Global quantitative synthesis of ecosystem functioning across climatic zones and ecosystem types

Isabelle Gounand, Chelsea J Little, Eric Harvey, Florian Altermatt

Title: Global quantitative synthesis of ecosystem functioning across climatic zones and ecosystem types

Running header: Multivariate ecosystem functioning

Authors: Isabelle Gounand[*,1,2,3], Chelsea J. Little[1,2,4], Eric Harvey[1,2,5], Florian Altermatt[1,2]

Corresponding author: Isabelle Gounand – isabelle.gounand@upmc.fr

Affiliations:

[1] University of Zurich, Department of Evolutionary Biology and Environmental Studies, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland.

[2] Eawag: Swiss Federal Institute of Aquatic Science and Technology, Department of Aquatic Ecology, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland

Acknowledgements:

We thank Marcel Holyoak, Emanuel A. Fronhofer and Joanna R. Bernhardt for discussions and helpful suggestions. Funding is from the Swiss National Science Foundation Grants No PP00P3_150698 and PP00P3_179089, the University of Zurich Research Priority Programme *URPP Global Change and Biodiversity* (to F.A.) and the University of Zurich *Forschungskredit* (to I.G.).

[3] Present address: Sorbonne Université, CNRS, UPEC, CNRS, IRD, INRA, Institut d'écologie et des sciences de l'environnement, IEES, F-75005 Paris, France
[4] Present address: University of British Columbia, Department of Zoology biodiversity Research Center.
[5] Present address: Université de Montréal, Départment de Sciences Biologiques, Complexe des sciences, 1375 Avenue Thérèse-Lavoie-Roux, Montréal (Québec), H2V 0B3, Montréal, Canada, M5S 3B2.

Biosketch

The authors are part of the EMERGe (Eawag Meta-Ecosystem Research group) initiative. We are interested in bridging community and ecosystem-level processes through the lens of spatial ecology. Collectively, our current research aims at understanding the main spatial constraints on biodiversity and how those effects scale-up to influence ecosystem functioning in the landscape. (More on each author – **IG**: https://isabellegounand.wordpress.com, **CL**: https://chelseajeanlittle.com, **EH**: https://metecolab.org, **FA**: https://www.altermattlab.ch)

Abstract

Aim: Providing a quantitative overview of ecosystem functioning in a three-dimensional space defined by ecosystem stocks, fluxes, and rates, across major ecosystem types and climatic zones.

Location: Global

Time Period: 1966–2019

Major taxa studied: ecosystem-level measurements (all organism types)

Methods: We conducted a global quantitative synthesis of a wide range of ecosystem variables related to carbon stocks and fluxes. We gathered a total of 4,479 values from 1,223 individual sites (unique geographical coordinates) reported in the literature (604 studies), covering ecosystem variables including biomass and detritus stocks, gross primary production, ecosystem respiration, detritus decomposition and carbon uptake rates, across eight major aquatic and terrestrial ecosystem types and five broad climatic zones (arctic, boreal, temperate, arid, and tropical). We analysed the relationships among variables emerging from the comparisons of stocks, fluxes, and rates across ecosystem types and climates.

Results: Within our three-dimensional functioning space, average ecosystems align along a gradient from fast rates-low fluxes and stocks (freshwater and pelagic marine ecosystems) to low rates-high fluxes and stocks (forests), a gradient which we hypothesize results mainly from variation in primary producer characteristics. Moreover, fluxes and rates decrease from warm to colder climates, consistent with the metabolic theory of ecology. However, the strength of climatic effects differs among variables and ecosystem types, resulting, for instance, in opposing effects on net ecosystem production between terrestrial and freshwater ecosystems (positive *versus* negative effects).

Main conclusions: This large-scale synthesis provides a first quantified cross-ecosystem and cross-climate comparison of multivariate ecosystem functioning. This gives a basis for a mechanistic understanding of the interdependency of different aspects of ecosystem functioning and their sensitivity to global change. To anticipate responses to change at the ecosystem level, further work should investigate potential feedbacks between ecosystem variables at finer scales, which involves site-level quantifications of multivariate functioning and theoretical developments.

Keywords

carbon cycle, climate, ecosystem functioning, multifunctionality, metabolic theory of ecology, global change, meta-ecosystem, primary production, productivity, decomposition.

1 | INTRODUCTION

Ecosystems provide multiple services, such as food, carbon storage, or detritus recycling, that benefit humans (Alsterberg et al., 2017; Byrnes et al., 2014; Hector & Bagchi, 2007). These services result from the functioning of ecosystems, which is often described in studies either by individual ecosystem functions (e.g., production, stability; de Mazancourt et al., 2013) or by proxies which integrate different functions mathematically but not mechanistically (e.g., indices of multifunctionality; Soliveres et al., 2016). While both approaches possess strengths to address specific questions (e.g., relationship with biodiversity, ecosystem state assessment), it is also important to consider the dynamic processes underlying ecosystem functioning, because ecosystem functions are not independent from one another. This becomes increasingly important in the context of global change, because perturbations affecting some functions of an ecosystem, for instance trophic cascades affecting primary production, might then cascade to others, such as on carbon storage (Atwood et al., 2015). To better forecast ecosystem response to such change, we need a mechanistic understanding of how the multiple aspects of ecosystem functioning constrain one another. With this study, we aim to advance in this direction by providing a quantitative synthesis of multiple measures of ecosystem functioning in a mechanistic framework allowing comparisons across major ecosystem types.

We propose to consider the loop of matter transformation as the central process driving functioning at the ecosystem level, a process fundamental enough to be common to all ecosystem types, thus allowing cross-system comparisons, and linking mechanistically different essential ecosystem functions (see conceptual framework in Fig. 1). Biological communities build biomass from inorganic material, respire and produce detritus that is then decomposed and mineralized into new inorganic material. This material processing loop generates fluxes connecting the different ecosystem compartments (such as with primary production, detritus production, or decomposition), occurring at different speeds, hereafter called rates (e.g., uptake or decomposition rates). In our framework, we distinguish rates –defined as mass-specific fluxes– from fluxes themselves, because rates provide discriminating information on environmental and physiological constraints driving processes among ecosystem types (e.g., organism efficiency), which is entangled with community dynamics and organism abundance in fluxes. Overall, the balance of ecosystem fluxes results in specific distributions of matter among living and non-living ecosystem compartments – the stocks (i.e., biomass, detritus, nutrients). Stocks, fluxes, and rates –the three dimensions of our ecosystem functioning space– relate commonly used descriptors of ecosystem functioning associated with ecosystem services (e.g., biomass production, recycling of detritus, carbon storage). Their interdependency implies potential feedbacks; for instance perturbations may increase the levels of dissolved organic carbon in lakes, which can boost phytoplankton production, and eventually lead to lake eutrophication (Brothers et al., 2014). This illustrates the need of adopting a comprehensive approach, integrating the whole loop of matter transformation when studying ecosystem functioning.

However, we still lack a general and quantitative synthesis linking stocks, fluxes and rates and comparing them across ecosystem types and climates. Knowledge on ecosystem functioning is concentrated in studies examining either individual aspects of ecosystem functioning in isolation (e.g., BEF approaches (Loreau et al., 2001) or cross-system comparisons of single functions (Tiegs et al 2019)), or whole functioning in specific ecosystems (e.g., ecosystem ecology approach with fluxes and stocks budgets, for instance in Eyre & McKee (2002)). A comparative synthesis of ecosystem functioning would reveal potential covariations among ecosystem fluxes, stocks, and rates across ecosystem types, from which a holistic understanding of ecosystem functioning could emerge. Moreover, ecosystem functioning varies according to climatic constraints. For example, ecosystem processes, such as respiration or decomposition, slow down under colder climates (Tiegs et al., 2019; Yvon-Durocher et al., 2012). The metabolic theory of ecology scales up the well-known relationship between body size and biological rates, and its dependency on temperature, to ecosystem processes (Brown, Gillooly, Allen, Savage, & West, 2004; Schramski et al., 2015). This provides predictions for changes in ecosystem fluxes and rates across temperature gradients (Schramski et al., 2015). Integrating this knowledge in a multivariate view of ecosystem functioning across ecosystem types and climates would allow to characterize ecosystems based on functional differences. This step is crucial to anticipate changes in ecosystem functions in response to global changes, and to upscale to global nutrient and carbon cycles.

In this study, we provide a quantified multivariate view of ecosystem functioning across major ecosystem types and climatic zones (i.e., at the biome scale; see Fig. 1b). We focus on carbon, unified for stocks and fluxes across time and area, as a common currency to make the material loop comparable across systems. We assemble extensive empirical data from the literature on ecosystem carbon stocks (i.e., biomass, organic carbon, detritus), fluxes (i.e., gross primary production, ecosystem respiration), and rates (i.e., uptake and decomposition rates). We then examine the variation and covariation of these ecosystem variables across ecosystem types and climatic zones. Our analysis characterizes broad types of functioning as well as patterns of functioning variation with climatic constraints, that we discuss in the light of the metabolic theory of ecology.

2 | METHODS

2.1 | Study design

We collected empirical data of carbon stocks (biomass, detritus, and organic carbon), fluxes (gross primary production (GPP), ecosystem respiration (ER), and net ecosystem production (NEP)), and rates (community carbon uptake rate, i.e., mass-specific GPP = GPP/ autotroph biomass, and decomposition rate as described by the k constant) from the literature (Fig. 1a), for eight major ecosystem types, both terrestrial (forest, grassland and shrubland –thereafter called “grassland” for simplicity–, agroecosystem, and desert) and aquatic (stream, lake, ocean pelagic, ocean benthic), and for five climatic zones (arctic, boreal, temperate, tropical, and arid). We lumped climatic zones of ocean pelagic and benthic systems into “Cold” and “Warm” to account for lower climatic imprint on marine systems (see Fig. 1b for the combinations considered and Table S1.1 of Appendix S1 in Supporting Information for definitions). Note that, as rates are fluxes normalized by stocks, uptake and decomposition rates represent respectively the mass of carbon taken up per biomass unit, and the proportion of detritus decomposed in a given time (T^{-1} dimension). Notably, uptake rate conveys information informs about producers’ biological efficiency and physiological constraints, while GPP also includes information on their abundance. We aimed at covering a wide range of ecosystem x climate x variable combinations, and retrieved at least ten independent values for each of these combinations (see Appendix S1 for extended methods and a decision tree on study selection for data collection, and Appendix S2 in Supporting Information for a detailed presentation of the dataset). Overall, we compiled a dataset of 4,479 data points from 1,223 individual sites (unique geographical coordinates) distributed across the globe (Fig. 2), extracted from 604 published studies. The list of data sources is provided in Appendix 1.

2.2 | Conversions

To make the dataset consistent, we homogenized the units of stocks, fluxes and rates into gC m^{-2}, gC m^{-2} $year^{-1}$, and $year^{-1}$, respectively (noted as "g g^{-1} $year^{-1}$" for uptake rates, for clarity). Data originally not provided in carbon units (21%) were converted with commonly accepted conversion factors, using preferentially the most specific one depending on the level of information available (see Table S1.2 for factors). Flux and rate data provided on timescales shorter than a year (19%) were scaled up to a year assuming standardized numbers of growing days per climatic zone (Garonna et al., 2014). We also had to convert volume to areal units for some data on aquatic systems. We integrated metrics over the relevant depth of water column, which could be average depth (e.g., shallow stream) or depth relevant to pelagic production (e.g., Secchi depth for gross primary production in pelagic systems). We standardized soil and sediment organic carbon data by integrating values over the first 30 centimetres depth. Complete details on these unit conversions are provided in extended methods (see Appendix S1).

2.3 | Data analysis

Our goal was to analyse the variation and covariation of the focal ecosystem variables across ecosystem types, E, and climatic zones, C. To reach this goal we used three complementary steps: (1) we used linear models to quantify the relative contribution of E and C in explaining the variance, and to test mean differences within each ecosystem variable; (2) then, we examined covariation between ecosystem variables with Pearson's correlation tests, using a bootstrapping procedure so that we could include the variance even though data for the different ecosystem variables were measured in different sites; (3) finally we used Pearson's correlation to test the relationships between ecosystem variables and latitude for each ecosystem type, to further analyse climatic modulation of ecosystem functioning. Together, these three approaches provide a holistic view on ecosystem functioning in the three-dimensional space of stocks, fluxes, and rates.

2.3.1 | Differences among climatic zones (C) and ecosystem types (E)

As a first step, we ran a two-way ANOVA on each ecosystem variable to evaluate the extent to which they were explained by climatic zones (C), ecosystem type (E) and their interaction (C:E). We applied the linear model y ~ C + E + C:E to log-transformed data. The few zero values of biomass, detritus and GPP (seven in total) were removed from this analysis to allow for log-transformation. NEP data were not log-transformed due to negative values. We also carried out these two-way ANOVAs on pooled categories of variables, for stocks (biomass, detritus, and organic carbon), gross fluxes (i.e., GPP, ER), and rates (uptake and decomposition rates). We scaled each variable between 0 and 1 before grouping to avoid giving different weights to variables among E x C combinations due to different numbers of data points. Because the residuals were not homogenously distributed, we repeated the model design using more conservative non-parametric Kruskal-Wallis tests on ranks, followed by post-hoc multiple comparisons based on rank sums to identify the groups that were significantly different; parametric and non-parametric tests give the same results on effect significance, so we report ANOVAs results here to visualize the variance partitioning, and non-parametric tests are reported in the supporting information (see full statistical results in Appendix S3 in Supporting Information, Tables S3.1 to S3.7). Finally, since C was found to be an important driver of fluxes and decomposition rate in the above analysis, and C:E interactions were significant, we investigated further climate sensitivity of these variables by comparing the variance explained by C within each ecosystem type. For that, we ran a series of one-way ANOVAs on GPP, ER and decomposition rates of each individual ecosystem type with C as the explanatory variable. Desert and Agroecosystem were excluded from this last analysis since we only had data from one climatic zone.

2.3.2 | Covariation among ecosystem variables

As a second step, we examined the correlations among ecosystem variables across ecosystems and climates. Since data were measured at different sites for each ecosystem variable, we did not have measurements of all the variables per site. We therefore adopted a bootstrapping procedure (sampling with replacement) to integrate the variability present in our data. For each pair of ecosystem variables, we randomly sampled one value of each variable in the subsets of data corresponding to each Ecosystem type x Climatic zone combination (E x C), and tested the correlation between variables with Pearson's test. We repeated the sampling and test 10,000 times. All values were log-transformed; therefore, we excluded the few zero values mentioned above. We display the distributions of the 10,000 Pearson correlation coefficients, and provide the mean of these distributions and the percentage of significant correlations to assess the direction and strength of the relationships between ecosystem variable pairs. Correlations on subsets of data in which pairs of variables were available per site confirm that the bootstrapping approach is conservative (Appendix S2.4, Figs S2.10 and S2.11, Table S3.13). Finally, we synthetize the average trends in ecosystem functioning by displaying the median values of each E x C combination in the 3-D space defined by stocks (biomass, organic carbon, and detritus), gross fluxes (GPP and ER) and rates (uptake and decomposition). We scaled the values of each ecosystem variable between 0 and 1 before pooling them in broader categories (i.e., stocks, fluxes and rates) to avoid biases due to different numbers of data point per E x C x V combination (V for ecosystem variable).

2.3.3 | Latitudinal trends

As a third and final step, we analysed the correlations between ecosystem variables and latitude for each ecosystem type covered on multiple climatic zones (agroecosystem and desert were excluded) using Pearson's two-sided correlation tests (Table S3.8) This analysis was carried out on the 87% of the data for which we could obtain geographical coordinates. The rest of the data originates from sites with unspecified coordinates, or were estimated at scales too broad (e.g., GPP of boreal forest in Canada) for coordinates to be meaningful.

2.4 | Software

We analysed the data and plotted the figures with the open source software R version 3.3.3, using the R-packages *maps* (Becker & Wilks, 2018), *vioplot* (Adler, 2018), *minpack.lm* (Elzhov, Mullen, Spiess, & Bolker, 2016), *plot3D* (Soetaert, 2017) and *dunn.test* (Dinno, 2017). See Appendix S1 for more details. Final artwork was realized with Illustrator CC 22.0.1.

3 | RESULTS

3.1 | Variance explained by ecosystem types (E) and climatic zones (C)

All stocks, gross fluxes (GPP and ER), and rates vary significantly among ecosystem types (E) and climatic zones (C), (see Fig. 3) according to both parametric and non-parametric tests (see Tables S3.1-S3.5). Main and interactive effects (C, E versus C:E) for each ecosystem variable are all highly significant (Table S3.1). The ANOVAs on pooled categories (stocks, fluxes and rates) show that E, C and E:C explained about 58% of the total variance (Table S3.2). When considering individual ecosystem variables, the 2-way ANOVAs show that more variance is explained for organic carbon (91%) and biomass (78%) and less for NEP (39%), GPP (57%), and detritus (55%) (Fig. 4a). On average across the different ecosystem variables, C, E, and C:E represent 18%, 71% and 11% of the variance explained, respectively. While ecosystem type (E) corresponds to most of the explained variance, notably for stocks (91%), climatic zones also modulate ecosystem variables, especially fluxes and decomposition rates (C effect represents 42% and 27% of the explained variance, respectively, compared to 5% in stocks). This climatic modulation, however, is highly variable among ecosystem types for some variables, for instance for GPP, which depends strongly on climatic zones for forests (where climate explains 66% of the variance) but not for streams (where climate is not significant). By contrast, the climatic effect on ecosystem respiration (ER) is relatively homogenous across ecosystems (see Fig. 4c, Tables S3.6 and S3.7). Lastly, interactive effects between ecosystem types and climatic zones appear to be especially important for NEP and detritus (27% and 22% of explained variance, respectively; see Fig. 4a and Table S3.1), indicating that the direction of climatic effects varies across ecosystem types.

3.2 | Stocks, fluxes, and rates' variation across ecosystem types

Stocks, fluxes, and rates vary widely but consistently among ecosystem types. Moreover, ecosystem types cluster at distinct positions in the space defined by ecosystem variable pairs, and this clustering drives most of the correlations observed between variables (Figs. 5 and S4.1). On a log-log scale, stocks, fluxes and rates correlate positively within each category. For instance, ecosystem types displaying high biomass also have high organic carbon stocks (Fig. 5a), and those displaying high GPP also show high ER (Fig. 5b). While such relationship between GPP and ER is expected in systems where productivity is driven by autotrophic organisms like in terrestrial ecosystems (Chen et al., 2015; see Fig. S2.10, and discussion in Appendix S2.4), it could be assumed to be disconnected in heterotrophic ecosystems where production is mainly driven by the detritivore biotic loop (e.g., in freshwater ecosystems). Surprisingly, we observe it across all ecosystem types regardless of their average auto- or heterotrophic status. On the whole, correlations we observe within stock, flux, and rate categories emerge mainly from differences among ecosystems types: globally, terrestrial ecosystems have high stocks and fluxes and low rates while aquatic ecosystems have low stocks and fluxes and high uptake and decomposition rates. Looking more into detail, stocks and fluxes decrease from forests to agroecosystems, grasslands, deserts and benthic marine systems, to finally be the lowest in streams, lakes, and pelagic marine systems (Figs. 5a, 5b), while rates are higher in streams and pelagic marine ecosystems than in the rest of ecosystem types (see Fig. 5c; see significantly different groups in Table S3.4). Stocks generally correlate positively with fluxes, such as biomass with GPP, but negatively with rates, such as biomass with uptake rate (Fig. 5 panels d and e, and Fig. S4.1), the later relation being also strongly conserved within ecosystems (Fig. S2.10). Thus, in systems sustaining more standing biomass, more biomass is produced in total but at a lower rate. The negative stock-rate relationships, however, does not hold for detritus and decomposition rates (Fig. 5f; but see the relatively opposed directions of these variables in a PCA on median ecosystems in Fig. S4.2).

