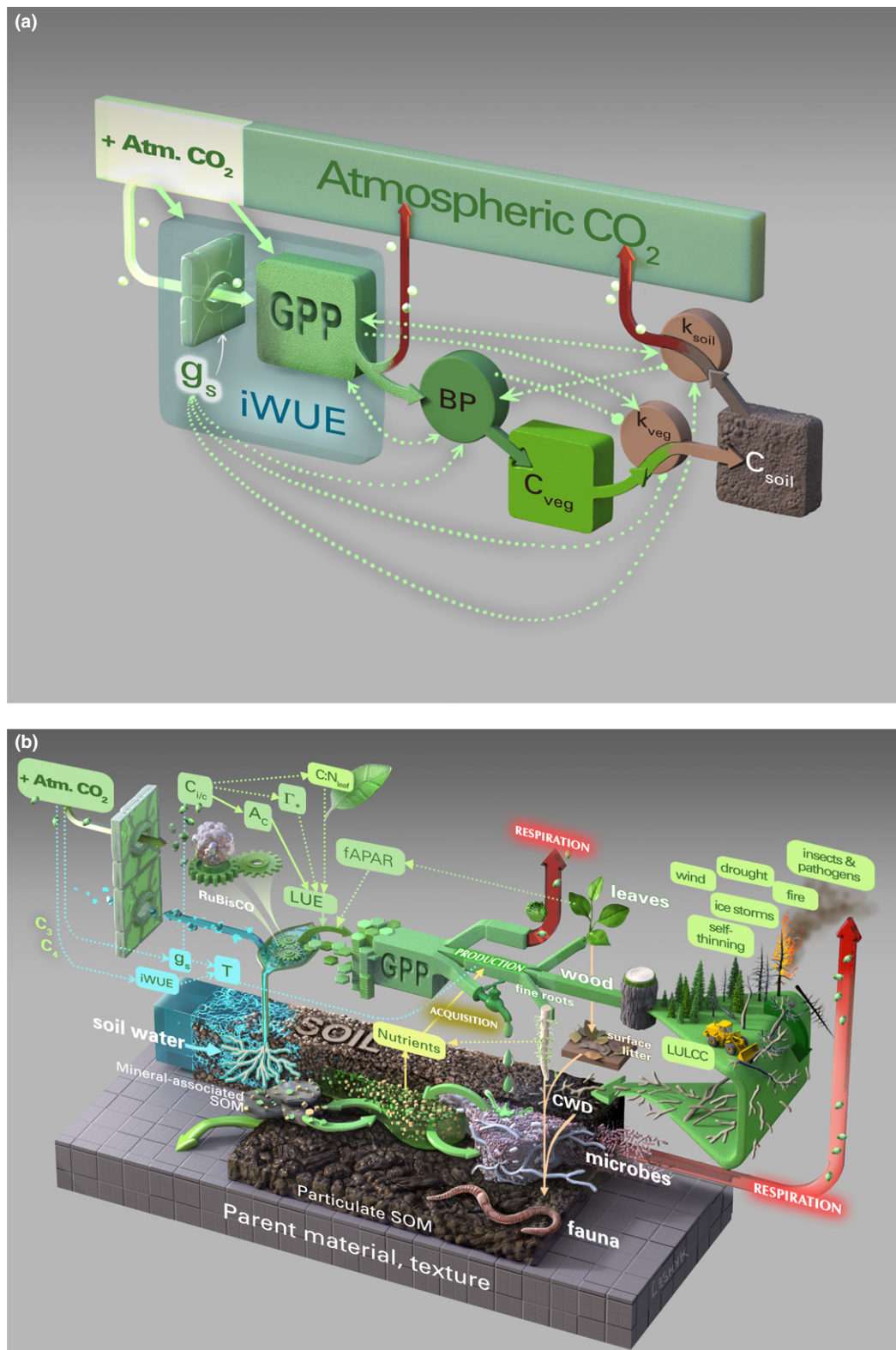
Biomass production is also carbon sink-limited by stoichiometric nutrient requirements (Elser *et al.*, 2010). Thus increased BP requires either increased nutrient acquisition or increased stoichiometric carbon-to-nutrient ratios. Increased plant-available carbon may be able to 'pay' for increased nutrient acquisition via a number of mechanisms (e.g. increased fine-root BP, mycorrhizal investment, exudation, atmospheric N fixation) (Luxmoore, 1981; Hungate *et al.*, 1999; Fleischer *et al.*, 2019). Changing stoichiometry may result in feedbacks that compound nutrient limitations by reducing decomposition rates and nutrient availability (Comins & McMurtrie, 1993), known as progressive nitrogen limitation (Luo *et al.*, 2004).

In environments where BP is primarily sink-limited (e.g. tree-lines (temperature limitation), arid and semiarid (water limitation)), increased carbon availability may have little effect on BP (Kramer, 1981; Körner, 2003b). However, in water-limited environments, increased iWUE could increase BP (Mooney *et al.*, 1991; Wullschlegel *et al.*, 2002). LAI may also be limited by water availability (Woodward, 1987; Yang *et al.*, 2018) and increased WUE may increase LAI and light absorption, leading to indirect positive feedback on GPP and transpiration (Fatichi *et al.*, 2016; Trancoso *et al.*, 2017).

If BP is restricted by sink limitation, BP efficiency (BP per unit GPP) would decrease and the labile products of photosynthesis would accumulate. If BP is stimulated this may be as short-lived, primary tissues (leaves and fine-roots) or long-lived, secondary tissues (wood) (De Kauwe *et al.*, 2014). Division of carbon among these tissues determines the residence time of carbon in plant biomass. Wood has greater residence time and thus greater potential to increase  $C_{\text{veg}}$  accumulation over multiple years. Greater production of short-lived tissues (i.e. leaves and fine-roots) may increase resource capture and will increase litter carbon inputs to the soil.

### 3. Plant mortality

Increases in mortality rates reduce vegetation residence times and have the potential to offset any biomass gains resulting from



**Fig. 1** Conceptual diagrams of the terrestrial carbon cycle and the action of elevated atmospheric [CO<sub>2</sub>] (eCO<sub>2</sub>). (a) Simple pool and flux (three-dimensional 3D) shapes diagram of the terrestrial carbon cycle showing key pools, fluxes, and processes relevant to the CO<sub>2</sub>-fertilization hypothesis as described in Box 1. Two-dimensional (2D) arrows represent direct (solid) or indirect (dashed) positive influences (triangular arrow heads), or the possibility of both positive and negative (circular) influences of eCO<sub>2</sub>. (b) Rich conceptual diagram of a landscape-scale carbon cycle and the influence of eCO<sub>2</sub> showing more processes (see Section II) and their interconnected, multiscale nature. Solid arrows (3D and 2D) represent material (mostly carbon) flows, dotted arrows represent influence. Abbreviations not in Table 1: C<sub>ic</sub>, internal or chloroplastic [CO<sub>2</sub>]; A<sub>c</sub>, carboxylation limited photosynthesis; Γ\*, photorespiration; C : N<sub>leaf</sub>, leaf carbon : nitrogen ratio; T, transpiration; LULCC, land-use and land cover change; CWD, coarse woody debris.

**Box 2** Evidence themes.**Theme 1: Direct exposure to elevated CO<sub>2</sub>**

Experiments in which plants are grown in CO<sub>2</sub>-enriched air and observations of plants growing close to geological CO<sub>2</sub> sources provide the only direct evidence of plant and soil responses to future [CO<sub>2</sub>]. The first eCO<sub>2</sub> experiments were typically at the scales of leaves or small, individual plants. Ecosystem-scale open-top chambers (OTCs) and larger free-air CO<sub>2</sub> enrichment (FACE) experiments have since been implemented over decades in more natural settings. All of these experiments provide evidence for the direct CO<sub>2</sub> effect on photosynthesis and stomatal conductance. These experiments also provide valuable data on biomass production, allocation to organs, and transpiration. The timescale of most experiments (< 10 yr), however, is generally much shorter than many ecosystem processes, and evidence for CO<sub>2</sub> effects on mortality, plant community dynamics, or changes in soil carbon stocks is limited.

**Theme 2: Tree growth measurements**

Tree rings and forest inventories provide long-term estimates of wood BP in forest ecosystems across the globe (e.g. Hember *et al.*, 2019; Hubau *et al.*, 2020). Tree ring data are annually resolved estimates of individual stem growth over the past decades to millennia (e.g. Babst *et al.*, 2014). These data provide insights into individual growth variability in relation to environmental changes including soil moisture, temperature and potentially also iCO<sub>2</sub>. Repeated inventories of forest ecosystems offer an assessment of forest-scale dynamics and the demographic processes of recruitment, growth, and mortality over previous decades and in some cases around century length (Pretzsch *et al.*, 2014). Inventories tend to have a coarser temporal resolution (5–10 yr resurveys) but represent forest-stand spatial scales, albeit that plot scale varies widely: 0.067 ha forest inventory analysis, c. 1–2 ha (e.g. Brienen *et al.*, 2015; Hubau *et al.*, 2020), 50 ha ForestGEO network (e.g. Chave *et al.*, 2008).

**Theme 3: Ecosystem monitoring**

Ecosystem eddy-covariance and global remote sensing may detect effects of iCO<sub>2</sub> on carbon, water, and energy fluxes over recent decades. Tower-based sensors are used to calculate ecosystem-scale (c. 1 km) carbon, water, and energy fluxes from the covariance of gas concentrations and vertical wind velocity (Baldocchi, 2003). A global network of continental networks (<http://fluxnet.fluxdata.org>) synthesizes flux-tower data from 916 sites, some in operation for over two decades, while the majority have run for a decade or less and are located in temperate ecosystems (Chu *et al.*, 2017). Satellite and other aircraft-borne Earth observing systems have been measuring the reflectance of electromagnetic radiation from the Earth's surface, used to infer changes in vegetation cover, leaf area, and biomass at a global scale (Fensholt *et al.*, 2004; Smith *et al.*, 2020). Reflected wavelengths from Landsat (first launched in 1972), MODIS, and other instruments can be used to measure the fraction of absorbed photosynthetically active radiation (FAPAR) and greenness indices, which are further used to infer leaf area index (LAI), GPP, and NPP with the help of simple models (Myneni *et al.*, 1997; Field *et al.*, 1998). Microwave wavelengths are used to measure vegetation optical depth (VOD, first available in the early 1980s) which can be used to infer vegetation water content and, by extension, vegetation biomass (Liu *et al.*, 2015).

**Theme 4: Large-scale constraints**

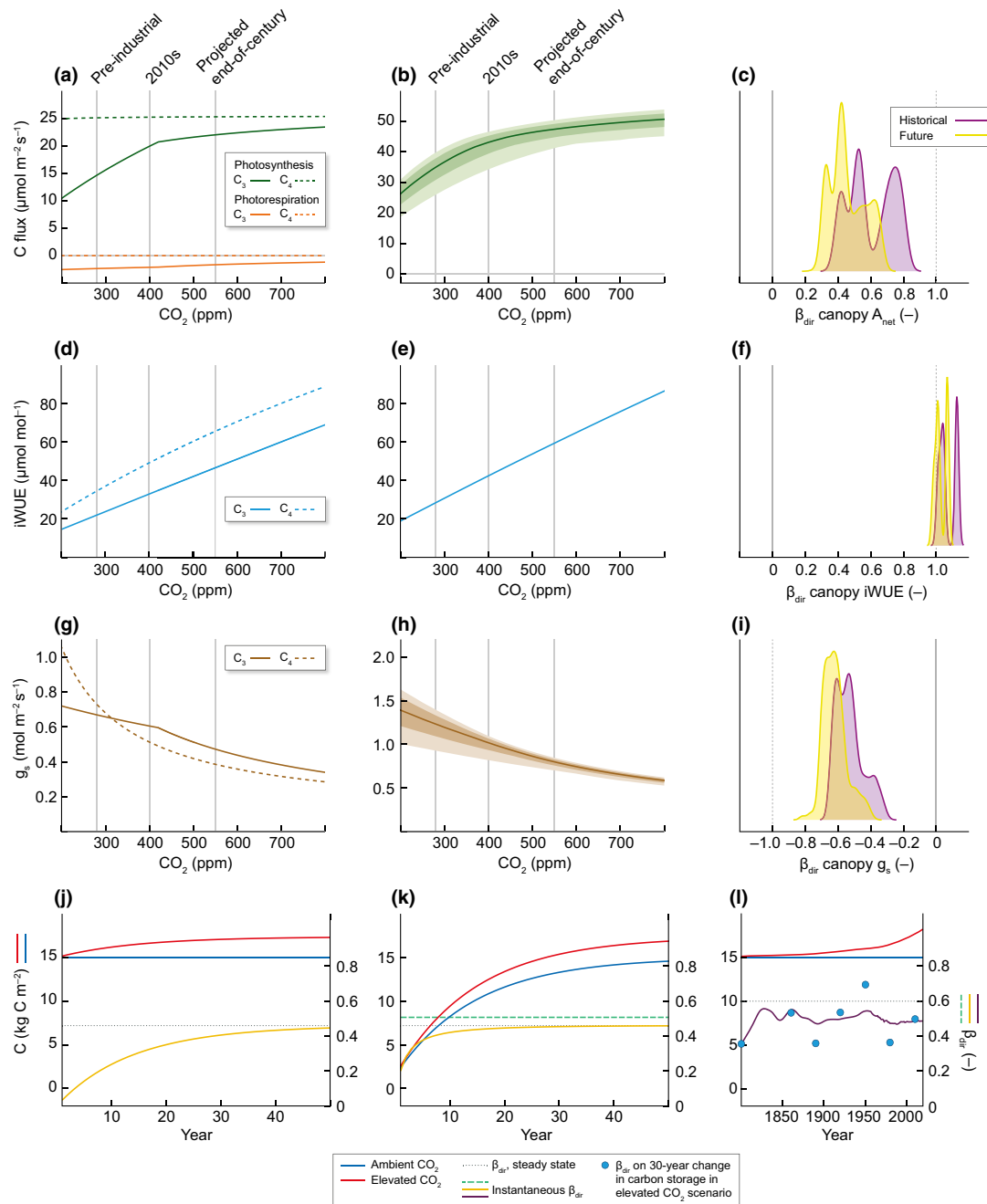
At regional-to-global scales, several long-term data streams provide constraints on the global carbon budget and its change over time. These data streams include near-surface and vertical profiles of atmospheric CO<sub>2</sub> concentration and δ<sup>13</sup>C, global water-cycle measurements, and atmospheric composition from ice cores. Atmospheric CO<sub>2</sub> measurements can be combined with other data and models to infer the global carbon budget and spatial details of land carbon uptake (Peylin *et al.*, 2013; Friedlingstein *et al.*, 2019). The impact of vegetation responses to iCO<sub>2</sub> on the hydrological cycle measured by stream gauges can also act as further indirect evidence (Ukkola *et al.*, 2016; Trancoso *et al.*, 2017). Carbonyl sulphide (OCS) can be used to infer global carbon assimilation because it is taken up by plants through stomata and is transformed by carbonic anhydrase (Wohlfahrt *et al.*, 2012; Whelan *et al.*, 2018).

increased BP (Eqn B3) (Bugmann & Bigler, 2011; Körner, 2017). Hydraulic failure and, to a lesser extent, carbon starvation are thought to be interrelated mechanisms of plant death (McDowell *et al.*, 2008). By easing the carbon and hydraulic impacts of abiotic and biotic stressors such as drought, or pest and pathogen attack, eCO<sub>2</sub> could potentially decrease mortality. Greater carbon resources could supply greater maintenance respiration, stored carbon reserves or synthesis of defence compounds (McDowell *et al.*, 2008). More efficient water use (Section II.1) could delay the onset or intensity of drought, which could reduce the risk of xylem-conductivity losses.

Indirect influences on mortality may emerge from the acceleration of individual size growth. Increased growth could reduce small-size-related mortality by speeding individuals out of the hazards of early life (e.g. browsing) and increasing their ability to

acquire resources (Metcalf *et al.*, 2014; Hülsmann *et al.*, 2018). Conversely, increased growth could increase large-size mortality risk, with tall trees being more susceptible to hydraulic stress, windthrow, lightning, and certain pests or pathogens (Bugmann & Bigler, 2011; Bennett *et al.*, 2015; Körner, 2017; Trugman *et al.*, 2018).

At the stand scale, increased growth may accelerate post-disturbance successional dynamics (McDowell *et al.*, 2020). Intensified competition for light, water, and nutrients could lead to earlier reorganization and transition (self-thinning) phases of development (Bormann & Likens, 1979), but also an earlier switch from transition to steady-state phases (Miller *et al.*, 2016). Acceleration of stand development by eCO<sub>2</sub> may or may not change self-thinning relationships (tree size to stem density) of a forest stand, with no change leading to no change in biomass. However, acceleration of



**Fig. 2** (a–l) Modelled theoretical responses to atmospheric  $\text{CO}_2$  concentration ( $[\text{CO}_2]$ , ppm) of photosynthesis,  $A_{\text{net}}$  ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ , dark green) (a–c) and photorespiration ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ , orange) (a); intrinsic water-use efficiency (iWUE,  $\mu\text{mol mol}^{-1}$ ) (d–f); stomatal conductance,  $g_s$  ( $\text{mol m}^{-2} \text{s}^{-1}$ ) (g–i); and carbon storage ( $\text{kg C m}^{-2}$ ) (j–l) under ambient (blue) and elevated (red)  $[\text{CO}_2]$ . Leaf (a, d, g) and canopy (b, e, h) scale for  $\text{C}_3$  (solid line) and  $\text{C}_4$  (dashed, leaf-scale only) plants. Variation in (b), (e) and (h) from a 1000-member ensemble (mean, SD, and 95 percentile shown) – a factorial combination of 100 top-of-canopy photosynthetic carboxylation capacity ( $V_{\text{cmax}}$ ) values (mean = 60, SD = 10) and 10 values of the maximum electron transport rate ( $J_{\text{max}}$ ) to  $V_{\text{cmax}}$  slope (mean = 1.63, SD = 0.2), the iWUE response does not vary in this ensemble. Distributions of direct  $\text{CO}_2$  responses ( $\beta_{\text{dir}}$ ) for historical (purple, 280–400 ppm) and future (yellow, 400–550 ppm)  $[\text{CO}_2]$  changes (c, f, i) of diurnally integrated, canopy-scale variables that include the same leaf physiology variation as in (b), (e), (h), plus three temperatures (10, 15, 25°C) and relative humidity (50%, 70%, 90%) combined in factorial. Trimodality in the gross primary production (GPP)  $\beta$  distributions results from the temperature variation.  $\beta$  distributions are weighted by the variables' absolute response to  $\text{CO}_2$ . Carbon storage (j–l) was calculated using a simple one-pool model with the mean future GPP response ( $\beta_{\text{dir, fut}}$ ) applied to biomass production (BP) for  $[\text{CO}_2]$  at 400 and 550 ppm when initial carbon stores are in equilibrium (j) or at 10% of equilibrium (k). (l) Historical response ( $\beta_{\text{dir, hist}}$ ) when initial carbon stores are assumed in equilibrium at 280 ppm and using the observed historical  $\text{CO}_2$  record. Instantaneous  $\beta_{\text{dir}}$  values for absolute carbon storage are shown (j–l, right y-axis, yellow or purple), as well as  $\beta_{\text{dir}}$  calculated using carbon storage increment (green dashed), and  $\beta_{\text{dir}}$  on 30 yr change in carbon storage in elevated  $\text{CO}_2$  scenario (blue points). Further modelling details are in Supporting Information Notes S3. Grey vertical lines (a, b, d, e, g, h) relate to pre-industrial era, 2010s, and projected end-of-century  $[\text{CO}_2]$  (280, 400, 550 ppm). Grey vertical lines (c, f, i) relate  $\beta_{\text{dir}}$  of 0 (solid) and 1 or –1 (dotted). Horizontal grey dotted lines (j–l) are  $\beta_{\text{dir}}$  when both ambient and elevated  $\text{CO}_2$  carbon pools are in a steady state.



stand development could increase biomass at the landscape scale by closing forest gaps more quickly. Differential mortality effects on different plant species could alter competitive dynamics, community composition, and associated stand properties (e.g. among fast-growing, ruderal/pioneer species and more conservative, slow-growing species; Ruiz-Benito *et al.*, 2017).

#### 4. Organic matter decomposition

Residence times of litter and SOM vary from minutes to millenia and can respond rapidly to environmental perturbation (Trumbore, 2009; Schmidt *et al.*, 2011; Dwivedi *et al.*, 2019). Increases in SOM decomposition rates reduce SOM residence times and have the potential to offset any eCO<sub>2</sub>-related increases in litter inputs. Accelerated decomposition of litter and particulate SOM (i.e. priming) can result from microbial responses to increased labile-carbon availability (Kuzyakov *et al.*, 2000; Blagodatskaya *et al.*, 2014), including at depth (Fontaine *et al.*, 2007). Organic acids produced by roots can destabilize mineral-associated SOM (Keiluweit *et al.*, 2015). eCO<sub>2</sub> effects on environmental conditions could also affect SOM decomposition. CO<sub>2</sub>-related increases in soil water (Section II.1) would probably stimulate decomposition in water-limited ecosystems (Castanha *et al.*, 2018), but could reduce oxygen availability (slowing decomposition) in energy-limited ecosystems.

Microbial activity has also been linked to the formation of mineral-associated SOM (Cotrufo *et al.*, 2013; Liang *et al.*, 2017), and potentially soil aggregates (Ge *et al.*, 2018), which might slow decomposition by restricting microbial access to SOM (Kögel-Knabner *et al.*, 2008). Changing litter stoichiometry might slow decomposition (Section II.2). Roots can distribute carbon deeper in the soil where decomposition is slower and capacity for mineral stabilization is higher (Jackson *et al.*, 2017; Hicks Pries *et al.*, 2018).

Greater decomposition rates might also increase soil nutrient availability, potentially reducing plant nutrient limitation (Treseder, 2004; Dijkstra, 2008) or increasing microbial immobilization. Over longer timescales, nutrient immobilization can reduce nutrient losses, leading to accumulation of ecosystem nutrient stocks which may enhance mineralization and progressively release plants from nutrient limitation (Rastetter *et al.*, 1997; Walker *et al.*, 2015).

#### 5. Terrestrial ecosystem carbon responses to CO<sub>2</sub>

The response of terrestrial carbon storage to eCO<sub>2</sub> ( $\Delta C_{\text{eco}}$ ) is the net result of the above described processes. Potential increases in BP and litter production are balanced by potential increases in loss rates (Eqns B3 and B4). Increased BP of short-lived primary tissues such as leaves and fine roots could lead to greater biomass of these transient C<sub>veg</sub> pools and to increased litter inputs to the soil. If wood BP is stimulated by eCO<sub>2</sub>, over medium timescales (annual to several decades) ecosystem biomass could increase as a result of the longer residence time of wood. However, wood BP is tied to tree size growth rates and the effects of tree size on mortality rates may be either positive or negative (Section II.3). Greater wood BP or greater wood mortality rates would result in greater coarse woody

debris, which may immobilize nutrients (e.g. Zimmerman *et al.*, 1995).

Increased plant inputs to litter and soil (e.g. wood, leaf and root litter, root exudates, and mycorrhizal subsidies) could increase C<sub>soil</sub>. However, the complex processes that drive the formation and decomposition of SOM make the response of C<sub>soil</sub> to eCO<sub>2</sub> difficult to predict (Schmidt *et al.*, 2011; Dwivedi *et al.*, 2019; Section II.4). Increased soil mineralization rates could lead to greater C<sub>eco</sub> if nutrients are redistributed from soils to plants, which have higher carbon: nutrient ratios and hence can store more carbon per unit nutrient (Rastetter *et al.*, 1992; Zaehle *et al.*, 2014).

A one-pool ecosystem carbon model (Box 1) with simplifying assumptions (BP  $\beta_{\text{dir}} = \text{GPP } \beta_{\text{dir}}$ ; residence time  $\beta_{\text{dir}} = 0$ ) provides baseline-expected  $\beta_{\text{dir}}$  for carbon storage (Fig. 2j–l). The model indicates that when starting carbon storage is nonzero,  $\beta_{\text{dir}}$  depends on the time of measurement (Fig. 2j,k). Based on the observed [CO<sub>2</sub>] trend (Le Quéré *et al.*, 2018), the model indicates that  $\beta_{\text{dir}}$  calculations over a 30 yr period (typical of forest-inventory analysis) are generally a little smaller ( $\beta_{\text{dir,hist}} \approx 0.5$ ) than steady-state ( $\beta_{\text{dir,hist}} = 0.6$ ; Fig 2l). Departures from these expected  $\beta$  values derived from GPP responses alone provide a guide to the magnitude of positive and negative feedbacks in eCO<sub>2</sub> studies and can help to guide iCO<sub>2</sub> attribution in historical studies.

### III. The evidence

#### 1. Physiology

**Carbon assimilation and GPP** Evidence across FACE experiments (11 sites, 45 species) shows that eCO<sub>2</sub> increased leaf-level, light-saturated photosynthesis ( $\beta_{\text{dir}} = 0.73 \pm 0.2$ ; see Notes S3 for methods), and supports differences between C<sub>3</sub> ( $\beta_{\text{dir}} = 0.79 \pm 0.2$ ) and C<sub>4</sub> species ( $\beta_{\text{dir}} = 0.27 \pm 0.2$ ) (Ainsworth & Long, 2005; all reported  $\beta$  values are in Table 2). Evidence suggests that maximum photosynthetic capacity acclimated (reduced) to eCO<sub>2</sub>, primarily maximum carboxylation capacity ( $\beta_{\text{dir}} = -0.38 \pm 0.1$ ) (Ainsworth & Long, 2005; Ainsworth & Rogers, 2007). Nevertheless, in many forest eCO<sub>2</sub> experiments, photosynthetic stimulation (> 5 yr) was only minimally affected by acclimation (Crous *et al.*, 2008; Bader *et al.*, 2010; Ellsworth *et al.*, 2017).

