WebPanel 1. Scale-specific nomenclature of carbon dynamics
At the global scale, gross global production (GGP; WebTable 1) can be approximated from satellite observations of normalized difference vegetation index (NDVI) in the terrestrial biosphere (effectively a measure of vegetation greenness) and estimates of chlorophyll concentration in marine ecosystems (Field et al. 1998). Based on this approach, net global production (NGP) has been estimated to be approximately 105 petagrams of carbon (C) per year (Pg C/year), with net terrestrial production (56 Pg C/year) slightly higher than net marine production (48 Pg C/year). However, several different approaches have been developed for approximating gross terrestrial production (GTP). Estimates using a light use efficiency model that assimilates satellite observations of NDVI yield relatively lower values for GTP (~110 Pg C/year; Kolby Smith et al. 2015) than estimates from eddy flux measurements up-scaled using satellite and climate data (GTP ~124 Pg C/year; Beer et al. 2010), estimates derived from the isotopic enrichment of surface waters as a result of evapotranspiration (GTP ~130 Pg C/year; Jasechko et al. 2013), and estimates derived from oxygen isotopes in carbon dioxide (CO₂; GTP ~150 Pg C/year; Welp et al. 2011). Net global exchange (NGE) is usually inferred as the difference between the amount of CO₂ emitted to the atmosphere (eg through the burning of fossil fuels and through land-use change) and the amount remaining in the atmosphere every year (ie the atmospheric CO₂ growth rate), which doubled from ~2.5 Pg C/year in 1960 to ~5.0 Pg C/year in 2010 (Ballantyne et al. 2012). Finally, this net global C uptake can be partitioned into net terrestrial exchange (NTE) by estimating ocean uptake independently due to air–sea gas exchange as a function of differences in partial pressure of CO₂ in the ocean with respect to the atmosphere, yielding estimates of NTE (~2.7 Pg C/year as of 2016; Le Quéré et al. 2016).

Total terrestrial respiration (TTR) is usually calculated as the difference between GTP and NTE (Anderegg et al. 2015), but is difficult to measure directly. Although trends in TTR inferred at the global scale (Ballantyne et al. 2017) are similar to trends estimated from soil respiration studies that have been extrapolated to the global scale (Bond-Lamberty and Thomson 2010), it is important to note that they differ in magnitude because, by definition, TTR includes aboveground autotrophic respiration that is not included in estimates of global soil respiration.

At the biome scale, gross biome production (GBP; WebTable 1) can also be estimated using remotely sensed vegetation indices (eg NDVI) that are commonly assimilated into a light use efficiency model and projected over estimates of leaf area index, which allows scientists to convert measurements of absorbed photosynthetically active radiation into a currency of C flux (teragrams [Tg] C/year) at the regional to continental scale (Running et al. 2004). In contrast, atmospheric inversion approaches allow estimation of net terrestrial exchange (NTE) from the global to biome scale (ie net biome exchange [NBE]). Atmospheric inversions are based on the same atmospheric CO₂ mass balance principle used to estimate NGE, but often rely on land-surface models for prior CO₂ flux predictions that are then conveyed by three-dimensional atmospheric transport models using observed atmospheric circulation data. These simulated
atmospheric CO₂ concentrations are then compared to atmospheric CO₂ observations and posterior surface fluxes are updated to provide regional scale estimates of NBE (Gurney et al. 2002). As these atmospheric inversion approaches become more advanced in their capacity to assimilate atmospheric CO₂ measurements from atmospheric profiles (Stephens et al. 2007) and satellite observations of total column CO₂ (XCO₂; Houweling et al. 2015), they will be able to resolve NBE at increasingly finer scales (Peylin et al. 2013). Similarly, total biome respiration (TBR) can be inferred as the difference between GBP and NBE, but the scale of spatial autocorrelation in the errors of GBP and NBE estimates may differ, and caution should therefore be taken when trying to calculate TBR at scales smaller than continental scales, especially where data are sparse (Liu et al. 2018).