Overall, positioning median ecosystems in the three-dimensional space of stocks, fluxes and rates results in a gradient of functioning types (Fig. 6): forest ecosystems have the largest stocks and fluxes but low rates. Grasslands also have relatively slow biological processes, but with lower stocks and fluxes than forests. Agroecosystems position close to grasslands but with noticeably higher rates. This is followed by deserts and benthic marine systems with intermediate stocks and fluxes. Finally, freshwater and pelagic marine ecosystems cluster in the region of lower stocks and fluxes but higher rates. In addition, fluxes and rates in freshwater and terrestrial ecosystems display a marked climatic-induced secondary gradient ranging from low values in arctic/boreal zones to higher values in temperate and arid zones, and highest values in tropical zones (see shapes in Fig. 6).

3.3 | Climatic modulation

A climatic imprint is most visible on fluxes and decomposition rates (Figs. 4a, 4b, Tables S3.1 and S3.2). In comparison, stocks vary less, and less consistently, with climate (Figs 4b, S4.3). For instance, while we note a significant decrease in biomass with latitude in forests, an opposing trend can be found in marine pelagic ecosystems (Fig. S4.3, Table S3.8). By contrast, GPP, ER and rates systematically decrease with latitude (Figs 7, S4.4), although the relationship is not significant in all ecosystem types: for instance, GPP does not correlate with latitude in streams (Fig. 7a). This absence of a climatic effect was also apparent when using discrete climatic zones (see Fig. 4c and Table S3.6). Moreover, different responses of GPP and ER to latitude within ecosystem types might result in opposite response of Net Ecosystem Production (NEP) to latitude, for instance in grasslands versus streams: NEP decreases significantly with latitude in grasslands, while it increases in streams (Fig. 7d), a pattern confirmed with discrete climatic zones when comparing mean NEP of these systems in arctic and tropical zones (Table S3.9).

4 | DISCUSSION

By integrating quantifications of ecosystem functioning in the 3-D space of stocks, fluxes and rates, this synthesis provides a global overview of ecosystem functioning, its characteristics and variability within and among ecosystem types. Compared to previous work, our comparative and multivariate approach reveals a gradient of functioning.

Analogous to r-K ecological strategies at the species level, ecosystems have different typologies, either with fast biological processes and low storage (e.g., freshwater and pelagic systems), or slower processes but with large storage and production capacity (e.g., forests). Climate regulates the speed of this processing, modulating the position of ecosystems in the functioning space.

4.1 | Ecosystem functioning types in a multi-dimensional space

Functioning types – how material is stored and processed within ecosystems – align on a gradient from terrestrial ecosystems with high storage capacities, high fluxes, but slow biological rates, to aquatic ecosystems with low stocks and fluxes but fast biological rates. Forests *versus* streams and pelagic marine systems occupy the respective extremes of this gradient.

We interpret these functioning differences observed at the ecosystem level as originating from fundamental differences in the type of organisms dominating resource use and primary production. Notably terrestrial *versus* aquatic physical conditions have selected contrasting producer types, especially in terms of individual size (Kenrick & Crane, 1997). Terrestrial systems are dominated by large primary producers (trees and grasses), harbouring complex structures to uptake nutrients in soils and access to light (roots and stems). In pelagic waters of freshwater and marine systems, carbon enters through microscopic producers (phytoplankton), whose small sizes are optimized for osmotrophic nutrient uptake mode (larger surface to volume ratios of small organisms) and sinking avoidance. These differences in producers primarily impact carbon uptake and decomposition rates. We observe higher uptake rates in systems having smaller producers than in those having large ones (e.g., forests versus stream in Table S3.4), in line with the metabolic theory of ecology (MTE) and previous data compilations (Brown et al., 2004; Cebrian, 1999; Schramski et al., 2015): smaller organisms grow faster (Gounand et al., 2016). Along with increasing size, which imposes energetic constraints on production rates, primary producers' stoichiometry shows increasing C:N ratios (Elser et al., 2000; Sitters, Atkinson, Guelzow, Kelly, & Sullivan, 2015), leading to decreasing decomposability from aquatic to lignin-rich terrestrial systems (Cebrian & Lartigue, 2004; Shurin, Gruner, & Hillebrand, 2006; Tiegs et al., 2019). Since aquatic conditions also favour decomposition, decomposition rates decrease from aquatic to terrestrial systems and indirectly correlate positively with carbon uptake rates (Fig. 5c; e.g., between forest and pelagic marine ecosystems Table S3.4); both ecological processes go faster in streams and pelagic marine systems, and slower in forests, with benthic and grassland systems processing material at intermediate speed.

Contrary to rates, stocks are higher in terrestrial than in aquatic systems. This necessarily results from among-ecosystem differences in input-to-output ratios for the different stocks. Indeed, forests accumulate more biomass and detritus than streams and pelagic systems, due to higher production to loss ratios, which could have several origins. Terrestrial systems experience less herbivory and slower decomposition due to a higher proportion of structural tissues and dry conditions (Cebrian, 1999; Cebrian & Lartigue, 2004). By contrast, biomass and detritus in aquatic communities experience higher output fluxes of consumption, mortality, respiration, and export by currents or sinking (McCoy & Gillooly, 2008). In benthic sediments, however, carbon could accumulate in large stocks when detritus production rates and sinking input exceed local mineralisation (Duarte & Cebrián, 1996; Fourqurean et al., 2012).

Ecosystems harbouring higher stocks also have higher fluxes (GPP and ER), resulting, for instance, in biomass correlating positively with GPP (Fig. 5d), as previously found for different community types (Hatton et al., 2015); the regression slope lower than 1 on log-log scale indicates, however, that mass-specific uptake rates decrease with biomass across ecosystems (Fig. 5e). This second relationship also holds with a surprising consistency within ecosystem types (Fig. S2.10), but explanations of change in uptake rates based on individual size variation fail because community biomass rarely correlates with mean individual body mass (Hatton et al., 2015). In similar ecosystems, slower uptake rates with increasing biomass is better explained by variation in competition: if biomass raises with abundance of primary producers, then shading would reduce community uptake rate in high biomass ecosystems. Across broad types of producers, however, differences in size in itself could drive negative biomass-uptake rate relationships because size integrate not only differences in uptake efficiency but also in structural and stoichiometric differences. This likely explains much of the difference in stocks, fluxes and rates at the ecosystem scale (Allen, Gillooly, & Brown, 2005; Schramski et al., 2015). For instance, trees build structural biomass involving complex molecules such as lignin and cellulose to optimize access to light and therefore production capacity, compared to algae, but this also lowers uptake and decomposition rates (Cebrian, 1999). In aquatic systems, uptake rate is fast but production capacity (GPP) is limited by access to light (Krause-Jensen & Sand-Jensen, 1998), notably in deep or turbid waters (84% of freshwater and 63% of benthic marine ecosystems in our data are net heterotrophic: more carbon is respired than locally produced). This interpretation is congruent with observations of strong positive correlations between carbon residence time and producer individual body mass across broad types of autotrophic ecosystems (Schramski et al., 2015).

Overall, despite considerable variability in our dataset (see presentation in Appendix S2), functioning types emerge that we hypothesize are driven by both the dominant primary producer categories (e.g., tree, grass, algae), which would determine stocks' general magnitude and potential activity rates, and by environmental constraints modulating the realized activity (e.g., water turbidity, water availability, temperature).

4.2 | Variation of ecosystem functioning with climatic constraints

The high variance observed in ecosystem variables at the broad organisational scale considered here must arise from variation in species' functional traits or food web structure (Cornwell et al., 2008; Datry et al., 2018), or different availability in nutrients, which we do not examine explicitly, and also in response to climatic constraints. In particular, rates and fluxes of production and respiration (GPP and ER) consistently decrease from warmer to colder climates (see Figs. 7, S4.4 and Tables S3.3 and S3.8) as predicted by the MTE (Brown et al., 2004; Clarke, 2006; Gillooly, Brown, West, Savage, & Charnov, 2001), and in line with the quite universal temperature-dependency of biological rates observed across many taxa and systems (Gillooly et al., 2001; Yvon-Durocher et al., 2012). Slowing down of biochemical reactions with decreasing temperature results in a relatively conserved decrease of biological rates along latitudes within ecosystems (see decomposition and uptake rates in Figs. 7 and S4.4). While the flux decrease with latitude is well quantified in some ecosystems, for instance thanks to the FLUXNET program (Yu et al., 2013), our results also show that the strength of the response to latitude might also vary among processes and ecosystems, such as with production (GPP) and respiration (ER). As a result, net ecosystem production can respond to latitude in opposite directions among ecosystem types. In grasslands, NEP decreases with latitude (Fig. 7d) meaning that ER decreases less rapidly than GPP (Yu et al., 2013), maybe due to differences in soil and air temperatures. Conversely, NEP increases with latitude in streams (Fig. 7d, Table S3.8), and between temperate and arctic lakes (Table S3.9). In fact, by slowing down detritivore activity (ER), cold temperatures make freshwater less heterotrophic, as found by Demars et al. (2011) in Icelandic streams of different temperatures, even in the absence of any significant GPP decline.

Stocks also vary among climates (see Tables S3.1–S3.3) but not in a systematic way across ecosystem types (Figs. S4.3, S4.6, Table S3.8). Environmental constraints which do not follow a latitudinal gradient, such as water availability in terrestrial systems, also affect the balance between input and output fluxes regulating stocks (Anderson-Teixeira, Delong, Fox, Brese, & Litvak, 2011; Yang, Yuan, Zhang, Tang, & Chen, 2011). For instance, drought limits more GPP than respiration, as observed in Europe during the exceptionally warm summer of 2003 (Ciais et al., 2005), and is associated with specific output fluxes such as erosion, depleting stocks in arid zones (Ravi, Breshears, Huxman, & D'Odorico, 2010). This illustrates how different constraints affecting fluxes in different ways might induce shifts in ecosystem functioning.

4.3 | Perspectives: ecosystem functioning facing changes

Integrating ecosystem stocks, fluxes, and rates in a single framework allows us to characterize a gradient of broad functioning types. Environmental constraints, such as climate, move the cursors of ecosystem within the functioning space, but the fine directions and possible magnitude of these movements are still to investigate. To develop fine predictions of process changes at the ecosystem level, we need more complete quantification of ecosystem functioning at the site level. The main limitation of our study is that not all variables are available for each site. Our bootstrapping procedure does not include constraints linking ecosystem variables within specific sites. Observing relationships despite this limitation demonstrates the strength of feedbacks between variables at the cross-ecosystem level. A more mechanistic understanding of these feedbacks would require examining systematically the persistence of these relationships within ecosystem types, which we were able to do for GPP-ER and Biomass-uptake rates variable pairs (Fig. S2.10). Quantification of multivariate functioning at the site level would further allow us to define reference states in the functioning space, and to analyse deviations from these states with changes in environmental constraints or in community composition. This would be a necessary step for early detection and prediction of ecosystem functioning changes (Petchey et al., 2015). To go further, simple models using this general framework matter transformation should allow to compare the responses to perturbations of different ecosystem types and to identify testable mechanisms for potential variations. In that respect, incorporating the decomposition process would constitute an interesting mechanistic expansion of the trophic-level-focused 'Madingley' model (General Ecosystem Model; Harfoot et al., (2014)) to investigate indirect feedbacks of perturbations on the structure of ecosystems. Moreover, the absence of negative relationships between decomposition and detritus in our data (Fig. 5f) might be the imprint of cross-ecosystem linkages playing a significant role in ecosystem functioning: the signal is blurred by the high variability of detritus stocks and decomposition in freshwater ecosystems, likely because detritus in these systems often comes from terrestrial inputs (Collins, Kohler, Thomas, Fetzer, & Flecker, 2016; Gounand, Little, Harvey, & Altermatt, 2018). Thus, anticipating changes in ecosystem functioning and in the global carbon cycle could necessitate consideration of ecological processes at both local and meta-ecosystem scales (Gounand, Harvey, Little, & Altermatt, 2018; Gounand, Little, et al., 2018). Overall, the patterns emerging from such global data synthesis could help evaluating mechanistic ecosystem models (e.g., Madingley) to generate hypotheses on dominant processes and factors driving ecosystem functioning.

5 | Conclusion

Acknowledging the multi-faceted nature of ecosystem functioning and the feedbacks linking these facets is crucial to develop a mechanistic understanding of ecosystems' response to change. Our quantified comparison of ecosystem functioning among broad ecosystem types and climatic zones integrates previous knowledge into a coherent framework based on material flow, and sets the basis for a mechanistic investigation of ecosystem multifunctionality.

References

Adler, D. (2018). vioplot: violin plot. *R Package Version 0.3.2*. Retrieved from https://github.com/TomKellyGenetics/vioplot

Allen, A. P., Gillooly, J. F., & Brown, J. H. (2005). Linking the global carbon cycle to individual metabolism. *Functional Ecology*, *19*(2), 202–213. https://doi.org/10.1111/j.1365-2435.2005.00952.x

Alsterberg, C., Roger, F., Sundbäck, K., Juhanson, J., Hulth, S., Hallin, S., & Gamfeldt, L. (2017). Habitat diversity and ecosystem multifunctionality — The importance of direct and indirect effects. *Science Advances*, *3*, e1601475 8. https://doi.org/10.1126/sciadv.1601475

Anderson-Teixeira, K. J., Delong, J. P., Fox, A. M., Brese, D. A., & Litvak, M. E. (2011). Differential responses of production and respiration to temperature and moisture drive the carbon balance across a climatic gradient in New Mexico. *Global Change Biology*, *17*(1), 410–424. https://doi.org/10.1111/j.1365-2486.2010.02269.x

Atwood, T. B., Connolly, R. M., Ritchie, E. G., Lovelock, C. E., Heithaus, M. R., Hays, G. C., … Macreadie, P. I. (2015). Predators help protect carbon stocks in blue carbon ecosystems. *Nature Climate Change*, *5*(12), 1038–1045. https://doi.org/10.1038/NCLIMATE2763

Becker, R. A., & Wilks, A. R. (original S. code). (2018). maps: Draw Geographical Maps. *R Version by Brownrigg, R. Enhancements by Minka, T. P. & Deckmyn, A., R Package Version 3.3.0.* Retrieved from https://cran.r-project.org/package=maps

Brothers, S. M., Köhler, J., Attermeyer, K., Grossart, H. P., Mehner, T., Meyer, N., … Hilt, S. (2014). A feedback loop links brownification and anoxia in a temperate, shallow lake. *Limnology and Oceanography*, *59*(4), 1388–1398. https://doi.org/10.4319/lo.2014.59.4.1388

Brown, J. H., Gillooly, J. F., Allen, A. P., Savage, V. M., & West, G. B. (2004). Toward a metabolic theory of ecology. *Ecology*, *85*(7), 1771–1789. https://doi.org/10.1890/03-9000

Byrnes, J. E. K., Gamfeldt, L., Isbell, F., Lefcheck, J. S., Griffin, J. N., Hector, A., … Emmett Duffy, J. (2014). Investigating the relationship between biodiversity and ecosystem multifunctionality: Challenges and solutions. *Methods in Ecology and Evolution*, *5*(2), 111–124. https://doi.org/10.1111/2041-210X.12143

Cebrian, J. (1999). Patterns in the Fate of Production in Plant Communities. *The American Naturalist*, *154*(4), 449–468. https://doi.org/10.1086/303244

Cebrian, J., & Lartigue, J. (2004). Patterns of herbivory and decomposition in aquatic and terrestrial ecosystems. *Ecological Monographs*, *74*(2), 237–259. https://doi.org/10.1890/03-4019

Chen, Z., Yu, G., Zhu, X., Wang, Q., Niu, S., & Hu, Z. (2015). Covariation between gross primary production and ecosystem respiration across space and the underlying mechanisms : A global synthesis. *Agricultural and Forest Meteorology*, *203*, 180–190. https://doi.org/10.1016/j.agrformet.2015.01.012

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogée, J., Allard, V., … Valentini, R. (2005). Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, *437*(7058), 529–533. https://doi.org/10.1038/nature03972

Clarke, A. (2006). Temperature and the metabolic theory of ecology. *Functional Ecology*, *20*(2), 405–412. https://doi.org/10.1111/j.1365-2435.2006.01109.x

Collins, S. M., Kohler, T. J., Thomas, S. A., Fetzer, W. W., & Flecker, A. S. (2016). The importance of terrestrial subsidies in stream food webs varies along a stream size gradient. *Oikos*, *125*(5), 674–685. https://doi.org/10.1111/oik.02713

Cornwell, W. K., Cornelissen, J. H. C., Amatangelo, K., Dorrepaal, E., Eviner, V. T., Godoy, O., … Westoby, M. (2008). Plant species traits are the predominant control on litter decomposition rates within biomes worldwide. *Ecology Letters*, *11*(10), 1065–1071. https://doi.org/10.1111/j.1461-0248.2008.01219.x

Datry, T., Foulquier, A., Corti, R., Von Schiller, D., Tockner, K., Mendoza-Lera, C., … Zoppini, A. (2018). A global analysis of terrestrial plant litter dynamics in non-perennial waterways. *Nature Geoscience*, *11*(7), 497–503. https://doi.org/10.1038/s41561-018-0134-4 de Mazancourt, C., Isbell, F., Larocque, A., Berendse, F., De Luca, E., Grace, J. B., … Loreau, M. (2013). Predicting ecosystem stability from community composition and biodiversity. *Ecology Letters*, *16*(5), 617–625. https://doi.org/10.1111/ele.12088

Demars, B. O. L., Russell Manson, J., Ólafsson, J. S., Gíslason, G. M., Gudmundsdóttir, R., Woodward, G., … Friberg, N. (2011). Temperature and the metabolic balance of streams. *Freshwater Biology*, *56*(6), 1106–1121. https://doi.org/10.1111/j.1365-2427.2010.02554.x

Dinno, A. (2017). dunn.test: Dunn’s Test of Multiple Comparisons Using Rank Sums. *R Package Version 1.3.5*. Retrieved from https://cran.r-project.org/package=dunn.test

Duarte, C. M., & Cebrián, J. (1996). The fate of marine autotrophic production. *Limnology and Oceanography*, *41*(8), 1758–1766. https://doi.org/10.4319/lo.1996.41.8.1758

Elser, J. J., Fagan, W. F. F., Denno, R. F., Dobberfuhl, D. R., Folarin, A., Huberty, A., … Sterner, R. W. (2000). Nutritional constraints in terrestrial and freshwater food webs. *Nature*, *408*(6812), 578–580. https://doi.org/10.1038/35046058

Elzhov, T. V., Mullen, K. M., Spiess, A.-N., & Bolker, B. (2016). minpack.lm: R Interface to the Levenberg-Marquardt Nonlinear Least-Squares Algorithm Found in MINPACK, Plus Support for Bounds. *R Package Version 1.2-1*. Retrieved from https://cran.r-project.org/package=minpack.lm

Enriquez, S., Duarte, C. M., & Sand-Jensen, K. (1993). Patterns in decomposition rates among photosynthetic organisms : the importance of detritus C : N : P content. *Oecologia*, *94*, 457–471.

Eyre, B. D., & Mckee, L. J. (2002). Carbon, nitrogen, and phosphorus budgets for a shallow subtropical coastal embayment (Moreton Bay, Australia). *Limnology and Oceanography*, *47*(4), 1043–1055. https://doi.org/10.4319/lo.2002.47.4.1043

Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., … Serrano, O. (2012). Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience*, *5*(7), 505–509. https://doi.org/10.1038/ngeo1477

Garonna, I., de Jong, R., de Wit, A. J. W., Mücher, C. A., Schmid, B., & Schaepman, M.