Indirect evidence also suggests increased photosynthesis with iCO<sub>2</sub>. Deuterium isotopomers of glucose in plant archives indicate that the leaf-level photorespiration: assimilation ratio has decreased since pre-industrial times ( $\beta_{\text{app}} = -0.99$ ) (Ehlers *et al.*, 2015), which translates to an increase in photosynthesis ( $\beta_{\text{app}} = 1.0$ ) (Ehlers *et al.*, 2015). GPP estimates from eddy-covariance (23 sites, c. 20 yr) suggest a recent increase ( $\beta_{\text{app}} = 1.6 \pm 0.9$ ), attributing a substantial iCO<sub>2</sub> contribution ( $\beta_{\text{dir,hist}} = 1.2 \pm 0.6$ ) (Fernández-Martínez *et al.*, 2017). Eddy-covariance data used to calibrate a model suggests a lower iCO<sub>2</sub> response ( $\beta_{\text{dir,hist}} = 0.5 \pm 0.2$ ) (Ueyama *et al.*, 2020).

Ice-core measurements of atmospheric carbonyl sulfide (OCS) combined with mass-balance analysis suggests that global GPP has increased since pre-industrial times ( $\beta_{\text{app}} = 0.95 \pm 0.2$ ) (Campbell *et al.*, 2017), as do ice-core measurements of atmospheric O<sub>2</sub>

Table 2 CO<sub>2</sub> responses across studies.

Process	eCO <sub>2</sub> /CO <sub>2</sub>	Study	Variable	Study type, location	Species, genus, biome	Plotted as	Start year <sup>†</sup>	End year <sup>†</sup>	Ambient/ start CO <sub>2</sub>	Elevated/ end CO <sub>2</sub>	Variable response ratio	95% CI	CO <sub>2</sub> response ratio	95% CI	β	95% CI
GPP	iCO <sub>2</sub>	Ehlers <i>et al.</i> (2015)	A:gsstar	Herbarium 2H isotopomers	<i>Brassica, Sphagnum, Eriophorum</i>	-	1890	2012	293.46	391.88	-25	-	34	-	-0.99	-
GPP	iCO <sub>2</sub>	Ehlers <i>et al.</i> (2015)	Asat	Herbarium 2H isotopomers model	<i>Brassica, Sphagnum, Eriophorum</i>	GPP	1890	2012	293.46	391.88	35	-	34	-	1	-
GPP	eCO <sub>2</sub>	Ainsworth & Long (2005)	Asat	FACE meta-analysis	Temperate	GPP	-	-	380	550	28	4.9	45	5.6	0.68	0.13
GPP	eCO <sub>2</sub>	Ainsworth & Long (2005)	Asat	FACE meta-analysis	Temperate	-	-	-	380	550	29	4.4	45	5.6	0.7	0.12
GPP	eCO <sub>2</sub>	Ainsworth & Long (2005)	Asat	FACE meta-analysis	Temperate	-	-	-	380	550	7	22	45	5.6	0.18	0.57
GPP	iCO <sub>2</sub>	Campbell <i>et al.</i> (2017)	GPP	Ice-core OCS	Global	GPP	1900	2013	296.57	394.6	31	5	33	2.8	0.95	0.15
GPP	iCO <sub>2</sub>	Cheng <i>et al.</i> (2017)	GPP	RS ET WUE model	Global best estimate	GPP	1982	2011	340.47	389.79	15	6.2	14	2.2	1.1	0.43
GPP	iCO <sub>2</sub>	Ciais <i>et al.</i> (2012)	GPP	Ice-core 18O	Global	GPP	1760	2010	276.58	387.99	54	120	40	3.1	1.3	2.3
GPP	iCO <sub>2</sub>	Fernandez-Martinez <i>et al.</i> (2017)	GPP	Flux-tower	Temperate	GPP	1992	2013	355.4	394.6	18	8.2	11	2.1	1.6	0.72
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Fernandez-Martinez <i>et al.</i> (2017)	GPP	Flux-tower, CO <sub>2</sub> attribution	Temperate	GPP	1992	2013	355.4	394.6	13	4.5	11	2.1	1.2	0.44
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	Flux-tower upscaled method 1	Global	GPP	2000	2014	368.23	396.7	-2.8	2.1	7.7	2	-0.39	0.3
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	Flux-tower upscaled method 2	Global	GPP	2000	2014	368.23	396.7	-1.9	1.9	7.7	2	-0.25	0.27
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	Flux-tower upscaled method 3	Global	GPP	2000	2014	368.23	396.7	-2.2	1.6	7.7	2	-0.29	0.24
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	RS fAPAR LUE model method 1	Global	GPP	2000	2014	368.23	396.7	6.2	6.3	7.7	2	0.8	0.82
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	RS fAPAR LUE model method 2	Global	GPP	2000	2014	368.23	396.7	9.6	3.4	7.7	2	1.2	0.52
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	RS fAPAR LUE model method 3	Multi-biome	GPP	2000	2014	368.23	396.7	4	4.3	7.7	2	0.53	0.57
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	RS fAPAR LUE model method 4	Multi-biome	GPP	2000	2014	368.23	396.7	0.11	3.3	7.7	2	0.014	0.44
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	RS fAPAR LUE model method 5	Global	GPP	2000	2014	368.23	396.7	5.6	3.5	7.7	2	0.73	0.48
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	Process model 1	Global	GPP	2000	2014	368.23	396.7	12	5.8	7.7	2	1.6	0.79
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	Process model 2	Global	GPP	2000	2014	368.23	396.7	4.4	5.4	7.7	2	0.57	0.72
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	Vegetation index method 1	Global	GPP	2000	2014	368.23	396.7	7.5	4.4	7.7	2	0.98	0.6
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	Vegetation index method 2	Global	GPP	2000	2014	368.23	396.7	2.3	2.7	7.7	2	0.31	0.36
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	Vegetation index method 3	Global	GPP	2000	2014	368.23	396.7	6	3.6	7.7	2	0.78	0.5
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Sun <i>et al.</i> (2019)	GPP	Vegetation index method 4	Global	GPP	2000	2014	368.23	396.7	5.5	4.8	7.7	2	0.72	0.63
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Ueyama <i>et al.</i> (2020)	GPP	Flux-tower constrained model, CO <sub>2</sub> attribution	Multi-biome	GPP	1990	2014	353.2	396.7	6	0.3	12	2.1	0.5	0.086

Table 2 (Continued)

Process	eCO <sub>2</sub> /iCO <sub>2</sub>	Study	Variable	Study type, location	Species, genus, biome	Plotted as	Start year†	End year†	Ambient/ start CO <sub>2</sub>	Elevated/ end CO <sub>2</sub>	Variable response ratio	CO <sub>2</sub> response ratio	95% CI	β	95% CI
GPP	eCO <sub>2</sub>	Ainsworth & Long (2005)	gs	FACE meta-analysis	Temperate	-	-	-	380	550	-20	45	2.7	-0.6	0.11
GPP	eCO <sub>2</sub>	Gimeno <i>et al.</i> (2015)	gs	FACE EucFACE	<i>Eucalyptus tereticornis</i>	-	-	-	400	550	-28	38	25	5.3	1.1
GPP	eCO <sub>2</sub>	Medlyn <i>et al.</i> (2001)	gs	eCO <sub>2</sub> meta-analysis	All	-	-	-	350	700	-14	100	9	-0.22	0.15
GPP	iCO <sub>2</sub> _CO <sub>2</sub> att.	Ueyama <i>et al.</i> (2020)	gs	Flux-tower constrained model, CO <sub>2</sub> attribution	Multi-biome	-	1990	2014	353.2	396.7	-3.2	12	0.26	-0.28	0.051
GPP	eCO <sub>2</sub>	Ainsworth & Long (2005)	iWUE	FACE meta-analysis	Temperate	WUE	-	-	380	550	54	45	17	1.2	0.33
GPP	eCO <sub>2</sub>	Barton <i>et al.</i> (2012)	iWUE	Whole tree chamber	<i>Eucalyptus saligna</i>	WUE	-	-	384.15	624.15	61	62	12	0.98	0.17
GPP	eCO <sub>2</sub>	Battipaglia <i>et al.</i> (2013)	iWUE	FACE Duke	<i>Liquidambar styraciflua</i>	WUE	-	-	381	546	75	43	26	1.6	0.45
GPP	eCO <sub>2</sub>	Battipaglia <i>et al.</i> (2013)	iWUE	FACE Duke	<i>Pinus taeda</i>	-	-	-	375	556	77	48	-	1.4	-
GPP	eCO <sub>2</sub>	Battipaglia <i>et al.</i> (2013)	iWUE	FACE ORNL	<i>Liquidambar styraciflua</i>	-	-	-	383	533	56	39	-	1.3	-
GPP	iCO <sub>2</sub> _CO <sub>2</sub> att.	Frank <i>et al.</i> (2015)	iWUE	Tree-ring	<i>Pinus</i>	WUE	1905	1997	297.87	362.51	22	22	12	1	0.51
GPP	iCO <sub>2</sub> _CO <sub>2</sub> att.	Frank <i>et al.</i> (2015)	iWUE	Tree-ring	<i>Quercus</i>	WUE	1905	1997	297.87	362.51	14	22	20	2.6	0.67
GPP	iCO <sub>2</sub>	Keeling <i>et al.</i> (2017)	iWUE	Atmospheric 13C	Global	WUE	1900	1999	296.57	367.06	20	24	18	2.7	0.85
GPP	iCO <sub>2</sub>	Penuelas <i>et al.</i> (2011)	iWUE	Tree-ring	Forests	WUE	1965	2005	319.56	378.23	20	18	13	2.4	1.1
GPP	iCO <sub>2</sub>	Saurer <i>et al.</i> (2004)	iWUE	Tree-ring	<i>Larix</i>	WUE	1875	1975	288.97	330.28	17	14	38	1.2	2.5
GPP	iCO <sub>2</sub>	Saurer <i>et al.</i> (2004)	iWUE	Tree-ring	<i>Picea</i>	WUE	1875	1975	288.97	330.28	23	14	25	1.5	1.6
GPP	iCO <sub>2</sub> _CO <sub>2</sub> att.	Saurer <i>et al.</i> (2004)	iWUE	Flux-tower constrained model, CO <sub>2</sub> attribution	Multi-biome	WUE	1875	1975	288.97	330.28	17	14	31	2.6	1.2
GPP	iCO <sub>2</sub> _CO <sub>2</sub> att.	Ueyama <i>et al.</i> (2020)	iWUE	Tree-ring	Multi-biome	WUE	1990	2014	353.2	396.7	8.8	12	0.26	0.73	0.12
GPP	iCO <sub>2</sub>	van der Sleen <i>et al.</i> (2015)	iWUE	Tree-ring	Multi-site-tropical	WUE	1864	2014	286.71	396.7	32	38	-	0.87	-
GPP	eCO <sub>2</sub>	Ainsworth & Long (2005)	N_leaf_area	FACE meta-analysis	Temperate	-	-	-	380	550	-4.9	45	2.6	-0.14	0.075
GPP	eCO <sub>2</sub>	Ainsworth & Long (2005)	v_cmax	FACE meta-analysis	Temperate	-	-	-	380	550	-13	45	2.5	-0.38	0.087
GPP	eCO <sub>2</sub>	Dekauwe <i>et al.</i> (2013)	T	FACE Duke	<i>Pinus taeda</i>	-	-	-	375	556	1	48	-	0.027	-
GPP	eCO <sub>2</sub>	Dekauwe <i>et al.</i> (2013)	T	FACE ORNL	<i>Liquidambar styraciflua</i>	-	-	-	383	533	-16	39	-	-0.54	-
GPP	eCO <sub>2</sub>	Dekauwe <i>et al.</i> (2013)	WUE	FACE Duke	<i>Pinus taeda</i>	WUE	-	-	375	556	29	48	18	0.65	0.36
GPP	eCO <sub>2</sub>	Dekauwe <i>et al.</i> (2013)	WUE	FACE ORNL	<i>Liquidambar styraciflua</i>	WUE	-	-	383	533	32	39	26	0.84	0.6
GPP	iCO <sub>2</sub>	FACE EucFACE Tang <i>et al.</i> (2014)	WUE	RS GPP and ET model	Global	-	2000	2013	368.23	394.6	-3.4	7.2	-	-0.49	-
GPP	iCO <sub>2</sub>	Xue <i>et al.</i> (2015)	WUE	RS GPP and ET model	Global	-	2000	2013	368.23	394.6	1.9	7.2	-	0.28	-
GPP	iCO <sub>2</sub>	Keenan <i>et al.</i> (2013)	WUE_inherent	Flux-towers	Multi-site-temperate	WUE	1992	2010	355.4	387.99	41	9.2	23	3.9	2.1
GPP	iCO <sub>2</sub>	Mastrotheodoros <i>et al.</i> (2017)	WUE_inherent	Flux-towers	Multi-site-temperate	WUE	1999	2014	367.06	396.7	20	8.1	15	2.4	1.7
GPP	iCO <sub>2</sub> _CO <sub>2</sub> att.	Ueyama <i>et al.</i> (2020)	gs	Flux-tower constrained model, CO <sub>2</sub> attribution	Multi-biome	-	1990	2014	353.2	396.7	-3.2	12	0.26	-0.28	0.051

Table 2 (Continued)

Process	eCO <sub>2</sub> /iCO <sub>2</sub>	Study	Variable	Study type, location	Species, genus, biome	Plotted as	Start year†	End year†	Ambient/ start CO <sub>2</sub>	Elevated/ end CO <sub>2</sub>	Variable response ratio	95% CI	CO <sub>2</sub> response ratio	95% CI	β	95% CI
GPP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Ueyama <i>et al.</i> (2020)	iWUE	Flux-tower constrained model, CO <sub>2</sub> attribution	Multi-biome	WUE	1990	2014	353.2	396.7	8.8	0.26	12	2.1	0.73	0.12
BP	eCO <sub>2</sub>	Körner <i>et al.</i> (2005)	BAI	FACE Swiss canopy crane	<i>Fagus</i>	BP	2001	2003	380	550	13	94	45	5.6	0.32	2.2
BP	eCO <sub>2</sub>	Körner <i>et al.</i> (2005)	BAI	FACE Swiss canopy crane	<i>Fagus</i>	-	2001	-	380	550	93	160	45	5.6	1.8	2.2
BP	eCO <sub>2</sub>	Körner <i>et al.</i> (2005)	BAI	FACE Swiss canopy crane	<i>Fagus</i>	-	2002	-	380	550	39	150	45	5.6	0.89	2.9
BP	eCO <sub>2</sub>	Körner <i>et al.</i> (2005)	BAI	FACE Swiss canopy crane	<i>Fagus</i>	-	2003	-	380	550	91	180	45	5.6	1.8	2.5
BP	eCO <sub>2</sub>	Klein <i>et al.</i> (2016)	BAI	FACE Swiss spruce	<i>Picea abies</i>	BP	-	-	420	554	-8	17	32	5	-0.3	0.67
BP	eCO <sub>2</sub>	Norby (1999)	BAI	eCO <sub>2</sub> spring Rapolano	<i>Quercus ilex</i>	BP	-	-	345	650	19	-	88	-	0.27	-
BP	eCO <sub>2</sub>	Hovenden <i>et al.</i> (2019)	BP	FACE synthesis	grassland	BP	-	-	375	618	9	3.4	65	5.8	0.17	0.064
BP	eCO <sub>2</sub>	Norby <i>et al.</i> (2005)	BP	FACE synthesis	Temperate forest	BP	-	-	377	546	23	4	45	5.6	0.56	0.11
BP	eCO <sub>2</sub>	Walker <i>et al.</i> (2019)	BP	FACE meta-analysis	Temperate forest	BP	-	-	377	576	23	12	53	5.7	0.49	0.24
BP	eCO <sub>2</sub>	Elisworth <i>et al.</i> (2017)	BP_abg	FACE EucFACE	<i>Eucalyptus tereticornis</i>	BP	-	-	399	549	-8	17	38	5.3	-0.26	0.58
BP	eCO <sub>2</sub>	Nie <i>et al.</i> (2013)	BP_fine-root	eCO <sub>2</sub> meta-analysis	Multi-biome	-	-	-	360	645	39	-	79	-	0.56	-
BP	eCO <sub>2</sub>	Nowak <i>et al.</i> (2004)	BP_fine-root	eCO <sub>2</sub> meta-analysis	Forest	-	-	-	380	675	70	-	78	-	0.92	-
BP	eCO <sub>2</sub>	Nowak <i>et al.</i> (2004)	BP_fine-root	eCO <sub>2</sub> meta-analysis	Grassland	-	-	-	380	675	11	-	78	-	0.18	-
BP	iCO <sub>2</sub>	Brienen <i>et al.</i> (2015)	BP_wood	Inventory	Amazon	BP	1983	2011	342.01	389.79	17	6.8	14	2.2	1.2	0.48
BP	iCO <sub>2</sub>	Hubau <i>et al.</i> (2020)	BP_wood	Inventory	Tropical Africa	BP	1983	2014	342.01	396.7	11	10	16	2.2	0.69	0.63
BP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Hubau <i>et al.</i> (2020)	BP_wood	Inventory, CO <sub>2</sub> attribution	Tropical Africa	BP	1983	2014	342.01	396.7	8.3	16	16	2.2	0.54	0.97
BP	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	BP_wood_abv	Inventory	Boreal	-	2001	2008	369.79	384.15	3.6	8.3	3.9	1.9	0.92	2.1
BP	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	BP_wood_abv	Inventory	Panbiome	BP	1990	2008	353.2	384.15	8.2	9.4	8.8	2.1	0.94	1.1
BP	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	BP_wood_abv	Inventory	Temperate	-	1990	2004	353.2	376.12	27	21	6.5	2.1	3.8	2.9
BP	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	BP_wood_abv	Inventory	Tropical	-	1994	2009	357.62	385.81	2.1	6.7	7.9	2.1	0.27	0.86
BP	eCO <sub>2</sub>	Ainsworth & Long (2005)	SLA	FACE meta-analysis	Temperate	-	-	-	380	550	-5.9	2.2	45	5.6	-0.16	0.066
BP	eCO <sub>2</sub>	Hattenschwiler <i>et al.</i> (1997)	TRW	eCO <sub>2</sub> spring Laiatico	<i>Quercus ilex</i>	-	1	-	320	650	41	-	100	-	0.49	-
BP	eCO <sub>2</sub>	Hattenschwiler <i>et al.</i> (1997)	TRW	eCO <sub>2</sub> spring Rapolano	<i>Quercus ilex</i>	-	1	-	320	650	77	-	100	-	0.81	-
BP	iCO <sub>2</sub>	Voelker <i>et al.</i> (2006)	TRW	Tree-ring	<i>Quercus Pinus</i> , 1st year	-	1851	1967	286.51	321.62	47	-	12	-	3.3	-
BP	iCO <sub>2</sub>	Voelker <i>et al.</i> (2006)	TRW	Tree-ring	<i>Quercus Pinus</i> , 50th year	BP	1879	2002	289.77	371.93	32	-	28	-	1.1	-
BP	eCO <sub>2</sub>	Bader <i>et al.</i> (2013)	TRW	FACE Swiss canopy crane	<i>Fagus</i>	BP	-	-	380	550	-3.5	51	45	5.6	-0.097	1.4
BP	eCO <sub>2</sub>	Bader <i>et al.</i> (2013)	TRW	FACE Swiss canopy crane	<i>Fagus</i>	-	-	-	380	550	-13	33	45	5.6	-0.38	1
BP	eCO <sub>2</sub>	Bader <i>et al.</i> (2013)	TRW	FACE Swiss canopy crane	<i>Fagus</i>	-	-	-	380	550	-9	24	45	5.6	-0.26	0.71
BP	eCO <sub>2</sub>	Bader <i>et al.</i> (2013)	TRW	FACE Swiss canopy crane	<i>Fagus</i>	-	-	-	380	550	16	59	45	5.6	0.4	1.4
BP	eCO <sub>2</sub>	Bader <i>et al.</i> (2013)	TRW	FACE Swiss canopy crane	<i>Quercus</i>	BP	-	-	380	550	22	75	45	5.6	0.55	1.7
BP	iCO <sub>2</sub>	Penuelas <i>et al.</i> (2011)	TRW	Tree-ring synthesis	Forests	BP	1965	2005	319.56	378.23	3.9	14	18	2.4	0.23	0.8

Table 2 (Continued)

Process	eCO <sub>2</sub> /iCO <sub>2</sub>	Study	Variable	Study type, location	Species, genus, biome	Plotted as	Start year†	End year†	Ambient/ start CO <sub>2</sub>	Elevated/ end CO <sub>2</sub>	Variable response ratio	95% CI	CO <sub>2</sub> response ratio	95% CI	β	95% CI
k_veg	iCO <sub>2</sub>	Peng <i>et al.</i> (2011)	k_veg_stem	Inventory	Canada	k_veg	1978	1999	334.57	367.06	99	-	9.7	-	7.4	-
k_veg	iCO <sub>2</sub>	Pretzsch <i>et al.</i> (1997)	k_veg_stem	Inventory	<i>Fagus sylvatica</i>	k_veg	1960	2000	316.57	368.23	-17	-	16	-	-1.2	-
k_veg	iCO <sub>2</sub>	van Mantgem <i>et al.</i> (2009)	k_veg_stem	Inventory	Western North America	k_veg	1981	2004	339.3	376.12	90	23	11	2.2	6.2	1.7
k_veg	iCO <sub>2</sub>	Brienen <i>et al.</i> (2015)	k_veg_stem	tropical_amazon_stems	Amazon	-	-	-	400	625	20	-	5.5	5.6	0.4	0.11
k_veg	eCO <sub>2</sub>	van Groenigen <i>et al.</i> (2014)	LP_veg_abg	eCO <sub>2</sub> meta-analysis	Multi-species	-	-	-	-	-	20	5.5	5.6	5.4	0.4	0.11
k_veg	iCO <sub>2</sub>	Brienen <i>et al.</i> (2015)	LP_wood	Inventory	Amazon	k_veg	1983	2011	342.01	389.79	38	24	14	2.2	2.5	1.4
k_veg	iCO <sub>2</sub>	Hubau <i>et al.</i> (2020)	LP_wood	Inventory	Tropical Africa	k_veg	1983	2014	342.01	396.7	-12	29	16	2.2	-0.88	2.2
k_veg	iCO <sub>2</sub>	Hubau <i>et al.</i> (2020)	LP_wood	Inventory	Tropical Africa	k_veg	1983	2014	342.01	396.7	30	68	16	2.2	1.8	3.6
k_veg	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	LP_wood_abv	Inventory	Boreal	-	2001	2008	369.79	384.15	6.3	-	3.9	-	1.6	-
k_veg	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	LP_wood_abv	Inventory	Panbiome	k_veg	1990	2008	353.2	384.15	29	26	8.8	2.1	3	2.5
k_veg	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	LP_wood_abv	Inventory	Temperate	-	1990	2004	353.2	376.12	28	-	6.5	-	3.9	-
k_veg	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	LP_wood_abv	Inventory	Tropical	-	1994	2009	357.62	385.81	28	-	7.9	-	3.3	-
k_soil	eCO <sub>2</sub>	Phillips <i>et al.</i> (2011)	C_exudate	FACE Duke, unfertilised	<i>Pinus taeda</i>	k_soil	-	-	375	556	56	32	48	5.7	1.1	0.53
k_soil	eCO <sub>2</sub>	Bader <i>et al.</i> (2010)	C_microbe	FACE Swiss canopy crane	temperate forest	k_soil	-	-	380	550	16	17	45	5.6	0.4	0.39
k_soil	eCO <sub>2</sub>	Phillips <i>et al.</i> (2011)	C_microbe	FACE Duke, unfertilised	<i>Pinus taeda</i>	k_soil	-	-	375	556	56	80	48	5.7	1.1	1.3
k_soil	eCO <sub>2</sub>	Cheng <i>et al.</i> (2012)	k_soil	FACE	<i>Avena fatua</i> AFM	k_soil	-	-	380	580	80	-	53	-	1.4	-
k_soil	eCO <sub>2</sub>	van Groenigen <i>et al.</i> (2014)	k_soil	eCO <sub>2</sub> meta-analysis	Multi-species	k_soil	-	-	400	625	17	7.3	56	5.4	0.34	0.14
k_soil	eCO <sub>2</sub>	Zak <i>et al.</i> (2003)	N_immobilisation	FACE synthesis	Temperate forest	-	-	-	380	550	15	71	45	5.6	0.37	1.7
k_soil	eCO <sub>2</sub>	Zak <i>et al.</i> (2003)	N_mineralisation_gross	FACE synthesis	temperate forest	k_soil	-	-	380	550	13	54	45	5.6	0.33	1.3
k_soil	iCO <sub>2</sub>	Fernandez-Martinez <i>et al.</i> (2017)	R_eco	Flux-tower synthesis	Multi-biome	k_soil	1992	2013	355.4	394.6	6.3	11	11	2.1	0.58	0.98
k_soil	iCO <sub>2</sub>	Bond-Lamberty <i>et al.</i> (2018)	R_h_to_R_soil_ratio	synthesis	Global	-	1990	2014	353.2	396.7	17	-	12	-	1.3	-
k_soil	eCO <sub>2</sub>	Bader <i>et al.</i> (2010)	R_soil	FACE Swiss canopy crane	Temperate forest	k_soil	-	-	380	550	-6.5	25	45	5.6	-0.18	0.71
k_soil	iCO <sub>2</sub>	Bond-Lamberty & Thomson (2010)	R_soil	synthesis	Global	k_soil	1989	2008	352.02	384.15	2	-	9.1	-	0.22	-
k_soil	eCO <sub>2</sub>	Drake <i>et al.</i> (2016)	R_soil	FACE EucFACE	<i>Eucalyptus tereticornis</i>	-	-	-	400	430	10	-	7.5	-	1.3	-
k_soil	eCO <sub>2</sub>	Drake <i>et al.</i> (2016)	R_soil	FACE EucFACE	<i>Eucalyptus tereticornis</i>	-	-	-	400	550	10	-	38	-	0.3	-
k_soil	eCO <sub>2</sub>	Drake <i>et al.</i> (2018)	R_soil	FACE EucFACE	<i>Eucalyptus tereticornis</i>	k_soil	-	-	400	550	7	-	38	-	0.21	-
k_soil	eCO <sub>2</sub>	Bader <i>et al.</i> (2010)	SWC	FACE Swiss canopy crane	Temperate forest	-	-	-	380	550	8.5	-	45	-	0.22	-
NEP	eCO <sub>2</sub>	Evans <i>et al.</i> (2014)	C_eco	FACE NDFP	Desert	C_eco	-	-	375	513	14	18	37	5.6	0.41	0.52
NEP	iCO <sub>2</sub>	Friedlingstein <i>et al.</i> (2019)	C_eco	Carbon budget, lower estimate	Global	C_eco	1959	2018	315.66	407.38	7.7	-	29	-	0.29	-
NEP	iCO <sub>2</sub>	Friedlingstein <i>et al.</i> (2019)	C_eco	Carbon budget, upper estimate	Global	C_eco	1959	2018	315.66	407.38	4.8	-	29	-	0.18	-
NEP	eCO <sub>2</sub>	Hungate <i>et al.</i> (2013)	C_eco	FACE KSCO	Oak scrub	C_eco	-	-	380	700	3.5	12	84	5.8	0.057	0.19
NEP	iCO <sub>2</sub>	Pan <i>et al.</i> (2011)	C_eco	Inventory, upscaled	Global forests	C_eco	1990	2007	353.2	382.25	8.3	2.8	8.2	2.1	1	0.41
NEP	iCO <sub>2</sub>	Pan <i>et al.</i> (2011)	C_eco	Inventory, upscaled	Global, intact forests	C_eco	1990	2007	353.2	382.25	5.4	1.9	8.2	2.1	0.66	0.28
NEP	eCO <sub>2</sub>	Iversen <i>et al.</i> (2012)	C_fine-root	FACE ORNL, 0-90cm	<i>Liquidambar styraciflua</i>	-	-	-	383	533	57	61	39	5.5	1.4	1.2
NEP	iCO <sub>2</sub>	Pan <i>et al.</i> (2011)	C_litter	Inventory, upscaled	Global	C_soil	1990	1999	353.2	367.06	3.6	-	3.9	-	0.92	-
NEP	eCO <sub>2</sub>	Evans <i>et al.</i> (2014)	C_soil	FACE NDFP	Desert	C_soil	-	-	375	513	20	23	37	5.6	0.59	0.6