At the ecosystem scale, a great deal has been learned about C-cycle dynamics through eddy covariance measurements (Verma et al. 1986). Eddy covariance measures the net ecosystem exchange of CO₂ (NEE; WebTable 1) between the Earth’s surface and the atmosphere, but only intermittent measurements of respiration using sparse nighttime observations are possible. Models for total ecosystem respiration (TER) are often used to estimate gross ecosystem production (GEP), and recent studies emphasize the importance of daytime TER suppression as a critical mechanism that needs to be integrated into eddy covariance-based GEP estimates (Wehr et al. 2016; Keenan et al. 2019). There are two common complementary methods that are used to estimate these opposing fluxes: (1) extrapolate nighttime respiration to the daytime using a temperature sensitivity function to infer GEP (Reichstein et al. 2005), or (2) use a light use efficiency model to convert absorbed photosynthetically active radiation into the GEP C flux and then infer TER as the difference between GEP and NEE (Lasslop et al. 2010). It is important to note that the strong suppression of turbulence in the early evening, when soils are relatively warm, often results in a sampling bias toward colder periods at night (van Gorsel et al. 2007). Moreover, ecosystem respiration may be greatly reduced during daylight hours, and extrapolating nighttime values may therefore overestimate TER, and consequently GEP (Wehr et al. 2016; Keenan et al. 2019).

Freshwater aquatic ecosystems may encompass only a small proportion of the terrestrial biosphere, but streams and lakes play major roles in the transport and transformation of C from ecosystem to terrestrial biosphere scales (see Figure 1 in the main text). At the ecosystem scale, inland waters collect and process a fraction of terrestrial NEP of the catchment, and therefore this fraction of C appears to be lost from the terrestrial ecosystem. This C can then be transported downstream, where a portion of it is lost through efflux to the atmosphere or settling to sedimentation. Most aquatic ecosystems are supersaturated with respect to the partial pressure of CO₂ (pCO₂; Cole et al. 1994) and globally release ~2.1 Pg C/year to the atmosphere, with a larger efflux from streams (1.8 Pg C/year) than from lakes (0.3 Pg C/year) due to more efficient gas transfer in moving waters. However, these estimates are calculated from gas transfer velocities and pCO₂ measurements with respect to the atmosphere and are not direct measurements (Raymond et al. 2013). The second major C loss pathway in aquatic ecosystems is via sedimentation, which can be calculated by accumulation rates from sediment cores collected
from lakes and reservoirs that have been extrapolated globally to yield estimates of 0.2 Pg C/year (Cole et al. 2007).

While we are now able to describe and estimate major C-cycle processes from ecosystem to global scales, terminology to describe these processes has not necessarily been revised. For instance, the terms “net ecosystem exchange”, “net biome production”, and “net ecosystem carbon balance” are often used interchangeably to describe the difference between all C gain and all C loss pathways regardless of scale, with the assumption that more C pathways are integrated as the scale of mass balance increases (Schulze et al. 2000; Randerson et al. 2002; Chapin et al. 2006). We propose that a revised C-cycle nomenclature that describes consistent C-cycle processes across scales may help to alleviate confusion within and among research communities conducting C-cycle research (WebTable 1).

**Conceptual model for C balance**

The mass balance of CO$_2$ can be approximated from global to ecosystem scales, such that slight imbalances in CO$_2$ gain through photosynthesis and CO$_2$ loss through respiration are indicative of net CO$_2$ uptake or loss. This can be easily visualized by simply plotting CO$_2$ lost through respiration as a function of CO$_2$ gain from photosynthesis (WebFigure 1). Based on this conceptual model, and ignoring lateral transports or transformations of C, the 1:1 line represents an ecosystem in steady state (ie GEP ~ TER); ecosystems with a slope less than one (ie GEP > TER) are CO$_2$ sinks, and ecosystems with a slope greater than one (ie TER > GEP) are CO$_2$ sources. If we set the intercept to zero, this conceptual model provides a useful framework for comparing C dynamics from the ecosystem to terrestrial biosphere scale. The relative slope term ($m$) is unitless and can be compared across scales, such that net CO$_2$ exchange efficiency is equivalent to $(1 - m) \times GPP$, with positive values representing net CO$_2$ uptake and negative values representing net CO$_2$ release to the atmosphere. This is analogous to C use efficiency (CUE), which is the amount of atmospheric C that is transferred to terrestrial biomass (where $CUE = NPP/GPP$). CUE is approximately 0.53 for forest ecosystems globally, but values vary considerably among forest types, with older forests and boreal forests having the lowest CUE values (DeLucia et al. 2007). Similarly, we can use estimates of gross primary production (GPP) and net ecosystem exchange (NEE) to estimate C exchange efficiency (CEE, where $CEE = NEE/GPP$ or $CEE = [1 - m] \times GPP$) as a scale-independent diagnostic metric that can be used to compare C dynamics of ecosystems within biomes or of biomes within the terrestrial biosphere (WebFigure 1).

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