E. (2014). Strong contribution of autumn phenology to changes in satellite-derived growing season length estimates across Europe (1982-2011). *Global Change Biology*, *20*(11), 3457–3470. https://doi.org/10.1111/gcb.12625

Gillooly, J. F., Brown, J. H., West, G. B., Savage, V. M., & Charnov, E. L. (2001). Effects of size and temperature on metabolic rate. *Science (New York, N.Y.)*, *293*(5538), 2248–2251. https://doi.org/10.1126/science.1061967

Gounand, I., Daufresne, T., Gravel, D., Bouvier, C., Bouvier, T., Combe, M., … Mouquet, N. (2016). Size evolution in microorganisms masks trade-offs predicted by the growth rate hypothesis. *Proceedings of the Royal Society B*, *283*(1845), 20162272. https://doi.org/10.1098/rspb.2016.2272

Gounand, I., Harvey, E., Little, C. J., & Altermatt, F. (2018). Meta-Ecosystems 2.0 : Rooting the Theory into the Field. *Trends in Ecology & Evolution*, *33*(1), 36–46. https://doi.org/10.1016/j.tree.2017.10.006

Gounand, I., Little, C. J., Harvey, E., & Altermatt, F. (2018). Cross-ecosystem carbon flows connecting ecosystems worldwide. *Nature Communications*, *9*(1), 4825. https://doi.org/10.1038/s41467-018-07238-2

Harfoot, M. B. J., Newbold, T., Tittensor, D. P., Emmott, S., Hutton, J., Lyutsarev, V., … Purves, D. W. (2014). Emergent global patterns of ecosystem structure and function from a mechanistic general ecosystem model. *PLoS Biology*, *12*(4), e1001841. https://doi.org/10.1371/journal.pbio.1001841

Hatton, I. A., McCann, K. S., Fryxell, J. M., Davies, T. J., Smerlak, M., Sinclair, A. R. E., & Loreau, M. (2015). The predator-prey power law: Biomass scaling across terrestrial and aquatic biomes. *Science*, *349*(6252), aac6284–aac6284. https://doi.org/10.1126/science.aac6284

Hector, A., & Bagchi, R. (2007). Biodiversity and ecosystem multifunctionality. *Nature*, *448*(12), 188–191. https://doi.org/10.1038/nature05947

Kenrick, P., & Crane, P. R. (1997). The origin and early evolution of plants on land. *Nature*, *389*, 33–39. https://doi.org/10.1038/37918

Krause-Jensen, D., & Sand-Jensen, K. (1998). Light attenuation and photosynthesis of aquatic plant communities. *Limnology*, *43*(3), 396–407. https://doi.org/10.4319/lo.1998.43.3.0396

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J. P., Hector, A., … Wardle, D. A. (2001). Biodiversity and ecosystem functioning: current knowledge and future challenges. *Science (New York, N.Y.)*, *294*(5543), 804–808. https://doi.org/10.1126/science.1064088

McCoy, M. W., & Gillooly, J. F. (2008). Predicting natural mortality rates of plants and animals. *Ecology Letters*, *11*(7), 710–716. https://doi.org/10.1111/j.1461-0248.2008.01190.x

Petchey, O. L., Pontarp, M., Massie, T. M., Kéfi, S., Ozgul, A., Weilenmann, M., … Pearse, I. S. (2015). The ecological forecast horizon, and examples of its uses and determinants. *Ecology Letters*, *18*(7), 597–611. https://doi.org/10.1111/ele.12443

Ravi, S., Breshears, D. D., Huxman, T. E., & D'Odorico, P. (2010). Land degradation in drylands: Interactions among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology*, *116*(3–4), 236–245. https://doi.org/10.1016/j.geomorph.2009.11.023

Schramski, J. R., Dell, A. I., Grady, J. M., Sibly, R. M., Brown, J. H., Silby, R. M., & Brown, J. H. (2015). Metabolic theory predicts whole-ecosystem properties. *Proceedings of the National Academy of Sciences*, *112*(8), 2617–2622. https://doi.org/10.1073/pnas.1423502112

Shurin, J. B., Gruner, D. S., & Hillebrand, H. (2006). All wet or dried up? Real differences between aquatic and terrestrial food webs. *Proceedings. Biological Sciences / The Royal Society*, *273*(1582), 1–9. https://doi.org/10.1098/rspb.2005.3377

Sitters, J., Atkinson, C. L., Guelzow, N., Kelly, P., & Sullivan, L. L. (2015). Spatial stoichiometry: Cross-ecosystem material flows and their impact on recipient ecosystems and organisms. *Oikos*, *124*(7), 920–930. https://doi.org/10.1111/oik.02392

Soetaert, K. (2017). plot3D: Plotting Multi-Dimensional Data. *R Package Version 1.1.1*.

Retrieved from https://cran.r-project.org/package=plot3D

Soliveres, S., van der Plas, F., Manning, P., Prati, D., Gossner, M. M., Renner, S. C., … Allan, E. (2016). Biodiversity at multiple trophic levels is needed for ecosystem multifunctionality. *Nature*, *536*(7617), 456–459. https://doi.org/10.1038/nature19092

Tiegs, S. D., Costello, D. M., Isken, M. W., Woodward, G., Mcintyre, P. B., Gessner, M. O., … Zwart, J. A. (2019). Global patterns and drivers of ecosystem functioning in rivers and riparian zones, 1–9.

Yang, H., Yuan, Y., Zhang, Q., Tang, J., & Chen, X. (2011). Changes in soil organic carbon , total nitrogen , and abundance of arbuscular mycorrhizal fungi along a large-scale aridity gradient. *Catena*, *87*(1), 70–77. https://doi.org/10.1016/j.catena.2011.05.009

Yu, G. R., Zhu, X. J., Fu, Y. L., He, H. L., Wang, Q. F., Wen, X. F., … Tong, C. L. (2013). Spatial patterns and climate drivers of carbon fluxes in terrestrial ecosystems of China. *Global Change Biology*, *19*(3), 798–810. https://doi.org/10.1111/gcb.12079

Yvon-Durocher, G., Caffrey, J. M., Cescatti, A., Dossena, M., Giorgio, P. Del, Gasol, J. M., … Allen, A. P. (2012). Reconciling the temperature dependence of respiration across timescales and ecosystem types. *Nature*, *487*(7408), 472–476. https://doi.org/10.1038/nature11205

Data accessibility

The dataset is available in xlsx file format from a Zenodo public repository, doi: 10.5281/zenodo.3644247. R scripts to reproduce the figures and statistical results are available.

Supporting information

Additional Supporting Information may be found online in the supporting information tab for this article.

Figures

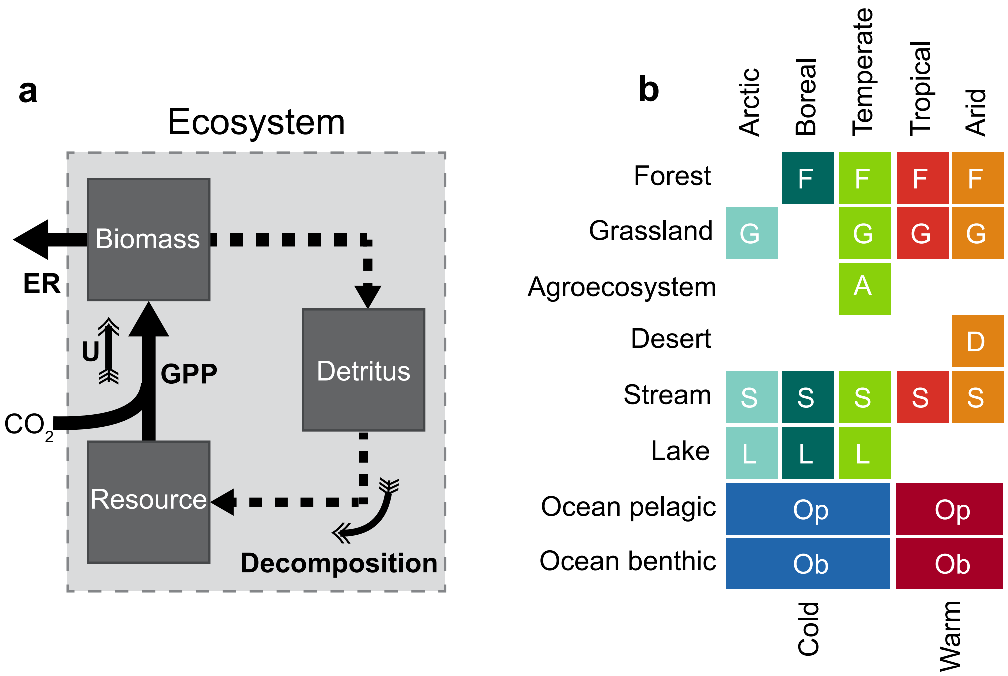

Figure 1 | Study design.

a) Ecosystem functioning variables considered in the study for each Ecosystem type x Climatic zone combination shown in panel **b**. We compiled values of stocks (squares in **a**), fluxes (solid large arrows), and rates (arrows with feathers) from the literature. The dotted arrows denote production of detritus and decomposition flux, for which we did not gathered estimates. For decomposition, we compiled rates (arrow with feathers) –the proportion of detritus processed per unit of time– because they were more available than fluxes. GPP, ER, and U stand for Gross Primary Production, Ecosystem Respiration, and Uptake rate, respectively. Note that GPP is a flux, that is an amount of matter produced per unit of time and area, while U is a rate (i.e., mass-specific GPP), expressed in mass of carbon uptake per unit of biomass and time. In addition, we also gathered values of Net Ecosystem production (not shown in **a**) for all combinations displayed in panel **b**.

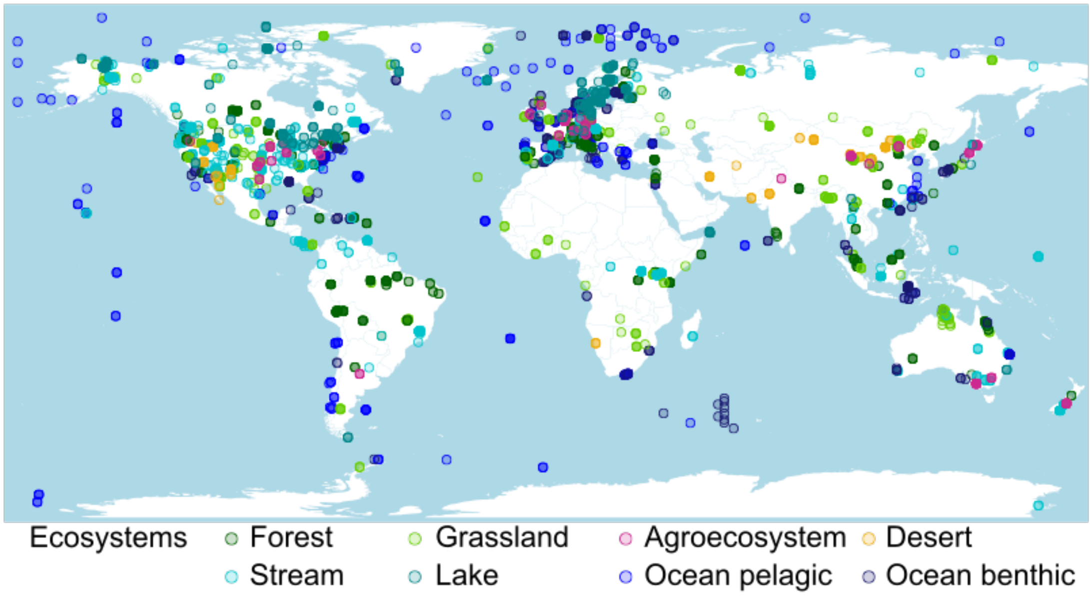

Figure 2 | Geographical distribution of the data.

Each dot shows the geographic location of sites from which we obtained data. Colours denote the different ecosystem types. Note that for about 13% of the data either the coordinates are not provided or the geographical scale given is too large or too coarse to be meaningfully reflected in the map (e.g., geographical scale in original study given as "boreal forests of Canada"), thus these data points are not displayed here. The map is made with Natural Earth. Free vector and raster map data @ naturalearthdata.com.

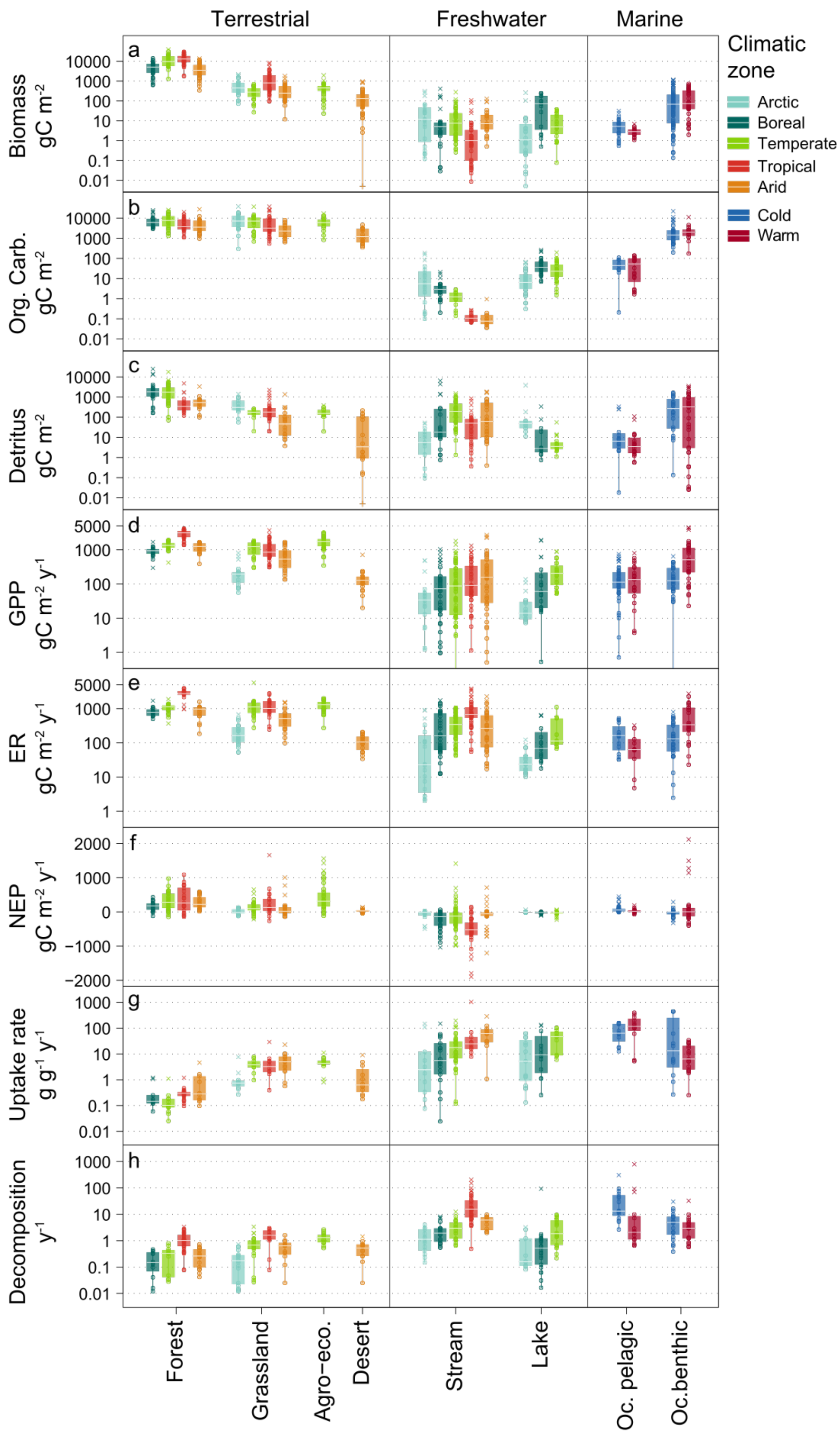

Figure 3 | Carbon stocks, fluxes, and rate across ecosystems and climates.

Panels show different ecosystem functioning variables (top to bottom) across different ecosystem types (left to right) and for different climatic zones (colours). Ecosystem variables considered are **a** biomass, **b** organic carbon, **c** detritus stocks, **d** gross primary production (GPP), **e** ecosystem respiration (ER), **f** net ecosystem production (NEP), **g** uptake rate (i.e., mass-specific GPP), and **h** decomposition rate. Points give values, with "x" denoting outliers. Zero values are replaced by 0.005 to be displayed despite log scales and are given as "+" in the figure panels **a**, **c and h**). Boxplots give median (white line), 25% and 75% percentiles (box), extended by 1.5* inter-quartile range (whiskers). Scales were adapted to maximise clarity. For that purpose, 3 very low values of NEP in tropical streams and 5 null values of GPP in temperate streams and an aphotic benthic site are not displayed here (but see figure 7). Tables S3.11 and S3.12 of Appendix S3 in Supporting Information report the numbers of values of each Variable x Ecosystem type x Climatic zone combination, and the groups given by non-parametric post-hoc test of multiple mean comparisons within each variable, following a significant Kruskal-Wallis test (see methods).

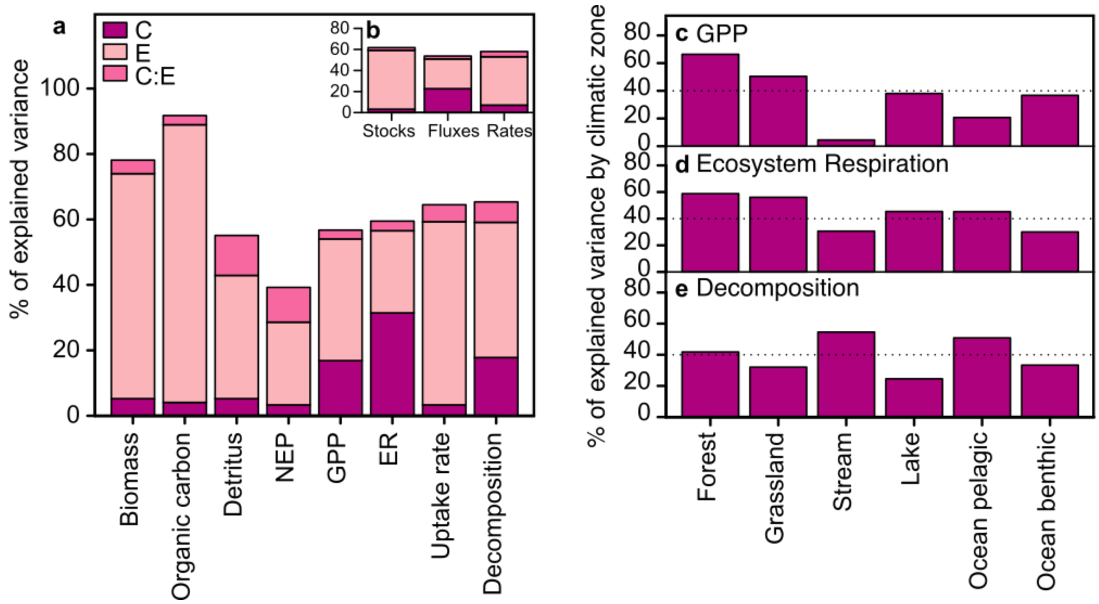

Figure 4 | Variance of ecosystem variables explained by climatic zone and ecosystem type.

a Proportion of variance explained in a series of two-way ANOVAs performed on log-transformed values of each individual ecosystem variable, with climatic zone (C) and ecosystem type (E) as explanatory variables; model: y ~ C + E + C:E. NEP, GPP, and ER stand for Net Ecosystem Production, Gross Primary Production and Ecosystem Respiration, respectively. One null value of biomass and of detritus in a desert and 5 of GPP were removed to allow log-transformation. In **b**, stocks (Biomass, Organic carbon, detritus), fluxes (GPP and ER) and rates (uptake and decomposition) are pooled into broader categories after the individual ecosystem variables are individually scaled. Panels **c**, **d**, and **e** show the variance explained by climatic zone in a series of one-way ANOVAs performed individually on GPP, ER, and decomposition rate for each ecosystem type (18 models). Agroecosystem and desert ecosystems are removed because they are represented in only one climatic zone (temperate and arid, respectively). See full statistical results in Tables S3.1, S3.2 and S3.6.