Table 2 (Continued)

Process	eCO <sub>2</sub> /iCO <sub>2</sub>	Study	Variable	Study type, location	Species, genus, biome	Plotted as	Start year†	End year†	Ambien/ start CO <sub>2</sub>	Elevated/ end CO <sub>2</sub>	Variable response ratio	95% CI	CO <sub>2</sub> response ratio	95% CI	β	95% CI
NEP	eCO <sub>2</sub>	Hungate <i>et al.</i> (2009)	C_soil	eCO <sub>2</sub> meta-analysis	Multi-biome	-	-	-	380	550	1.4	1.1	45	5.6	0.039	0.03
NEP	eCO <sub>2</sub>	Hungate <i>et al.</i> (2009)	C_soil	eCO <sub>2</sub> meta-analysis, natural studies	Multi-biome	C_soil	-	-	380	550	0.2	1.1	45	5.6	0.0054	0.03
NEP	eCO <sub>2</sub>	Hungate <i>et al.</i> (2013)	C_soil	FACE KSCO	Oak scrub	C_soil	-	-	380	700	-8.8	27	84	5.8	-0.15	0.49
NEP	eCO <sub>2</sub>	Iversen <i>et al.</i> (2012)	C_soil	FACE ORNL, 0-90cm	<i>Liquidambar styraciflua</i>	C_soil	-	-	383	533	19	23	39	5.5	0.51	0.59
NEP	eCO <sub>2</sub>	Jastrow <i>et al.</i> (2005)	C_soil	eCO <sub>2</sub> meta-analysis	Meta-analysis	C_soil	-	-	380	550	5.6	2.8	45	5.6	0.15	0.073
NEP	eCO <sub>2</sub>	Lajtha <i>et al.</i> (2014)	C_soil	Litter addition, Noe	Temperate	-	-	-	350	700	29	13	100	6.4	0.37	0.15
NEP	eCO <sub>2</sub>	Lajtha <i>et al.</i> (2014)	C_soil	Litter addition, Wingsra	Temperate	-	-	-	350	700	33	28	100	6.4	0.41	0.3
NEP	iCO <sub>2</sub>	Pan <i>et al.</i> (2011)	C_soil	Inventory, 1m, upscaled	Global	C_soil	1990	1999	353.2	367.06	1.2	-	3.9	-	0.31	-
NEP	eCO <sub>2</sub>	Zaehle <i>et al.</i> (2014)	C_soil	FACE ORNL	<i>Liquidambar styraciflua</i>	C_soil	-	-	383	533	2.2	-	39	5.5	0.066	-
NEP	eCO <sub>2</sub>	Iversen <i>et al.</i> (2012)	c_soil_maom	FACE ORNL, 0-90cm	<i>Liquidambar styraciflua</i>	-	-	-	383	533	13	51	39	5.5	0.38	1.4
NEP	eCO <sub>2</sub>	Iversen <i>et al.</i> (2012)	C_soil_pom	FACE ORNL, 0-90cm	<i>Liquidambar styraciflua</i>	-	-	-	383	533	25	41	39	5.5	0.68	0.99
NEP	iCO <sub>2</sub>	Chave <i>et al.</i> (2008)	C_veg	Inventory	Tropical forest	C_veg	1985	2005	344.99	378.23	2.8	1.9	9.6	2.2	0.3	0.21
NEP	iCO <sub>2</sub>	Chave <i>et al.</i> (2008)	C_veg	Inventory	Tropical forest, ex. Sinharaja	-	1985	2005	344.99	378.23	3.8	2	9.6	2.2	0.4	0.23
NEP	iCO <sub>2</sub>	Friedlingstein <i>et al.</i> (2019)	C_veg	Carbon budget, lower estimate	Global	C_veg	1959	2018	315.66	407.38	43	-	29	-	1.4	-
NEP	iCO <sub>2</sub>	Friedlingstein <i>et al.</i> (2019)	C_veg	Carbon budget, upper estimate	Global	C_veg	1959	2018	315.66	407.38	27	-	29	-	0.93	-
NEP	eCO <sub>2</sub>	Hungate <i>et al.</i> (2013)	C_veg	FACE KSCO	Oak scrub	C_veg	-	-	380	700	23	14	84	5.8	0.33	0.19
NEP	iCO <sub>2</sub>	Pan <i>et al.</i> (2011)	C_veg	Inventory, upscaled	Global forests	C_veg	1990	1999	353.2	367.06	7.7	-	3.9	-	1.9	-
NEP	iCO <sub>2</sub>	Pretzsch <i>et al.</i> (1997)	C_veg	Inventory	<i>Fagus sylvatica</i>	C_veg	1960	2000	316.57	368.23	7	-	16	-	0.45	-
NEP	iCO <sub>2</sub>	Pretzsch <i>et al.</i> (1997)	C_veg	Inventory	<i>Picea abies</i>	C_veg	1960	2000	316.57	368.23	6	-	16	-	0.39	-
NEP	eCO <sub>2</sub>	Terrer <i>et al.</i> (2019)	C_veg	FACE meta-analysis, upscaled	Global	C_veg	-	-	375	625	12	6	67	5.8	0.22	0.11
NEP	eCO <sub>2</sub>	Evans <i>et al.</i> (2014)	C_veg_abg	FACE NDF	Desert	-	-	-	375	513	-13	30	37	5.6	-0.44	1.1
NEP	eCO <sub>2</sub>	Baig <i>et al.</i> (2015)	C_veg_abg_inc	eCO <sub>2</sub> meta-analysis, factorial studies	Multi-biome	-	-	-	362.5	665	21	11	83	6.1	0.32	0.15
NEP	eCO <sub>2</sub>	Evans <i>et al.</i> (2014)	C_veg_bg	FACE NDF	Desert	-	-	-	375	513	-9.4	32	37	5.6	-0.31	1.1
NEP	eCO <sub>2</sub>	Baig <i>et al.</i> (2015)	C_veg_bg_inc	eCO <sub>2</sub> meta-analysis, factorial studies	Multi-biome	-	-	-	362.5	665	35	18	83	6.1	0.5	0.22
NEP	eCO <sub>2</sub>	Baig <i>et al.</i> (2015)	C_veg_inc	eCO <sub>2</sub> meta-analysis, open ground studies	Multi-biome	C_veg_inc	-	-	360	550	22	6.2	53	5.9	0.47	0.13
NEP	iCO <sub>2</sub>	Pretzsch <i>et al.</i> (1997)	C_veg_inc	Inventory	<i>Fagus sylvatica</i>	C_veg_inc	1960	2000	316.57	368.23	30	-	16	-	1.7	-
NEP	iCO <sub>2</sub>	Pretzsch <i>et al.</i> (1997)	C_veg_inc	Inventory	<i>Picea abies</i>	C_veg_inc	1960	2000	316.57	368.23	10	-	16	-	0.63	-
NEP	eCO <sub>2</sub>	Walker <i>et al.</i> (2019)	C_veg_inc	FACE meta-analysis	temperate forest	C_veg_inc	-	-	377	576	29	23	53	5.7	0.6	0.43
NEP	eCO <sub>2</sub>	Nie <i>et al.</i> (2013)	C_veg_root	eCO <sub>2</sub> meta-analysis	Multi-biome	-	-	-	360	645	29	-	79	-	0.43	-
NEP	eCO <sub>2</sub>	Hattenschwiler <i>et al.</i> (1997)	C_wood	eCO <sub>2</sub> spring Laiatico	<i>Quercus ilex</i>	C_veg	30	-	345	650	16	-	88	-	0.23	-
NEP	eCO <sub>2</sub>	Hattenschwiler <i>et al.</i> (1997)	C_wood	eCO <sub>2</sub> spring Rapolano	<i>Quercus ilex</i>	C_veg	30	-	345	650	28	-	88	-	0.39	-
NEP	iCO <sub>2</sub>	Hubau <i>et al.</i> (2020)	C_wood	Inventory	Tropical Amazon	C_veg	1983	2014	342.01	396.7	12	-	16	2.2	0.77	-
NEP	iCO <sub>2</sub>	Brienen <i>et al.</i> (2015)	C_wood_abg	Inventory	Tropical Africa	C_veg	1983	2011	342.01	389.79	7.5	-	14	-	0.55	-

Table 2 (Continued)

Process	eCO <sub>2</sub> /iCO <sub>2</sub>	Study	Variable	Study type, location	Species, genus, biome	Plotted as	Start year <sup>†</sup>	End year <sup>†</sup>	Ambient/ start CO <sub>2</sub>	Elevated/ end CO <sub>2</sub>	Variable response ratio	95% CI	CO <sub>2</sub> response ratio	95% CI	β	95% CI
NEP	iCO <sub>2</sub>	McMahon <i>et al.</i> (2011)	C_wood_abg	Inventory, 100 years	Temperate forest	C_veg	1987	2005	348.17	378.23	18	3.6	8.6	2.1	2	0.59
NEP	iCO <sub>2</sub>	McMahon <i>et al.</i> (2011)	C_wood_abg	Inventory, 50 years	Temperate forest	C_veg	1987	2005	348.17	378.23	27	5.7	8.6	2.1	2.9	0.87
NEP	iCO <sub>2</sub>	Qie <i>et al.</i> (2017)	C_wood_abg	Inventory	Borneo, intact plots	C_veg	1985	2010	344.99	387.99	5.8	3.4	12	2.2	0.48	0.28
NEP	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	C_wood_abv	Inventory	Boreal	-	2001	2008	369.79	384.15	4.9	-	3.9	-	1.3	-
NEP	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	C_wood_abv	Inventory	Panbiome	C_veg	1990	2008	353.2	384.15	7.1	2.4	8.8	2.1	0.82	0.32
NEP	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	C_wood_abv	Inventory	Temperate	-	1990	2004	353.2	376.12	0	-	6.5	-	0	-
NEP	iCO <sub>2</sub>	Yu <i>et al.</i> (2019)	C_wood_abv	Inventory	Tropical	-	1994	2009	357.62	385.81	9	-	7.9	-	1.1	-
NEP	iCO <sub>2</sub>	Brienen <i>et al.</i> (2015)	C_wood_inc	Inventory	Tropical Amazon	C_veg_inc	1983	2011	342.01	389.79	-68	66	14	2.2	-8.8	16
NEP	iCO <sub>2</sub>	Hubau <i>et al.</i> (2020)	C_wood_inc	Inventory	Tropical Africa	C_veg_inc	1983	2014	342.01	396.7	130	180	16	2.2	5.6	5.5
NEP	iCO <sub>2</sub>	Pan <i>et al.</i> (2011)	C_woodnecromass	Inventory, upscaled	Global	C_veg_inc	1990	1999	353.2	367.06	2.5	-	3.9	-	0.64	-
NEP	iCO <sub>2</sub>	Fernandez-Martinez <i>et al.</i> (2017)	NEP	Flux-tower	Ecosystem	NEP	1992	2013	355.4	394.6	57	24	11	2.1	4.3	1.7
NEP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Fernandez-Martinez <i>et al.</i> (2017)	NEP	Flux-tower, CO <sub>2</sub> attribution	Ecosystem	NEP	1992	2013	355.4	394.6	62	13	11	2.1	4.6	1.1
NEP	iCO <sub>2</sub>	Fernandez-Martinez <i>et al.</i> (2019)	NEP	Atmospheric CO <sub>2</sub> inversion, CO <sub>2</sub> attribution, method 1	Global	NEP	1995	2014	359.52	396.7	560	51	10	2.1	19	3.7
NEP	iCO <sub>2</sub>	Fernandez-Martinez <i>et al.</i> (2019)	NEP	Atmospheric CO <sub>2</sub> inversion, CO <sub>2</sub> attribution, method 2	Global	NEP	1995	2014	359.52	396.7	190	19	10	2.1	11	2.2
NEP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Fernandez-Martinez <i>et al.</i> (2019)	NEP	Atmospheric CO <sub>2</sub> inversion, method 1	Global	NEP	1995	2014	359.52	396.7	380	32	10	2.1	16	3.1
NEP	iCO <sub>2</sub> -CO <sub>2</sub> att.	Fernandez-Martinez <i>et al.</i> (2019)	NEP	Atmospheric CO <sub>2</sub> inversion, method 2	Global	NEP	1995	2014	359.52	396.7	190	7.6	10	2.1	11	2.1
NEP	iCO <sub>2</sub>	Li <i>et al.</i> (2016)	NEP	Carbon budget, data assimilation	Global	NEP	1980	2014	337.85	396.7	380	350	17	2.3	9.8	4.7
NEP	iCO <sub>2</sub>	Graven <i>et al.</i> (2013)	SCA	Atmospheric CO <sub>2</sub> , 45-85 north, 500mb	Northern extra-tropics	NEP	1959	2010	315.66	387.99	58	14	23	2.5	2.2	0.48

abg, aboveground; bg, belowground; gstar, gamma star, photorespiratory compensation point; iCO<sub>2</sub>-CO<sub>2</sub>att., historical study where the change in a variable caused solely by a change in CO<sub>2</sub> has been attributed; inc, increment; LP, Litter production (includes tree wood mortality when expressed as a mass flux); maom, mineral-associated SOM; NDFF, Nevada desert FACE facility; pom, particulate SOM; RS, remote sensing; Vcmax, maximum rate of carboxylation.

<sup>†</sup>Where < 100 value refers to tree age or age since disturbance.

isotopes combined with models ( $\beta_{\text{app}} = 1.3 \pm 2.3$ ) (Ciais *et al.*, 2012). Satellite-based evapotranspiration combined with an ecosystem WUE model estimated increased GPP over recent decades ( $\beta_{\text{app}} = 1.1 \pm 0.5$ ) (Cheng *et al.*, 2017). Fourteen methods to estimate GPP from satellite-based fAPAR resulted in wide-ranging  $i\text{CO}_2$  sensitivities ( $\beta_{\text{dir}}$  range:  $-0.39 \pm 0.34$  to  $1.6 \pm 1$ , mean =  $0.52 \pm 0.3$ ; 2000–2014) (Sun *et al.*, 2019).

**Water-use efficiency, stomatal conductance, and transpiration** Experimental evidence also supports increased  $i\text{WUE}$  in response to  $e\text{CO}_2$  ( $\beta_{\text{dir}} = 1.2 \pm 0.4$ ; four sites, seven species) (Ainsworth & Long, 2005). In two FACE experiments (Duke University and Oak Ridge National Laboratory, ORNL), tree-ring  $\delta^{13}\text{C}$  implies increased  $i\text{WUE}$  ( $\beta_{\text{dir}} = 1.4$  and  $1.3$ , respectively) (Battipaglia *et al.*, 2013). Tree-ring  $\delta^{13}\text{C}$  samples from across the globe suggest increased  $i\text{WUE}$  in many biomes since pre-industrial times in northern boreal gymnosperms ( $\beta_{\text{app}} = 1.2 \pm 2$  to  $1.5 \pm 1.6$ ) (Saurer *et al.*, 2004), tropical forests ( $\beta_{\text{app}} = 1.0$ ) (van der Sleen *et al.*, 2015), and a wide range of forest biomes ( $\beta_{\text{app}} = 1.19$ ; Keller *et al.*, 2017). Attribution to  $i\text{CO}_2$  also suggests increases in  $i\text{WUE}$  in European *Pinus* and *Quercus* ( $\beta_{\text{dir}} = 1.0 \pm 0.6$  and  $0.67 \pm 0.9$ ; nine to 14 sites) (Frank *et al.*, 2015). Additional environmental factors have contributed to observed  $i\text{WUE}$  trends (e.g. drying trends have increased  $i\text{WUE}$ ; Saurer *et al.*, 2014).

$\delta^{13}\text{C}$  in atmospheric  $\text{CO}_2$  combined with mass-balance modelling suggests a global increase in  $i\text{WUE}$  since pre-industrial times ( $\beta_{\text{app}} = 0.94 \pm 0.2$ ) (Keeling *et al.*, 2017).

Evidence from Duke and ORNL FACE experiments supports increases in ecosystem-scale plant WUE (annual BP/Transpiration;  $\beta_{\text{dir,hist}} = 0.76$  and  $1.1$ , respectively) (De Kauwe *et al.*, 2013). Inferred from eddy-covariance, 'inherent' WUE (vapour pressure deficit (VPD)  $\times$  GPP/ evapotranspiration (ET)) increased in temperate and boreal forests with notably higher magnitude ( $\beta_{\text{app}} = 4.72$ ; 21 sites) (Keenan *et al.*, 2013). A follow-up study reduced this estimate ( $\beta_{\text{app}} = 2.5$ ) (Mastrotheodoros *et al.*, 2017). An eddy-covariance calibrated, canopy-scale model suggested  $i\text{CO}_2$  reduced  $g_s$  ( $\beta_{\text{dir,hist}} = -0.28 \pm 0.09$ ) and increased  $i\text{WUE}$  ( $\beta_{\text{dir,hist}} = 0.73 \pm 0.2$ ) (Ueyama *et al.*, 2020). Satellite-based models (2000–2013) of GPP and ET suggest smaller or decreased WUE (GPP/ET) ( $\beta_{\text{app}} = -0.49$  and  $0.28$ ) (Tang *et al.*, 2014; Xue *et al.*, 2015).

Experimental evidence has thoroughly demonstrated reduced leaf-scale  $g_s$  in response to  $e\text{CO}_2$  ( $\beta_{\text{dir,fut}} = -0.22 \pm 0.15$ ) (Medlyn *et al.*, 2001). Averaged across FACE experiments (12 sites, 40 species),  $e\text{CO}_2$  reduced  $g_s$  ( $\beta_{\text{dir,fut}} = -0.60 \pm 0.2$ ) but with substantial variability across functional groups (Ainsworth & Long, 2005) and disturbance history (Donohue *et al.*, 2017). Notably for *Eucalyptus saligna* in whole-tree chambers, canopy-scale  $i\text{WUE}$  was very tightly constrained ( $\beta_{\text{dir,fut}} = 0.98 \pm 0.2$ ), and variability in the  $A_{\text{net}}$  response controlled the  $g_s$  response (Barton *et al.*, 2012).

Across four FACE experiments (Duke, EucFACE, ORNL, Swiss Canopy Crane), transpiration responses were only reduced by  $e\text{CO}_2$  at ORNL ( $\beta_{\text{dir,fut}} = -0.54$ ), an ecosystem that is rarely water-limited (Leuzinger & Körner, 2010) (De Kauwe *et al.*, 2013;

Gimeno *et al.*, 2018). Airborne remote sensing suggested decreased evapotranspiration with long-term volcanically derived  $e\text{CO}_2$  in California (Cawse-Nicholson *et al.*, 2018). Stream-gauge networks indicate global increases in runoff (Gedney *et al.*, 2006), in agreement with reduced  $g_s$  over the northern hemisphere extratropics (Knauer *et al.*, 2017). However, decreases in runoff have also been observed (Ukkola *et al.*, 2016; Trancoso *et al.*, 2017) and modest runoff increases across the tropics have been driven by precipitation increases (Yang *et al.*, 2016).

## 2. Biomass production

Elevated  $[\text{CO}_2]$  increased BP in four temperate-forest, stand-scale (25–30 m diameter) FACE experiments in the early years ( $\beta_{\text{dir,fut}} = 0.56 \pm 0.2$ ) (Norby *et al.*, 2005) and over a full decade ( $\beta_{\text{dir,fut}} = 0.49 \pm 0.3$ ) (Walker *et al.*, 2019). These forest ecosystems were in the early phases of secondary succession (initiated 1–13 yr after a major disturbance). In three later-succession forests (*c.* 100 yr old), BP did not respond to  $e\text{CO}_2$  (note fine-root BP was often not measured): deciduous broadleaved trees ( $\beta_{\text{dir,fut}} = -0.097 \pm 1.0$  to  $0.55 \pm 1.7$ ; 8 yr; Bader *et al.*, 2013), *Picea abies* ( $\beta_{\text{dir,fut}} = -0.30 \pm 0.7$ ; 5 yr  $e\text{CO}_2$ ; Klein *et al.*, 2016), and a low-productivity *Eucalyptus* woodland ( $\beta_{\text{dir,fut}} = -0.26 \pm 0.6$ ; 4 yr  $e\text{CO}_2$ ; Ellsworth *et al.*, 2017; Jiang *et al.*, 2020).

Elevated  $[\text{CO}_2]$  consistently decreased specific leaf area ( $\beta_{\text{dir,fut}} = -0.16 \pm 0.07$ ) (Ainsworth & Long, 2005), which requires increased leaf BP at a given LAI (De Kauwe *et al.*, 2014). Synthesis of experiments (19 sites) suggests that  $e\text{CO}_2$  increased grassland leaf and stem BP ( $\beta_{\text{dir,fut}} = 0.17 \pm 0.07$ ) (Hovenden *et al.*, 2019), related to summer water savings and spring water availability (Morgan *et al.*, 2004; Hovenden *et al.*, 2019). Meta-analysis found that  $e\text{CO}_2$  increased fine-root BP across experiments ( $\beta_{\text{dir,fut}} = 0.56$ ), in forests ( $\beta_{\text{dir,fut}} = 0.92$ ), and, to a lesser degree, in grasslands ( $\beta_{\text{dir,fut}} = 0.18$ ) (Nowak *et al.*, 2004).

Tree-ring analysis at  $\text{CO}_2$  springs in Italy (two sites) suggests that  $e\text{CO}_2$  increased *Quercus ilex* tree-ring width (a proxy for wood BP) initially ( $\beta_{\text{app}} = 0.49$ – $0.81$ ), and the increase diminished as trees aged (Hättenschwiler *et al.*, 1997). Basal-area increment (BAI) analysis showed the  $e\text{CO}_2$  response stabilized at around 10 yr ( $\beta_{\text{app}} = 0.27$ ) (Norby *et al.*, 1999).

A large number of tree-ring studies have found little evidence for increases in wood BP. No detectable trends in BAI were found across tropical forests (3 sites, 12 species) (van der Sleen *et al.*, 2015), and both increasing and decreasing trends were found across North American boreal forests (598 sites, 19 species) (Girardin *et al.*, 2016). Syntheses across biomes found no significant increase in tree-ring width since 1950 ( $\beta_{\text{app}} = 0.23 \pm 0.8$ ; 40 sites) (Peñuelas *et al.*, 2011) and variable responses of BAI ( $\beta_{\text{app}} = -0.45 \pm 0.7$ ; 37 sites, 22 species) (Silva & Anand, 2013). Conversely, *Pinus* and *Quercus* tree rings from Missouri showed a positive response to  $i\text{CO}_2$  that diminished with tree age ( $\beta_{\text{app}} = -3.3$ , at age 1 yr;  $\beta_{\text{app}} = 1.1$ , at age 50 yr) (Voelker *et al.*, 2006).

Evidence from multi-plot inventory data consistently show increasing wood biomass (Section III.5), but few of these studies quantify wood BP. A single census interval of eastern-US Forest Inventory Analysis plots (20 000) suggested very little change in



wood BP (Caspersen, 2000), but with high uncertainty (Joos *et al.*, 2002). Two large tropical-forest plots showed no change in above-ground wood BP (Clark *et al.*, 2010; Rutishauser *et al.*, 2020). By contrast, tropical forest-plot networks (321 and 244) suggest that above-ground wood BP increased in Amazonia ( $\beta_{\text{app}} = 1.2 \pm 0.6$ ) (Brienen *et al.*, 2015) and Africa ( $\beta_{\text{app}} = 0.69 \pm 0.63$ ) with a regression-attributed  $i\text{CO}_2$  response ( $\beta_{\text{app}} = 0.54 \pm 1$ ) (Hubau *et al.*, 2020). Analysis of worldwide forest plots (695) suggested that wood BP increased ( $\beta_{\text{app}} = 0.94 \pm 1.1$ ) over recent decades (Yu *et al.*, 2019).

**BP–nutrient interactions and progressive nitrogen limitation** At Duke FACE, nitrogen availability influenced the magnitude of BP responses (McCarthy *et al.*, 2010) and experiments in later-succession systems with no BP response were limited by nitrogen (Flakaliden; Sigurdsson *et al.*, 2013) and phosphorus (EucFACE; Ellsworth *et al.*, 2017). Limiting factors were not examined for a number of the other later-succession experiments (Bader *et al.*, 2013; Klein *et al.*, 2016).

Elevated  $[\text{CO}_2]$  experiments in early-succession ecosystems suggested that BP gains were supported by increased nitrogen acquisition rather than changes in stoichiometry (Finzi *et al.*, 2007; Zaehle *et al.*, 2014). Nitrogen acquisition was increased through increased fine-root BP (see earlier), changing root traits (Iversen, 2010; Nie *et al.*, 2013; Beidler *et al.*, 2015), and below-ground carbon flux to mycorrhizal symbionts and rhizosphere microbial associations (Section III.4; Drake *et al.*, 2011; Phillips *et al.*, 2011; Terrer *et al.*, 2018). Meta-analysis suggests that  $e\text{CO}_2$  increased nitrogen fixation in more intensively manipulated experiments but not in more natural settings (total 441 studies, rates were scaled to plant or ground-area units; B.A. Hungate, unpublished).

Experimental evidence for progressive nitrogen limitation is limited to a single forest (ORNL; Norby *et al.*, 2010) and a single grassland (Biocon; Reich *et al.*, 2006). Palaeoclimatic evidence suggests that despite increasing carbon storage the nitrogen cycle became more open between the Last Glacial Maximum and the industrial revolution (Fischer *et al.*, 2019; Jeltsch-Thömmes *et al.*, 2019).

**Leaf area, water, and land cover interactions** In some low LAI ecosystems,  $e\text{CO}_2$  increased LAI, but did not in higher LAI (*c.* 5) ecosystems (Norby & Zak, 2011; Bader *et al.*, 2013). However, low LAI (*c.* 1) at EucFACE did not respond to  $e\text{CO}_2$  (Duursma *et al.*, 2016). The LAI response to  $e\text{CO}_2$  in low LAI systems has been interpreted as  $\text{CO}_2$  accelerating open canopies towards closure (Körner, 2006). However, evidence from two FACE sites (Duke and Rhinelander) suggests that LAI can be higher at canopy closure (Walker *et al.*, 2019). Higher above-ground biomass in some grasslands (Hovenden *et al.*, 2019) indicates potential LAI increases, although increases in leaf mass per unit area would reduce the LAI response relative to the biomass response. High grassland biomass responses have been linked to low soil matric potential (Morgan *et al.*, 2004), although more complex interactions with precipitation seasonality have also been indicated (Hovenden *et al.*, 2019).

Satellite data show ‘greening’ trends over much of the planet, inferred as increasing LAI (Zhu *et al.*, 2016; Mao *et al.*, 2016) and with model-based attribution primarily to  $i\text{CO}_2$  (Zhu *et al.*, 2016). Consistent with theory, satellite greenness data suggest increased foliage cover in warm and semiarid regions, probably an  $i\text{CO}_2$  effect via increased WUE (Donohue *et al.*, 2013). Tree rings have indicated decreasing sensitivity to rainfall or drought in the eastern US, possibly indicating WUE-mediated  $i\text{CO}_2$  response (Wyckoff & Bowers, 2010; Helcoski *et al.*, 2019). However, less severe droughts, noted in the eastern US, probably appear as reduced growth sensitivity (Maxwell *et al.*, 2016). At the Florida scrub oak experiment,  $e\text{CO}_2$  alleviated drought-related declines in net ecosystem production (NEP; Li *et al.*, 2007) but the opposite was observed in the Nevada desert FACE (Jasoni *et al.*, 2005).

### 3. Plant mortality

Glasshouse experiments with potted plants have found little benefit of  $e\text{CO}_2$  on survival during drought or high temperature (e.g. Duan *et al.*, 2014; Bachofen *et al.*, 2018). However, remote-sensing evidence shows increased vegetation cover in drylands (Donohue *et al.*, 2013; Section III.2) which suggests a possible reduction in mortality in those regions.

We are unaware of direct or indirect evidence for  $\text{CO}_2$ -related increases in individual-scale mortality, but growth–mortality relationships provide some insights. Evidence supports both an interspecific growth–survival tradeoff (Wright *et al.*, 2010; Bugmann & Bigler, 2011) and an intraspecific tradeoff (Bigler & Veblen, 2009; Di Filippo *et al.*, 2012, 2015; Büntgen *et al.*, 2019). However, there are common exceptions, with some high-growth-rate species with long life spans (Rüger *et al.*, 2020) and other species that show no, or even negative, growth–mortality relationships (Ireland *et al.*, 2014; Cailleret *et al.*, 2017).

Experimental evidence for stand-scale mortality responses to  $e\text{CO}_2$  is rare. In the young, regenerating stand at Rhinelander FACE, over 11 yr of  $e\text{CO}_2$  lowered rates of self-thinning (i.e. higher stand basal area for any given stem density; Kubiske *et al.*, 2019).

At broader scales, most inventory networks have shown increases in stand-scale mortality rates. Increases in biomass mortality have been observed in Amazon forests ( $\beta_{\text{app}} = 2.4$ ) (Brienen *et al.*, 2015) and across continents ( $\beta_{\text{app}} = 1.6\text{--}3.9$ ) (Yu *et al.*, 2019). Tree stem mortality rates have increased, across species, elevation, and tree size, in the western US ( $\beta_{\text{app}} = 6.2 \pm 3$ ; van Mantgem *et al.*, 2009) and Canada ( $\beta_{\text{app}} = 6.1$ ) (Peng *et al.*, 2011). However, none of these studies conclusively attribute trends to  $i\text{CO}_2$  and other global change (e.g. temperature) and biotic (e.g. pest and pathogens) agents have often been attributed drivers of mortality trends (Peng *et al.*, 2011; Luo & Chen, 2015). Finally, several networks observed decreases or nonsignificant changes (e.g. in stem mortality rates in Germany (Pretzsch *et al.*, 2014) and biomass mortality in tropical Africa ( $\beta_{\text{app}} = -0.88 \pm 2$ )), although multiple regression estimated that  $\text{CO}_2$  increased mortality ( $\beta_{\text{dir,hist}} = 1.8 \pm 4$ ) (Hubau *et al.*, 2020).

#### 4. Organic matter decomposition

Evidence for changes in SOM decomposition rates comes primarily from experiments. Many eCO<sub>2</sub> experiments have demonstrated increased plant litter production and allocation of carbon below ground (e.g. Drake *et al.*, 2011; Iversen *et al.*, 2012). Meta-analysis (53 experiments, primarily FACE and OTC) showed that eCO<sub>2</sub> increased litter production ( $\beta_{\text{dir,fut}} = 0.4 \pm 0.1$ ) and SOM-decomposition rates ( $\beta_{\text{dir,fut}} = 0.34 \pm 0.2$ ) (van Groenigen *et al.*, 2014), yet priming effects are difficult to detect in field studies (van Groenigen *et al.*, 2014; Georgiou *et al.*, 2015).

Results from ecosystem-scale experiments indicate some heterogeneity and nuance in these responses. For example, in a scrub oak ecosystem, 6 yr of eCO<sub>2</sub> increased SOM decay despite unchanged microbial biomass (Carney *et al.*, 2007), and at ORNL FACE a decade of eCO<sub>2</sub> resulted in a small but nonsignificant increase in surface-soil SOM decomposition along with a reduction in microbial nitrogen (Iversen *et al.*, 2012). In a later-succession forest, eCO<sub>2</sub> increased microbial biomass ( $\beta_{\text{dir,fut}} = 0.40 \pm 0.4$ ) but with no change in soil respiration ( $\beta_{\text{dir,fut}} = -0.18 \pm 0.7$ ) (Bader & Körner, 2010). At EucFACE, +30 ppm eCO<sub>2</sub> increased soil respiration ( $\beta_{\text{dir,fut}} = 1.3$ ), but a further increase of 120 ppm produced no additional effect after 3 months ( $\beta_{\text{dir,fut}} = 0.3$ ) or 3 yr ( $\beta_{\text{dir,fut}} = 0.21$ ) (Drake *et al.*, 2016, 2018). This 3 yr response was nonsignificant but accounted for about half of the additional carbon acquired under eCO<sub>2</sub> (Jiang *et al.*, 2020).

Data on long-term changes in SOM decomposition in response to iCO<sub>2</sub> remain limited. Synthesis of 23 flux towers with increased GPP (Section III.1) suggested a nonsignificant increase in ecosystem respiration ( $R_e$ ;  $\beta_{\text{app}} = 0.58 \pm 1$ ) (Fernández-Martínez *et al.*, 2017). Synthesis and statistical upscaling of chamber measurements suggested that global soil respiration has increased ( $\beta_{\text{app}} = -0.22$ ) (Bond-Lamberty & Thomson, 2010). Statistical predictors of this trend include temperature anomaly and year (possibly an iCO<sub>2</sub> effect). Notably, heterotrophic respiration would be expected to increase if C<sub>soil</sub> increased, even with no change in decomposition rates.

Accelerated SOM-decomposition may release nutrients and feed back onto the activity of plant processes. For example, at Duke FACE, increased root exudation ( $\beta_{\text{dir,fut}} = 1.1 \pm 0.6$ ) was coupled with a nonsignificant but substantial increase in microbial biomass ( $\beta_{\text{dir,fut}} = 1.1 \pm 1.3$ ) and production of nitrogen-acquiring extracellular enzymes (Phillips *et al.*, 2011). Exoenzyme activity was increased at Duke and Rhinelander FACE (Larson *et al.*, 2002; Finzi *et al.*, 2006), although no change in nitrogen mineralization was observed in laboratory incubations (Zak *et al.*, 2003), perhaps suggesting that stimulation of microbial activity required plant inputs. Conversely, leaf  $\delta^{15}\text{N}$  suggests that eCO<sub>2</sub> may have increased nitrogen mineralization but not ring width in mature trees in a European forest (Bader *et al.*, 2013). eCO<sub>2</sub> increased nitrogen and phosphorus mineralization for a limited period at EucFACE (Hasegawa *et al.*, 2016) and enzyme activity in an alpine forest (Souza *et al.*, 2017). Conversely, meta-analysis suggests eCO<sub>2</sub> increased fine-root C : N ratios ( $\beta_{\text{dir,fut}} = 0.13$ ) (Nie *et al.*, 2013), which are associated with lower decomposability.

Contrasting mycorrhizal associations have been linked to biomass responses under low soil nitrogen conditions (Phillips *et al.*, 2013; Terrer *et al.*, 2016). Ectomycorrhizal (ECM) fungi are assumed capable of stimulating SOM decomposition, while arbuscular mycorrhizal (AM) fungi are not, resulting in increased nitrogen in above-ground BP in ECM trees but not in AM plants, primarily grasses (Terrer *et al.*, 2018). Conversely, AM association with *Avena fatua* in a laboratory and field setting increased SOM-decomposition rates under eCO<sub>2</sub> ( $\beta_{\text{dir,fut}} = 1.4$ ) (Cheng *et al.*, 2012).

#### 5. Terrestrial ecosystem carbon

**Direct evidence from site-scale studies** In the four longest-running FACE experiments eCO<sub>2</sub> over a decade increased C<sub>veg</sub> increment ( $\beta_{\text{dir,fut}} = 0.60 \pm 0.4$ ) in these early-succession temperate forests (Walker *et al.*, 2019). eCO<sub>2</sub> of geological origin increased tree basal area in 30-yr-old trees ( $\beta_{\text{dir,fut}} = 0.23\text{--}0.39$ ) (Hättenschwiler *et al.*, 1997). Conversely, in the later-succession forest at EucFACE, 4 yr of eCO<sub>2</sub> did not increase C<sub>veg</sub> increment (Jiang *et al.*, 2020), probably because of phosphorus limitation (Ellsworth *et al.*, 2017). Other experiments in later-succession forests did not quantify C<sub>veg</sub>. Meta-analysis and extrapolation (138 experiments) predicted a global increase in C<sub>veg</sub> ( $\beta_{\text{dir,fut}} = 0.22 \pm 0.1$ ) related to soil C : N ratio in AM-associated ecosystems and soil phosphorus in ECM-associated ecosystems (Terrer *et al.*, 2019). Biomass responses were generally higher in ECM systems than in AM systems (Terrer *et al.*, 2016), while another meta-analysis showed analogous biomass responses in trees compared with grasses (Song *et al.*, 2019).

Synthesis of meta-analyses found that eCO<sub>2</sub> increased C<sub>soil</sub> across all (> 200) experiments analysed ( $\beta_{\text{dir,fut}} = 0.039 \pm 0.03$ ) but not in field experiments lasting  $\geq 2$  yr without nitrogen addition (25) ( $\beta_{\text{dir,fut}} = 0.0054 \pm 0.03$ ) (Hungate *et al.*, 2009). However, C<sub>soil</sub> responses to eCO<sub>2</sub> at individual sites are mixed. For example, a decade of eCO<sub>2</sub> increased C<sub>soil</sub> at ORNL FACE ( $\beta_{\text{dir,fut}} = 0.51 \pm 0.6$ , 0–90 cm) (Iversen *et al.*, 2012) and in a desert ecosystem ( $\beta_{\text{dir,fut}} = 0.59 \pm 0.62$ ) (Evans *et al.*, 2014), but not in a scrub oak ecosystem ( $\beta_{\text{dir,fut}} = -0.15 \pm 0.5$ ) (Hungate *et al.*, 2013). In the desert ecosystem, inorganic carbonate pools may have contributed to increases in C<sub>soil</sub> through nocturnal CO<sub>2</sub> uptake (Hamerlynck *et al.*, 2013) although net effects are probably small (Soper *et al.*, 2017).

Given limited data, litter addition experiments can also provide some insights. Synthesis of priming responses to litter addition (26 studies) suggested that 32% of litter inputs accumulate as C<sub>soil</sub> (Liang *et al.*, 2018). Ten to 30 yr of doubled above-ground litter inputs in temperate forests increased C<sub>soil</sub> at two sites ( $29 \pm 13\%$  and  $33 \pm 28\%$ ) but had no effect at three sites (Lajtha *et al.*, 2018), or in one tropical forest (Sayer *et al.*, 2019). Based on these responses and assuming that doubled CO<sub>2</sub> doubles litter production (which is unlikely),  $\beta_{\text{dir,hist}}$  for C<sub>soil</sub> would range from 0 to  $0.41 \pm 0.3$ .

Measurement of NEP requires whole-ecosystem enclosure, and thus data are few. In a US salt marsh, higher rates of NEP were

sustained over 19 yr in both  $C_3$  and  $C_4$  communities (Drake, 2014). A data-assimilation approach provided a comprehensive carbon budget at EucFACE showing no change in  $C_{eco}$  (Jiang *et al.*, 2020).

**Indirect evidence from global and regional studies** Spatially explicit atmospheric  $[CO_2]$  measurements, fossil-fuel emissions, and other data are integrated using atmospheric transport models to infer terrestrial net biome production (NBP). These ‘inversions’ suggest a global NBP of  $2.3 \pm 0.9$  (MACC-II),  $2.3 \pm 1.5$  (Jena-CarboScope) (1995–2014; Fernández-Martínez *et al.*, 2019), and  $1.9 \pm 0.5$   $PgC\ yr^{-1}$  (2010–2014; Li *et al.*, 2018) and all estimated positive trends in global NBP ( $\beta_{app} = 19 \pm 7$ ,  $11 \pm 4$ ,  $9.8 \pm 5$ ). These estimates of NBP include both ‘natural’ NBP and land-use change-related (instantaneous and legacy) NBP.

Global land-use change-related NBP was estimated from bookkeeping models at  $-1.4 \pm 1.4$   $Pg\ C\ yr^{-1}$  (2000–2009; Friedlingstein *et al.*, 2019), and are predominantly in the tropics ( $-1.4 \pm 0.3$   $Pg\ C\ yr^{-1}$ ) with fluxes outside the tropics balancing to a net flux of near zero (Houghton & Nassikas, 2017). Regional analysis of NBP show a strong sink in northern hemisphere extratropics ( $2.3 \pm 0.6$   $Pg\ C\ yr^{-1}$  (1992–1996),  $2.2 \pm 0.5$   $Pg\ C\ yr^{-1}$  (2001–2004)) but a substantial source in the tropics ( $-1.1 \pm 1.5$  (1992–1996) and  $-0.9 \pm 0.9$   $PgC\ yr^{-1}$  (2001–2004)) (Gurney *et al.*, 2004; Peylin *et al.*, 2013). Combined with land-use change-related NBP, these inversion results suggest small ‘natural’ NBP in the tropics (*c.* 0.3–0.5). However, analysis of the vertical atmospheric  $[CO_2]$  gradient suggested close-to-neutral tropical NBP (Stephens *et al.*, 2007), implying ‘natural’ NBP of similar magnitude and opposite sign to land-use change-related NBP, attributed primarily to  $iCO_2$  (Schimel *et al.*, 2015).

Flask, aircraft, and satellite-based measurements show trends in the seasonal-cycle amplitude of  $[CO_2]$  since *c.* 1960 (Keeling *et al.*, 1996; Graven *et al.*, 2013; Yin *et al.*, 2018), implying seasonal intensification of northern NBP ( $\beta_{app} = 2.2 \pm 0.6$ ) (Graven *et al.*, 2013).  $iCO_2$  has been implicated as a major driver of these trends (Forkel *et al.*, 2016; Bastos *et al.*, 2019), although increasing crop production (Gray *et al.*, 2014; Zeng *et al.*, 2014) and warming-induced increasing vegetation cover (Keenan & Riley, 2018) are also likely candidates.

Carbon budgeting estimated global ‘natural’ NBP at  $3.6 \pm 1.0$   $Pg\ C\ yr^{-1}$  (2009–2018) and 141  $Pg\ C$  since 1959 from the budget residual, and  $3.2 \pm 1.2$   $Pg\ C\ yr^{-1}$  and 130  $Pg\ C$  from process-based models (Friedlingstein *et al.*, 2019). Based on the residual estimate of ‘natural’ NBP and the lower and upper bounds of either global vegetation or global ecosystem carbon stocks,  $\beta_{app} = 0.93$ – $1.4$  (assuming all the sink is in vegetation) or  $\beta_{app} = 0.18$ – $0.29$  for ecosystem carbon (global vegetation and nonpermafrost soils).

Synthesis and extrapolation of global inventory data suggested increased  $C_{eco}$  ( $\beta_{app} = 1.0 \pm 0.6$ ),  $C_{veg}$  ( $\beta_{app} = 1.9$ ),  $C_{soil}$  ( $\beta_{app} = 0.31$ ), litter carbon ( $\beta_{app} = 0.92$ ), and dead wood carbon ( $\beta_{app} = 0.64$ ) (Pan *et al.*, 2011). Few additional data on  $C_{soil}$  changes over the historical period are available. Evidence from multiplot forest-inventory data consistently shows net gains in wood  $C_{veg}$  in recent decades in tropical Africa ( $\beta_{app} = 0.77$ ; Hubau *et al.*, 2020), the Amazon ( $\beta_{app} = 0.69$ ; Brienen *et al.*, 2015),

Borneo ( $\beta_{app} = 0.48 \pm 0.3$ ; Qie *et al.*, 2017), and in large 50 ha plots across the tropics ( $\beta_{app} = 0.30 \pm 0.24$ ; Chave *et al.*, 2008). Wood  $C_{veg}$  also increased in plots across the eastern US ( $\beta_{app} = 2.9 \pm 1.5$ ; McMahon *et al.*, 2010) and globally ( $\beta_{app} = 0.82 \pm 0.5$ ; Yu *et al.*, 2019). Long-term geological  $CO_2$  release was associated with reduced lidar-estimated above-ground  $C_{veg}$  (Cawse-Nicholson *et al.*, 2018).

Flux towers measure NEP directly, yet have been running for a relatively short time. Synthesis of 23 flux towers indicate increased NEP ( $\beta_{app} = 4.3 \pm 2$ ), with high  $CO_2$  sensitivity ( $\beta_{dir,hist} = 4.6 \pm 2$ ) (Fernández-Martínez *et al.*, 2017).

## IV. Synthesis

### 1. Evidence for the $CO_2$ -fertilization hypothesis

In this section we integrate and interpret the evidence for change in the components of the carbon cycle during the historical record concurrent with increasing  $[CO_2]$  ( $iCO_2$ ; *c.* 280–400 ppm), in response to elevated  $[CO_2]$  ( $eCO_2$ ; *c.* 390–500 ppm), and the probability and magnitude of  $iCO_2$  as a driving factor in the historical change. In doing so we acknowledge that we are mixing evidence across scales, measurements, methods of analysis, and, in some cases, different variables that may not be perfectly comparable. However, this is required for a broad synthesis, and a formal meta-analysis is not our intention. We assign confidence as ‘high’ (all estimates agree), ‘medium’ (estimate means disagree, substantial overlap in confidence intervals), or ‘low’ (estimate means disagree, little overlap in confidence intervals).

**Physiology** A number of independent lines of indirect evidence – ice-core OCS (Campbell *et al.*, 2017) and  $O^{18}$  (Ciais *et al.*, 2012), glucose isotopomers (Ehlers *et al.*, 2015), satellite ET (Cheng *et al.*, 2017), and flux-partitioned eddy-covariance (Fernández-Martínez *et al.*, 2017) – provide high confidence that terrestrial GPP has increased concurrently with  $iCO_2$ . Estimates of the GPP increase disagree by a factor of 1.7 ( $\beta_{app} = 0.95$ – $1.6$ , mean = 1.2; Table 2), but overlap in confidence intervals (Figs 3, S2) indicates that these estimates are consistent and suggests medium confidence in the magnitude of the increase in GPP concurrent with  $iCO_2$ . Above the canopy-scale GPP can be measured only indirectly, and most of these estimates are a function of the  $[CO_2]$  trend (Box 3; isotopomers, satellite, OCS) which introduces a circularity. However, we place less confidence in estimates (usually satellite-based) that omit a  $CO_2$  effect from the theory used in their GPP estimation (Box 3; De Kauwe *et al.*, 2016). Flux-partitioned eddy-covariance provides the only estimate of GPP that does not require  $[CO_2]$  in its calculation and provides the highest  $\beta_{app}$  of  $1.6 \pm 0.9$  (Fernández-Martínez *et al.*, 2017). A smaller proportion of this change was attributed to  $iCO_2$  ( $\beta_{dir,hist} = 1.2 \pm 0.6$ ).

Synthesis of direct evidence from experiments provides high confidence that ecosystem-scale  $eCO_2$  increases diurnal photosynthesis in leaves ( $\beta_{dir,fit} = 0.68 \pm 0.2$ ). This increase is very similar to the theoretical value for a light-saturated leaf ( $\beta_{dir,fit} = 0.70 \pm 0.2$ , Table S1). The theoretical value for the canopy-scale photosynthesis response to  $iCO_2$  (280–410 ppm,

$\beta_{\text{dir,fut}} = 0.60 \pm 0.3$ ; Table S1) is about half the observed mean increase in GPP concurrent with  $i\text{CO}_2$  ( $\beta_{\text{dir,hist}} = 1.2$ ). For  $i\text{CO}_2$  to be the sole driver of the observed responses all leaves would have to be operating at the light-saturated rate of increase and there would have to be additional positive feedbacks of equivalent magnitude.

The majority of global models tend to follow the theoretical response to  $i\text{CO}_2$  (Keenan *et al.*, 2016). A carbon cycle model was able to replicate the OCS increase in GPP ( $\beta_{\text{app}} = 0.95 \pm 0.2$ ) and change in northern seasonal  $[\text{CO}_2]$  amplitude by hypothesizing leaf optimization and predicting a substantial increase in LAI (note the phosphorus cycle was disabled) (Haverd *et al.*, 2020). However, it is not clear that leaves optimize as hypothesized (Smith & Keenan, 2020), and models consistently represent allocation and LAI simplistically. For example, LAI trends are inferred in high-LAI tropical rainforests (Zhu *et al.*, 2016). In these regions models are probably predicting an increase in maximum LAI, which conflicts with experimental evidence and resource investment theory. An alternative hypothesis is that  $i\text{CO}_2$  accelerates the recovery of forest gaps such that landscape-scale LAI is greater – a hypothesis not represented by any of the models used for attribution. Outside of tropical forests, changes in LAI are related to both  $i\text{CO}_2$  (Donohue *et al.*, 2013) and temperature-stimulated increases in growing season length (Keenan & Riley, 2018). An additional consideration is that models tend to underestimate GPP relative to solar-induced fluorescence (a GPP proxy) in agricultural regions (Guanter *et al.*, 2014; Walker *et al.*, 2017), agriculture being another major factor of global change. Taken together, we are confident that the historical GPP increase was primarily driven by  $i\text{CO}_2$  and also that  $i\text{CO}_2$  was not the sole driving factor. However, it is unclear which factors might be driving the additional change in GPP.

A number of independent lines of indirect evidence – tree-ring  $\delta^{13}\text{C}$  (e.g. Saurer *et al.*, 2004; Peñuelas *et al.*, 2011; Frank *et al.*, 2015), flux-partitioned eddy-covariance (Keenan *et al.*, 2013; Mastrotheodorus *et al.*, 2017), and atmospheric  $\delta^{13}\text{C}$  (Keeling *et al.*, 2017) – provide high confidence that  $i\text{WUE}$  (across leaf to global scales) and WUE (across leaf to ecosystem scales) have increased over the historical period ( $\beta_{\text{app}} = 0.85\text{--}3.9$ , mean = 1.5). There remain large differences (factor of 5) between these estimates of the increase, primarily as a result of the eddy-covariance estimates ( $\beta_{\text{app}} = 2.4 \pm 2.0$  and  $3.9 \pm 2.5$ ). The causes for these differences are not fully understood, although scale (Medlyn *et al.*, 2017), plasticity (Mastrotheodorus *et al.*, 2017), high variability and short timescales (indicated by the high uncertainty), and GPP trends that are higher than expected from  $i\text{CO}_2$  alone (see earlier) all play a role. Eddy covariance estimates skew the mean and the modal change is around  $\beta_{\text{app}} = 1$  (Fig. 3), similar to the mean for  $i\text{CO}_2$ -attribution studies ( $\beta_{\text{dir,hist}} = 0.80$ ) and the theoretical value for  $i\text{WUE}$  ( $\beta_{\text{dir,hist}} = 1.1$ ). As with GPP, other than eddy covariance these indirect methods use  $[\text{CO}_2]$  in their calculation (Box 3). Satellite estimates of WUE suffer from very short time periods (13 yr) with low signal-to-noise ratio, leaving little confidence in these trend estimates. Direct evidence from multiple experiments support  $i\text{WUE}$  and WUE increases ( $\beta_{\text{dir,fut}} = 0.65\text{--}1.6$ , mean = 1.1) in agreement with predictions from theory (Fig. 2). Taken together this evidence provides high confidence

that  $i\text{CO}_2$  has increased  $i\text{WUE}$ , medium confidence that the magnitude is in accordance with theory, and low confidence in the magnitude of the historical change in WUE.