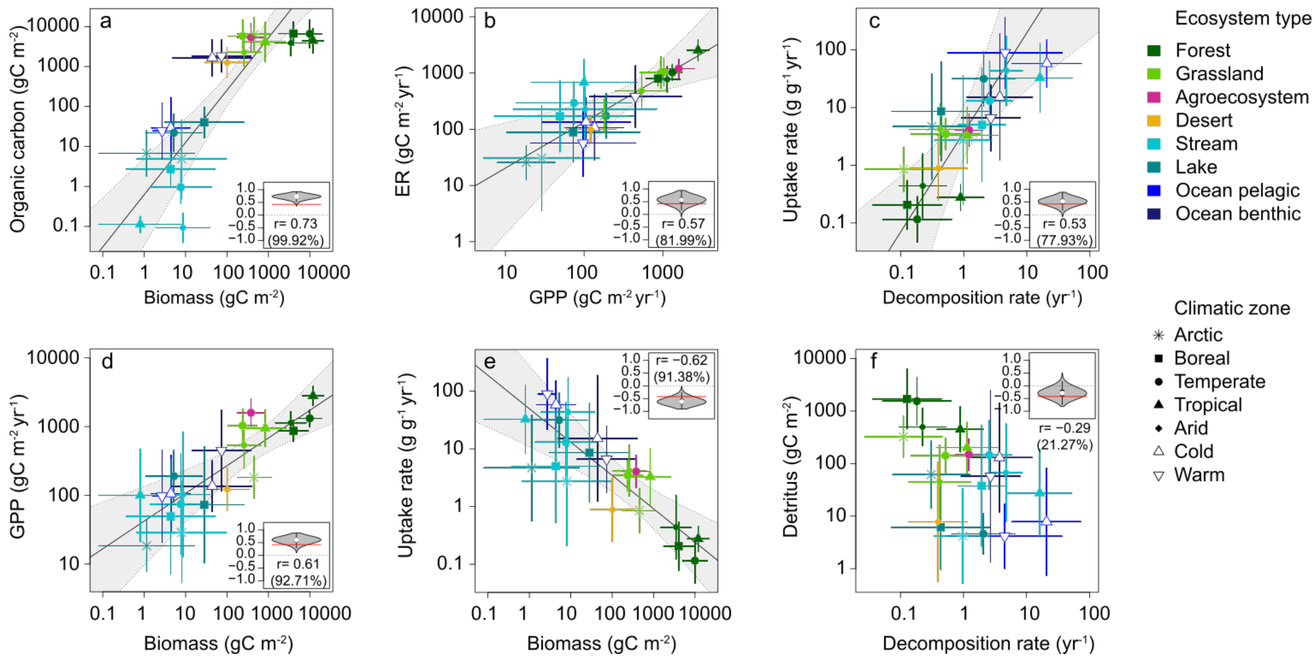

Figure 5 | Relationships between ecosystem variables from bootstrap procedure.

Points and bars give mean and standard deviation values, respectively, for the given ecosystem variables in each ecosystem type (colours) – climatic zone (shapes) combination. GPP and ER stand for gross primary production and ecosystem respiration, respectively. Black lines and grey areas give the mean linear regressions and the 95% confidence interval, respectively, of regressions realized in 10,000 iterations of bootstrapped values for each ecosystem x climatic zone combination (see methods and Appendix S1). The violin plots within panels show the distributions of Pearson's correlation coefficients for these 10,000 series of bootstrapped values; the numbers give the mean value of this distribution and the percentage of significant correlations into brackets. The red lines show the limit value above and below which the correlation is significant, for positive and negative coefficients respectively. Mean and quantile regressions are not displayed when less than 75% of the correlations are significant (**d**). The equations for the mean regressions in log-log space are: **(a)** y = 1.31*x -0.48, **(b)** y = 0.82*x + 1.13, **(c)** y = 1.72*x + 1.31, **(d)** y = 0.4*x + 3.75, **(e)** y = -0.58*x + 3.91. See relations from bootstrap procedure between other pairs of ecosystem variables in Fig. S4.1, and correlations for subsets of empirical data for which pairs of variables are available per site in Table S3.13, Figs S2.10 and S2.11, and Appendix S2.4 for discussion.

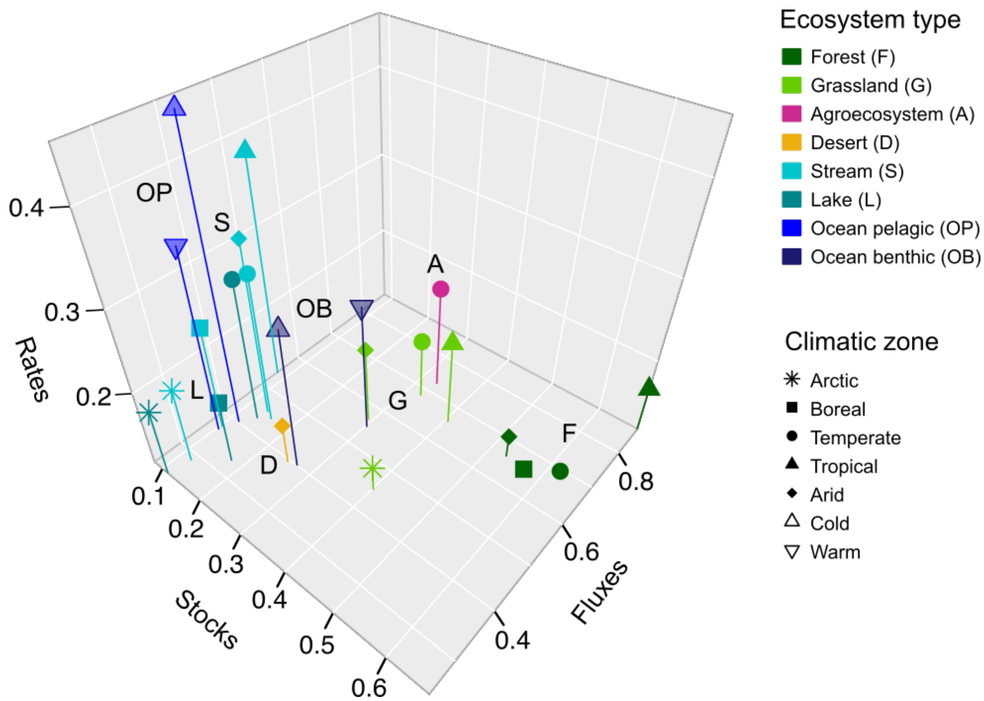

Figure 6 | Relative positions of median ecosystems in the ecosystem functioning space.

Ecosystem types (colours, labels) in each climatic zone (shapes) according to the medians of stocks (biomass, organic carbon, detritus), fluxes (gross primary production, ecosystem respiration), and rates (mass-specific uptake and decomposition rates). Values are scaled between 0 and 1 within each ecosystem variable before pooling them into broader categories (i.e., stocks, fluxes, and rates) to avoid biases resulting from different numbers of data points among ecosystem x climate x variable combinations. Note that in each category, variables are pooled and not summed because it would be only meaningful for stocks. Then each variable has the same weight within each category of stocks, fluxes or rates. For purpose of clarity, scaled median values are double square root-transformed.

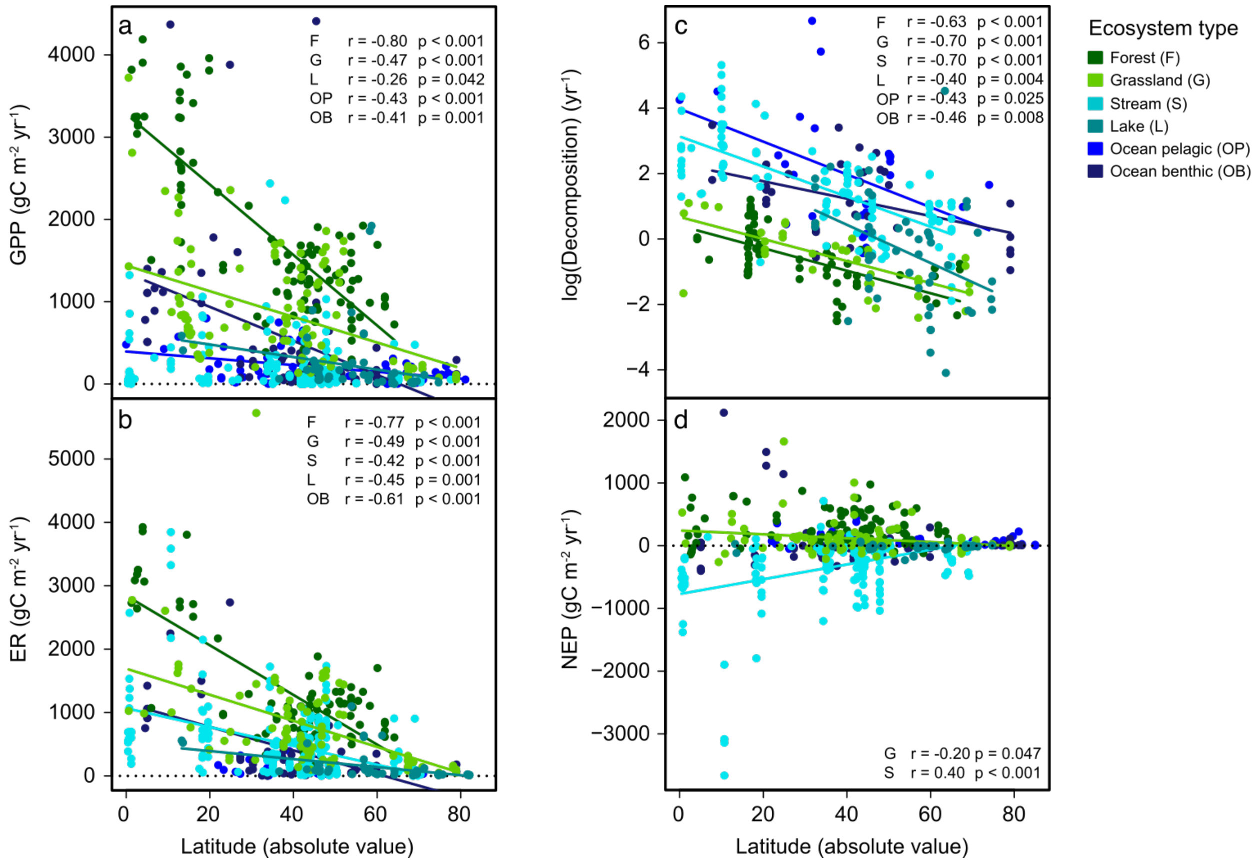

Figure 7 | Latitudinal trends in decomposition rates and Net Ecosystem Production.

Regression lines for significant correlations between latitude and **a** gross primary production (GPP), **b** ecosystem respiration (ER), **c** decomposition rates (log-transformed values) or **d** net ecosystem production (NEP) and latitude, based on two-sided Pearson's two-sided correlation tests. Solid circles show the data points. Colours denote ecosystem types. Pearson correlation coefficients and p-values are provided for the significant relationships (see colour legend for abbreviations of ecosystem types, and full details on statistical tests in Table S3.8). Significant correlations of stocks, uptake rates, and GPP/ER ratios with latitude are available in Figs. S4.3, S4.4 and S4.5, respectively.

List of Supplementary items in the Supporting information

(See new section after page 134, at the end of this file)

Appendix S4 Supplementary figures

Appendix 1 – Data sources

Aanderud, Z. T., Richards, J. H., Svejcar, T., & James, J. J. (2010). A shift in seasonal rainfall reduces soil organic carbon storage in a cold desert. *Ecosystems*, *13*(5), 673–682. https://doi.org/10.1007/s10021-010-9346-1

Abdala, G. C., Caldas, L. S., Haridasan, M., & Eiten, G. (1998). Above and belowground organic matter and root, shoot ratio in a cerrado in Central Brazil. *Brazilian Journal of Ecology*, *2*, 11–23.

Abelho, M., Moretti, M., França, J., & Callisto, M. (2010). Nutrient addition does not enhance leaf decomposition in a Southeastern Brazilian stream (Espinhaço mountain range). *Brazilian Journal of Biology = Revista Brasleira de Biologia*, *70*(3 Suppl), 747–754. https://doi.org/10.1590/S1519-69842010000400007

Åberg, J., Bergström, A. K., Algesten, G., Söderback, K., & Jansson, M. (2004). A comparison of the carbon balances of a natural lake (L. Örträsket) and a hydroelectric reservoir (L. Skinnmuddselet) in northern Sweden. *Water Research*, *38*(3), 531–538. https://doi.org/10.1016/j.watres.2003.10.035

Acuña, V., Giorgi, A., Muñoz, I., Uehlinger, U., & Sabater, S. (2004). Flow extremes and benthic organic matter shape the metabolism of a headwater Mediterranean stream. *Freshwater Biology*, *49*(7), 960–971. https://doi.org/10.1111/j.1365-2427.2004.01239.x

Adachi, M., Ito, A., Ishida, A., Kadir, W. R., Ladpala, P., & Yamagata, Y. (2011). Carbon budget of tropical forests in Southeast Asia and the effects of deforestation :

an approach using a process-based model and field measurements. *Biogeosciences*, *8*, 2635–2647. https://doi.org/10.5194/bg-8-2635-2011

Aguiar, M. I., Fialho, J. S., Campanha, M. M., & Oliveira, T. S. (2014). Carbon sequestration and nutrient reserves under different land use systems. *Revista Arvore*, *38*(1), 81–93. https://doi.org/10.1590/S0100-67622014000100008

Aguila-Pasquel del, J., Doughty, C. E., Metcalfe, D. B., Silva-Espejo, J. E., Girardin, C. A. J., Chung Gutierrez, J. A., … Malhi, Y. (2014). The seasonal cycle of productivity, metabolism and carbon dynamics in a wet aseasonal forest in north-west Amazonia (Iquitos, Peru). *Plant Ecology & Diversity*, *7*(1–2), 71–83. https://doi.org/10.1080/17550874.2013.798365

Aires, L. M. I., Pio, C. A., & Pereira, J. S. (2008). Carbon dioxide exchange above a Mediterranean C3/C4 grassland during two climatologically contrasting years. *Global Change Biology*, *14*(3), 539–555. https://doi.org/10.1111/j.1365-2486.2007.01507.x

Aizaki, M., & Takamura, N. (1991). Regeneration of nutrient and detritus formation from aerobic decomposition of natural phytoplankton. *Japanese Journal of Limnology*, *52*(2), 83–94. https://doi.org/10.3739/rikusui.52.83

Alberti, G., Vicca, S., Inglima, I., Belelli-Marchesini, L., Genesio, L., Miglietta, F., … Cotrufo, M. F. (2015). Soil C : N stoichiometry controls carbon sink partitioning between above-ground tree biomass and soil organic matter in high fertility forests. *IForest*, *8*(1), 195–206. https://doi.org/10.3832/ifor1196-008

Alexander, H. D., Mack, M. C., Goetz, S., Beck, P. S. A., & Belshe, E. F. (2012).

Implications of increased deciduous cover on stand structure and aboveground carbon pools of Alaskan boreal forests. *Ecosphere*, *3*(5), art45. https://doi.org/10.1890/ES11-00364.1

Algesten, G., Sobek, S., Bergström, A. K., Jonsson, A., Tranvik, L. J., & Jansson, M. (2005). Contribution of sediment respiration to summer CO2 emission from low productive boreal and subarctic lakes. *Microbial Ecology*, *50*(4), 529–535. https://doi.org/10.1007/s00248-005-5007-x

Allard, V., Ourcival, J. M., Rambal, S., Joffre, R., & Rocheteau, A. (2008). Seasonal and annual variation of carbon exchange in an evergreen Mediterranean forest in southern France. *Global Change Biology*, *14*(4), 714–725. https://doi.org/10.1111/j.1365-2486.2008.01539.x

Alonso-Pérez, F., Ysebaert, T., & Castro, C. G. (2010). Effects of suspended mussel culture on benthic-pelagic coupling in a coastal upwelling system (Ría de Vigo, NW Iberian Peninsula). *Journal of Experimental Marine Biology and Ecology*, *382*(2), 96–107. https://doi.org/10.1016/j.jembe.2009.11.008

Alonso-Pérez, F., Zúñiga, D., Arbones, B., Figueiras, F. G., & Castro, C. G. (2015). Benthic fluxes, net ecosystem metabolism and seafood harvest: Completing the organic carbon balance in the Ría de Vigo (NW Spain). *Estuarine, Coastal and Shelf Science*, *163*, 54–63. https://doi.org/10.1016/j.ecss.2015.05.038

Althouse, B., Higgins, S., & Vander Zanden, M. J. (2014). Benthic and planktonic primary production along a nutrient gradient in Green Bay, Lake Michigan, USA. *Freshwater Science*, *33*(2), 487–498. https://doi.org/10.1086/676314.

Álvarez, M., & Pardo, I. (2009). Dynamics in the trophic structure of the macroinvertebrate community in a Mediterranean, temporary stream. *Aquatic Sciences*, *71*(2), 202–213. https://doi.org/10.1007/s00027-009-9160-z

Alvim, E., Medeiros, A. O., Rezende, R. S., & Gonçalves Júnior, J. F. (2015). Leaf breakdown in a natural tropical stream. *Journal of Limnology*, *74*(2), 248–260. https://doi.org/10.1002/iroh.200510826

Ambrose Jr, W. G., & Renaud, P. E. (1995). Benthic response to water column productivity patterns: Evidence for benthic-pelagic coupling in the Northeast Water Polynya. *Journal of Geophysical Research*, *100*(C3), 4411–4421. https://doi.org/10.1029/94JC01982

Ammann, C., Flechard, C. R., Leifeld, J., Neftel, A., & Fuhrer, J. (2007). The carbon budget of newly established temperate grassland depends on management intensity. *Agriculture, Ecosystems and Environment*, *121*(1–2), 5–20. https://doi.org/10.1016/j.agee.2006.12.002

Ammann, Christof, Spirig, C., Leifeld, J., & Neftel, A. (2009). Assessment of the nitrogen and carbon budget of two managed temperate grassland fields. *Agriculture, Ecosystems and Environment*, *133*(3–4), 150–162. https://doi.org/10.1016/j.agee.2009.05.006

Anderson-Teixeira, K. J., Delong, J. P., Fox, A. M., Brese, D. A., & Litvak, M. E. (2011). Differential responses of production and respiration to temperature and moisture drive the carbon balance across a climatic gradient in New Mexico. *Global Change Biology*, *17*(1), 410–424. https://doi.org/10.1111/j.1365-2486.2010.02269.x

Andersson, E., & Kumblad, L. (2006). A carbon budget for an oligotrophic clearwater lake in mid-Sweden. *Aquatic Sciences*, *68*(1), 52–64. https://doi.org/10.1007/s00027-005-0807-0

Aponte, C., García, L. V., & Marañón, T. (2012). Tree species effect on litter decomposition and nutrient release in mediterranean oak forests changes over time. *Ecosystems*, *15*(7), 1204–1218. https://doi.org/10.1007/s10021-012-9577-4

Apostolaki, E. T., Holmer, M., Marbà, N., & Karakassis, I. (2010). Metabolic imbalance in coastal vegetated (Posidonia oceanica) and unvegetated benthic ecosystems. *Ecosystems*, *13*(3), 459–471. https://doi.org/10.1007/s10021-010-9330-9

Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R., … Vinson, T. S. (1993). Boreal forests and tundra. In Joe Wisniewski & R. N. Sampson (Eds.), *Terrestrial Biospheric Carbon Fluxes: Quantification of Sinks and Sources of C02* (p. 693). Bad Harzburg, Germany: Springer-Science+Buisness Media, B.V.

Araujo-Murakami, A., Doughty, C. E., Metcalfe, D. B., Silva-espejo, J. E., Arroyo, L., Heredia, J. P., … The, Y. M. (2014). Plant Ecology & Diversity The productivity , allocation and cycling of carbon in forests at the dry margin of the Amazon forest in Bolivia. *Plant Ecology and Diversity*, *7*(1–2), 55–69. https://doi.org/10.1080/17550874.2013.798364

Ardon, M., Stallcup, L. A., & Pringle, C. M. (2006). Does leaf quality mediate the stimulation of leaf breakdown by phosphorus in Neotropical streams? *Freshwater Biology*, *51*(4), 618–633. https://doi.org/10.1111/j.1365-2427.2006.01515.x

Aristegi, L., Izagirre, O., & Elosegi, A. (2010). Metabolism of Basque streams measured with incubation chambers. *Limnetica*, *29*(2), 301–310.