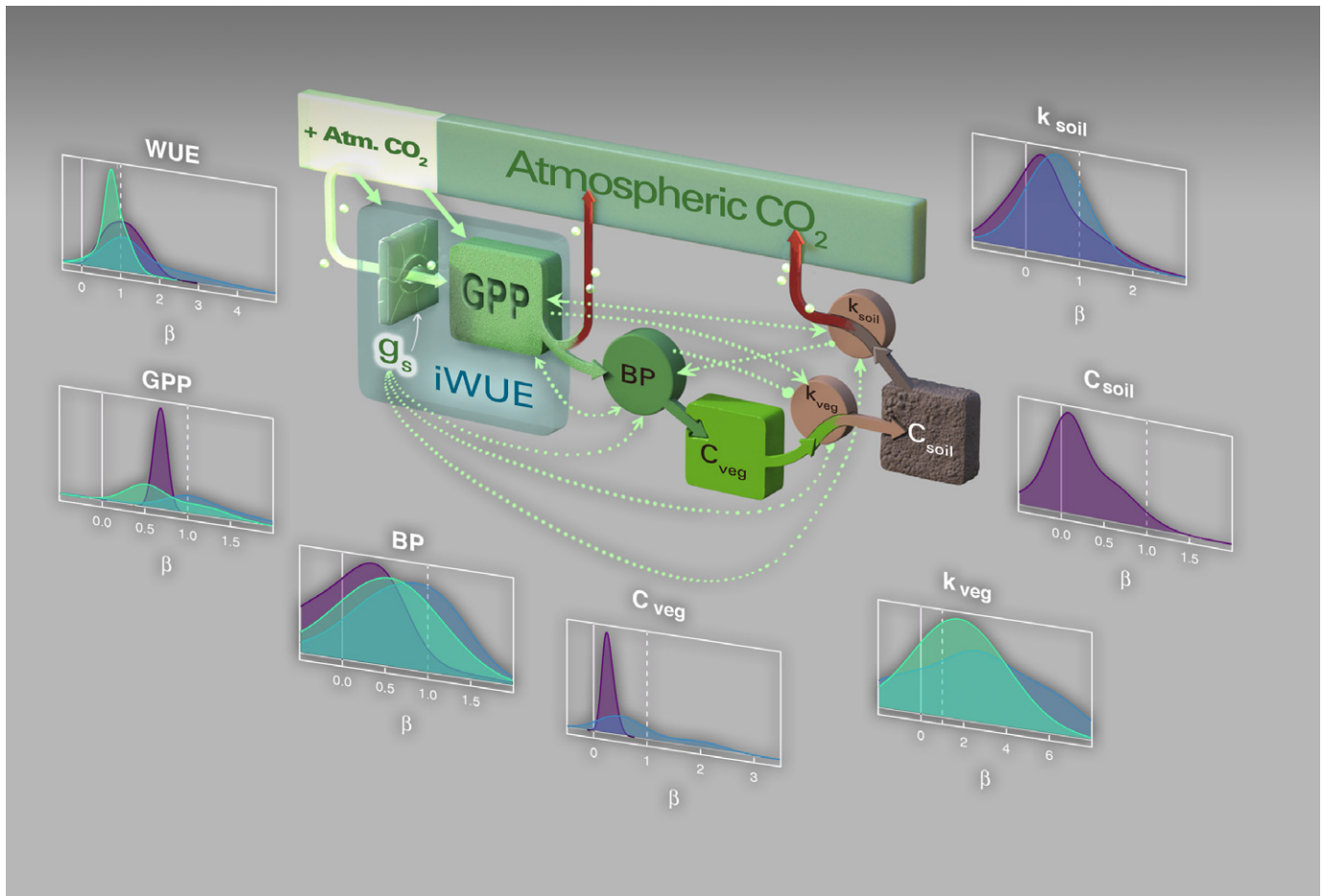
How do these changes in  $i\text{WUE}$  translate to changes in water use? Theory predicts that  $i\text{WUE}$  ( $A_{\text{net}}/g_s$ ) responses are very tightly constrained ( $\beta_{\text{dir}} \approx 1$ ), so if the change in  $A_{\text{net}}$  is below 1,  $g_s$  will decrease (Barton *et al.*, 2012). The observed changes in GPP ( $\beta_{\text{app}} \approx 1$ ) suggest that widespread and broad-scale reductions in  $g_s$  might not have occurred. Reductions in stomatal conductance could occur at points in time or space, but as spatial and temporal scale increases,  $i\text{CO}_2$ -induced decreases in stomatal conductance probably translate into smaller decreases in transpiration (Field *et al.*, 1995; Körner *et al.*, 2007).

Increased vegetation cover in semiarid regions (Donohue *et al.*, 2013; Ukkola *et al.*, 2016), increased rooting depth (Y. Yang *et al.*, unpublished; Iversen, 2010), soil–water feedback on  $g_s$ , competition and atmospheric coupling (Jarvis & McNaughton, 1986; Buckley *et al.*, 2017; Sperry *et al.*, 2019; Sabot *et al.*, 2020) are all mechanisms that may lead to no change in water use at larger scales. This is particularly likely to be the case in water-limited regions where long-term transpiration is primarily precipitation-driven (Fatichi *et al.*, 2016), that is, plants use the water that is available.

**Biomass production** Ecosystem-scale forest-inventory networks suggest increases in wood BP concurrent with  $i\text{CO}_2$  (mean  $\beta_{\text{app}} \approx 1$ ; Brienen *et al.*, 2015; Yu *et al.*, 2019; Hubau *et al.*, 2020). Conversely, evidence from tree rings is mixed (e.g. Peñuelas *et al.*, 2011; Silva & Anand, 2013). Both of these methods are subject to potential sampling biases (Box 3). However, the tree-ring biases are potentially larger and can be either positive (Nehbas-Ahles *et al.*, 2014) or negative (Brienen *et al.*, 2016). The inventory evidence provides medium confidence in an increase in wood BP over the historical period, with low confidence in the magnitude ( $\beta_{\text{app}} < 1$ ). However, this is an area of disagreement among several in our authorship group.

Many studies show increased BP in response to  $e\text{CO}_2$  (e.g. Baig *et al.*, 2015), but these studies are often short-lived and under artificial conditions. Evidence from long-term, large-scale FACE experiments ( $< 10$  experiments) is mixed, with both increases (e.g. Norby *et al.*, 2005) and no change in BP observed (e.g. Bader *et al.*, 2013; Jiang *et al.*, 2020) ( $\beta_{\text{dir,fut}} = -0.3$  to  $0.56$ , mean =  $0.19$ ). Many studies show a BP response to  $e\text{CO}_2$  that is higher at sites with higher nutrient availability (e.g. Terrer *et al.*, 2018), greater when nutrients were added (e.g. Reich *et al.*, 2006; Sigurdsson *et al.*, 2013), or show no response when nutrients are low (e.g. Sigurdsson *et al.*, 2013; Ellsworth *et al.*, 2017). However, strong evidence for the widely held progressive nitrogen limitation hypothesis is restricted to two experiments (Biocon, ORNL) (Reich *et al.*, 2006; Norby *et al.*, 2010). At both of these experiments nutrient dynamics also caused declining BP in the ambient treatments, indicating that  $e\text{CO}_2$  responses can be tied, via nutrient availability, to underlying ecosystem dynamics.

Biomass production responses were observed in earlier-succession more-disturbed ecosystems, which also tend to have higher nutrient availability (Körner, 2006). The experiments with no response were often situated in later-succession forests, some of



**Fig. 3**  $\beta$  distributions based on data from Table 2 for water-use efficiency (WUE), gross primary production (GPP), biomass production (BP), turnover rate of vegetation ( $k_{veg}$ ) and soil organic matter ( $k_{soil}$ ), and plant ( $C_{veg}$ ) and soil ( $C_{soil}$ ) carbon. Data are organized by  $CO_2$  response category – increasing  $[CO_2]$  (i $CO_2$ , blue), attribution to i $CO_2$  (green), and elevated  $[CO_2]$  (e $CO_2$ , purple). See Supporting Information Figs S2–S4 for further details.

which were also severely limited by nutrients. The forest inventories in which BP increases concurrently with i $CO_2$  were observed in later-succession, primarily tropical, forests that are assumed to be strongly nutrient-limited. These inventory responses are high ( $\beta_{app} \approx 1$ ) compared with the results from experiments even in earlier-succession forests ( $\beta_{dir,fut} = 0.49 \pm 0.3$ ). However, the evidence is insufficient to robustly evaluate how e $CO_2$  affects late-successional and tropical forests. Taken together, this evidence suggests high confidence that e $CO_2$  can stimulate BP ( $\beta_{dir,fut} \approx 0.5$ ), that the response is diminished by nutrient limitations, and that the observed inventory response is probably a result of i $CO_2$  and additional factors.

**Vegetation mortality** A number of independent plot networks provide high confidence that tree mortality has increased over the historical period but low confidence in the magnitude ( $\beta_{app} = -1.2$ – $7.4$ , mean =  $2.8$ ; Figs 3, S3). The greatest changes are primarily attributed to drought. Causes of mortality are often stochastic, multifactorial, and play out over long time periods, making trend identification and attribution at ecosystem and landscape scales uncertain (McMahon *et al.*, 2019). For individual scale mortality, an intraspecific growth–survival tradeoff is

apparent for some species (e.g. Di Filippo *et al.*, 2015), which would reduce life spans if i $CO_2$  increases wood BP. However an intraspecific growth–survival tradeoff is not ubiquitous among species (e.g. Cailleret *et al.*, 2017).

Glasshouse e $CO_2$  experiments suggest that e $CO_2$  does not reduce drought-related mortality (e.g. Duan *et al.*, 2014; Bachofen *et al.*, 2018). However, e $CO_2$  commonly increased leaf area in these experiments, increasing transpiration which probably exacerbated mortality risk (Duan *et al.*, 2018). What does this mean for e $CO_2$  responses in ecosystems? Owing to the juvenile growth stage of these plants, leaf area increases were much higher than expected in closed canopy systems (see Box 3), and increased root BP from e $CO_2$  would exacerbate pot-volume constraints on root proliferation. Inference from these experiments is limited. At the stand scale there is very limited evidence that e $CO_2$  might change self-thinning relationships allowing higher basal area for a given stem density (Kubiske *et al.*, 2019). Evidence for changes in mortality caused by i $CO_2$  is weak and mostly indirect with limited support for both increases and decreases in individual and stand-scale mortality rates. Taken together the response of mortality to i $CO_2$  and e $CO_2$  is unknown, even the direction of change is unclear.

**Organic matter decomposition** The few studies of soil or ecosystem respiration show small ( $\beta_{\text{app}} = 0.22$ ; Bond-Lamberty & Thompson, 2010) or nonsignificant increases ( $\beta_{\text{app}} = 0.58 \pm 1$ ; Fernández-Martínez *et al.*, 2017). These trends could possibly be related to increasing heterotrophic respiration and decomposition, but increasing temperature is inferred as the cause, not  $i\text{CO}_2$  (e.g. Bond-Lamberty *et al.*, 2018). Owing to the low number of studies, there is low confidence that SOM decomposition has increased over the historical period and it is unknown whether SOM decomposition rates have increased.

Evidence from  $e\text{CO}_2$  experiments generally supports the theory that rising  $[\text{CO}_2]$  increases SOM-decomposition rates (e.g. van Greonigen *et al.*, 2015) as a result of increases in microbial biomass, rhizosphere priming, mycorrhizal association and increases in soil water content (see references in Section III.4). Smaller changes in decomposition rates have been associated with lower microbial biomass and higher soil water (Bader & Körner, 2010; Iversen *et al.*, 2012). Taken together, the evidence suggests there is medium confidence that  $e\text{CO}_2$  increases rates of SOM decomposition but with low confidence in the magnitude. Increasing SOM decomposition will also release nutrients that may be available for plant growth and BP. Plant nutrient acquisition through mycorrhizal and other root–microbe interactions are probably mediators of this process (Terrer *et al.*, 2018). Notably, the large step-change in  $e\text{CO}_2$  experiments compared with the more gradual  $i\text{CO}_2$  could lead to a greater imbalance of available resources resulting in a carbon surplus (Box 3) which could fuel greater microbial activity. It is worth noting that increased SOM-decomposition rates do not necessarily imply lower  $C_{\text{soil}}$  if litter inputs are also increasing (Liang *et al.*, 2018).

**Terrestrial ecosystem carbon** Multiple independent lines of evidence – global-scale carbon budgeting (Friedlingstein *et al.*, 2019), atmospheric inversions (e.g. Peylin *et al.*, 2016; Fernández-Martínez *et al.*, 2019), seasonal  $[\text{CO}_2]$  amplitude trends (Graven *et al.*, 2013), and forest inventories (e.g. Pan *et al.*, 2011; Hubau *et al.*, 2020) – imply a  $\text{CO}_2$  sink in terrestrial ecosystems (Figs 3, S4). This evidence provides high confidence that terrestrial ecosystem carbon has increased over the historical period, with substantial changes in the ‘natural’ carbon sink almost balanced by a net carbon source from land-use change. Global carbon budgeting and global forest analysis suggest responses concurrent with  $i\text{CO}_2$  in the range,  $\beta_{\text{app}} = 0.18$ – $1.0$ . The ‘natural’ carbon store response estimated for global intact forests ( $\beta_{\text{app}} = 0.66 \pm 0.4$ ; Pan *et al.*, 2011) is higher than estimated for the ‘natural’ land surface ( $\beta_{\text{app}} = 0.18$ – $0.29$ ; Friedlingstein *et al.*, 2019). Trends observed in eddy-covariance NEP (site-scale ‘natural’ sink) and inversion NBP (global-scale combined ‘natural’ and land-use sink) are extremely high ( $\beta_{\text{app}} = 4.3$ – $19$ , mean 11). The extremely high  $\beta_{\text{app}}$  for global NBP (and, to a lesser degree, NEP) results from global NBP being near zero as the ‘natural’ sink is almost balanced by the net source from land-use change, and thus small absolute changes can be high in relative terms (Box 3).

$\text{CO}_2$  effects on terrestrial carbon are convolved with the effects of concurrent anthropogenic changes in climate, nitrogen

deposition, and land-use change, including agricultural intensification and fire management. Attribution analyses indicate a primary role for  $i\text{CO}_2$  (e.g. Schimel *et al.*, 2015; Keenan *et al.*, 2016; Bastos *et al.*, 2019; Fernández-Martínez *et al.*, 2019; Haverd *et al.*, 2020). These analyses depend on the inclusion of accurate explanatory-variable datasets and accurate process representation in models, which may not be the case. Quantification of the effect of  $i\text{CO}_2$  on global carbon storage in terrestrial ecosystems remains elusive.

As with BP responses, studies of forest inventories show higher  $C_{\text{veg}}$  responses ( $\beta_{\text{app}} = 0.3$ – $2$ , mean =  $0.85$ ) than studies of  $e\text{CO}_2$  experiments ( $\beta_{\text{app}} = 0.22$ – $0.39$ ) (Fig. 3). However, the highest values come from two analyses: one that includes global forest regrowth ( $\beta_{\text{app}} = 1.9$ ; Pan *et al.*, 2011) and younger (c. 50–100 yr old) temperate forests ( $\beta_{\text{app}} = 2 \pm 1$ ; McMahon *et al.*, 2011). Exclusion of these higher change studies results in a narrower range ( $\beta_{\text{app}} = 0.3$ – $0.85$ , mean =  $0.57$ ). This exclusion narrows the difference between responses inferred from  $i\text{CO}_2$  and  $e\text{CO}_2$  studies, which is consistent with theory as relative stock changes are underestimated more in short-term experiments than in inventory-type studies (Fig. S2). Responses of vegetation carbon increment may give a more accurate estimate of responses in systems that are far from equilibrium when initially exposed to  $e\text{CO}_2$  (Fig. S2). Vegetation carbon increment responses estimated from FACE experiments ( $\beta_{\text{app}} = 0.60 \pm 0.4$ ; Walker *et al.*, 2019) are consistent with the reduced range from inventory studies. However, the theoretical underestimation of undisturbed forest-inventory responses (Fig. S2) yet similarity of these responses with those from disturbed forests subjected to  $e\text{CO}_2$  and not the lower values from undisturbed forests (e.g. Jiang *et al.*, 2020) requires further consideration. Either  $e\text{CO}_2$  experiments are underestimating responses or other factors have affected the inventory evidence. Both of these evidence types are likely to be missing the full extent of mortality (e.g. Chambers *et al.*, 2013), and evidence from larger-scale 50 ha plots suggests a lower response for intact tropical forests ( $\beta_{\text{app}} = 0.30 \pm 0.2$ ; Chave *et al.*, 2008).

Evidence of changes in  $C_{\text{soil}}$  is mixed and context-dependent. On average there is no detectable response across experiments (Hungate *et al.*, 2009), although at some individual sites,  $C_{\text{soil}}$  did accumulate (e.g. Iversen *et al.*, 2012; Evans *et al.*, 2014). The only study (to our knowledge) of soil carbon changes concurrent with  $i\text{CO}_2$  suggests a relative response in global forests ( $\beta_{\text{app}} = 0.31$ ; Pan *et al.*, 2011), which would be substantial if extrapolated to mineral soils globally. As with vegetation carbon stocks, the long-term, relative responses of soil carbon stocks are probably underestimated by short-term  $e\text{CO}_2$  experiments (Fig. S2). Taken together, evidence suggests medium confidence that  $e\text{CO}_2$  increases ecosystem carbon stocks over short to medium timescales and that  $i\text{CO}_2$  has contributed to the change over the historical period, but with low confidence in the magnitude.

## 2. What we need to know

Confidence in the magnitude of  $\text{CO}_2$  effects is generally low. In particular,  $i\text{CO}_2$  attribution is a major challenge in testing the  $\text{CO}_2$ -fertilization hypothesis over the historical period. Attribution

often relies on empirical regression that simply indicates correlation; anything with a trend over the historical period will be correlated with  $i\text{CO}_2$ . We advocate using  $\log\text{-}\log\beta$  as a stable (Notes S1; Fig. S1), relativized metric for comparison with theoretical expectations and other studies.

Process-based models are also used to deconvolve causation from multiple global-change factors. Models often represent key mechanisms oversimplistically and yet are also equifinal, while model ensembles represent a nonrandom sample of nonindependent models (Beven, 2006; Fatichi *et al.*, 2019; Sanderson & Fisher, 2020). Thus, models need always to be interpreted in the context of the mechanisms they represent, those they do not, how representations might bias results, and how well they reproduce observations (e.g. Medlyn *et al.*, 2015). Mechanistic models (or modules) of BP, resource acquisition and allocation, how soil and plant water status affect  $g_s$ , plant–microbe effects on soil decomposition, vegetation structure and demography (e.g. competition, mortality), and land-use need to be developed and applied more extensively to the  $\text{CO}_2$ -fertilization hypothesis. Alternative hypotheses to explain observed phenomena should be evaluated within model ensembles, and calibrated to allow the hypotheses to compete on an equal footing (e.g. Zhang *et al.*, 2015). Agile and extensible models (e.g. Clark *et al.*, 2015; Walker *et al.*, 2018) will be needed to rapidly incorporate this understanding, including uncertainty, into the internally consistent and quantitative systems-level theory that models represent.

It is crucial that future  $e\text{CO}_2$  experiments are designed and resourced to understand the mechanistic basis for responses (or lack thereof) and do not simply report significance or effect sizes. Integration with extensible, process-based models will help us to evaluate and explore the mechanistic basis for observed responses (Medlyn *et al.*, 2015). During the lifetime of long-term experiments, new hypotheses will arise to explain unexpected or key observations that may help to provide context and mechanisms underlying the observed responses. These long-term experiments represent very large investments, and for relatively small additional investment, related studies can test mechanistic hypotheses as they arise during an experiment's lifetime.

### 3. Suggestions for high-priority future studies

- *Understanding the mechanistic basis for GPP increases observed over the historical period and how this relates to water use.* GPP,  $i\text{WUE}$ , and water use are intimately tied. The mechanisms by which plants might adjust to  $i\text{CO}_2$  (photosynthetic acclimation/optimization, more and deeper roots,  $g_s$  responses to water status) are not fully understood and thus not well explored within models. A quantitative synthesis of canopy or stand-scale photosynthetic responses in  $e\text{CO}_2$  experiments would be informative.
- *Biomass production* inferred from tree rings and forest inventories reach very different conclusions. Where possible, studies that can integrate these two types of evidence, such as tree-ring sampling at inventory sites (e.g. Dye *et al.*, 2016; Evans *et al.*, 2017), acknowledging respective biases, will be fruitful. The mechanisms underlying how increased GPP leads to increased BP and increased nutrient acquisition through plant–microbe associations are key

areas for future study, especially over successional gradients.  $e\text{CO}_2$  studies in mid- and late-succession ecosystems, and tropical, boreal, semiarid, and savannah ecosystems will help to address the young, temperate ecosystem bias in  $e\text{CO}_2$  studies.

- *How  $i\text{CO}_2$  affects mortality* is key to understanding  $C_{\text{veg}}$  and community responses to  $i\text{CO}_2$ . As mortality is a relatively rare event in established vegetation, change detection and attribution of causation require large-scale, long-term monitoring and, ideally, experiments (Hartmann *et al.*, 2018). Understanding the mechanics of observed growth–mortality tradeoffs and whether  $i\text{CO}_2$  may be alleviating mortality in semiarid regions is a high priority.
- *Studies of the  $C_{\text{soil}}$  decomposition rate* over the historical period are practically nonexistent; additional studies are required. As with BP, efforts to fully understand plant–microbe–soil (and probably invertebrate), carbon–nutrient interactions continue to be a high priority. Furthermore, investigation of responses in deep soil layers are few or nonexistent. Understanding how the opposing processes of increased litter production, root–microbe interactions, increased decomposition rates, and rates of mineral-associated SOM formation balance to affect  $C_{\text{soil}}$  throughout the soil profile will be key to predictive understanding. This may be especially relevant in nonforest ecosystems, where the largest potential change in carbon storage is below ground.
- *$i\text{CO}_2$  affects ecosystem carbon primarily through effects on NEP, and thus understanding of  $C_{\text{eco}}$  responses to  $i\text{CO}_2$*  will emerge from these research priorities. Further, NBP is what the atmosphere ‘sees’, which includes additional nonrespiratory carbon losses caused by fire (anthropogenic and wild), hydrological export, and export of consumer goods.  $i\text{CO}_2$  may interact with some nonNEP fluxes (e.g. greater grassland BP, leading to higher fuel loads, greater BP in regrowing forests following land-use change). Land-use change NBP is often calculated without considering  $i\text{CO}_2$  and separately from ‘natural’ NBP caused by  $i\text{CO}_2$ , climate change, nitrogen deposition, and other factors (e.g. Friedlingstein *et al.*, 2019), although the boundary between these fluxes is blurred (Pongratz *et al.*, 2014). Integrated studies that consider all of these factors, especially land-use change (including  $i\text{CO}_2$  acceleration of regrowth following disturbance; e.g. Pugh *et al.*, 2019), agriculture, and ‘natural’ fluxes, will yield further insights.

### V. Conclusions

To evaluate the  $\text{CO}_2$ -fertilization hypothesis, we synthesized evidence from wide-ranging disciplines within an integrated theoretical framework. We have medium or high confidence that GPP,  $i\text{WUE}$ , BP, and mortality have all increased over the historical period. However, we frequently have low or medium confidence in the magnitude, and low confidence in how much of the change is attributable to  $i\text{CO}_2$ .

The complex nature of the problem demands integrated studies, and further integration is required to fully combine the broad evidence in a way that is scale-, bias-, and uncertainty-aware (Box 3). Inference regarding trends and responses (or lack thereof) should always be grounded in the context-dependence and biases associated with a particular study. Further experiments and observations are needed to help reconcile differences among evidence streams. For example, tree-ring sampling at flux sites or

**Box 3** Consideration of methods and bias.

**In eCO<sub>2</sub> experiments**, confinement of roots in pots can limit below-ground resources. While eCO<sub>2</sub> can accelerate leaf area gain in open-grown plants, leading to compound interest that does not occur with closed canopies (Norby *et al.*, 1999). These experiments represent early post-disturbance 'reorganizing', and possibly open-canopy ecosystems but are not representative of closed-canopy ecosystems. Oscillating [CO<sub>2</sub>] may lessen physiological responses (Allen *et al.*, 2020). The step-change in [CO<sub>2</sub>] results in a large shift in the ecosystem resource balance (Walker *et al.*, 2015), while soil disturbance can increase nutrient availability (Körner, 2006). Many experiments (and evidence themes more broadly) do not quantify total BP, especially root BP. Even the longest-running experiments are short-lived relative to the life span of trees. Landscape-scale atmospheric feedbacks (e.g. increased VPD that could mitigate reductions in transpiration) cannot be accounted for (Leuzinger *et al.*, 2015).

**Many 'measurements' rely on models in their calculation**, and thus have the potential to omit or presuppose a CO<sub>2</sub> effect. For example, satellite gross primary production (GPP; e.g. Sun *et al.*, 2018) and net primary production (NPP; e.g. Kolby-Smith *et al.*, 2016) are calculated from the fraction of absorbed photosynthetically active radiation (fAPAR) using a light-use efficiency model (Monteith, 1972) that often does not include the CO<sub>2</sub> effect on photosynthesis (De Kauwe *et al.*, 2016). Thus, changes in GPP result only from changes in leaf area index (fAPAR) or climate. Conversely, measurement models that include a CO<sub>2</sub> effect are thus not independent of iCO<sub>2</sub> (e.g. iWUE from δ<sup>13</sup>C, carbonyl sulphide, or isotopomers) and thus have the potential to presuppose a CO<sub>2</sub>-related trend.

**Carbon isotope discrimination during photosynthesis** reduces the <sup>13</sup>C : <sup>12</sup>C ratio (δ<sup>13</sup>C) in plant material and is used to calculate iWUE from δ<sup>13</sup>C (Farquhar *et al.*, 1982; Farquhar & Cernusak, 2012). The commonly used model neglects mesophyll and photorespiration discrimination (Farquhar *et al.*, 1982; Farquhar & Cernusak, 2012), and accounting for these effects can increase iWUE trends by c. 50% (Keeling *et al.*, 2017).

**Tree-ring trends are subject to sampling and survivorship biases** (Brienen *et al.*, 2012; Peters *et al.*, 2015) that can affect growth trends by up to 200% (Hember *et al.*, 2019; Nehrbass-Ahles *et al.*, 2014), leading some to question whether tree rings should be used for trend detection at all (Brienen *et al.*, 2012). However, tree rings are the only data that offer insights into tree BP since the industrial revolution.