Armstrong, R. D., Eagle, C., & Flood, R. (2015). Improving grain yields on a sodic clay soil in a temperate, medium-rainfall cropping environment. *Crop and Pasture Science*, *66*(5), 492–505. https://doi.org/10.1071/CP14210

Arscott, D. B., Bowden, W. B., & Finlay, J. C. (1998). Comparison of epilithic algal and bryophyte metabolism in an arctic tundra stream, Alaska. *Journal of the North American Benthological Society*, *17*(2), 210–227. https://doi.org/10.2307/1467963

Asao, S., Parton, W. J., Chen, M., & Gao, W. (2018). Photodegradation accelerates ecosystem N cycling in a simulated California grassland. *Ecosphere*, *9*(8), e02370. https://doi.org/10.1002/ecs2.2370

Ask, J., Karlsson, J., Persson, L., Ask, P., Byström, P., & Jansson, M. (2009). Whole-lake estimates of carbon flux through algae and bacteria in benthic and pelagic habitats of clear-water lakes. *Ecology*, *90*(7), 1923–1932. https://doi.org/10.1890/07-1855.1

Attard, K. M., Rodil, I. F., Glud, R. N., Berg, P., Norkko, J., & Norkko, A. (2019). Seasonal ecosystem metabolism across shallow benthic habitats measured by aquatic eddy covariance. *Limnology and Oceanography Letters*, *4*(3), 79–86. https://doi.org/10.1002/lol2.10107

Austin, A. T., Sala, O. E., & Jackson, R. B. (2006). Inhibition of nitrification alters carbon turnover in the Patagonian steppe. *Ecosystems*, *9*(8), 1257–1265. https://doi.org/10.1007/s10021-005-0039-0

Austin, A. T., & Vivanco, L. (2006). Plant litter decomposition in a semi-arid ecosystem controlled by photodegradation. *Nature*, *442*(7102), 555–558.

https://doi.org/10.1038/nature05038

Bachman, S., Heisler-White, J. L., Pendall, E., Williams, D. G., Morgan, J. A., & Newcomb, J. (2010). Elevated carbon dioxide alters impacts of precipitation pulses on ecosystem photosynthesis and respiration in a semi-arid grassland. *Oecologia*, *162*(3), 791–802. https://doi.org/10.1007/s00442-009-1511-x

Bajgain, R., Xiao, X., Basara, J., Wagle, P., Zhou, Y., Mahan, H., … Steiner, J. (2018). Carbon dioxide and water vapor fluxes in winter wheat and tallgrass prairie in central Oklahoma. *Science of the Total Environment*, *644*, 1511–1524. https://doi.org/10.1016/j.scitotenv.2018.07.010

Banta, G. T., Giblin, A. E., Hobbie, J. E., & Tucker, J. (1995). Benthic respiration and nitrogen release in Buzzards Bay, Massachusetts. *Journal of Marine Research*, *53*(1), 107–135. https://doi.org/10.1357/0022240953213287

Barausse, A., Duci, A., Mazzoldi, C., Artioli, Y., & Palmeri, L. (2009). Trophic network model of the Northern Adriatic Sea: Analysis of an exploited and eutrophic ecosystem. *Estuarine, Coastal and Shelf Science*, *83*(4), 577–590. https://doi.org/10.1016/j.ecss.2009.05.003

Bardgett, R. D., van der Wal, R., Jónsdóttir, I. S., Quirk, H., & Dutton, S. (2007). Temporal variability in plant and soil nitrogen pools in a high-Arctic ecosystem. *Soil Biology and Biochemistry*, *39*(8), 2129–2137. https://doi.org/10.1016/j.soilbio.2007.03.016

Barr, A. G., Black, T. A., Hogg, E. H., Griffis, T. J., Morgenstern, K., Kljun, N., … Nesic, Z. (2007). Climatic controls on the carbon and water balances of a boreal aspen forest, 1994-2003. *Global Change Biology*, *13*(3), 561–576. https://doi.org/10.1111/j.1365-2486.2006.01220.x

Barrón, C., Marbà, N., Terrados, J., Kennedy, H., & Duarte, C. M. (2009). Community metabolism and carbon budget along a gradient of seagrass (Cymodocea nodosa) colonization. *Limnology and Oceanography*, *49*(5), 1642–1651. https://doi.org/10.4319/lo.2004.49.5.1642

Barrón, Cristina, & Duarte, C. M. (2009). Dissolved organic matter release in a Posidonia oceanica meadow. *Marine Ecology Progress Series*, *374*, 75–84. https://doi.org/10.3354/meps07715

Barrón, Cristina, Duarte, C. M., Frankignoulle, M., & Vieira Borges, A. (2006). Organic Carbon Metabolism and Carbonate Dynamics in a Mediterranean Seagrass (Posidonia oceanica) Meadow. *Estuaries and Coasts*, *29*(3), 417–426. https://doi.org/https://doi.org/10.1007/BF02784990

Behrendt, H., & Nixdorf, B. (1993). The Carbon Balance of Phytoplankton Production and Loss Processes Based on in situ Measurements in a Shallow Lake. *Internationale Revue Der Gesamten Hydrobiologie Und Hydrographie*, *78*(3), 439–458. https://doi.org/10.1002/iroh.19930780314

Belsky, A. J., Amundson, R. G., Duxbury, J. M., Riha, S. J., Ali, A. R., & Mwonga, S. M. (1989). The Effects of Trees on their Physical, chemical and biological environments in a semi-arid savanna in Kenya. *Journal of Applied Ecology*, *26*(3), 1005–1024. https://doi.org/10.2307/2403708

Benson, E. R., Wipfli, M. S., Clapcott, J. E., & Hughes, N. F. (2013). Relationships between ecosystem metabolism, benthic macroinvertebrate densities, and environmental variables in a sub-arctic Alaskan river. *Hydrobiologia*, *701*(1), 189–207. https://doi.org/10.1007/s10750-012-1272-0

Benstead, J. P. (1996). Macroinvertebrates and the Processing of Leaf Litter in a Tropical Stream. *Biotropica*, *28*(3), 367–375. https://doi.org/10.2307/2389200

Benstead, J. P., Deegan, L. A., Peterson, B. J., Huryn, A. D., Bowden, W. B., Suberkropp, K., … Vacca, J. A. (2005). Responses of a beaded Arctic stream to short-term N and P fertilisation. *Freshwater Biology*, *50*(2), 277–290. https://doi.org/10.1111/j.1365-2427.2004.01319.x

Benstead, J. P., Douglas, M. M., & Pringle, C. M. (2003). Relationships of Stream Invertebrate Communities To Deforestation in Eastern Madagascar. *Ecological Applications*, *13*(5), 1473–1490. https://doi.org/10.1890/02-5125

Benstead, J. P., March, J. G., Pringle, C. M., Ewel, K. C., & Short, J. W. (2008). Biodiversity and ecosystem function in species-poor communities: community structure and leaf litter breakdown in a Pacific island stream. *Journal of North American Benthological Society*, *28*(2), 454–465. https://doi.org/10.1899/07

Bergfur, J., Johnson, R. K., Sandin, L., Goedkoop, W., & Nygren, K. (2007). Effects of nutrient enrichment on boreal streams: Invertebrates, fungi and leaf-litter breakdown. *Freshwater Biology*, *52*(8), 1618–1633. https://doi.org/10.1111/j.1365-2427.2007.01770.x

Bernot, M. J., Sobota, D. J., Hall, R. O., Mulholland, P. J., Dodds, W. K., Webster, J. R., … Wilson, K. (2010). Inter-regional comparison of land-use effects on stream metabolism. *Freshwater Biology*, *55*(9), 1874–1890. https://doi.org/10.1111/j.1365-2427.2010.02422.x

Betts, E. F., & Jones, J. B. (2009). Impact of wildfire on stream nutrient chemistry and ecosystem metabolism in boreal forest catchments of interior Alaska. *Source: Arctic, Antarctic, and Alpine Research Arctic, Antarctic, and Alpine Research*, *41*(4), 407–417. https://doi.org/10.1657/1938-4246-41.4.407

Bierman, V. J., Hinz, S. C., Zhu, D.-W., Wiseman, W. J., Rabalais, N. N., & Turner, E. R. (1994). A preliminary mass balance model of primary productivity and dissolved oxygen in the Mississippi river plume / inner gulf shelf region. *Estuaries*, *17*(4), 886–899. https://doi.org/10.2307/1352756

Blanchet, H., Montaudouin, X. De, Lucas, A., & Chardy, P. (2004). Heterogeneity of macrozoobenthic assemblages within a Zostera noltii seagrass bed : diversity, abundance, biomass and structuring factors. *Estuarine, Coastal and Shelf Science*, *61*, 111–123. https://doi.org/10.1016/j.ecss.2004.04.008

Bliss, L. C. (1975). Devon Island, Canada. In: Structure and function of tundra ecosystem. *Ecological Bulletins (Stockholm)*, *20*, 17–60.

Bocaniov, S. A., Schiff, S. L., & Smith, R. E. H. (2012). Plankton metabolism and physical forcing in a productive embayment of a large oligotrophic lake: insights from stable oxygen isotopes. *Freshwater Biology*, *57*(3), 481–496. https://doi.org/10.1111/j.1365-2427.2011.02715.x

Bode, A., & Varela, M. (1994). Planktonic carbon and nitrogen budgets for the N-NW Spanish shelf: The role of pelagic nutrient regeneration during upwelling events.

Scientia Marina, *58*(3), 221–231.

Bohman, I. M., & Herrmann, J. (2006). The timing of winter-growing shredder species and leaf litter turnover rate in an oligotrophic lake, SE Sweden. *Hydrobiologia*, *556*(1), 99–108. https://doi.org/10.1007/s10750-005-1052-1

Bott, T. L., Brock, J. T., Dunn, C. S., & Naiman, R. J. (1985). Benthic community metabolism in four temperate stream systems: an inter-biome comparison and evaluation of the river continuum concept. *Hydrobiologia*, *123*(1), 3–45. https://doi.org/10.1007/BF00006613

Bowden, W. B., Peterson, B. J., Finlay, J. C., & Tucker, J. (1992). Epilithic chlorophyll a, photosynthesis, and respiration in control and fertilized reaches of a tundra stream. *Hydrobiologia*, *240*(1–3), 121–131. https://doi.org/10.1007/BF00013457

Brady-Campbell, M. M., Campbell, D. B., & Harlin, M. M. (1984). Productivity of kelp (Laminaria spp .) near the southern limit in the Northwestern Atlantic Ocean. *Marine Ecology Progress Series*, *18*, 79–88. https://doi.org/10.3354/meps018079

Bremer, D. J., Ham, J. M., Owensby, C. E., & Knapp, A. K. (1998). Responses of soil respiration to clipping and grazing in a tallgrass prairie. *Journal of Environmental Quality*, *27*(6), 1539–1548. https://doi.org/10.2134/jeq1998.00472425002700060034x

Britton, A. J., Helliwell, R. C., Lilly, A., Dawson, L., Fisher, J. M., Coull, M., & Ross, J. (2011). An integrated assessment of ecosystem carbon pools and fluxes across an oceanic alpine toposequence. *Plant and Soil*, *345*(1), 287–302. https://doi.org/10.1007/s11104-011-0781-3

Brogaard, S., Runnström, M., & Seaquist, J. W. (2005). Primary production of Inner Mongolia, China, between 1982 and 1999 estimated by a satellite data-driven light use efficiency model. *Global and Planetary Change*, *45*(4), 313–332. https://doi.org/10.1016/j.gloplacha.2004.09.012

Brothers, S M, Köhler, J., Attermeyer, K., Grossart, H. P., Mehner, T., Meyer, N., … Hilt, S. (2014). A feedback loop links brownification and anoxia in a temperate, shallow lake. *Limnology and Oceanography*, *59*(4), 1388–1398. https://doi.org/10.4319/lo.2014.59.4.1388

Brothers, Soren M, Hilt, S., Attermeyer, K., Grossart, H. P., Kosten, S., Lischke, B., … Koehler, J. (2013). A regime shift from macrophyte to phytoplankton dominance enhances carbon burial in a shallow , eutrophic lake. *Ecosphere*, *4*(11), 1–17. https://doi.org/10.1890/ES13-00247.1

Bruder, A., Schindler, M. H., Moretti, M. S., & Gessner, M. O. (2014). Litter decomposition in a temperate and a tropical stream: The effects of species mixing, litter quality and shredders. *Freshwater Biology*, *59*(3), 438–449. https://doi.org/10.1111/fwb.12276

Brye, K. R., Gower, S. T., Norman, J. M., & Bundy, L. G. (2002). Carbon budgets for a prairie and agroecosystems: effects of land use and interannual variability. *Ecological Applications*, *12*(4), 962–979. https://doi.org/10.1890/1051-0761(2002)012[0962%3ACBFAPA]2.0.CO%3B2

Buesseler, K. O., Lamborg, C. H., Boyd, P. W., Lam, P. J., Trull, T. W., Bidigare, R. R., … Wilson, S. (2007). Revisiting carbon flux through the Ocean's twilight zone.

Science, *316*(April), 567–570. https://doi.org/10.1126/science.1137959

Buffam, I., Turner, M. G., Desai, A. R., Hanson, P. C., Rusak, J. A., Lottig, N. R., … Carpenter, S. R. (2011). Integrating aquatic and terrestrial components to construct a complete carbon budget for a north temperate lake district. *Global Change Biology*, *17*(2), 1193–1211. https://doi.org/10.1111/j.1365-2486.2010.02313.x

Bunn, S. E., Davies, P. M., & Mosisch, T. D. (1999). Ecosystem measures of river health and their response to riparian and catchment degradation. *Freshwater Biology*, *41*(2), 333–345. https://doi.org/10.1046/j.1365-2427.1999.00434.x

Bunnell, F. L., Maclean Jr, S. F., & Brown, J. (1975). Barrow , Alaska , USA. In: Structure and function of tundra ecosystem. *Ecological Bulletins (Stockholm)*, *20*, 73–124.

Burford, M. A., Alongi, D. M., McKinnon, A. D., & Trott, L. A. (2008). Primary production and nutrients in a tropical macrotidal estuary, Darwin Harbour, Australia. *Estuarine, Coastal and Shelf Science*, *79*(3), 440–448. https://doi.org/10.1016/j.ecss.2008.04.018

Burford, Michele A., Cook, A. J., Fellows, C. S., Balcombe, S. R., & Bunn, S. E. (2008). Sources of carbon fuelling production in an arid floodplain river. *Marine and Freshwater Research*, *59*(3), 224–234. https://doi.org/10.1071/MF07159

Busch, D. E., & Fisher, S. G. (1981). Metabolism of a Desert Stream. *Freshwater Biology*, *11*, 301–307. https://doi.org/10.1111/j.1365-2427.1981.tb01263.x

Buysse, P., Bodson, B., Debacq, A., Ligne, A. De, Heinesch, B., Manise, T., … Aubinet, M. (2017). Carbon budget measurement over 12 years at a crop production site in the silty-loam region in Belgium. *Agricultural and Forest Meteorology*, *246*(June), 241–255. https://doi.org/10.1016/j.agrformet.2017.07.004

Caffrey, J. M. (2004). Factors controlling net ecosystem metabolism in U.S. estuaries. *Estuaries*, *27*(1), 90–101. https://doi.org/10.1007/BF02803563

Caldwell, M. M., White, R. S., Moore, R. T., & Camp, L. B. (1977). Carbon balance, productivity, and water use of cold-winter desert shrub communities dominated by C3 and C4 species. *Oecologia*, *29*(4), 275–300. https://doi.org/10.1007/BF00345803

Callisto, M., Gonçalves Jr, J. F., Graça, M. A. S., Gonçalves, J. F., & Graça, M. A. S. (2007). Leaf litter as a possible food source for chironomids (Diptera) in Brazilian and Portuguese headwater streams. *Revista Brasileira de Zoologia*, *24*(2), 442–448. https://doi.org/10.1590/S0101-81752007000200023

Cao, M., & Woodward, F. (1998). Net primary and ecosystem production and carbon stocks of terrestrial ecosystems and their responses to climate change. *Global Change Biology*, *4*(2), 185–198. https://doi.org/10.1046/j.1365-2486.1998.00125.x

Caquet, B., De Grandcourt, A., Thongo M'bou, A., Epron, D., Kinana, A., Saint André, L., & Nouvellon, Y. (2012). Soil carbon balance in a tropical grassland: Estimation of soil respiration and its partitioning using a semi-empirical model. *Agricultural and Forest Meteorology*, *158–159*, 71–79. https://doi.org/10.1016/j.agrformet.2012.02.008

Carlson, C. A., Ducklow, H. W., Hansell, D. A., & Smith, W. O. (1998). Organic carbon partitioning during spring phytoplankton blooms in the Ross Sea polynya and the Sargasso Sea. *Limnology and Oceanography*, *43*(3), 375–386.

https://doi.org/10.4319/lo.1998.43.3.0375

Carlson, K. M., Curran, L. M., Ponette-González, A. G., Ratnasari, D., Ruspita, Lisnawati, N., … Raymond, P. A. (2014). Influence of watershed-climate interactions on stream temperature, sediment yield, and metabolism along a land use intensity gradient in Indonesian Borneo Kimberly. *Journal of Geophysical Reserch: Biogeosciences*, *119*(6), 1110–1128. https://doi.org/10.1002/2014JG002705.Received

Carmack, E. C., Macdonald, R. W., & Jasper, S. (2004). Phytoplankton productivity on the Canadian Shelf of the Beaufort Sea. *Marine Ecology Progress Series*, *277*, 37–50. https://doi.org/10.3354/meps277037

Carpenter, S. R., Cole, J. J., Pace, M. L., Bogert, M. Van de, Bade, D. L., Bastviken, D., … Kritzberg, E. S. (2005). Ecosystem subsidies: terrestrial support of aquatic food webs from 13C addition to contrasting lakes. *Ecology*, *86*(10), 2737–2750. https://doi.org/10.1890/04-1282

Carrara, A., Janssens, I. A., Curiel Yuste, J., & Ceulemans, R. (2004). Seasonal changes in photosynthesis, respiration and NEE of a mixed temperate forest. *Agricultural and Forest Meteorology*, *126*(1–2), 15–31. https://doi.org/10.1016/j.agrformet.2004.05.002

Carrillo, Y., Pendall, E., Dijkstra, F. A., Morgan, J. A., & Newcomb, J. M. (2011). Response of soil organic matter pools to elevated CO2 and warming in a semi-arid grassland. *Plant and Soil*, *347*(1), 339–350. https://doi.org/10.1007/s11104-011-0853-4

Carstensen, J., Conley, D., & Müller-Karulis, B. (2003). Spatial and temporal resolution of carbon fluxes in a shallow coastal ecosystem, the Kattegat. *Marine Ecology Progress Series*, *252*, 35–50. https://doi.org/10.3354/meps252035

Castro, H., & Freitas, H. (2009). Above-ground biomass and productivity in the Montado: From herbaceous to shrub dominated communities. *Journal of Arid Environments*, *73*(4–5), 506–511. https://doi.org/10.1016/j.jaridenv.2008.12.009

Catalán, N., Marcé, R., Kothawala, D. N., & Tranvik, L. J. (2016). Organic carbon decomposition rates controlled by water retention time across inland waters. *Nature Geoscience*, *9*(May), 1–7. https://doi.org/10.1038/ngeo2720

Cebrian, J., & Duarte, C. M. (2001). Detrital stocks and dynamics of the seagrass Posidonia oceanica (L.) Delile in the Spanish Mediterranean. *Aquatic Botany*, *70*(4), 295–309. https://doi.org/10.1016/S0304-3770(01)00154-1

Cebrian, J., & Lartigue, J. (2004). Patterns of herbivory and decomposition in aquatic and terrestrial ecosystems. *Ecological Monographs*, *74*(2), 237–259. https://doi.org/10.1890/03-4019

Chardy, P., & Dauvin, J. C. (1992). Carbon flows in a subtidal fine sand community from the western English Channel: a simulation analysis. *Marine Ecology Progress Series*, *81*(2), 147–161. https://doi.org/10.3354/meps081147

Chen, B. M., Wang, G. X., & Peng, S. L. (2009). Role of desert annuals in nutrient flow in arid area of Northwestern China: A nutrient reservoir and provider. *Plant Ecology*, *201*, 401–409. https://doi.org/10.1007/978-90-481-2798-6_3

Chen, X., Hutley, L. B., & Eamus, D. (2003). Carbon balance of a tropical savanna of northern Australia. *Oecologia*, *137*(3), 405–416. https://doi.org/10.1007/s00442-003-1358-5

Chen, Y., Mu, S., Sun, Z., Gang, C., Li, J., Padarian, J., … Li, S. (2016). Grassland Carbon Sequestration Ability in China: A New Perspective from Terrestrial Aridity Zones. *Rangeland Ecology and Management*, *69*(1), 84–94. https://doi.org/10.1016/j.rama.2015.09.003

Cheng, J., Jing, G., Wei, L., & Jing, Z. (2016). Long-term grazing exclusion effects on vegetation characteristics, soil properties and bacterial communities in the semi-arid grasslands of China. *Ecological Engineering*, *97*, 170–178. https://doi.org/10.1016/j.ecoleng.2016.09.003

Cheshire, A. C., Westphalen, G., Wenden, A., Scriven, L. J., & Rowland, B. C. (1996). Photosynthesis and respiration of phaeophycean-dominated macroalgal communities in summer and winter. *Aquatic Botany*, *55*, 159–170. https://doi.org/10.1016/S0304-3770(96)01071-6

Chidami, S., & Amyot, M. (2008). Fish decomposition in boreal lakes and biogeochemical implications. *Limnology and Oceanography*, *53*(5), 1988–1996. https://doi.org/10.4319/lo.2008.53.5.1988

Chiu, S. H., Huang, Y. H., & Lin, H. J. (2013). Carbon budget of leaves of the tropical intertidal seagrass Thalassia hemprichii. *Estuarine, Coastal and Shelf Science*, *125*, 27–35. https://doi.org/10.1016/j.ecss.2013.03.026

Chmiel, H. E., Kokic, J., Denfeld, B. A., Einarsdóttir, K., Wallin, M. B., Koehler, B., … Sobek, S. (2016). The role of sediments in the carbon budget of a small boreal lake.