**Many studies use tree-ring width as a proxy for wood BP** because it is a direct measurement. However, trees grow in three dimensions and change in the one-dimensional ring width does not directly scale with wood volume growth and thus BP in different sized trees. Conversion to the two-dimensional basal area increment (BAI) helps to unify this size mismatch, but again does not account for nonlinear change in wood BP with tree size (Anderson-Teixeira *et al.*, 2015). Allometric scaling should be applied to ring width and BAI to attempt a best possible estimate of wood BP (e.g. Dye *et al.*, 2016). Static allometric relationships over time can introduce bias where environmental changes have altered resource allocation. For example, shifting allocation from wood to leaves in Russian forests reconciled apparently conflicting inventory data that suggested BP declines, while remote sensing suggested increases (Lapenis *et al.*, 2017). Furthermore, wood volume growth does not always scale with BP as wood density can also change (Pretzsch *et al.*, 2018).

**Forest inventory plots (c. 1 ha and less) can undersample mortality**, resulting in overestimates of biomass accumulation (Chambers *et al.*, 2013). Generally, statistical power for detecting and attributing change in mortality and SOM is often low (Hungate *et al.*, 2009; Sulman *et al.*, 2018; McMahon *et al.*, 2019). Statistical power for detection is low as a result of measurement uncertainty, low signal-to-noise, heterogeneity, and potential pretreatment differences. Low statistical power presents a real challenge for attribution when employing commonly used binary mortality assessments or bulk SOM measurements (Sulman *et al.*, 2018; McMahon *et al.*, 2019). Furthermore, satellite data, flux towers, and experiments all suffer from short time periods, often with much background variability that can obscure or amplify trends.

**Quantification of global 'natural' NBP is confounded** with quantification of land-use change-related NBP which is uncertain (95% CI is 92% of the mean flux; Friedlingstein *et al.*, 2019). Land-use change-related NBP is calculated using bookkeeping models that account for complex legacy effects and many elements of land-use change, which adds to the uncertainty (Pongratz *et al.*, 2014). Furthermore, potentially substantial interactions of land-use change-related NBP and iCO<sub>2</sub> are not considered by these methods. C<sub>veg</sub> and C<sub>soil</sub> changes, loss of storage/sink capacity, and potential CO<sub>2</sub> interactions with secondary succession all convolve land-use change and 'natural' NBP fluxes, suggesting a false dichotomy in these flux calculations.

**Calculating and interpreting β, or any relative response, is challenging for carbon stocks** in which pre-change values can be large, change is the product of two opposing fluxes cumulative over multiple years, and concepts of steady state and nonsteady state apply. Ideally we would like to know β from pre-change steady state to post-change steady state. However, an ecosystem may not be in steady state before change and post-change ecosystems enter a transient phase and can take a long time to reach steady state. Calculated during the transient phase, β will be a function of initial stocks and the developmental stage explored (seedling, sapling, mature tree) and signals will accumulate over time. For ecosystems not in steady state pre-change, β of the changes in the stock increment is not sensitive to initial stocks, but could be large where pre-change increments are small (i.e. when pre-change the system is close to steady state). For steady-state ecosystems pre-change, acknowledgment that β is nonsteady state is needed and a β that explicitly includes temporal scale should be sought.

forest-inventory plots, proximal remote sensing at flux and experiment sites, and model-data integration to reconcile diverse data streams would all help to provide an integrated understanding of this complex problem. A holistic, community-based approach will enable the greatest advances and provide the most robust information to decision-makers.

The required size of climate-change mitigation efforts depends directly on how future terrestrial carbon storage evolves. Evidence for the CO<sub>2</sub>-fertilization hypothesis suggests a highly valuable

ecosystem service that is buying us time in the fight against climate change, although the size of this subsidy remains unclear. Based on diminishing theoretical GPP responses, probable increasing nutrient limitations, increasing mortality, and other negative temperature-related effects (Peñuelas *et al.*, 2017) it is highly likely that increases in terrestrial carbon storage as a result of iCO<sub>2</sub> will decline into the future. A decline in this subsidy will result in accelerated climate change on the current trajectory of anthropogenic CO<sub>2</sub> emissions.



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## Author contributions

APW conceived and wrote the paper, with major contributions from MGDK, AB, KG and SM. APW, ASP and BT collated the data. The ICOFEST meeting was organized by APW, SB, KGC, MGDK, RK, BM, DJPM, RJN and SZ. All authors attended or

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## Data availability

Data and analysis scripts used in this publication can be found at ESS-DIVE (<https://data.ess-dive.lbl.gov/view/doi:10.15485/1644687>).

## References

- Ainsworth EA, Long SP. 2005. What have we learned from 15 years of free-air CO<sub>2</sub> enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy. *New Phytologist* 165: 351–371.
- Ainsworth EA, Rogers A. 2007. The response of photosynthesis and stomatal conductance to rising [CO<sub>2</sub>]: mechanisms and environmental interactions. *Plant, Cell & Environment* 30: 258–270.
- Allen LH, Kimball BA, Bunce JA, Yoshimoto M, Harazono Y, Baker JT, Boote KJ, White JW. 2020. Fluctuations of CO<sub>2</sub> in Free-Air CO<sub>2</sub> Enrichment (FACE) depress plant photosynthesis, growth, and yield. *Agricultural and Forest Meteorology* 284: 107899.
- Anderson-Teixeira KJ, McGarvey JC, Muller-Landau HC, Park JY, Gonzalez-Akre EB, Herrmann V, Bennett AC, So CV, Bourg NA, Thompson JR *et al.* 2015. Size-related scaling of tree form and function in a mixed-age forest. *Functional Ecology* 29: 1587–1602.
- Anderson-Teixeira KJ, Wang MMH, McGarvey JC, LeBauer DS. 2016. Carbon dynamics of mature and regrowth tropical forests derived from a pantropical database (TropForC-db). *Global Change Biology* 22: 1690–1709.
- Arora VK, Katavouta A, Williams RG, Jones CD, Brovkin V, Friedlingstein P, Schwinger J, Bopp L, Boucher O, Cadule P *et al.* 2019. Carbon-concentration and carbon-climate feedbacks in CMIP6 models, and their comparison to CMIP5 models. *Biogeosciences Discussions* 1–124.
- Babst F, Alexander MR, Szejn P, Bouriaud O, Klesse S, Roden J, Ciais P, Poulter B, Frank D, Moore DJP *et al.* 2014. A tree-ring perspective on the terrestrial carbon cycle. *Oecologia* 176: 307–322.
- Bacastow R, Keeling CK. 1973. Atmospheric carbon dioxide and radiocarbon in the natural carbon cycle: II. Changes from A. D. 1700 to 2070 as deduced from a geochemical model. *Brookhaven Symposia in Biology* 30: 86–135.
- Bachofen C, Moser B, Hoch G, Ghazoul J, Wohlgemuth T. 2018. No carbon “bet hedging” in pine seedlings under prolonged summer drought and elevated CO<sub>2</sub>. *Journal of Ecology* 106: 31–46.
- Bader MK-F, Körner C. 2010. No overall stimulation of soil respiration under mature deciduous forest trees after 7 years of CO<sub>2</sub> enrichment. *Global Change Biology* 16: 2830–2843.
- Bader MK-F, Leuzinger S, Keel SG, Siegwolf RTW, Hagedorn F, Schleppl P, Körner C. 2013. Central European hardwood trees in a high-CO<sub>2</sub> future: synthesis of an 8-year forest canopy CO<sub>2</sub> enrichment project. *Journal of Ecology* 101: 1509–1519.
- Bader MK-F, Siegwolf R, Körner C. 2010. Sustained enhancement of photosynthesis in mature deciduous forest trees after 8 years of free air CO<sub>2</sub> enrichment. *Planta* 232: 1115–1125.
- Bahuguna RN, Jagadish KSV. 2015. Temperature regulation of plant phenological development. *Environmental and Experimental Botany* 111: 83–90.
- Baig S, Medlyn BE, Mercado LM, Zaehle S. 2015. Does the growth response of woody plants to elevated CO<sub>2</sub> increase with temperature? A model-oriented meta-analysis. *Global Change Biology* 21: 4303–4319.
- Baldocchi DD. 2003. Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. *Global Change Biology* 9: 479–492.
- Barton CVM, Duursma RA, Medlyn BE, Ellsworth DS, Eamus D, Tissue DT, Adams MA, Conroy J, Crous KY, Liberloo M *et al.* 2012. Effects of elevated atmospheric [CO<sub>2</sub>] on instantaneous transpiration efficiency at leaf and canopy scales in *Eucalyptus saligna*. *Global Change Biology* 18: 585–595.
- Bastos A, Ciais P, Chevallier F, Rödenbeck C, Ballantyne AP, Maignan F, Yin Y, Fernández-Martínez M, Friedlingstein P, Peñuelas J *et al.* 2019. Contrasting effects of CO<sub>2</sub> fertilization, land-use change and warming on seasonal amplitude of Northern Hemisphere CO<sub>2</sub> exchange. *Atmospheric Chemistry and Physics* 19: 12361–12375.
- Battipaglia G, Saurer M, Cherubini P, Calfapietra C, McCarthy HR, Norby RJ, Francesca Cotrufo M. 2013. Elevated CO<sub>2</sub> increases tree-level intrinsic water use efficiency: insights from carbon and oxygen isotope analyses in tree rings across three forest FACE sites. *New Phytologist* 197: 544–554.
- Beidler KV, Taylor BN, Strand AE, Cooper ER, Schönholz M, Pritchard SG. 2015. Changes in root architecture under elevated concentrations of CO<sub>2</sub> and nitrogen reflect alternate soil exploration strategies. *New Phytologist* 205: 1153–1163.
- Bennett AC, McDowell NG, Allen CD, Anderson-Teixeira KJ. 2015. Larger trees suffer most during drought in forests worldwide. *Nature Plants* 1: 15139.
- Bereiter B, Eggleston S, Schmitt J, Nehrbass-Ahles C, Stocker TF, Fischer H, Kipfstuhl S, Chappellaz J. 2015. Revision of the EPICA Dome C CO<sub>2</sub> record from 800 to 600 kyr before present: analytical bias in the EDC CO<sub>2</sub> record. *Geophysical Research Letters* 42: 542–549.
- Beven K. 2006. A manifesto for the equifinality thesis. *Journal of Hydrology* 320: 18–36.
- Bigler C, Veblen TT. 2009. Increased early growth rates decrease longevity of conifers in subalpine forests. *Oikos* 118: 1130–1138.
- Blagodatskaya E, Blagodatsky S, Anderson T-H, Kuzyakov Y. 2014. Microbial growth and carbon use efficiency in the rhizosphere and root-free soil. *PLoS ONE* 9: e93282.
- Bloom AJ, Asensio JSR, Randall L, Rachmilevitch S, Cousins AB, Carlisle EA. 2012. CO<sub>2</sub> enrichment inhibits shoot nitrate assimilation in C<sub>3</sub> but not C<sub>4</sub> plants and slows growth under nitrate in C<sub>3</sub> plants. *Ecology* 93: 355–367.
- Bloom AJ, Chapin FS III, Mooney HA. 1985. Resource limitation in plants—an economic analogy. *Annual Review of Ecology and Systematics* 16: 363–392.
- Bond-Lamberty B, Bailey VL, Chen M, Gough CM, Vargas R. 2018. Globally rising soil heterotrophic respiration over recent decades. *Nature* 560: 80–83.
- Bond-Lamberty B, Thomson A. 2010. Temperature-associated increases in the global soil respiration record. *Nature* 464: 579–582.
- Bormann FH, Likens GE. 1979. Catastrophic disturbance and the steady state in northern hardwood forests: a new look at the role of disturbance in the development of forest ecosystems suggests important implications for land-use policies. *American Scientist* 67: 660–669.
- Bowes G. 1991. Growth at elevated CO<sub>2</sub>: photosynthetic responses mediated through Rubisco. *Plant, Cell & Environment* 14: 795–806.
- Brienen RJW, Gloor E, Zuidema PA. 2012. Detecting evidence for CO<sub>2</sub> fertilization from tree ring studies: the potential role of sampling biases: CO<sub>2</sub> fertilization from tree rings. *Global Biogeochemical Cycles* 26: GB1025.
- Brienen RJW, Gloor M, Ziv G. 2016. Tree demography dominates long-term growth trends inferred from tree rings. *Global Change Biology* 23: 474–484.
- Brienen RJW, Phillips OL, Feldpausch TR, Gloor E, Baker TR, Lloyd J, Lopez-Gonzalez G, Monteagudo-Mendoza A, Malhi Y, Lewis SL *et al.* 2015. Long-term decline of the Amazon carbon sink. *Nature* 519: 344–348.
- Buckley TN, Sack L, Farquhar GD. 2017. Optimal plant water economy. *Plant, Cell & Environment* 40: 881–896.
- Bugmann H, Bigler C. 2011. Will the CO<sub>2</sub> fertilization effect in forests be offset by reduced tree longevity? *Oecologia* 165: 533–544.
- Büntgen U, Krusic PJ, Piermattei A, Coomes DA, Esper J, Myglan VS, Kirilyanov AV, Camarero JJ, Crivellaro A, Körner C. 2019. Limited capacity of tree growth to mitigate the global greenhouse effect under predicted warming. *Nature Communications* 10: 2171.
- Cailleret M, Jansen S, Robert EMR, Desoto L, Aakala T, Antos JA, Beikircher B, Bigler C, Bugmann H, Caccianiga M *et al.* 2017. A synthesis of radial growth patterns preceding tree mortality. *Global Change Biology* 23: 1675–1690.
- Calvin M, Benson AA. 1948. The path of carbon in photosynthesis. *Science* 107: 476–480.

- Campbell JE, Berry JA, Seibt U, Smith SJ, Montzka SA, Launois T, Belviso S, Bopp L, Laine M. 2017. Large historical growth in global terrestrial gross primary production. *Nature* 544: 84–87.
- Carney KM, Hungate BA, Drake BG, Megonigal JP. 2007. Altered soil microbial community at elevated CO<sub>2</sub> leads to loss of soil carbon. *Proceedings of the National Academy of Sciences, USA* 104: 4990–4995.
- Caspersen JP. 2000. Contributions of land-use history to carbon accumulation in U.S. Forests. *Science* 290: 1148–1151.
- Castanha C, Zhu B, Hicks Pries CE, Georgiou K, Torn MS. 2018. The effects of heating, rhizosphere, and depth on root litter decomposition are mediated by soil moisture. *Biogeochemistry* 137: 267–279.
- Cawse-Nicholson K, Fisher JB, Famiglietti CA, Braverman A, Schwandner FM, Lewicki JL, Townsend PA, Schimel DS, Pavlick R, Bormann KJ *et al.* 2018. Ecosystem responses to elevated CO<sub>2</sub> using airborne remote sensing at Mammoth Mountain, California. *Biogeosciences* 15: 7403–7418.
- Chambers JQ, Negron-Juarez RI, Marra DM, Di Vittorio A, Tews J, Roberts D, Ribeiro GHPM, Trumbore SE, Higuchi N. 2013. The steady-state mosaic of disturbance and succession across an old-growth Central Amazon forest landscape. *Proceedings of the National Academy of Sciences, USA* 110: 3949–3954.
- Chave J, Condit R, Muller-Landau HC, Thomas SC, Ashton PS, Bunyavechewin S, Co LL, Dattaraja HS, Davies SJ, Esufali S *et al.* 2008. Assessing evidence for a pervasive alteration in tropical tree communities. *PLoS Biology* 6: e45.
- Cheng L, Booker FL, Tu C, Burkey KO, Zhou L, Shew HD, Rufty TW, Hu S. 2012. Arbuscular mycorrhizal fungi increase organic carbon decomposition under elevated CO<sub>2</sub>. *Science* 337: 1084–1087.
- Cheng L, Zhang L, Wang Y-P, Canadell JG, Chiew FHS, Beringer J, Li L, Miralles DG, Piao S, Zhang Y. 2017. Recent increases in terrestrial carbon uptake at little cost to the water cycle. *Nature Communications* 8: 110.
- Chu H, Baldocchi DD, John R, Wolf S, Reichstein M. 2017. Fluxes all of the time? A primer on the temporal representativeness of FLUXNET. *Journal of Geophysical Research: Biogeosciences* 122: 289–307.
- Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, Canadell J, Chhabra A, DeFries R, Galloway J, Heimann M *et al.* 2014. Carbon and other biogeochemical cycles. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press, 465–570.
- Ciais P, Tagliabue A, Cuntz M, Bopp L, Scholze M, Hoffmann G, Lourantou A, Harrison SP, Prentice IC, Kelley DI *et al.* 2012. Large inert carbon pool in the terrestrial biosphere during the Last Glacial Maximum. *Nature Geoscience* 5: 74–79.
- Clark DB, Clark DA, Oberbauer SF. 2010. Annual wood production in a tropical rain forest in NE Costa Rica linked to climatic variation but not to increasing CO<sub>2</sub>. *Global Change Biology* 16: 747–759.
- Clark MP, Nijssen B, Lundquist JD, Kavetski D, Rupp DE, Woods RA, Freer JE, Gutmann ED, Wood AW, Brekke LD *et al.* 2015. A unified approach for process-based hydrologic modeling: 1. Modeling concept. *Water Resources Research* 51: 2498–2514.
- Collatz GJ, Ribas-Carbo M, Berry JA. 1992. Coupled photosynthesis-stomatal conductance model for leaves of C<sub>4</sub> plants. *Australian Journal of Plant Physiology* 19: 519–538.
- Comins HN, McMurtrie RE. 1993. Long-term response of nutrient-limited forests to CO<sub>2</sub> enrichment; equilibrium behavior of plant-soil models. *Ecological Applications* 3: 666–681.
- Cotrufo MF, Wallenstein MD, Boot CM, Denef K, Paul E. 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Global Change Biology* 19: 988–995.
- Cowan IR. 1982. Regulation of water use in relation to carbon gain in higher plants. In: Lange OL, Nobel PS, Osmond CB, Ziegler H, eds. *Encyclopedia of plant physiology. Physiological plant ecology II: water relations and carbon assimilation*. Berlin, Heidelberg: Springer, 589–613.
- Crous KY, Walters MB, Ellsworth DS. 2008. Elevated CO<sub>2</sub> concentration affects leaf photosynthesis-nitrogen relationships in *Pinus taeda* over nine years in FACE. *Tree Physiology* 28: 607–614.
- De Kauwe MG, Keenan TF, Medlyn BE, Prentice IC, Terrer C. 2016. Satellite based estimates underestimate the effect of CO<sub>2</sub> fertilization on net primary productivity. *Nature Climate Change* 6: 892–893.
- De Kauwe MG, Medlyn BE, Zaehle S, Walker AP, Dietze MC, Hickler T, Jain AK, Luo Y, Parton WJ, Prentice IC *et al.* 2013. Forest water use and water use efficiency at elevated CO<sub>2</sub>: a model-data intercomparison at two contrasting temperate forest FACE sites. *Global Change Biology* 19: 1759–1779.
- De Kauwe MG, Medlyn BE, Zaehle S, Walker AP, Dietze MC, Wang YP, Luo Y, Jain AK, El-Masri B, Hickler T *et al.* 2014. Where does the carbon go? A model-data intercomparison of vegetation carbon allocation and turnover processes at two temperate forest free-air CO<sub>2</sub> enrichment sites. *New Phytologist* 203: 883–899.
- Dewar R, Muraenen A, Mäkelä A, Hölttä T, Medlyn B, Vesala T. 2018. New insights into the covariation of stomatal, mesophyll and hydraulic conductances from optimization models incorporating nonstomatal limitations to photosynthesis. *New Phytologist* 217: 571–585.
- Di Filippo A, Biondi F, Maugeri M, Schirone B, Piovesan G. 2012. Bioclimate and growth history affect beech lifespan in the Italian Alps and Apennines. *Global Change Biology* 18: 960–972.
- Di Filippo A, Pederson N, Baliva M, Brunetti M, Dinella A, Kitamura K, Knapp HD, Schirone B, Piovesan G. 2015. The longevity of broadleaf deciduous trees in Northern Hemisphere temperate forests: insights from tree-ring series. *Frontiers in Ecology and Evolution* 3: 46.
- Dijkstra FA. 2008. Long-term enhancement of N availability and plant growth under elevated CO<sub>2</sub> in a semi-arid grassland. *Functional Ecology* 22: 975–982.
- Donohue RJ, Roderick ML, McVicar TR, Farquhar GD. 2013. Impact of CO<sub>2</sub> fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophysical Research Letters* 40: 3031–3035.
- Donohue RJ, Roderick ML, McVicar TR, Yang Y. 2017. A simple hypothesis of how leaf and canopy-level transpiration and assimilation respond to elevated CO<sub>2</sub> reveals distinct response patterns between disturbed and undisturbed vegetation. *Journal of Geophysical Research: Biogeosciences* 122: 168–184.
- Drake BG. 2014. Rising sea level, temperature, and precipitation impact plant and ecosystem responses to elevated CO<sub>2</sub> on a Chesapeake Bay wetland: review of a 28-year study. *Global Change Biology* 20: 3329–3343.
- Drake BG, González-Meler MA, Long SP. 1997. MORE EFFICIENT PLANTS: a consequence of rising atmospheric CO<sub>2</sub>? *Annual Review of Plant Physiology and Plant Molecular Biology* 48: 609–639.
- Drake JE, Gallet-Budynek A, Hofmockel KS, Bernhardt ES, Billings SA, Jackson RB, Johnsen KS, Lichter J, McCarthy HR, McCormack ML *et al.* 2011. Increases in the flux of carbon belowground stimulate nitrogen uptake and sustain the long-term enhancement of forest productivity under elevated CO<sub>2</sub>. *Ecology Letters* 14: 349–357.
- Drake JE, Macdonald CA, Tjoelker MG, Crous KY, Gimeno TE, Singh BK, Reich PB, Anderson IC, Ellsworth DS. 2016. Short-term carbon cycling responses of a mature eucalypt woodland to gradual stepwise enrichment of atmospheric CO<sub>2</sub> concentration. *Global Change Biology* 22: 380–390.
- Drake JE, Macdonald CA, Tjoelker MG, Reich PB, Singh BK, Anderson IC, Ellsworth DS. 2018. Three years of soil respiration in a mature eucalypt woodland exposed to atmospheric CO<sub>2</sub> enrichment. *Biogeochemistry* 139: 85–101.
- Duan H, Chaszar B, Lewis JD, Smith RA, Huxman TE, Tissue DT, Way D. 2018. CO<sub>2</sub> and temperature effects on morphological and physiological traits affecting risk of drought-induced mortality. *Tree Physiology* 38: 1138–1151.
- Duan H, Duursma RA, Huang G, Smith RA, Choat B, Ogrady AP, Tissue DT. 2014. Elevated [CO<sub>2</sub>] does not ameliorate the negative effects of elevated temperature on drought-induced mortality in *Eucalyptus radiata* seedlings. *Plant, Cell & Environment* 37: 1598–1613.
- Duursma RA, Gimeno TE, Boer MM, Crous KY, Tjoelker MG, Ellsworth DS. 2016. Canopy leaf area of a mature evergreen Eucalyptus woodland does not respond to elevated atmospheric [CO<sub>2</sub>] but tracks water availability. *Global Change Biology* 22: 1666–1676.
- Dwivedi D, Tang J, Bouskill N, Georgiou K, Chacon SS, Riley WJ. 2019. Abiotic and biotic controls on soil organo-mineral interactions: developing model structures to analyze why soil organic matter persists. *Reviews in Mineralogy and Geochemistry* 85: 329–348.