Limnology and Oceanography, *61*(5), 1814–1825. https://doi.org/10.1002/lno.10336

Cho, B. C., & Azam, F. (1988). Major role of bacteria in biogeochemical fluxes in the ocean’s interior. *Nature*, *332*, 441–443. https://doi.org/10.1038/332441a0

Christiansen, C. T., Haugwitz, M. S., Priemé, A., Nielsen, C. S., Elberling, B., Michelsen, A., … Blok, D. (2017). Enhanced summer warming reduces fungal decomposer diversity and litter mass loss more strongly in dry than in wet tundra. *Global Change Biology*, *23*, 406–420. https://doi.org/10.1111/gcb.13362

Clay, P. A., Muehlbauer, J. D., & Doyle, M. W. (2015). Effect of tributary and braided con fl uences on aquatic macroinvertebrate communities and geomorphology in an alpine river watershed. *Freshwater Science, 34*(3), 845–856. https://doi.org/10.1086/682329.

Cochran, R. L., Collins, H. P., Kennedy, A., & Bezdicek, D. F. (2007). Soil carbon pools and fluxes after land conversion in a semiarid shrub-steppe ecosystem. *Biology and Fertility of Soils*, *43*(4), 479–489. https://doi.org/10.1007/s00374-006-0126-1

Codispoti, L. A., Kelly, V., Thessen, A., Matrai, P., Suttles, S., Hill, V., … Light, B. (2013). Synthesis of primary production in the Arctic Ocean: III. Nitrate and phosphate based estimates of net community production. *Progress in Oceanography*, *110*, 126–150. https://doi.org/10.1016/j.pocean.2012.11.006

Coll, M., Palomera, I., Tudela, S., & Dowd, M. (2008). Food-web dynamics in the South Catalan Sea ecosystem (NW Mediterranean) for 1978-2003. *Ecological Modelling*, *217*(1–2), 95–116. https://doi.org/10.1016/j.ecolmodel.2008.06.013

Collins, N. M. (1981). The role of termites in the decomposition of wood and leaf litter in the Southern Guinea savanna of Nigeria. *Oecologia*, *51*(3), 389–399.

Collins, S. M., Thomas, S. A., Heatherly II, T., MacNeill, K. L., Leduc, A. O. H. C., López-Sepulcre, A., … Flecker, A. S. (2016). Fish introductions and light modulate food web fluxes in tropical streams : a whole-ecosystem experimental approach. *Ecology*, *97*(11), 3154–3166. https://doi.org/10.1002/ecy.1530

Colon-Gaud, C., Peterson, S., Whiles, M. R., Kilham, S. S., Lips, K. R., & Pringle, C. M. (2008). Allochthonous litter inputs, organic matter standing stocks, and organic seston dynamics in upland Panamanian streams: Potential effects of larval amphibians on organic matter dynamics. *Hydrobiologia*, *603*(1), 301–312. https://doi.org/10.1007/s10750-008-9294-3

Compson, Z. G., Adams, K. J., Edwards, J. A., Maestas, J. M., Whitham, T. G., & Marks, J. C. (2013). Leaf litter quality affects aquatic insect emergence: Contrasting patterns from two foundation trees. *Oecologia*, *173*(2), 507–519. https://doi.org/10.1007/s00442-013-2643-6

Conti, G., & Díaz, S. (2013). Plant functional diversity and carbon storage - an empirical test in semi-arid forest ecosystems. *Journal of Ecology*, *101*(1), 18–28. https://doi.org/10.1111/1365-2745.12012

Copertino, M., Connell, S. D., & Cheshire, A. (2005). The prevalence and production of turf-forming algae on a temperate subtidal coast. *Phycologia*, *44*(3), 241–248. https://doi.org/10.2216/0031-8884(2005)44[241:TPAPOT]2.0.CO_2

Cory, R. M., Ward, C. P., Crump, B. C., & Kling, G. W. (2014). Sunlight controls water column processing of carbon in arctic fresh waters. *Science*, *345*(6199), 925–928.

https://doi.org/10.1126/science.1253119

Costa, T. L., Sampaio, E. V. S. B. S. B., Sales, M. F., Accioly, L. J. O. O., Althoff, T. D., Pareyn, F. G. C. C., … Menezes, R. S. C. C. (2014). Root and shoot biomasses in the tropical dry forest of semi-arid Northeast Brazil. *Plant and Soil*, *378*(1–2), 113–123. https://doi.org/10.1007/s11104-013-2009-1

Cotner, J. B., Montoya, J. V., Roelke, D. L., & Winemiller, K. O. (2006). Seasonally variable riverine production in the Venezuelan llanos. *Journal of the North American Benthological Society*, *25*(1), 171–184. https://doi.org/10.1899/0887-3593(2006)25[171:SVRPIT]2.0.CO;2

Cotrufo, M. F., Raschi, A., Lanini, M., & Ineson, P. (1999). Decomposition and nutrient dynamics of Quercus pubescens leaf litter in a naturally enriched CO2 Mediterranean ecosystem. *Functional Ecology*, *13*(3), 343–351. https://doi.org/10.1046/j.1365-2435.1999.00328.x

Cotrufo, M. Francesca, Soong, J. L., Horton, A. J., Campbell, E. E., Haddix, M. L., Wall, D. H., & Parton, W. J. (2015). Formation of soil organic matter via biochemical and physical pathways of litter mass loss. *Nature Geoscience*, *8*(10), 776–779. https://doi.org/10.1038/ngeo2520

Cowan, C. A., & Oswood, M. W. (1983). Input and storage of benthic detritus in an Alaskan subarctic stream. *Polar Biology*, *2*, 35–40. https://doi.org/10.1007/BF00258283

Craig, N., Jones, S. E., Weidel, B. C., & Solomon, C. T. (2015). Habitat, not resource availability, limits consumer production in lake ecosystems. *Limnology and*

Oceanography, *60*, 2079–2089. https://doi.org/10.1002/lno.10153

Cremona, F., Kõiv, T., Kisand, V., Laas, A., Zingel, P., Agasild, H., … Nõges, T. (2014). From bacteria to piscivorous fish: Estimates of whole-lake and component-specific metabolism with an ecosystem approach. *PLoS ONE*, *9*(7), e101845. https://doi.org/10.1371/journal.pone.0101845

Cronan, C. S. (2003). Belowground biomass, production, and carbon cycling in mature Norway spruce, Maine, U.S.A. *Canadian Journal of Forest Research*, *33*(2), 339–350. https://doi.org/doi: 10.1139/X02-189

Cross, J. N., Mathis, J. T., Lomas, M. W., Moran, S. B., Baumann, M. S., Shull, D. H., … Grebmeier, J. M. (2014). Integrated assessment of the carbon budget in the southeastern Bering Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, *109*, 112–124. https://doi.org/10.1016/j.dsr2.2014.03.003

Crowl, T. a, Welsh, V., Heartsill-Scalley, T., & Covich, A. P. (2006). Effects of different types of conditioning on rates of leaf-litter shredding by Xiphocaris elongata, a Neotropical freshwater shrimp. *Journal of the North American Benthological Society*, *25*(1), 196–206. https://doi.org/10.1899/0887-3593(2006)25[198:eodtoc]2.0.co;2

Cushing, C. E., & Wolf, E. G. (1984). Primary production in Rattlesnake Springs, a cold desert spring-stream. *Hydrobiologia*, *114*, 229–236. https://doi.org/10.1007/BF00031874

Daneri, G., Dellarossa, V., Quiñones, R., Jacob, B., Montero, P., & Ulloa, O. (2000). Primary production and community respiration in the Humboldt Current System off

Chile and associated oceanic areas. *Marine Ecology Progress Series*, *197*, 41–49. https://doi.org/10.3354/meps197041

Daniels, W. C., Kling, G. W., & Giblin, A. E. (2015). Benthic community metabolism in deep and shallow Arctic lakes during 13 years of whole-lake fertilization. *Limnology and Oceanography*, *60*(5), 1604–1618. https://doi.org/10.1002/lno.10120

Danovaro, R., Gambi, C., & Mirto, S. (2002). Meiofaunal production and energy transfer efficiency in a seagrass Posidonia oceanica bed in the western Mediterranean. *Marine Ecology Progress Series*, *234*, 95–104. https://doi.org/10.3354/meps234095

Davis, C. J., Fritsen, C. H., Wirthlin, E. D., & Memmott, J. C. (2012). High rates of primary productivity in a semi-arid tailwater: Implications for self-regulated production. *River Research and Applications*, *28*(10), 1820–1829. https://doi.org/10.1002/rra

Day, T. A., Guénon, R., & Ruhland, C. T. (2015). Photodegradation of plant litter in the Sonoran Desert varies by litter type and age. *Soil Biology and Biochemistry*, *89*, 109–122. https://doi.org/10.1016/j.soilbio.2015.06.029

De Angelis, P., Chigwerewe, K. S., & Mugnozza, G. E. S. (2000). Litter quality and decomposition in a CO_2-enriched Mediterranean forest ecosystem. *Plant and Soil*, *224*(1), 31–41. https://doi.org/10.1023/A:1004790328560

De Boer, W. F. (2000). Biomass dynamics of seagrasses and the role of mangrove and seagrass vegetation as different nutrient sources for an intertidal ecosystem. *Aquatic Botany*, *66*(3), 225–239. https://doi.org/10.1016/S0304-3770(99)00072-8

de Carvalho Conceicão Telles, E., Camargo, B. de P., Martinelli, L. A., Trumbore, S. E., Salazar da Costa, E., Santos, J., … Cosme Oliveira Jr, R. (2003). Influence of soil texture on carbon dynamics and storage potential in tropical forest soils of Amazonia. *Global Biogeochemical Cycles*, *17*(2), 1–12. https://doi.org/10.1029/2002GB001953

De Castro, E. A. (1996). *Biomass, nutrient pools and response to fire in the Brazilian Cerrado*. *MSc Thesis*. Oregon State University.

De Marco, A., Fioretto, A., Giordano, M., Innangi, M., Menta, C., Papa, S., & De Santo, A. V. (2016). C stocks in forest floor and mineral soil of two mediterranean beech forests. *Forests*, *7*(8), 1–20. https://doi.org/10.3390/f7080181

De Souza, M. L., & Moulton, T. P. (2005). The effects of shrimps on benthic material in a Brazilian island stream. *Freshwater Biology*, *50*(4), 592–602. https://doi.org/10.1111/j.1365-2427.2005.01348.x

Deininger, A., Jonsson, A., Karlsson, J., & Bergström, A.-K. (2019). Pelagic food webs of humic lakes show low short-term response to forest harvesting. *Ecological Applications*, *29*(1), e01813. https://doi.org/10.1002/eap.1813

Demars, B. O. L., Russell Manson, J., Ólafsson, J. S., Gíslason, G. M., Gudmundsdóttir, R., Woodward, G., … Friberg, N. (2011). Temperature and the metabolic balance of streams. *Freshwater Biology*, *56*(6), 1106–1121. https://doi.org/10.1111/j.1365-2427.2010.02554.x

Deng, L., Liu, S., Dong, S., An, N., Zhao, H., & Liu, Q. (2015). Application of Ecopath model on trophic interactions and energy flows of impounded Manwan reservoir ecosystem in Lancang River, southwest China. *Journal of Freshwater Ecology*, *30*(2), 281–297. https://doi.org/10.1080/02705060.2014.942893

Descy, J., Darchambeau, F., Lambert, T., Stoyneva-Gaertner, M. P., Bouillon, S., & Borges, A. V. (2017). Phytoplankton dynamics in the Congo River. *Freshwater Biology*, *62*, 87–101. https://doi.org/10.1111/fwb.12851

Dhital, D., Yashiro, Y., Ohtsuka, T., Noda, H., Shizu, Y., & Koizumi, H. (2010). Carbon dynamics and budget in a Zoysia japonica grassland, central Japan. *Journal of Plant Research*, *123*(4), 519–530. https://doi.org/10.1007/s10265-009-0289-6

Dobson, Michael, Mathooko, J. M., Ndegwa, F. K., & M'Erimba, C. (2004). Leaf litter processing rates in a Kenyan highland stream, the Njoro River. *Hydrobiologia*, *519*(1–3), 207–210. https://doi.org/10.1023/B:HYDR.0000026592.50734.ea

Dobson, Mike, Magana, A., Mathooko, J. M., & Ndegwa, F. K. (2002). Detritivores in Kenyan highland streams: More evidence for the paucity of shredders in the tropics? *Freshwater Biology*, *47*(5), 909–919. https://doi.org/10.1046/j.1365-2427.2002.00818.x

Dodds, W. K., Hutson, R. E., Eichem, A. C., Evans, M. A., Gudder, D. A., Fritz, K. M., & Gray, L. (1996). The relationship of floods, drying, flow and light to primary production and producer biomass in a prairie stream. *Hydrobiologia*, *333*, 151–159. https://doi.org/10.1007/BF00013429

Dold, C., Büyükcangaz, H., Rondinelli, W., Prueger, J. H., Sauer, T. J., & Hatfield, J. L. (2017). Long-term carbon uptake of agro-ecosystems in the Midwest. *Agricultural and Forest Meteorology*, *232*, 128–140. https://doi.org/10.1016/j.agrformet.2016.07.012

Domene, X., Mattana, S., Hanley, K., Enders, A., & Lehmann, J. (2014). Medium-term effects of corn biochar addition on soil biota activities and functions in a temperate soil cropped to corn. *Soil Biology and Biochemistry*, *72*, 152–162. https://doi.org/10.1016/j.soilbio.2014.01.035

Domínguez, A., Bedano, J. C., Becker, A. R., & Arolfo, R. V. (2014). Organic farming fosters agroecosystem functioning in Argentinian temperate soils: Evidence from litter decomposition and soil fauna. *Applied Soil Ecology*, *83*, 170–176. https://doi.org/10.1016/j.apsoil.2013.11.008

Dubois, K., Carignan, R., & Veizer, J. (2009). Can pelagic net heterotrophy account for carbon fluxes from eastern Canadian lakes? *Applied Geochemistry*, *24*(5), 988–998. https://doi.org/10.1016/j.apgeochem.2009.03.001

Dubourg, P., North, R. L., Hunter, K., Vandergucht, D. M., Abirhire, O., Silsbe, G. M., … Hudson, J. J. (2015). Light and nutrient co-limitation of phytoplankton communities in a large reservoir : Lake Diefenbaker, Saskatchewan, Canada. *Journal of Great Lakes Research*, *41*, 129–143. https://doi.org/10.1016/j.jglr.2015.10.001

Ducklow, H. W. (1999). Minireview: The bacterial content of the oceanic euphotic zone. *FEMS Microbiology-Ecology*, *30*, 1–10. https://doi.org/10.1016/S0168-6496(99)00031-8

Duffer, W. R., & Dowis, T. C. (1966). Primary productivity in a southern Great Plains stream. *Limnology and Oceanography*, *11*(2), 143–151. https://doi.org/10.4319/lo.1966.11.2.0143

Eldridge, P. M., & Jackson, G. A. (1993). Benthic trophic dynamics in California coastalbasin and continental slope communities inferred using inverse analysis. *Marine Ecology Progress Series*, *99*, 115–135. https://doi.org/10.3354/meps099115

Emerson, S. (2014). Annual net community production and the biological carbon flux in the ocean. *Global Biogeochemical Cycles*, *28*, 14–28. https://doi.org/10.1002/2013GB004680

Emmerich, W. E. (2003). Carbon dioxide fluxes in a semiarid environment with high carbonate soils. *Agricultural and Forest Meteorology*, *116*(1–2), 91–102. https://doi.org/http://dx.doi.org/10.1016/S0168-1923(02)00231-9

Emmerton, C. A., Lesack, L. F. W., & Vincent, W. F. (2008). Nutrient and organic matter patterns across the Mackenzie River, estuary and shelf during the seasonal recession of sea-ice. *Journal of Marine Systems*, *74*(3–4), 741–755. https://doi.org/10.1016/j.jmarsys.2007.10.001

Erftemeijer, P. L. A., & Middelburg, J. J. (1995). Mass balance constraints on nutrient cycling in tropical seagrass beds. *Aquatic Botany*, *50*(1), 21–36. https://doi.org/10.1016/0304-3770(94)00440-W

Erftemeijer, P. L. A., Osinga, R., & Mars, A. E. (1993). Primary production of seagrass beds in South Sulawesi (Indonesia): a comparison of habitats, methods and species. *Aquatic Botany*, *46*(1), 67–90. https://doi.org/10.1016/0304-3770(93)90065-5

Euskirchen, E. S., Bret-Harte, M. S., Scott, G. J., Edgar, C., & Shaver, G. R. (2012). Seasonal patterns of carbon dioxide and water fluxes in three representative tundra ecosystems in northern Alaska. *Ecosphere*, *3*(1), art4. https://doi.org/10.1890/ES11-

00202.1

Evrendilek, F., Berberoglu, S., Taskinsu-Meydan, S., & Yilmaz, E. (2006). Quantifying carbon budgets of conifer Mediterranean forest ecosystems, Turkey. *Environmental Monitoring and Assessment*, *119*(1–3), 527–543. https://doi.org/10.1007/s10661-005-9041-4

Eyre, B. D., Ferguson, A. J. P., Webb, A., Maher, D., & Oakes, J. M. (2011). Metabolism of different benthic habitats and their contribution to the carbon budget of a shallow oligotrophic sub-tropical coastal system (southern Moreton Bay, Australia). *Biogeochemistry*, *102*(1), 87–110. https://doi.org/10.1007/s10533-010-9424-7

Eyre, B. D., & Mckee, L. J. (2002). Carbon, nitrogen, and phosphorus budgets for a shallow subtropical coastal embayment (Moreton Bay, Australia). *Limnology and Oceanography*, *47*(4), 1043–1055. https://doi.org/10.4319/lo.2002.47.4.1043

Fahey, T. J., Siccama, T. G., Driscoll, C. T., Likens, G. E., Campbell, J., Johnson, C. E., … Yanai, R. D. (2005). The biogeochemistry of carbon at Hubbard Brook. *Biogeochemistry*, *75*, 109–176. https://doi.org/10.1007/s10533-004-6321-y

Falge, E., Baldocchi, D., Tenhunen, J., Aubinet, M., Bakwin, P., Berbigier, P., … Wofsy, S. (2002). Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements. *Agricultural and Forest Meteorology*, *113*(1–4), 53–74. https://doi.org/10.1016/S0168-1923(02)00102-8

Fallon, R. D., & Brock, T. D. (1979). Decomposition of blue-green algal (cyanobacterial) blooms in Lake Mendota, Wisconsin. *Applied and Environmental Microbiology*, *37*(5), 820–830.