- Dye A, Plotkin AB, Bishop D, Pederson N, Poulter B, Hessel A. 2016. Comparing tree-ring and permanent plot estimates of aboveground net primary production in three eastern U.S. forests. *Ecosphere* 7: e01454.
- Ehleringer J, Björkman O. 1977. Quantum yields for CO<sub>2</sub> uptake in C<sub>3</sub> and C<sub>4</sub> plants: dependence on temperature, CO<sub>2</sub>, and O<sub>2</sub> concentration. *Plant Physiology* 59: 86–90.
- Ehlers I, Augusti A, Betson TR, Nilsson MB, Marshall JD, Schleucher J. 2015. Detecting long-term metabolic shifts using isotopomers: CO<sub>2</sub>-driven suppression of photorespiration in C<sub>3</sub> plants over the 20th century. *Proceedings of the National Academy of Sciences, USA* 112: 15585–15590.
- Ellsworth DS, Anderson IC, Crous KY, Cooke J, Drake JE, Gherlenda AN, Gimeno TE, Macdonald CA, Medlyn BE, Powell JR *et al.* 2017. Elevated CO<sub>2</sub> does not increase eucalypt forest productivity on a low-phosphorus soil. *Nature Climate Change* 7: 279–282.
- Elser JJ, Fagan WF, Kerkhoff AJ, Swenson NG, Enquist BJ. 2010. Biological stoichiometry of plant production: metabolism, scaling and ecological response to global change: tansley review. *New Phytologist* 186: 593–608.
- Evans MEK, Falk DA, Arizpe A, Swetnam TL, Babst F, Holsinger KE. 2017. Fusing tree-ring and forest inventory data to infer influences on tree growth. *Ecosphere* 8: e01889.
- Evans RD, Koyama A, Sonderegger DL, Charlet TN, Newingham BA, Fenstermaker LF, Harlow B, Jin VL, Ogle K, Smith SD *et al.* 2014. Greater ecosystem carbon in the Mojave Desert after ten years exposure to elevated CO<sub>2</sub>. *Nature Climate Change* 4: 394–397.
- Farquhar GD, Cernusak LA. 2012. Ternary effects on the gas exchange of isotopologues of carbon dioxide. *Plant, Cell & Environment* 35: 1221–1231.
- Farquhar GD, O'Leary MH, Berry JA. 1982. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. *Functional Plant Biology* 9: 121–137.
- Farquhar GD, Sharkey TD. 1982. Stomatal conductance and photosynthesis. *Annual Review of Plant Physiology* 33: 317–345.
- Farquhar GD, von Caemmerer S, Berry JA. 1980. A biochemical model of photosynthetic CO<sub>2</sub> assimilation in leaves of C<sub>3</sub> species. *Planta* 149: 78–90.
- Fatichi S, Leuzinger S, Paschalis A, Langley JA, Donnellan Barraclough A, Hovenden MJ. 2016. Partitioning direct and indirect effects reveals the response of water-limited ecosystems to elevated CO<sub>2</sub>. *Proceedings of the National Academy of Sciences, USA* 113: 12757–12762.
- Fatichi S, Pappas C, Zscheischler J, Leuzinger S. 2019. Modelling carbon sources and sinks in terrestrial vegetation. *New Phytologist* 221: 652–668.
- Feng W, Plante AF, Six J. 2013. Improving estimates of maximal organic carbon stabilization by fine soil particles. *Biogeochemistry* 112: 81–93.
- Fensholt R, Sandholt I, Rasmussen MS. 2004. Evaluation of MODIS LAI, fAPAR and the relation between fAPAR and NDVI in a semi-arid environment using in situ measurements. *Remote Sensing of Environment* 91: 490–507.
- Fernández-Martínez M, Sardans J, Chevallier F, Ciais P, Obersteiner M, Vicca S, Canadell JG, Bastos A, Friedlingstein P, Sitch S *et al.* 2019. Global trends in carbon sinks and their relationships with CO<sub>2</sub> and temperature. *Nature Climate Change* 9: 73–79.
- Fernández-Martínez M, Vicca S, Janssens IA, Ciais P, Obersteiner M, Bartrons M, Sardans J, Verger A, Canadell JG, Chevallier F *et al.* 2017. Atmospheric deposition, CO<sub>2</sub>, and change in the land carbon sink. *Scientific Reports* 7: 1–13.
- Field CB, Behrenfeld MJ, Randerson JT, Falkowski P. 1998. Primary production of the biosphere: integrating terrestrial and oceanic components. *Science* 281: 237–240.
- Field CB, Jackson RB, Mooney HA. 1995. Stomatal responses to increased CO<sub>2</sub>: implications from the plant to the global scale. *Plant, Cell & Environment* 18: 1214–1225.
- Finzi AC, Moore DJP, DeLucia EH, Lichter J, Hofmockel KS, Jackson RB, Kim H-S, Matamala R, McCarthy HR, Oren R *et al.* 2006. Progressive nitrogen limitation of ecosystem processes under elevated CO<sub>2</sub> in a warm-temperate forest. *Ecology* 87: 15–25.
- Finzi AC, Norby RJ, Calfapietra C, Gallet-Budynek A, Gielen B, Holmes WE, Hoosbeek MR, Iversen CM, Jackson RB, Kubiske ME *et al.* 2007. Increases in nitrogen uptake rather than nitrogen-use efficiency support higher rates of temperate forest productivity under elevated CO<sub>2</sub>. *Proceedings of the National Academy of Sciences, USA* 104: 14014–14019.
- Fischer H, Schmitt J, Bock M, Seth B, Joos F, Spahni R, Lienert S, Battaglia G, Stocker BD, Schilt A *et al.* 2019. N<sub>2</sub>O changes from the Last Glacial Maximum to the preindustrial – Part 1: Quantitative reconstruction of terrestrial and marine emissions using N<sub>2</sub>O stable isotopes in ice cores. *Biogeosciences* 16: 3997–4021.
- Fleischer K, Rammig A, Kauwe MGD, Walker AP, Domingues TF, Fuchslueger L, Garcia S, Goll DS, Grandis A, Jiang M *et al.* 2019. Amazon forest response to CO<sub>2</sub> fertilization dependent on plant phosphorus acquisition. *Nature Geoscience* 12: 736–741.
- Fontaine S, Barot S, Barré P, Bdioui N, Mary B, Rumpel C. 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* 450: 277–280.
- Forkel M, Carvalhais N, Rödenbeck C, Keeling R, Heimann M, Thonicke K, Zaehle S, Reichstein M. 2016. Enhanced seasonal CO<sub>2</sub> exchange caused by amplified plant productivity in northern ecosystems. *Science* 351: 696–699.
- Fowler D, Coyle M, Skiba U, Sutton MA, Cape JN, Reis S, Sheppard LJ, Jenkins A, Grizzetti B, Galloway JN *et al.* 2013. The global nitrogen cycle in the twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences* 368: 20130164.
- Frank DC, Poulter B, Saurer M, Esper J, Huntingford C, Helle G, Treydte K, Zimmermann NE, Schleser GH, Ahlström A *et al.* 2015. Water-use efficiency and transpiration across European forests during the Anthropocene. *Nature Climate Change* 5: 579–583.
- Friedlingstein P, Fung I, Holland E, John J, Brasseur G, Erickson D, Schimel D. 1995. On the contribution of CO<sub>2</sub> fertilization to the missing biospheric sink. *Global Biogeochemical Cycles* 9: 541–556.
- Friedlingstein P, Jones MW, O'Sullivan M, Andrew RM, Hauck J, Peters GP, Peters W, Pongratz J, Sitch S, Le Quéré C *et al.* 2019. Global carbon budget 2019. *Earth System Science Data* 11: 1783–1838.
- Gedney N, Cox PM, Betts RA, Boucher O, Huntingford C, Stott PA. 2006. Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* 439: 835–838.
- Georgiou K, Koven CD, Riley WJ, Torn MS. 2015. Toward improved model structures for analyzing priming: potential pitfalls of using bulk turnover time. *Global Change Biology* 21: 4298–4302.
- Ge Z, Fang S, Chen HYH, Zhu R, Peng S, Ruan H. 2018. Soil aggregation and organic carbon dynamics in poplar plantations. *Forests* 9: 508.
- Gimeno TE, McVicar TR, O'Grady AP, Tissue DT, Ellsworth DS. 2018. Elevated CO<sub>2</sub> did not affect the hydrological balance of a mature native Eucalyptus woodland. *Global Change Biology* 24: 3010–3024.
- Girardin MP, Bouriaud O, Hogg EH, Kurz W, Zimmermann NE, Metsaranta JM, de Jong R, Frank DC, Esper J, Büntgen U *et al.* 2016. No growth stimulation of Canada's boreal forest under half-century of combined warming and CO<sub>2</sub> fertilization. *Proceedings of the National Academy of Sciences, USA* 113: E8406–E8414.
- Graven HD, Keeling RF, Piper SC, Patra PK, Stephens BB, Wofsy SC, Welp LR, Sweeney C, Tans PP, Kelley JJ *et al.* 2013. Enhanced seasonal exchange of CO<sub>2</sub> by northern ecosystems since 1960. *Science* 341: 1085–1089.
- Gray JM, Frolking S, Kort EA, Ray DK, Kucharik CJ, Ramankutty N, Friedl MA. 2014. Direct human influence on atmospheric CO<sub>2</sub> seasonality from increased cropland productivity. *Nature* 515: 398–401.
- van Groenigen KJ, Qi X, Osenberg CW, Luo Y, Hungate BA. 2014. Faster decomposition under increased atmospheric CO<sub>2</sub> limits soil carbon storage. *Science* 344: 508–509.
- Guanter L, Zhang Y, Jung M, Joiner J, Voigt M, Berry JA, Frankenberg C, Huete AR, Zarco-Tejada P, Lee J-E *et al.* 2014. Global and time-resolved monitoring of crop photosynthesis with chlorophyll fluorescence. *Proceedings of the National Academy of Sciences, USA* 111: E1327–E1333.
- Gurney KR, Law RM, Denning AS, Rayner PJ, Pak BC, Baker D, Bousquet P, Bruhwiler L, Chen Y-H, Ciais P *et al.* 2004. Transcom 3 inversion intercomparison: Model mean results for the estimation of seasonal carbon sources and sinks. *Global Biogeochemical Cycles* 18: GB1010.
- Hamerlynek EP, Scott RL, Sánchez-Cañete EP, Barron-Gafford GA. 2013. Nocturnal soil CO<sub>2</sub> uptake and its relationship to subsurface soil and ecosystem carbon fluxes in a Chihuahuan Desert shrubland. *Journal of Geophysical Research: Biogeosciences* 118: 1593–1603.

- Hartmann H, Moura CF, Anderegg WRL, Ruehr NK, Salmon Y, Allen CD, Arndt SK, Breshears DD, Davi H, Galbraith D *et al.* 2018. Research frontiers for improving our understanding of drought-induced tree and forest mortality. *New Phytologist* 218: 15–28.
- Hasegawa S, Macdonald CA, Power SA. 2016. Elevated carbon dioxide increases soil nitrogen and phosphorus availability in a phosphorus-limited Eucalyptus woodland. *Global Change Biology* 22: 1628–1643.
- Hättenschwiler S, Franco Miglietta, Antonio Raschi, Christian Körner. 1997. Thirty years of in situ tree growth under elevated CO<sub>2</sub>: a model for future forest responses? *Global Change Biology* 3: 463–471.
- Haverd V, Smith B, Canadell JG, Cuntz M, Mikaloff-Fletcher S, Farquhar G, Woodgate W, Briggs PR, Trudinger CM. 2020. Higher than expected CO<sub>2</sub> fertilization inferred from leaf to global observations. *Global Change Biology* 26: 2390–2402.
- Helcoski R, Tepley AJ, Pederson N, McGarvey JC, Meakem V, Herrmann V, Thompson JR, Anderson-Teixeira KJ. 2019. Growing season moisture drives interannual variation in woody productivity of a temperate deciduous forest. *New Phytologist* 223: 1204–1216.
- Hember RA, Kurz WA, Girardin MP. 2019. Tree ring reconstructions of stemwood biomass indicate increases in the growth rate of black spruce trees across boreal forests of Canada. *Journal of Geophysical Research: Biogeosciences* 124: 2460–2480.
- Hicks Pries CE, Sulman BN, West C, O'Neill C, Poppleton E, Porras RC, Castanha C, Zhu B, Wiedemeier DB, Torn MS. 2018. Root litter decomposition slows with soil depth. *Soil Biology and Biochemistry* 125: 103–114.
- Houghton RA, Nassikas AA. 2016GB. Global and regional fluxes of carbon from land use and land cover change 1850–2015. *Global Biogeochemical Cycles* 31: 456–472.
- Hovenden MJ, Leuzinger S, Newton PCD, Fletcher A, Fatichi S, Lüscher A, Reich PB, Andresen LC, Beier C, Blumenthal DM *et al.* 2019. Globally consistent influences of seasonal precipitation limit grassland biomass response to elevated CO<sub>2</sub>. *Nature Plants* 5: 167.
- Hubau W, Lewis SL, Phillips OL, Affum-Baffoe K, Beeckman H, Cuní-Sanchez A, Daniels AK, Ewango CEN, Fauset S, Mukinzi JM *et al.* 2020. Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature* 579: 80–87.
- Hülsmann L, Bugmann H, Cailleret M, Brang P. 2018. How to kill a tree: empirical mortality models for 18 species and their performance in a dynamic forest model. *Ecological Applications* 28: 522–540.
- Hungate BA, Dijkstra P, Johnson DW, Hinkle CR, Drake BG. 1999. Elevated CO<sub>2</sub> increases nitrogen fixation and decreases soil nitrogen mineralization in Florida scrub oak. *Global Change Biology* 5: 781–789.
- Hungate BA, Dijkstra P, Wu Z, Duval BD, Day FP, Johnson DW, Megonigal JP, Brown ALP, Garland JL. 2013. Cumulative response of ecosystem carbon and nitrogen stocks to chronic CO<sub>2</sub> exposure in a subtropical oak woodland. *New Phytologist* 200: 753–766.
- Hungate BA, van Groenigen K-J, Six J, Jastrow JD, Luo Y, de Graaff M-A, van Kessel C, Osenberg CW. 2009. Assessing the effect of elevated carbon dioxide on soil carbon: a comparison of four meta-analyses. *Global Change Biology* 15: 2020–2034.
- Huntzinger DN, Michalak AM, Schwalm C, Ciais P, King AW, Fang Y, Schaefer K, Wei Y, Cook RB, Fisher JB *et al.* 2017. Uncertainty in the response of terrestrial carbon sink to environmental drivers undermines carbon-climate feedback predictions. *Scientific Reports* 7: 4765.
- Ireland KB, Moore MM, Fulé PZ, Ziegler TJ, Keane RE. 2014. Slow lifelong growth predisposes *Populus tremuloides* trees to mortality. *Oecologia* 175: 847–859.
- Iversen CM. 2010. Digging deeper: fine-root responses to rising atmospheric CO<sub>2</sub> concentration in forested ecosystems. *New Phytologist* 186: 346–357.
- Iversen CM, Keller JK, Garten CT, Norby RJ. 2012. Soil carbon and nitrogen cycling and storage throughout the soil profile in a sweetgum plantation after 11 years of CO<sub>2</sub>-enrichment. *Global Change Biology* 18: 1684–1697.
- Jackson RB, Lajtha K, Crow SE, Hugelius G, Kramer MG, Piñeiro G. 2017. The ecology of soil carbon: pools, vulnerabilities, and biotic and abiotic controls. *Annual Review of Ecology, Evolution, and Systematics* 48: 419–445.
- Jastrow JD, Michael Miller R, Matamala R, Norby RJ, Boutton TW, Rice CW, Owensby CE. 2005. Elevated atmospheric carbon dioxide increases soil carbon. *Global Change Biology* 11: 2057–2064.
- Jarvis PG, McNaughton KG. 1986. Stomatal control of transpiration: scaling up from leaf to region. In: MacFadyen A, Ford ED, eds. *Advances in ecological research, vol. 15*. London, UK: Academic Press, Elsevier, 1–49.
- Jasoni RL, Smith SD, Arnone JA. 2005. Net ecosystem CO<sub>2</sub> exchange in Mojave Desert shrublands during the eighth year of exposure to elevated CO<sub>2</sub>. *Global Change Biology* 11: 749–756.
- Jeltsch-Thömmes A, Battaglia G, Cartapanis O, Jaccard SL, Joos F. 2019. Low terrestrial carbon storage at the Last Glacial Maximum: constraints from multi-proxy data. *Climate of the Past* 15: 849–879.
- Jiang M, Medlyn BE, Drake JE, Duursma RA, Anderson IC, Barton CVM, Boer MM, Carrillo Y, Castañeda-Gómez L, Collins L *et al.* 2020. The fate of carbon in a mature forest under carbon dioxide enrichment. *Nature* 580: 227–231.
- Joos F, Prentice IC, House JI. 2002. Growth enhancement due to global atmospheric change as predicted by terrestrial ecosystem models: consistent with US forest inventory data. *Global Change Biology* 8: 299–303.
- Keeling CD, Chin JFS, Whorf TP. 1996. Increased activity of northern vegetation inferred from atmospheric CO<sub>2</sub> measurements. *Nature* 382: 146–149.
- Keeling RF, Graven HD, Welp LR, Resplandy L, Bi J, Piper SC, Sun Y, Bollenbacher A, Meijer HAJ. 2017. Atmospheric evidence for a global secular increase in carbon isotopic discrimination of land photosynthesis. *Proceedings of the National Academy of Sciences, USA* 114: 10361–10366.
- Keenan TF, Hollinger DY, Bohrer G, Dragoni D, Munger JW, Schmid HP, Richardson AD. 2013. Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. *Nature* 499: 324–327.
- Keenan TF, Prentice IC, Canadell JG, Williams CA, Wang H, Raupach M, Collatz GJ. 2016. Recent pause in the growth rate of atmospheric CO<sub>2</sub> due to enhanced terrestrial carbon uptake. *Nature Communications* 7: 13428.
- Keenan TF, Riley WJ. 2018. Greening of the land surface in the world's cold regions consistent with recent warming. *Nature Climate Change* 8: 825–828.
- Keenan TF, Williams CA. 2018. The terrestrial carbon sink. *Annual Review of Environment and Resources* 43: 219–243.
- Keiluweit M, Bougoure JJ, Nico PS, Pett-Ridge J, Weber PK, Kleber M. 2015. Mineral protection of soil carbon counteracted by root exudates. *Nature Climate Change* 5: 588–595.
- Keller KM, Lienert S, Bozbiyik A, Stocker TF, Churakova(Sidorova) OV, Frank DC, Klesse S, Koven CD, Leuenberger M, Riley WJ *et al.* 2017. 20th century changes in carbon isotopes and water-use efficiency: tree-ring-based evaluation of the CLM4.5 and LPX-Bern models. *Biogeosciences* 14: 2641–2673.
- Klein T, Bader MK-F, Leuzinger S, Mildner M, Schleppl P, Siegwolf RTW, Körner C. 2016. Growth and carbon relations of mature *Picea abies* trees under 5 years of free-air CO<sub>2</sub> enrichment. *Journal of Ecology* 104: 1720–1733.
- Knauer J, Zaehle S, Reichstein M, Medlyn BE, Forkel M, Hagemann S, Werner C. 2017. The response of ecosystem water-use efficiency to rising atmospheric CO<sub>2</sub> concentrations: sensitivity and large-scale biogeochemical implications. *New Phytologist* 213: 1654–1666.
- Körner C, Asshoff R, Bignucolo O, Hättenschwiler S, Keel SG, Peláez-Riedl S, Pepin S, Siegwolf RTW, Zotz G. 2005. Carbon flux and growth in mature deciduous forest trees exposed to elevated CO<sub>2</sub>. *Science* 309: 1360–1362.
- Kögel-Knabner I, Guggenberger G, Kleber M, Kandeler E, Kalbitz K, Scheu S, Eusterhues K, Leinweber P. 2008. Organo-mineral associations in temperate soils: Integrating biology, mineralogy, and organic matter chemistry. *Journal of Plant Nutrition and Soil Science* 171: 61–82.
- Kolby Smith W, Reed SC, Cleveland CC, Ballantyne AP, Anderegg WRL, Wieder WR, Liu YY, Running SW. 2016. Large divergence of satellite and Earth system model estimates of global terrestrial CO<sub>2</sub> fertilization. *Nature Climate Change* 6: 306–310.
- Körner C. 2003a. Ecological impacts of atmospheric CO<sub>2</sub> enrichment on terrestrial ecosystems. *Philosophical Transactions of the Royal Society of London Series A: Mathematical Physical and Engineering Sciences* 361: 2023–2041.
- Körner C. 2003b. Carbon limitation in trees. *Journal of Ecology* 91: 4–17.
- Körner C. 2006. Plant CO<sub>2</sub> responses: an issue of definition, time and resource supply. *New Phytologist* 172: 393–411.
- Körner C. 2017. A matter of tree longevity. *Science* 355: 130–131.

- Körner C, Morgan J, Norby R. 2007. CO<sub>2</sub> fertilization: when, where, how much? In: Canadell JG, Pataki DE, Pitelka LF, eds. *Global Change — The IGBP Series. Terrestrial ecosystems in a changing world*. Berlin/Heidelberg, Germany: Springer, 9–21.
- Koven C, Piao SL. 2012. Large inert carbon pool in the terrestrial biosphere during the Last Glacial Maximum. *Nature Geoscience* 5: 74–79.
- Kramer PJ. 1981. Carbon dioxide concentration, photosynthesis, and dry matter production. *BioScience* 31: 29–33.
- Kubiske ME, Woodall CW, Kern CC. 2019. Increasing atmospheric CO<sub>2</sub> concentration stand development in trembling aspen forests: are outdated density management guidelines in need of revision for all species? *Journal of Forestry* 117: 38–45.
- Kuzaykov Y, Friedel JK, Stahr K. 2000. Review of mechanisms and quantification of priming effects. *Soil Biology and Biochemistry* 32: 1485–1498.
- Lajtha K, Bowden RD, Crow S, Fekete I, Kotrocó Z, Plante A, Simpson MJ, Nadelhoffer KJ. 2018. The detrital input and removal treatment (DIRT) network: Insights into soil carbon stabilization. *Science of the Total Environment* 640–641: 1112–1120.
- Lajtha K, Bowden RD, Nadelhoffer K. 2014. Litter and root manipulations provide insights into soil organic matter dynamics and stability. *Soil Science Society of America Journal* 78: S261–S269.
- Lapenis AG, Lawrence GB, Buyantuev A, Jiang S, Sullivan TJ, McDonnell TC, Bailey S. 2017. A newly identified role of the deciduous forest floor in the timing of green-up. *Journal of Geophysical Research: Biogeosciences* 122: 2876–2891.
- Larson JL, Zak DR, Sinsabaugh RL. 2002. Extracellular enzyme activity beneath temperate trees growing under elevated carbon dioxide and ozone. *Soil Science Society of America Journal* 66: 1848–1856.
- Leakey ADB, Bernacchi CJ, Dohleman FG, Ort DR, Long SP. 2004. Will photosynthesis of maize (*Zea mays*) in the US Corn Belt increase in future [CO<sub>2</sub>] rich atmospheres? An analysis of diurnal courses of CO<sub>2</sub> uptake under free-air concentration enrichment (FACE). *Global Change Biology* 10: 951–962.
- Leonardi S, Gentilella T, Guerrieri R, Ripullone F, Magnani F, Mencuccini M, Noije TV, Borghetti M. 2012. Assessing the effects of nitrogen deposition and climate on carbon isotope discrimination and intrinsic water-use efficiency of angiosperm and conifer trees under rising CO<sub>2</sub> conditions. *Global Change Biology* 18: 2925–2944.
- Le Quéré C, Andrew RM, Friedlingstein P, Sitch S, Hauck J, Pongratz J, Pickers PA, Korsbakken JI, Peters GP, Canadell JG *et al.* 2018. Global carbon budget 2018. *Earth System Science Data* 10: 2141–2194.
- Leuzinger S, Fatichi S, Cusens J, Körner C, Niklaus PA. 2015. The ‘island effect’ in terrestrial global change experiments: a problem with no solution? *AoB Plants* 7: plv092.
- Leuzinger S, Körner C. 2010. Rainfall distribution is the main driver of runoff under future CO<sub>2</sub>-concentration in a temperate deciduous forest. *Global Change Biology* 16: 246–254.
- Li JH, Johnson DP, Dijkstra P, Hungate BA, Hinkle CR, Drake BG. 2007. Elevated CO<sub>2</sub> mitigates the adverse effects of drought on daytime net ecosystem CO<sub>2</sub> exchange and photosynthesis in a Florida scrub-oak ecosystem. *Photosynthetica* 45: 51–58.
- Li W, Ciais P, Wang Y, Peng S, Broquet G, Ballantyne AP, Canadell JG, Cooper L, Friedlingstein P, Quéré CL *et al.* 2016. Reducing uncertainties in decadal variability of the global carbon budget with multiple datasets. *Proceedings of the National Academy of Sciences, USA* 113: 13104–13108.
- Li W, Ciais P, Wang Y, Yin Y, Peng S, Zhu Z, Bastos A, Yue C, Ballantyne AP, Broquet G *et al.* 2018. Recent changes in global photosynthesis and terrestrial ecosystem respiration constrained from multiple observations. *Geophysical Research Letters* 45: 1058–1068.
- Liang C, Schimel JP, Jastrow JD. 2017. The importance of anabolism in microbial control over soil carbon storage. *Nature Microbiology* 2: 1–6.
- Liang J, Zhou Z, Huo C, Shi Z, Cole JR, Huang L, Konstantinidis KT, Li X, Liu B, Luo Z *et al.* 2018. More replenishment than priming loss of soil organic carbon with additional carbon input. *Nature Communications* 9: 1–9.
- Lin Y-S, Medlyn BE, Duursma RA, Prentice IC, Wang H, Baig S, Eamus D, de Dios VR, Mitchell P, Ellsworth DS *et al.* 2015. Optimal stomatal behaviour around the world. *Nature Climate Change* 5: 459–464.
- Liu YY, van Dijk AIJM, de Jeu RAM, Canadell JG, McCabe MF, Evans JP, Wang G. 2015. Recent reversal in loss of global terrestrial biomass. *Nature Climate Change* 5: 470–474.
- Lloyd J, Farquhar GD. 2008. Effects of rising temperatures and [CO<sub>2</sub>] on the physiology of tropical forest trees. *Philosophical Transactions of the Royal Society B: Biological Sciences* 363: 1811–1817.
- Luo Y, Chen HYH. 2015. Climate change-associated tree mortality increases without decreasing water availability. *Ecology Letters* 18: 1207–1215.
- Luo Y, Su B, Currie WS, Dukes JS, Finzi AC, Hartwig U, Hungate B, McMurtrie RE, Oren R, Parton WJ *et al.* 2004. Progressive nitrogen limitation of ecosystem responses to rising atmospheric carbon dioxide. *BioScience* 54: 731–739.
- Luxmoore R. 1981. CO<sub>2</sub> and phytomass. *BioScience* 31: 626.
- van Mantgem PJ, Stephenson NL, Byrne JC, Daniels LD, Franklin JF, Fule PZ, Harmon ME, Larson AJ, Smith JM, Taylor AH *et al.* 2009. Widespread increase of tree mortality rates in the Western United States. *Science* 323: 521–524.
- Manzoni S, Taylor P, Richter A, Porporato A, Ågren GI. 2012. Environmental and stoichiometric controls on microbial carbon-use efficiency in soils. *New Phytologist* 79–91.
- Mao J, Ribes A, Yan B, Shi X, Thornton PE, Séférian R, Ciais P, Myneni RB, Douville H, Piao S *et al.* 2016. Human-induced greening of the northern extratropical land surface. *Nature Climate Change* 6: 959–963.
- Mastrotheodoros T, Pappas C, Molnar P, Burlando P, Keenan TF, Gentine P, Gough CM, Fatichi S. 2017. Linking plant functional trait plasticity and the large increase in forest water use efficiency. *Journal of Geophysical Research: Biogeosciences* 122: 2393–2408.
- Maxwell JT, Harley GL, Robeson SM. 2016. On the declining relationship between tree growth and climate in the Midwest United States: the fading drought signal. *Climatic Change* 138: 127–142.
- McCarthy HR, Oren R, Johnsen KH, Gallet-Budynek A, Pritchard SG, Cook CW, LaDeau SL, Jackson RB, Finzi AC. 2010. Re-assessment of plant carbon dynamics at the Duke free-air CO<sub>2</sub> enrichment site: interactions of atmospheric [CO<sub>2</sub>] with nitrogen and water availability over stand development. *New Phytologist* 185: 514–528.
- McDowell NG, Allen CD, Anderson-Teixeira K, Aukema BH, Bond-Lamberty B, Chini L, Clark JS, Dietze M, Grossiord C, Hanbury-Brown A *et al.* 2020. Pervasive shifts in forest dynamics in a changing world. *Science* 368: eaaz9463.
- McDowell N, Pockman WT, Allen CD, Breshears DD, Cobb N, Kolb T, Plaut J, Sperry J, West A, Williams DG *et al.* 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytologist* 178: 719–739.
- McMahon SM, Arellano G, Davies SJ. 2019. The importance and challenges of detecting changes in forest mortality rates. *Ecosphere* 10: e02615.
- McMahon SM, Parker GG, Miller DR. 2010. Evidence for a recent increase in forest growth. *Proceedings of the National Academy of Sciences, USA* 107: 3611–3615.
- Medlyn BE, Barton CVM, Broadmeadow MSJ, Ceulemans R, Angelis PD, Forstreuter M, Freeman M, Jackson SB, Kellomäki S, Laita E *et al.* 2001. Stomatal conductance of forest species after long-term exposure to elevated CO<sub>2</sub> concentration: a synthesis. *New Phytologist* 149: 247–264.
- Medlyn BE, De Kauwe MG, Lin Y-S, Knauer J, Duursma RA, Williams CA, Arneht A, Clement R, Isaac P, Limousin J-M *et al.* 2017. How do leaf and ecosystem measures of water-use efficiency compare? *New Phytologist* 216: 758–770.
- Medlyn BE, Duursma RA, Eamus D, Ellsworth DS, Prentice IC, Barton CVM, Crous KY, De Angelis P, Freeman M, Wingate L. 2011. Reconciling the optimal and empirical approaches to modelling stomatal conductance. *Global Change Biology* 17: 2134–2144.
- Medlyn BE, Zaehle S, De Kauwe MG, Walker AP, Dietze MC, Hanson PJ, Hickler T, Jain AK, Luo Y, Parton W *et al.* 2015. Using ecosystem experiments to improve vegetation models. *Nature Climate Change* 5: 528–534.
- Metcalfe DB, Asner GP, Martin RE, Espejo JES, Huasco WH, Amézquita FFF, Carranza-Jimenez L, Cabrera DFG, Baca LD, Sinca F *et al.* 2014. Herbivory makes major contributions to ecosystem carbon and nutrient cycling in tropical forests. *Ecology Letters* 17: 324–332.
- Miller AD, Dietze MC, DeLucia EH, Anderson-Teixeira KJ. 2016. Alteration of forest succession and carbon cycling under elevated CO<sub>2</sub>. *Global Change Biology* 22: 351–363.