Federle, T. W., & Vestal, J. R. (1980). Microbial colonization and decomposition of Carex litter in an arctic lake. *Applied and Enviromental Microbiology*, *39*(4), 888–893.

Fei, X., Jin, Y., Zhang, Y., Sha, L., Liu, Y., Song, Q., … Li, P. (2017). Eddy covariance and biometric measurements show that a savanna ecosystem in Southwest China is a carbon sink. *Scientific Reports*, *7*, 41025. https://doi.org/10.1038/srep41025

Fellows, A. W., Flerchinger, G. N., Lohse, K. A., & Seyfried, M. S. (2018). Rapid Recovery of Gross Production and Respiration in a Mesic Mountain Big Sagebrush Ecosystem Following Prescribed Fire. *Ecosystems*, *21*(7), 1283–1294. https://doi.org/10.1007/s10021-017-0218-9

Fenoglio, S., Bo, T., Cammarata, M., López-Rodríguez, M. J., & Tierno De Figueroa, J. M. (2015). Seasonal variation of allochthonous and autochthonous energy inputs in an Alpine stream. *Journal of Limnology*, *74*(2), 272–277. https://doi.org/10.4081/jlimnol.2014.1082

Findlay, S., Tank, J., Dye, S., Valett, H. M., Mulholland, P. J., McDowell, W. H., … Bowden, W. B. (2002). A cross-system comparison of bacterial and fungal biomass in detritus pools of headwaterstreams. *Microbial Ecology*, *43*, 55–66. https://doi.org/10.1007/10.007/s00248-001-1020-x

Fischer, M. L., Torn, M. S., Billesbach, D. P., Doyle, G., Northup, B., & Biraud, S. C. (2012). Carbon, water, and heat flux responses to experimental burning and drought in a tallgrass prairie. *Agricultural and Forest Meteorology*, *166–167*, 169–174. https://doi.org/10.1016/j.agrformet.2012.07.011

Fisher, S. G. (1977). Organic matter processing by a stream-segment ecosystem: Fort River, Massachusetts, U.S.A. *Internationale Revue Der Gesamten Hydrobiologie Und Hydrographie*, *62*(6), 701–727. https://doi.org/10.1002/iroh.1977.3510620601

Fisher, S. G., & Gray, J. (1983). Secondary production and organic matter processing by collector macroinvetebrates in a desert stream. *Ecology*, *64*(5), 1217–1224.

Fisher, S. G., & Likens, G. E. (1973). Energy flow in Bear Brook, New Hampshire: an integrative approach to stream ecosystem metabolism. *Ecological Monographs*, *43*(4), 421–439. https://doi.org/10.2307/1942301

Flanagan, L. B., Wever, L. A., & Carlson, P. J. (2002). Seasonal and interannual variation in carbon dioxide exchange and carbon balance in a northern temperate grassland. *Global Change Biology*, *8*(7), 599–615. https://doi.org/10.1046/j.1365-2486.2002.00491.x

Forest, A., Tremblay, J. E., Gratton, Y., Martin, J., Gagnon, J., Darnis, G., … Piepenburg, D. (2011). Biogenic carbon flows through the planktonic food web of the Amundsen Gulf (Arctic Ocean): A synthesis of field measurements and inverse modeling analyses. *Progress in Oceanography*, *91*(4), 410–436. https://doi.org/10.1016/j.pocean.2011.05.002

Fourqurean, J. W., Duarte, C. M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M. A., … Serrano, O. (2012). Seagrass ecosystems as a globally significant carbon stock. *Nature Geoscience*, *5*(7), 505–509. https://doi.org/10.1038/ngeo1477

França, J. S., Gregório, R. S., D’Arc De Paula, J., Gonçalves Júnior, J. F., Ferreira, F. A., & Callisto, M. (2009). Composition and dynamics of allochthonous organic matter inputs and benthic stock in a Brazilian stream. *Marine and Freshwater Research*, *60*(10), 990–998. https://doi.org/10.1071/MF08247

Frank, A. B., Liebig, M. A., & Hanson, J. D. (2002). Soil carbon dioxide fluxes in northern semiarid grasslands. *Soil Biology and Biochemistry*, *34*(9), 1235–1241. https://doi.org/10.1016/S0038-0717(02)00062-7

Franz, D., Koebsch, F., Larmanou, E., Augustin, J., & Sachs, T. (2016). High net CO_2 and CH_4 release at a eutrophic shallow lake on a formerly drained fen. *Biogeosciences*, *13*(10), 3051–3070. https://doi.org/10.5194/bg-13-3051-2016

Fraser, T. J., & Amiro, B. D. (2013). Initial carbon dynamics of perennial grassland conversion for annual cropping in Manitoba. *Canadian Journal of Soil Science*, *93*, 379–391. https://doi.org/10.4141/CJSS2012-109

Fu, Y., Zheng, Z., Yu, G., Hu, Z., Sun, X., Shi, P., … Zhao, X. (2009). Environmental influences on carbon dioxide fluxes over three grassland ecosystems in China. *Biogeosciences*, *6*(12), 2879–2893. https://doi.org/10.5194/bg-6-2879-2009

Fugère, V., Jacobsen, D., Finestone, E. H., & Chapman, L. J. (2018). Ecosystem structure and function of afrotropical streams with contrasting land use. *Freshwater Biology*, *63*(June), 1498–1513. https://doi.org/10.1111/fwb.13178

Gaedke, U., & Straile, D. (1994). Seasonal changes of the quantitative importance of protozoans in a large lake: An ecosystem approach using mass-balanced carbon flow diagrams. *Marine Microbial Food Webs*, *8*(1–2), 163–188.

Gallardo Lancho, J. F., & González Hernández, M. I. (2004). Sequestration of C in Spanish deciduous oak forests. *Advances in Geoecology*, (37), 341–351.

Gan, S., Wu, Y., & Zhang, J. (2016). Bioavailability of dissolved organic carbon linked with the regional carbon cycle in the East China Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, *124*, 19–28. https://doi.org/10.1016/j.dsr2.2015.06.024

Garcia, E. A., Towsend, S. A., & Douglas, M. M. (2015). Context dependency of top-down and bottom-up effects in a Northern Australian tropical river. *Freshwater Science*, *34*(2), 679–690. https://doi.org/10.1086/681106

Gasith, A., & Hasler, A. D. (1976). Airborne litterfall as a source of organic matter in lakes. *Limnology and Oceanography*, *21*(2), 253–258. https://doi.org/10.4319/lo.1976.21.2.0253

Gaumont-Guay, D., Black, T. A., Griffis, T. J., Barr, A. G., Morgenstern, K., Jassal, R. S., & Nesic, Z. (2006). Influence of temperature and drought on seasonal and interannual variations of soil, bole and ecosystem respiration in a boreal aspen stand. *Agricultural and Forest Meteorology*, *140*(1–4), 203–219. https://doi.org/10.1016/j.agrformet.2006.08.002

Gea-Izquierdo, G., Guibal, F., Joffre, R., Ourcival, J. M., Simioni, G., & Guiot, J. (2015). Modelling the climatic drivers determining photosynthesis and carbon allocation in evergreen Mediterranean forests using multiproxy long time series. *Biogeosciences*, *12*, 3695–3712. https://doi.org/10.5194/bg-12-3695-2015

Gebhardt, A. C., Gaye-Haake, B., Unger, D., Lahajnar, N., & Ittekkot, V. (2004). Recent particulate organic carbon and total suspended matter fluxes from the Ob and Yenisei Rivers into the Kara Sea (Siberia). *Marine Geology*, *207*(1–4), 225–245.

https://doi.org/10.1016/j.margeo.2004.03.010

Gessner, M. O., Schieferstein, B., Müller, U., Barkmann, S., & Lenfers, U. A. (1996). A partial budget of primary organic carbon flows in the littoral zone of a hardwater lake. *Aquatic Botany*, *55*(2), 93–105. https://doi.org/10.1016/S0304-3770(96)01064-9

Gessner, M. O., Thomas, M., Jean-Louis, A. M., & Chauvet, E. (1993). Stable successional patterns of aquatic hyphomycetes on leaves decaying in a summer cool stream. *Mycological Research*, *97*(2), 163–172. https://doi.org/10.1016/S0953-7562(09)80238-4

Giardina, C. P., Ryan, M. G., Binkley, D., & Fownes, J. H. (2003). Primary production and carbon allocation in relation to nutrient supply in a tropical experimental forest. *Global Change Biology*, *9*, 1438–1450. https://doi.org/10.1046/j.1365-2486.2003.00558.x

Giesler, R., Lyon, S. W., Mörth, C. M., Karlsson, J., Karlsson, E. M., Jantze, E. J., … Humborg, C. (2014). Catchment-scale dissolved carbon concentrations and export estimates across six subarctic streams in northern Sweden. *Biogeosciences*, *11*(2), 525–537. https://doi.org/10.5194/bg-11-525-2014

Gilmanov, T. G., Soussana, J. F., Aires, L., Allard, V., Ammann, C., Balzarolo, M., … Wohlfahrt, G. (2007). Partitioning European grassland net ecosystem CO2 exchange into gross primary productivity and ecosystem respiration using light response function analysis. *Agriculture, Ecosystems and Environment*, *121*(1–2), 93–120. https://doi.org/10.1016/j.agee.2006.12.008

Gilmanov, Tagir G., Parton, W. J., & Ojima, D. S. (1997). Testing the ’ CENTURY ’ ecosystem level model on data sets from eight grassland sites in the former USSR representing a wide climatic / soil gradient. *Ecological Modelling*, *96*, 191–210. https://doi.org/10.1016/S0304-3800(96)00067-1

Glenday, J. (2008). Carbon storage and emissions offset potential in an African dry forest, the Arabuko-Sokoke Forest, Kenya. *Environmental Monitoring and Assessment*, *142*(1–3), 85–95. https://doi.org/10.1007/s10661-007-9910-0

Glud, R. N., Berg, P., Hume, A., Batty, P., Blicher, M. E., Lennert, K., & Rysgaard, S. (2010). Benthic O2 exchange across hard-bottom substrates quantified by eddy correlation in a sub-Arctic fjord. *Marine Ecology Progress Series*, *417*, 1–12. https://doi.org/10.3354/meps08795

Gomez-Casanovas, N., DeLucia, N. J., Bernacchi, C. J., Boughton, E. H., Sparks, J. P., Chamberlain, S. D., & DeLucia, E. H. (2018). Grazing alters net ecosystem C fluxes and the global warming potential of a subtropical pasture. *Ecological Applications*, *28*(2), 557–572. https://doi.org/10.1002/eap.1670

Gómez-Gener, L., Obrador, B., von Schiller, D., Marcé, R., Casas-Ruiz, J. P., Proia, L., … Koschorreck, M. (2015). Hot spots for carbon emissions from Mediterranean fluvial networks during summer drought. *Biogeochemistry*, *125*(3), 409–426. https://doi.org/10.1007/s10533-015-0139-7

Gonçalves, J. F., Graça, M. A. S., & Callisto, M. (2006). Leaf-litter breakdown in 3 streams in temperate, Mediterranean, and tropical Cerrado climates. *Journal of the North American Benthological Society*, *25*(2), 344–355.

https://doi.org/10.1899/0887-3593(2006)25[344:LBISIT]2.0.CO;2

González, H. E., Castro, L., Daneri, G., Iriarte, J. L., Silva, N., Vargas, C. A., … Sánchez, N. (2011). Seasonal plankton variability in Chilean Patagonia fjords: Carbon flow through the pelagic food web of Aysen Fjord and plankton dynamics in the Moraleda Channel basin. *Continental Shelf Research*, *31*(3–4), 225–243. https://doi.org/10.1016/j.csr.2010.08.010

Gough, L., & Hobbie, S. E. (2003). Responses of moist non-acidic arctic tundra to altered environment: productivity, biomass, and species richness. *Oikos*, *103*(1), 204–216. https://doi.org/10.1034/j.1600-0706.2003.12363.x

Graça, M. A. S., Ferreira, R. C. F., & Coimbra, C. N. (2001). Litter processing along a stream gradient: the role of invertebrates and decomposers. *Journal of the North American Benthological Society*, *20*(3), 408–420. https://doi.org/10.2307/1468038

Grace, J., José, J. S., Meir, P., Miranda, H. S., & Montes, R. A. (2006). Productivity and carbon fluxes of tropical savannas. *Journal of Biogeography*, *33*(3), 387–400. https://doi.org/10.1111/j.1365-2699.2005.01448.x

Graf, G., Gerlach, S. A., Linke, P., Queisser, W., Ritzrau, W., Scheltz, A., … Witte, U. (1995). Benthic-pelagic coupling in the Greenland-Norwegian Sea and its effect on the geological record. *Geologische Rundschau*, *84*(1), 49–58. https://doi.org/10.1007/BF00192241

Granier, A., Bréda, N., Longdoz, B., Gross, P., & Ngao, J. (2008). Ten years of fluxes and stand growth in a young beech forest at Hesse, North-eastern France. *Annals of Forest Science*, *64*, 704. https://doi.org/10.1051/forest:2008052

Grégoire, M., & Soetaert, K. (2010). Carbon, nitrogen, oxygen and sulfide budgets in the Black Sea: A biogeochemical model of the whole water column coupling the oxic and anoxic parts. *Ecological Modelling*, *221*(19), 2287–2301. https://doi.org/10.1016/j.ecolmodel.2010.06.007

Grünzweig, J. M., Lin, T., Rotenberg, E., Schwartz, A., & Yakir, D. (2003). Carbon sequestration in arid-land forest. *Global Change Biology*, *9*(5), 791–799. https://doi.org/10.1046/j.1365-2486.2003.00612.x

Gücker, B., Boëchat, I. G., & Giani, A. (2009). Impacts of agricultural land use on ecosystem structure and whole-stream metabolism of tropical Cerrado streams. *Freshwater Biology*, *54*(10), 2069–2085. https://doi.org/10.1111/j.1365-2427.2008.02069.x

Gudasz, C., Bastviken, D., Premke, K., Steger, K., & Tranvik, L. J. (2012). Constrained microbial processing of allochthonous organic carbon in boreal lake sediments. *Limnology and Oceanography*, *57*(1), 163–175. https://doi.org/10.4319/lo.2012.57.1.0163

Gudasz, C., Sobek, S., Bastviken, D., Koehler, B., & Tranvik, L. J. (2015). Temperature sensitivity of organic carbon mineralization in contrasting lake sediments. *Journal of Geophysical Research*, *120*, 1215–1225. https://doi.org/10.1002/2015JG002928.Received

Guillemette, F., McCallister, S. L., & Del Giorgio, P. A. (2013). Differentiating the degradation dynamics of algal and terrestrial carbon within complex natural dissolved organic carbon in temperate lakes. *Journal of Geophysical Research:*

Biogeosciences, *118*(3), 963–973. https://doi.org/10.1002/jgrg.20077

Guo, Q., Li, S., Hu, Z., Zhao, W., Yu, G., Sun, X., … Bai, W. (2016). Responses of gross primary productivity to different sizes of precipitation events in a temperate grassland ecosystem in Inner Mongolia, China. *Journal of Arid Land*, *8*(1), 36–46. https://doi.org/10.1007/s40333-015-0136-7

Gurung, M. B., Bigsby, H., Cullen, R., & Manandhar, U. (2015). Estimation of carbon stock under different management regimes of tropical forest in the Terai Arc Landscape, Nepal. *Forest Ecology and Management*, *356*, 144–152. https://doi.org/10.1016/j.foreco.2015.07.024

Gustafsson, P., Greenberg, L. A., & Bergman, E. (2014). Woody debris and terrestrial invertebrates – effects on prey resources for brown trout (Salmo trutta) in a boreal stream. *Environmental Biology of Fishes*, *97*(5), 529–542. https://doi.org/10.1007/s10641-014-0250-y

Haapala, A., Muotka, T., & Markkola, A. (2001). Breakdown and macroinvertebrate and fungal colonization of alder, birch, and willow leaves in a boreal forest stream. *Journal of the North American Benthological Society*, *20*(3), 395–407. https://doi.org/10.2307/1468037

Hagen, E. M., McTammany, M. E., Webster, J. R., & Benfield, E. F. (2010). Shifts in allochthonous input and autochthonous production in streams along an agricultural land-use gradient. *Hydrobiologia*, *655*(1), 61–77. https://doi.org/10.1007/s10750-010-0404-7

Hagen, E. M., & Sabo, J. L. (2014). Temporal variability in insectivorous bat activity along two desert streams with contrasting patterns of prey availability. *Journal of Arid Environments*, *102*, 104–112. https://doi.org/10.1016/j.jaridenv.2013.11.016

Halfon, E. (1984). The composition of particulate organic matter in the euphotic zone of Lake Superior. *Journal of Great Lakes Research*, *10*(3), 299–306. https://doi.org/10.1016/S0380-1330(84)71843-0

Hall, R. O., Likens, G. E., & Malcom, H. M. (2001). Trophic basis of invertebrate production in 2 streams at the Hubbard Brook Experimental Forest. *Journal of the North American Benthological Society*, *20*(3), 432–447.

Hall, R. O., & Tank, J. L. (2003). Ecosystem metabolism controls nitrogen uptake in streams in Grand Teton National Park, Wyoming. *Limnology and Oceanography*, *48*(3), 1120–1128. https://doi.org/10.4319/lo.2003.48.3.1120

Hall, R. O., Taylor, B. W., & Flecker, A. S. (2011). Detritivorous fish indirectly reduce insect secondary production in a tropical river. *Ecosphere*, *2*(12), 1–13. https://doi.org/10.1890/ES11-00042.1

Hall, R. O., Wallace, J. B., & Eggert, S. L. (2000). Organic matter flow in stream food webs with reduced detrital resource base. *Ecology*, *81*(12), 3445–3463. https://doi.org/10.1890/0012-9658(2000)081[3445:OMFISF]2.0.CO;2

Hammerly, J., Leguizamon, M., Maine, M. A., Suñe, N., & Pizarro, M. J. (1992). Decomposition rate of plant material in the Parana Medio River (Argentina). *Hydrobiologia*, *230*(3), 157–164. https://doi.org/10.1007/BF00036562

Hanlon, R. D. G. (1982). The breakdown and decomposition of allochthonous and autochthonous plant litter in an oligotrophic lake (Llyn Frongoch). *Hydrobiologia*, *88*(3), 281–288. https://doi.org/10.1007/BF00008508

Hansson, K., Fröberg, M., Helmisaari, H. S., Kleja, D. B., Olsson, B. A., Olsson, M., & Persson, T. (2013). Carbon and nitrogen pools and fluxes above and below ground in spruce, pine and birch stands in southern Sweden. *Forest Ecology and Management*, *309*, 28–35. https://doi.org/10.1016/j.foreco.2013.05.029

Hargrave, B. T., Harding, G. C., Drinkwater, K. F., Lambert, T. C., & Harrison, W. G. (1985). Dynamics of the pelagic food web in St. Georges Bay, southern Gulf of St. Lawrence. *Marine Ecology Progress Series*, *20*, 221–240. https://doi.org/meps/20/m020p221

Harmon, M., Bible, K., Ryan, M., Shaw, D., Chen, H., Klopatek, J., & Li, X. (2004). Production, respiration, and overall carbon balance in an old-growth Pseudotsuga-Tsuga forest ecosystem. *Ecosystems*, *7*, 498–512. https://doi.org/10.1007/s10021-004-0140-9

Harris, Z. M., Alberti, G., Viger, M., Jenkins, J. R., Rowe, R., McNamara, N. P., & Taylor, G. (2017). Land-use change to bioenergy: grassland to short rotation coppice willow has an improved carbon balance. *Global Change Biology*, *9*, 469–484. https://doi.org/10.1111/gcbb.12347

Hart, S. C., Firestone, M. K., & Paul, E. A. (1992). Decomposition of ponderosa pine needles in a Mediterranean-type climate. *Canadian Journal of Forest Research*, *22*(3), 306–314. https://doi.org/10.1017/CBO9781107415324.004

Harvey, C. J., Peterson, B. J., Bowden, W. B., Deegan, L. A., Jacques, C., Hershey, A. E., … Mar, N. (1997). Organic Matter Dynamics in the Kuparuk River, a Tundra River in Alaska, USA. *Journal of the North American Benthological Society*, *16*(1), 18–23. https://doi.org/10.2307/1468225

Hastings, S. J., Oechel, W. C., & Muhlia-Melo, A. (2005). Diurnal, seasonal and annual variation in the net ecosystem CO_2 exchange of a desert shrub community (Sarcocaulescent) in Baja California, Mexico. *Global Change Biology*, *11*(6), 927–939. https://doi.org/10.1111/j.1365-2486.2005.00951.x

Heath, L. S., Kauppi, P. E., Burschel, P., Heinz-Detlev, G., Guderian, R., Kohlmaier, G. H., … Weber, M. (1993). Contribution of temperature forests to the world's carbon budget. In J. Wisniewski & R. N. Sampson (Eds.), *Terrestrial Biospheric Carbon Fluxes: Quantification of Sinks and Sources of C02* (p. 693). Bad Harzburg, Germany: Springer-Science+Business Media, B.V.