- Monteith JL. 1972. Solar radiation and productivity in tropical ecosystems. *Journal of Applied Ecology* 9: 747–766.
- Mooney HA, Drake BG, Luxmoore RJ, Oechel WC, Pitelka LF. 1991. Predicting ecosystem responses to elevated CO<sub>2</sub> concentrations. *BioScience* 41: 96–104.
- Morgan JA, Pataki DE, Körner C, Clark H, Del Grosso SJ, Grünzweig JM, Knapp AK, Mosier AR, Newton PCD, Niklaus PA *et al.* 2004. Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO<sub>2</sub>. *Oecologia* 140: 11–25.
- Muller B, Pantin F, Génard M, Turc O, Freixes S, Piques M, Gibon Y. 2011. Water deficits uncouple growth from photosynthesis, increase C content, and modify the relationships between C and growth in sink organs. *Journal of Experimental Botany* 62: 1715–1729.
- Myneni RB, Keeling CD, Tucker CJ, Asrar G, Nemani RR. 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature* 386: 698–702.
- Nehrbass-Ahles C, Babst F, Klesse S, Nötzli M, Bouriaud O, Neukom R, Dobbertin M, Frank D. 2014. The influence of sampling design on tree-ring-based quantification of forest growth. *Global Change Biology* 20: 2867–2885.
- Nie M, Lu M, Bell J, Raut S, Pendall E. 2013. Altered root traits due to elevated CO<sub>2</sub>: a meta-analysis. *Global Ecology and Biogeography* 22: 1095–1105.
- Norby RJ, De Kauwe MG, Domingues TF, Duursma RA, Ellsworth DS, Goll DS, Lapola DM, Luus KA, MacKenzie AR, Medlyn BE *et al.* 2016. Model–data synthesis for the next generation of forest free-air CO<sub>2</sub> enrichment (FACE) experiments. *New Phytologist* 209: 17–28.
- Norby RJ, DeLucia EH, Gielen B, Calfapietra C, Giardina CP, King JS, Ledford J, McCarthy HR, Moore DJP, Ceulemans R *et al.* 2005. Forest response to elevated CO<sub>2</sub> is conserved across a broad range of productivity. *Proceedings of the National Academy of Sciences, USA* 102: 18052–18056.
- Norby RJ, Kauwe MGD, Walker AP, Werner C, Zaehle S, Zak DR. 2017. Comment on “Mycorrhizal association as a primary control of the CO<sub>2</sub> fertilization effect”. *Science* 355: 358.
- Norby RJ, Warren JM, Iversen CM, Medlyn BE, McMurtrie RE. 2010. CO<sub>2</sub> enhancement of forest productivity constrained by limited nitrogen availability. *Proceedings of the National Academy of Sciences, USA* 107: 19368–19373.
- Norby RJ, Wullschlegel S, Gunderson CA, Johnson DW, Ceulemans R. 1999. Tree responses to rising CO<sub>2</sub> in field experiments: implications for the future forest. *Plant, Cell & Environment* 22: 683–714.
- Norby RJ, Zak DR. 2011. Ecological Lessons from Free-Air CO<sub>2</sub> Enrichment (FACE) Experiments. In: Futuyama DJ, Shaffer HB, Simberloff D, eds. *Annual review of ecology, evolution, and systematics*, vol. 42. Palo Alto: Annual Reviews, 181–203.
- Nowak RS, Ellsworth DS, Smith SD. 2004. Functional responses of plants to elevated atmospheric CO<sub>2</sub>—do photosynthetic and productivity data from FACE experiments support early predictions? *New Phytologist* 162: 253–280.
- Olson JS. 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology* 44: 322–331.
- Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, Phillips OL, Shvidenko A, Lewis SL, Canadell JG *et al.* 2011. A large and persistent carbon sink in the world’s forests. *Science* 333: 988–993.
- Peng C, Ma Z, Lei X, Zhu Q, Chen H, Wang W, Liu S, Li W, Fang X, Zhou X. 2011. A drought-induced pervasive increase in tree mortality across Canada’s boreal forests. *Nature Climate Change* 1: 467–471.
- Peñuelas J, Canadell JG, Ogaya R. 2011. Increased water-use efficiency during the 20th century did not translate into enhanced tree growth. *Global Ecology and Biogeography* 20: 597–608.
- Peñuelas J, Ciais P, Canadell JG, Janssens IA, Fernández-Martínez M, Carnicer J, Obersteiner M, Piao S, Vautard R, Sardans J. 2017. Shifting from a fertilization-dominated to a warming-dominated period. *Nature Ecology & Evolution* 1: 1438–1445.
- Peters RL, Groenendijk P, Vlam M, Zuidema PA. 2015. Detecting long-term growth trends using tree rings: a critical evaluation of methods. *Global Change Biology* 21: 2040–2054.
- Peylin P, Bacour C, MacBean N, Leonard S, Rayner P, Kuppel S, Koffi E, Kane A, Maignan F, Chevallier F *et al.* 2016. A new stepwise carbon cycle data assimilation system using multiple data streams to constrain the simulated land surface carbon cycle. *Geoscientific Model Development* 9: 3321–3346.
- Peylin P, Law RM, Gurney KR, Chevallier F, Jacobson AR, Maki T, Niwa Y, Patra PK, Peters W, Rayner PJ *et al.* 2013. Global atmospheric carbon budget: results from an ensemble of atmospheric CO<sub>2</sub> inversions. *Biogeosciences* 10: 6699–6720.
- Phillips RP, Brzostek E, Midgley MG. 2013. The mycorrhizal-associated nutrient economy: a new framework for predicting carbon–nutrient couplings in temperate forests. *New Phytologist* 199: 41–51.
- Phillips RP, Finzi AC, Bernhardt ES. 2011. Enhanced root exudation induces microbial feedbacks to N cycling in a pine forest under long-term CO<sub>2</sub> fumigation. *Ecology Letters* 14: 187–194.
- Pongratz J, Reick CH, Houghton R, House J. 2014. Terminology as a key uncertainty in net land use and land cover change carbon flux estimates. *Earth System Dynamics* 5: 177–195.
- Pretzsch H, Biber P, Schütze G, Kemmerer J, Uhl E. 2018. Wood density reduced while wood volume growth accelerated in Central European forests since 1870. *Forest Ecology and Management* 429: 589–616.
- Pretzsch H, Biber P, Schütze G, Uhl E, Rötzer T. 2014. Forest stand growth dynamics in Central Europe have accelerated since 1870. *Nature Communications* 5: 4967.
- Pugh TAM, Lindeskog M, Smith B, Poulter B, Arneeth A, Haverd V, Calle L. 2019. Role of forest regrowth in global carbon sink dynamics. *Proceedings of the National Academy of Sciences, USA* 116: 4382–4387.
- Qie L, Lewis SL, Sullivan MJP, Lopez-Gonzalez G, Pickavance GC, Sunderland T, Ashton P, Hubau W, Salim KA, Aiba S-I *et al.* 2017. Long-term carbon sink in Borneo’s forests halted by drought and vulnerable to edge effects. *Nature Communications* 8: 1966.
- Rastetter EB, Agren GI, Shaver GR. 1997. Responses of N-limited ecosystems to increased CO<sub>2</sub>: a balanced-nutrition, coupled-element-cycles model. *Ecological Applications* 7: 444–460.
- Rastetter E, Mckane R, Shaver G, Melillo J. 1992. Changes in C-storage by terrestrial ecosystems – how C-N interactions restrict responses to CO<sub>2</sub> and temperature. *Water Air and Soil Pollution* 64: 327–344.
- Reich PB, Hobbie SE, Lee T, Ellsworth DS, West JB, Tilman D, Knops JMH, Naeem S, Trost J. 2006. Nitrogen limitation constrains sustainability of ecosystem response to CO<sub>2</sub>. *Nature* 440: 922–925.
- Ruiz-Benito P, Ratcliffe S, Zavala MA, Martínez-Vilalta J, Vilà-Cabrera A, Lloret F, Madrigal-González J, Wirth C, Greenwood S, Kändler G *et al.* 2017. Climate- and successional-related changes in functional composition of European forests are strongly driven by tree mortality. *Global Change Biology* 23: 4162–4176.
- Rüger N, Condit R, Dent DH, DeWalt SJ, Hubbell SP, Lichstein JW, Lopez OR, Wirth C, Farrior CE. 2020. Demographic trade-offs predict tropical forest dynamics. *Science* 368: 165–168.
- Rutishauser E, Wright SJ, Condit R, Hubbell SP, Davies SJ, Muller-Landau HC. 2020. Testing for changes in biomass dynamics in large-scale forest datasets. *Global Change Biology* 26: 1485–1498.
- Sabot MEB, Kauwe MGD, Pitman AJ, Medlyn BE, Verhoef A, Ukkola AM, Abramowitz G. 2020. Plant profit maximization improves predictions of European forest responses to drought. *New Phytologist* 226: 1638–1655.
- Sanderson BM, Fisher RA. 2020. A fiery wake-up call for climate science. *Nature Climate Change* 10: 175–177.
- Saurer M, Siegwolf RTW, Schweingruber FH. 2004. Carbon isotope discrimination indicates improving water-use efficiency of trees in northern Eurasia over the last 100 years. *Global Change Biology* 10: 2109–2120.
- Saurer M, Spahni R, Frank DC, Joos F, Leuenberger M, Loader NJ, McCarroll D, Gagen M, Poulter B, Siegwolf RTW *et al.* 2014. Spatial variability and temporal trends in water-use efficiency of European forests. *Global Change Biology* 20: 3700–3712.
- Sayer EJ, Lopez-Sangil L, Crawford JA, Bréchet LM, Birkett AJ, Baxendale C, Castro B, Rodtassana C, Garnett MH, Weiss L *et al.* 2019. Tropical forest soil carbon stocks do not increase despite 15 years of doubled litter inputs. *Scientific Reports* 9: 1–9.
- Schimel D, Schneider FD. 2019. Flux towers in the sky: global ecology from space. *New Phytologist* 224: 570–584.
- Schimel D, Stephens BB, Fisher JB. 2015. Effect of increasing CO<sub>2</sub> on the terrestrial carbon cycle. *Proceedings of the National Academy of Sciences, USA* 112: 436–441.

- Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Kögel-Knabner I, Lehmann J, Manning DAC *et al.* 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478: 49–56.
- Schwartz MD. 2013. *Phenology: an integrative environmental science*. Dordrecht, the Netherlands: Springer.
- Sigurdsson BD, Medhurst JL, Wallin G, Eggertsson O, Linder S. 2013. Growth of mature boreal Norway spruce was not affected by elevated [CO<sub>2</sub>] and/or air temperature unless nutrient availability was improved. *Tree Physiology* 33: 1192–1205.
- Silva LCR, Anand M. 2013. Probing for the influence of atmospheric CO<sub>2</sub> and climate change on forest ecosystems across biomes. *Global Ecology and Biogeography* 22: 83–92.
- van der Sleen P, Groenendijk P, Vlam M, Anten NPR, Boom A, Bongers F, Pons TL, Terburg G, Zuidema PA. 2015. No growth stimulation of tropical trees by 150 years of CO<sub>2</sub> fertilization but water-use efficiency increased. *Nature Geoscience* 8: 24–28.
- Smith NG, Keenan TF. 2020. Mechanisms underlying leaf photosynthetic acclimation to warming and elevated CO<sub>2</sub> as inferred from least-cost optimality theory. *Global Change Biology* 26: 5202–5216.
- Smith WK, Fox AM, MacBean N, Moore DJP, Parazoo NC. 2020. Constraining estimates of terrestrial carbon uptake: new opportunities using long-term satellite observations and data assimilation. *New Phytologist* 225: 105–112.
- Song J, Wan S, Piao S, Knapp AK, Classen AT, Vicca S, Ciais P, Hovenden MJ, Leuzinger S, Beier C *et al.* 2019. A meta-analysis of 1,119 manipulative experiments on terrestrial carbon-cycling responses to global change. *Nature Ecology & Evolution* 3: 1309–1320.
- Soper FM, McCalley CK, Sparks K, Sparks JP. 2017. Soil carbon dioxide emissions from the Mojave desert: Isotopic evidence for a carbonate source: abiotic soil CO<sub>2</sub> emissions. *Geophysical Research Letters* 44: 245–251.
- Souza RC, Solly EF, Dawes MA, Graf F, Hagedorn F, Egli S, Clement CR, Nagy L, Rixen C, Peter M. 2017. Responses of soil extracellular enzyme activities to experimental warming and CO<sub>2</sub> enrichment at the alpine treeline. *Plant and Soil* 416: 527–537.
- Sperry JS, Venturas MD, Todd HN, Trugman AT, Anderegg WRL, Wang Y, Tai X. 2019. The impact of rising CO<sub>2</sub> and acclimation on the response of US forests to global warming. *Proceedings of the National Academy of Sciences, USA* 116: 25734–25744.
- Stephens BB, Gurney KR, Tans PP, Sweeney C, Peters W, Bruhwiler L, Ciais P, Ramonet M, Bousquet P, Nakazawa T *et al.* 2007. Weak Northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO<sub>2</sub>. *Science* 316: 1732–1735.
- Strain BR, Bazzaz FA. 1983. Terrestrial plant communities. In: Lemon ER, ed. *CO<sub>2</sub> and plants: the response of plants to rising levels of atmospheric carbon dioxide*. Boulder, CO, USA: Westview Press.
- Sulman BN, Moore JAM, Abramoff R, Averill C, Kivlin S, Georgiou K, Sridhar B, Hartman MD, Wang G, Wieder WR *et al.* 2018. Multiple models and experiments underscore large uncertainty in soil carbon dynamics. *Biogeochemistry* 141: 109–123.
- Sun Y, Frankenberg C, Wood JD, Schimel DS, Jung M, Guanter L, Drewry DT, Verma M, Porcar-Castell A, Griffis TJ *et al.* 2017. OCO-2 advances photosynthesis observation from space via solar-induced chlorophyll fluorescence. *Science* 358: eaam5747.
- Sun Z, Wang X, Zhang X, Tani H, Guo E, Yin S, Zhang T. 2019. Evaluating and comparing remote sensing terrestrial GPP models for their response to climate variability and CO<sub>2</sub> trends. *Science of the Total Environment* 668: 696–713.
- Tang X, Li H, Desai AR, Nagy Z, Luo J, Kolb TE, Oliosio A, Xu X, Yao L, Kutsch W *et al.* 2014. How is water-use efficiency of terrestrial ecosystems distributed and changing on Earth? *Scientific Reports* 4: 1–11.
- Terrer C, Jackson RB, Prentice IC, Keenan TF, Kaiser C, Vicca S, Fisher JB, Reich PB, Stocker BD, Hungate BA *et al.* 2019. Nitrogen and phosphorus constrain the CO<sub>2</sub> fertilization of global plant biomass. *Nature Climate Change* 9: 684–689.
- Terrer C, Vicca S, Hungate BA, Phillips RP, Prentice IC. 2016. Mycorrhizal association as a primary control of the CO<sub>2</sub> fertilization effect. *Science* 353: 72–74.
- Terrer C, Vicca S, Stocker BD, Hungate BA, Phillips RP, Reich PB, Finzi AC, Prentice IC. 2018. Ecosystem responses to elevated CO<sub>2</sub> governed by plant–soil interactions and the cost of nitrogen acquisition. *New Phytologist* 217: 507–522.
- Trancoso R, Larsen JR, McVicar TR, Phinn SR, McAlpine CA. 2017. CO<sub>2</sub>-vegetation feedbacks and other climate changes implicated in reducing base flow. *Geophysical Research Letters* 44: 2310–2318.
- Treseder KK. 2004. A meta-analysis of mycorrhizal responses to nitrogen, phosphorus, and atmospheric CO<sub>2</sub> in field studies. *New Phytologist* 164: 347–355.
- Trugman AT, Medvigy D, Anderegg WRL, Pacala SW. 2018. Differential declines in Alaskan boreal forest vitality related to climate and competition. *Global Change Biology* 24: 1097–1107.
- Trumbore S. 2009. Radiocarbon and soil carbon dynamics. *Annual Review of Earth and Planetary Sciences* 37: 47–66.
- Ueyama M, Ichii K, Kobayashi H, Kumagai T, Beringer J, Merbold L, Euskirchen ES, Hirano T, Marchesini LB, Baldocchi D *et al.* 2020. Inferring CO<sub>2</sub> fertilization effect based on global monitoring land–atmosphere exchange with a theoretical model. *Environmental Research Letters*. doi: 10.1088/1748-9326/ab79e5.
- Ukkola AM, Prentice IC, Keenan TF, van Dijk AIJM, Viney NR, Myneni RB, Bi J. 2016. Reduced streamflow in water-stressed climates consistent with CO<sub>2</sub> effects on vegetation. *Nature Climate Change* 6: 75–78.
- Vicca S, Luysaert S, Peñuelas J, Campioli M, Chapin FS, Ciais P, Heinemeyer A, Höglberg P, Kutsch WL, Law BE *et al.* 2012. Fertile forests produce biomass more efficiently. *Ecology Letters* 15: 520–526.
- Voelker SL, Muzika R-M, Guyette RP, Stambaugh MC. 2006. Historical CO<sub>2</sub> growth enhancement declines with age in *Quercus* and *Pinus*. *Ecological Monographs* 76: 549–564.
- Walker AP, Kauwe MGD, Medlyn BE, Zaehle S, Iversen CM, Asao S, Guenet B, Harper A, Hickler T, Hungate BA *et al.* 2019. Decadal biomass increment in early secondary succession woody ecosystems is increased by CO<sub>2</sub> enrichment. *Nature Communications* 10: 454.
- Walker AP, Quaife T, van Bodegom PM, De Kauwe MG, Keenan TF, Joiner J, Lomas MR, MacBean N, Xu C, Yang X *et al.* 2017. The impact of alternative trait-scaling hypotheses for the maximum photosynthetic carboxylation rate ( $V_{cmax}$ ) on global gross primary production. *New Phytologist* 215: 1370–1386.
- Walker AP, Ye M, Lu D, Kauwe MGD, Gu L, Medlyn BE, Rogers A, Serbin SP. 2018. The multi-assumption architecture and testbed (MAAT v1.0): R code for generating ensembles with dynamic model structure and analysis of epistemic uncertainty from multiple sources. *Geoscientific Model Development* 11: 3159–3185.
- Walker AP, Zaehle S, Medlyn BE, De Kauwe MG, Asao S, Hickler T, Parton W, Ricciuto DM, Wang Y-P, Wårlind D *et al.* 2015. Predicting long-term carbon sequestration in response to CO<sub>2</sub> enrichment: How and why do current ecosystem models differ? *Global Biogeochemical Cycles* 29: 476–495.
- Whelan ME, Lennartz ST, Gimeno TE, Wehr R, Wohlfahrt G, Wang Y, Kooijmans LMJ, Hilton TW, Belviso S, Peylin P *et al.* 2018. Reviews and syntheses: carbonyl sulfide as a multi-scale tracer for carbon and water cycles. *Biogeosciences* 15: 3625–3657.
- Wohlfahrt G, Brilli F, Hörtnagl L, Xu X, Bingemer H, Hansel A, Loreto F. 2012. Carbonyl sulfide (COS) as a tracer for canopy photosynthesis, transpiration and stomatal conductance: potential and limitations†. *Plant, Cell & Environment* 35: 657–667.
- Woodward FI. 1987. *Climate and plant distribution*. Cambridge, UK: Cambridge University Press.
- Wright SJ, Kitajima K, Kraft NJB, Reich PB, Wright IJ, Bunker DE, Condit R, Dalling JW, Davies SJ, Díaz S *et al.* 2010. Functional traits and the growth–mortality trade-off in tropical trees. *Ecology* 91: 3664–3674.
- Wullschlegel SD, Tschaplinski TJ, Norby RJ. 2002. Plant water relations at elevated CO<sub>2</sub>—implications for water-limited environments. *Plant, Cell & Environment* 25: 319–331.
- Würth MKR, Peláez-Riedl S, Wright SJ, Körner C. 2005. Non-structural carbohydrate pools in a tropical forest. *Oecologia* 143: 11–24.
- Wyckoff PH, Bowers R. 2010. Response of the prairie–forest border to climate change: impacts of increasing drought may be mitigated by increasing CO<sub>2</sub>. *Journal of Ecology* 98: 197–208.
- Xue B-L, Guo Q, Otto A, Xiao J, Tao S, Li L. 2015. Global patterns, trends, and drivers of water use efficiency from 2000 to 2013. *Ecosphere* 6: art174.



- Yang Y, Donohue RJ, McVicar TR, Roderick ML, Beck HE. 2016. Long-term CO<sub>2</sub> fertilization increases vegetation productivity and has little effect on hydrological partitioning in tropical rainforests. *Journal of Geophysical Research: Biogeosciences* 121: 2125–2140.
- Yang J, Medlyn BE, Kauwe MGD, Duursma RA. 2018. Applying the concept of ecohydrological equilibrium to predict steady state leaf area index. *Journal of Advances in Modeling Earth Systems* 10: 1740–1758.
- Yin Y, Ciais P, Chevallier F, Li W, Bastos A, Piao S, Wang T, Liu H. 2018. Changes in the response of the northern hemisphere carbon uptake to temperature over the last three decades. *Geophysical Research Letters* 45: 4371–4380.
- Yu K, Smith WK, Trugman AT, Condit R, Hubbell SP, Sardans J, Peng C, Zhu K, Peñuelas J, Cailleret M *et al.* 2019. Pervasive decreases in living vegetation carbon turnover time across forest climate zones. *Proceedings of the National Academy of Sciences, USA* 116: 24662–24667.
- Zahle S, Medlyn BE, De Kauwe MG, Walker AP, Dietze MC, Hickler T, Luo Y, Wang Y-P, El-Masri B, Thornton P *et al.* 2014. Evaluation of 11 terrestrial carbon–nitrogen cycle models against observations from two temperate free-Air CO<sub>2</sub> enrichment studies. *New Phytologist* 202: 803–822.
- Zak DR, Holmes WE, Finzi AC, Norby RJ, Schlesinger WH. 2003. Soil nitrogen cycling under elevated CO<sub>2</sub>: a synthesis of forest face experiments. *Ecological Applications* 13: 1508–1514.
- Zeng N, Zhao F, Collatz GJ, Kalnay E, Salawitch RJ, West TO, Guanter L. 2014. Agricultural Green Revolution as a driver of increasing atmospheric CO<sub>2</sub> seasonal amplitude. *Nature* 515: 394–397.
- Zhang X, Niu G-Y, Elshall AS, Ye M, Barron-Gafford GA, Pavao-Zuckerman M. 2014GL. Assessing five evolving microbial enzyme models against field measurements from a semiarid savannah—what are the mechanisms of soil respiration pulses? *Geophysical Research Letters* 41: 6428–6434.
- Zhu Z, Piao S, Myneni RB, Huang M, Zeng Z, Canadell JG, Ciais P, Sitch S, Friedlingstein P, Arneeth A *et al.* 2016. Greening of the Earth and its drivers. *Nature Climate Change* 6: 791–795.
- Zimmerman JK, Pulliam WM, Lodge DJ, Quiñones-Orfila V, Fetcher N, Guzmán-Grajales S, Parrotta JA, Asbury CE, Walker LR, Waide RB. 1995.

Nitrogen immobilization by decomposing woody debris and the recovery of tropical wet forest from hurricane damage. *Oikos* 72: 314–322.

## Supporting Information

Additional Supporting Information may be found online in the Supporting Information section at the end of the article.

**Fig. S1** Comparison of alternatives methods to calculate  $\beta$ .

**Fig. S2** Evidence  $\beta$  values for GPP, WUE, and BP.

**Fig. S3** Evidence  $\beta$  values for  $k_{veg}$ ,  $k_{soil}$ , NEP, and  $C_{veg,increment}$ .

**Fig. S4** Evidence  $\beta$  values for  $C_{veg}$ ,  $C_{soil}$ , and  $C_{eco}$ .

**Notes S1** Standardizing CO<sub>2</sub> responses with a  $\beta$  factor.

**Notes S2** Calculation of  $\beta$  from different data types.

**Notes S3** Modelling leaf and canopy physiology.

**Table S1** Theoretical  $\beta$  values for photosynthesis.

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