Hecky, R. E., Campbell, P., & Hendzel, L. L. (1993). The stoichiometry of carbon, nitrogen, and phosphorus in particulate matter of lakes and oceans. *Limnology and Oceanography*, *38*(4), 709–724. https://doi.org/10.4319/lo.1993.38.4.0709

Heikkinen, J. E. P., Virtanen, T., Huttunen, J. T., Elaskov, V., & Martikainen, P. J. (2004). Carbon balance in East European tundra. *Global Biogeochemical Cycles*, *18*(1), GB1023. https://doi.org/10.1029/2003GB002054

Hessen, D. O., Andersen, T., & Lyche, A. (1990). Carbon metabolism in a humic lake: Pool sizes and cycling through zooplankton. *Limnology and Oceanography*, *35*(1), 84–99. https://doi.org/10.4319/lo.1990.35.1.0084

Hewins, D. B., Archer, S. R., Okin, G. S., McCulley, R. L., & Throop, H. L. (2013). Soil-litter mixing accelerates decomposition in a Chihuahuan desert grassland.

Ecosystems, *16*(2), 183–195. https://doi.org/10.1007/s10021-012-9604-5

Heymans, J. J., & Baird, D. (2000). A carbon flow model and network analysis of the northern Benguela upwelling system, Namibia. *Ecological Modelling*, *126*(1), 9–32. https://doi.org/10.1016/S0304-3800(99)00192-1

Higgs, N. D., Gates, A. R., & Jones, D. O. B. (2014). Fish food in the deep sea: Revisiting the role of large food-falls. *PLoS ONE*, *9*(5), e96016. https://doi.org/10.1371/journal.pone.0096016

Hilli, S., Stark, S., & Derome, J. (2010). Litter decomposition rates in relation to litter stocks in boreal coniferous forests along climatic and soil fertility gradients. *Applied Soil Ecology*, *46*(2), 200–208. https://doi.org/10.1016/j.apsoil.2010.08.012

Hinojo-Hinojo, C., Castellanos, A. E., Rodriguez, J. C., Delgado-Balbuena, J., Romo-León, J. R., Celaya-Michel, H., & Huxman, T. E. (2016). Carbon and water fluxes in an exotic buffelgrass savanna. *Rangeland Ecology and Management*, *69*(5), 334–341. https://doi.org/10.1016/j.rama.2016.04.002

Ho, B. S. K., & Dudgeon, D. (2016). Are high densities of fishes and shrimp associated with top-down control of tropical benthic communities? A test in three Hong Kong streams. *Freshwater Biology*, *61*(1), 57–68. https://doi.org/10.1111/fwb.12678

Hobbie, J. E. (1980). *Limnology of tundra ponds, Barrow, Alaska*. (J. E. Hobbie, Ed.). Stroudsburg, Pennsylvania: Dowden, Hutchinson & Ross, Inc.

Hoffmann, K., Hassenrück, C., Salman-Carvalho, V., Holtappels, M., & Bienhold, C. (2017). Response of bacterial communities to different detritus compositions in arctic deep-sea sediments. *Frontiers in Microbiology*, *8*, Art266.

https://doi.org/10.3389/fmicb.2017.00266

Hood, J. M., Benstead, J. P., Cross, W. F., Huryn, A. D., Johnson, P. W., Junker, J. R., … Tran, C. (2018). Increased resource use efficiency amplifies positive response of aquatic primary production to experimental warming. *Global Change Biology*, *24*, 1069–1084. https://doi.org/10.1111/gcb.13912

Hooker, K. L., & Marzolf, G. R. (1987). Differential Decomposition of Leaves in Grassland and Gallery Forest Reaches of Kings Creek. *Transactions of the Kansas Academy of Science (1903-)*, *90*(1/2), 17–24. https://doi.org/10.2307/3628107

Hopkinson, C., Chasmer, L., Barr, A. G., Kljun, N., Black, T. A., & Mccaughey, J. H. (2016). Monitoring boreal forest biomass and carbon storage change by integrating airborne laser scanning , biometry and eddy covariance data. *Remote Sensing of Environment*, *181*, 82–95. https://doi.org/10.1016/j.rse.2016.04.010

Hossain, M., Matsuishi, T., & Arhonditsis, G. (2010). Elucidation of ecosystem attributes of an oligotrophic lake in Hokkaido, Japan, using Ecopath with Ecosim (EwE). *Ecological Modelling*, *221*(13–14), 1717–1730. https://doi.org/10.1016/j.ecolmodel.2010.03.025

Huang, G., & Li, Y. (2015). Phenological transition dictates the seasonal dynamics of ecosystem carbon exchange in a desert steppe. *Journal of Vegetation Science*, *26*(2), 337–347. https://doi.org/10.1111/jvs.12236

Huang, W., McDowell, W. H., Zou, X., Ruan, H., Wang, J., & Li, L. (2013). Dissolved organic carbon in headwater streams and riparian soil organic carbon along an altitudinal gradient in the Wuyi Mountains, China. *PLoS ONE*, *8*(11), 1–8.

https://doi.org/10.1371/journal.pone.0078973

Huang, Y.-H., Lee, C.-L., Chung, C.-Y., Hsiao, S.-C., & Lin, H.-J. (2015). Carbon budgets of multispecies seagrass beds at Dongsha Island in the South China Sea. *Marine Environmental Research*, *106*, 92–102. https://doi.org/10.1016/j.marenvres.2015.03.004

Huettel, M., Berg, P., & Kostka, J. E. (2014). Benthic exchange and biogeochemical cycling in permeable sediments. *Annual Review of Marine Science*, *6*, 23–51. https://doi.org/10.1146/annurev-marine-051413-012706

Huryn, A. D., Benstead, J. P., & Parker, S. M. (2014). Seasonal changes in light availability modify the temperature dependence of ecosystem metabolism in an arctic stream. *Ecology*, *95*(10), 2840–2850. https://doi.org/10.1890/13-1963.1

Huryn, A. D., Slavik, K. A., Lowe, R. L., Parker, S. M., Anderson, D. S., & Peterson, B. J. (2005). Landscape heterogeneity and the biodiversity of Arctic stream communities: a habitat template analysis. *Canadian Journal of Fisheries and Aquatic Sciences*, *62*, 1905–1919. https://doi.org/10.1139/f05-100

Hussain, M. Z., Grünwald, T., Tenhunen, J. D., Li, Y. L., Mirzae, H., Bernhofer, C., … Owen, K. (2011). Summer drought influence on CO2 and water fluxes of extensively managed grassland in Germany. *Agriculture, Ecosystems & Environment*, *141*, 67–76. https://doi.org/10.1016/j.agee.2011.02.013

Hutchens, J. J., & Wallace, J. B. (2002). Ecosystem linkages between southern Appalachian headwater streams and their banks: Leaf litter breakdown and invertebrate assemblages. *Ecosystems*, *5*(1), 80–91. https://doi.org/10.1007/s10021-

001-0057-5

Hutley, L. B., Leuning, R., Beringer, J., & Cleugh, H. A. (2005). The utility of the eddy covariance techniques as a tool in carbon accounting: Tropical savanna as a case study. *Australian Journal of Botany*, *53*(7), 663–675. https://doi.org/10.1071/BT04147

Hutyra, L. R., Munger, J. W., Saleska, S. R., Gottlieb, E., Daube, B. C., Dunn, A. L., … Wofsy, S. C. (2007). Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. *Journal of Geophysical Research: Biogeosciences*, *112*(3), 1–16. https://doi.org/10.1029/2006JG000365

Iglesias, M. del R., Barchuk, A., & Grilli, M. P. (2012). Carbon storage, community structure and canopy cover: A comparison along a precipitation gradient. *Forest Ecology and Management*, *265*, 218–229. https://doi.org/10.1016/j.foreco.2011.10.036

Igushi, N., Iizumi, H., & Itano, H. (2010). Decomposition rate of the giant jellyfish Nemopilema nomurai in Sado Island. 海と空, *86*(1), 1-10 (in Japanese with English abstract).

Irons III, J. G., & Oswood, M. W. (1997). Organic matter dynamics in 3 subarctic streams of interior Alaska, USA. *Journal of the North American Benthological Society*, *16*(1), 23–28. https://doi.org/10.2307/1468226

Irons III, J. G., Oswood, M. W., Stout, R. J., & Pringle, C. M. (1994). Latitudinal patterns in leaf litter breakdown: Is temperature really important? *Freshwater Biology*, *32*(2), 401–411. https://doi.org/10.1111/j.1365-2427.1994.tb01135.x

Iversen, T. M. (1988). Secondary production and trophic relationships in a spring invertebrate community. *Limnology and Oceanography*, *33*(4), 582–592. https://doi.org/10.4319/lo.1988.33.4.0582

Iwata, T. (2007). Linking stream habitats and spider distribution: Spatial variations in trophic transfer across a forest-stream boundary. *Ecological Research*, *22*(4), 619–628. https://doi.org/10.1007/s11284-006-0060-6

Jackson, J. K., & Fisher, S. G. (1986). Secondary production, emergence, and export of aquatic insects of a Sonoran desert stream. *Ecology*, *67*(3), 629–638. https://doi.org/10.2307/1937686

Janjua, M. Y., & Gerdeaux, D. (2009). Preliminary trophic network analysis of subalpine Lake Annecy (France) using an Ecopath model. *Knowledge and Management of Aquatic Ecosystems*, *392*(2), 1–18. https://doi.org/10.1051/kmae/2009008

Jantze, E. J., Laudon, H., Dahlke, H. E., & Lyon, S. W. (2015). Spatial variability of dissolved organic and inorganic carbon in sub-arctic headwater streams. *Arctic, Antarctic, and Alpine Research*, *47*(3), 529–546. https://doi.org/10.1657/AAAR0014-044

Jarvis, P., Rey, A., Petsikos, C., Wingate, L., Rayment, M., Pereira, J., … Valentini, R. (2007). Drying and wetting of Mediterranean soils stimulates decomposition and carbon dioxide emission: the “Birch effect”. *Tree Physiology*, *27*(7), 929–940. https://doi.org/10.1093/treephys/27.7.929

Jasoni, R. L., Smith, S. D., & Arnone, J. A. (2005). Net ecosystem CO2 exchange in Mojave Desert shrublands during the eighth year of exposure to elevated CO2.

Global Change Biology, *11*(5), 749–756. https://doi.org/10.1111/j.1365-2486.2005.00948.x

Jeyanny, V., Husni, M. H. A., Wan Rasidah, K. ., Kumar, B. S., Arifin, A., & Hisham, M. K. (2014). Carbon stocks in different carbon pools of a tropical lowland forest and a montane forest with varying topography. *Journal of Tropical Forest Science*, *26*(4), 560–571.

Jin, C., Xiao, X., Merbold, L., Arneth, A., Veenendaal, E., & Kutsch, W. L. (2013). Phenology and gross primary production of two dominant savanna woodland ecosystems in Southern Africa. *Remote Sensing of Environment*, *135*(March), 189–201. https://doi.org/10.1016/j.rse.2013.03.033

Jing, Y., Wang, A., Guan, D., Wu, J., Yuan, F., & Jin, C. (2014). Carbon dioxide fluxes over a temperate meadow in eastern Inner Mongolia, China. *Environmental Earth Sciences*, *72*(11), 4401–4411. https://doi.org/10.1007/s12665-014-3341-3

Johannsson, O. E., Dermott, R., Graham, D. M., Dahl, J. A., Scott Millard, E., Myles, D. D., & LeBlanc, J. (2000). Benthic and pelagic secondary production in lake Erie after the invasion of Dreissena spp. with implications for fish production. *Journal of Great Lakes Research*, *26*(1), 31–54. https://doi.org/10.1016/S0380-1330(00)70671-X

Johnston, N. T., Macisaac, E. A., Tschaplinski, P. J., & Hall, K. J. (2004). Effects of the abundance of spawning sockeye salmon (Oncorhynchus nerka) on nutrients and algal biomass in forested streams. *Canadian Journal of Fisheries and Aquatic Sciences*, *61*, 384–403. https://doi.org/10.1139/F03-172

Jonasson, P. M. (1992). The ecosystem of Thingvallavatn: a synthesis. *Oikos*, *64*(1–2), 405–434. https://doi.org/10.2307/3545062

Jones, J. B., Schade, J. D., Fisher, S. G., & Grimm, N. B. (1997). Organic matter dynamics in Sycamore Creek, a desert stream in Arizona, USA. *Journal of North American Benthological Society*, *16*(1), 78–82. https://doi.org/10.2307/1468238

Jonsson, A., Algesten, G., Bergström, A. K., Bishop, K., Sobek, S., Tranvik, L. J., & Jansson, M. (2007). Integrating aquatic carbon fluxes in a boreal catchment carbon budget. *Journal of Hydrology*, *334*(1–2), 141–150. https://doi.org/10.1016/j.jhydrol.2006.10.003

Jonsson, Anders, Meili, M., Bergström, A.-K., & Jansson, M. (2001). Whole-lake mineralization of allochthonous and autochthonous organic carbon in a large humic lake (Örträsket, N. Sweden). *Limnology and Oceanography*, *46*(7), 1691–1700. https://doi.org/10.4319/lo.2001.46.7.1691

Jonsson, M., Malmqvist, B., & Hoffsten, P. O. (2001). Leaf litter breakdown rates in boreal streams: Does shredder species richness matter? *Freshwater Biology*, *46*(2), 161–171. https://doi.org/10.1046/j.1365-2427.2001.00655.x

Juutinen, S., Väliranta, M., Kuutti, V., Laine, A. M., Virtanen, T., Seppä, H., … Tuittila, E. S. (2013). Short-term and long-term carbon dynamics in a northern peatland-stream-lake continuum: A catchment approach. *Journal of Geophysical Research: Biogeosciences*, *118*(1), 171–183. https://doi.org/10.1002/jgrg.20028

K'Otuto, G. O., Otieno, D. O., Onyango, J. C., & Ogindo, H. O. (2014). Seasonal dynamics in carbon dioxide fluxes of the herbaceous layer of moist Kenyan savannah. *Applied Ecology and Environmental Research*, *12*(1), 63–82. https://doi.org/10.15666/aeer/1201_063082

Kallio, P. (1975). Kevo, Finland. In: Structure and function of tundra ecosystems. *Ecological Bulletins (Stockholm)*, *20*, 193–223.

Kamruzzaman, M., Osawa, A., Deshar, R., Sharma, S., & Mouctar, K. (2017). Species composition, biomass, and net primary productivity of mangrove forest in Okukubi River, Okinawa Island, Japan. *Regional Studies in Marine Science*, *12*, 19–27. https://doi.org/10.1016/j.rsma.2017.03.004

Kankaala, P, Kaki, T., & Ojala, A. (2003). Quality of detritus impacts on spatial variation of methane emissions from littoral sediment of a boreal lake. *Archiv Fur Hydrobiologie*, *157*(1), 47–66. https://doi.org/Doi 10.1027/0003-9136/2003/0157-0047

Kankaala, Paula, Käki, T., Mäkelä, S., Ojala, A., Pajunen, H., & Arvola, L. (2005). Methane efflux in relation to plant biomass and sediment characteristics in stands of three common emergent macrophytes in boreal mesoeutrophic lakes. *Global Change Biology*, *11*(1), 145–153. https://doi.org/10.1111/j.1365-2486.2004.00888.x

Kanniah, K. D., Beringer, J., & Hutley, L. B. (2011). Environmental controls on the spatial variability of savanna productivity in the Northern Territory, Australia. *Agricultural and Forest Meteorology*, *151*(11), 1429–1439. https://doi.org/10.1016/j.agrformet.2011.06.009

Kao, Y. C., Adlerstein, S. A., & Rutherford, E. S. (2016). Assessment of Top-Down and Bottom-Up Controls on the Collapse of Alewives (Alosa pseudoharengus) in Lake

Huron. *Ecosystems*, *19*(5), 803–831. https://doi.org/10.1007/s10021-016-9969-y

Karlsson, J., Berggren, M., Ask, J., Byström, P., Jonsson, A., Laudon, H., & Jansson, M. (2012). Terrestrial organic matter support of lake food webs: Evidence from lake metabolism and stable hydrogen isotopes of consumers. *Limnology and Oceanography*, *57*(4), 1042–1048. https://doi.org/10.4319/lo.2012.57.4.1042

Katayama, A., Kume, T., Komatsu, H., Saitoh, T. M., Ohashi, M., Nakagawa, M., … Kumagai, T. (2013). Carbon allocation in a Bornean tropical rainforest without dry seasons. *Journal of Plant Research*, *126*(4), 505–515. https://doi.org/10.1007/s10265-012-0544-0

Kato, T., Tang, Y., Gu, S., Hirota, M., Du, M., Li, Y., & Zhao, X. (2006). Temperature and biomass influences on interannual changes in CO2 exchange in an alpine meadow on the Qinghai-Tibetan Plateau. *Global Change Biology*, *12*(7), 1285–1298. https://doi.org/10.1111/j.1365-2486.2006.01153.x

Kawada, K., Borjigin, W., & Nakamura, T. (2015). Agricultural Activities of a Meadow Eliminated Plant Litter from the Periphery of a Farmland in Inner Mongolia, China. *Plos One*, *10*(8), 1–13. https://doi.org/10.1371/journal.pone.0135077

Kawahigashi, M., Kaiser, K., Kalbitz, K., Rodionov, A., & Guggenberger, G. (2004). Dissolved organic matter in small streams along a gradient from discontinuous to continuous permafrost. *Global Change Biology*, *10*(9), 1576–1586. https://doi.org/10.1111/j.1365-2486.2004.08827.x

Kazanjian, G., Flury, S., Attermeyer, K., Kalettka, T., Hilt, S., Kleeberg, A., … Hilt. (2018). Primary production in nutrient-rich kettle holes and consequences for nutrient and carbon cycling. *Hydrobiologia*, *806*(1), 77–93. https://doi.org/10.1007/s10750-017-3337-6

Kendall, C., Silva, S. R., & Kelly, V. J. (2001). Carbon and nitrogen isotopic compositions of particulate organic matter in four large river systems across the United States. *Hydrological Processes*, *15*(7), 1301–1346. https://doi.org/10.1002/hyp.216

Kendrick, M. R., & Huryn, A. D. (2015). Discharge, legacy effects and nutrient availability as determinants of temporal patterns in biofilm metabolism and accrual in an arctic river. *Freshwater Biology*, *60*(11), 2323–2336. https://doi.org/10.1111/fwb.12659

Khan, D., Faheemuddin, M., Shaukat, S. S., & Alam, M. M. (2000). Seasonal variation in structure, composition, phytomass, and net primary productivity in a Lasiurus scindicus Henr., and Cenchrus setigerus Vahl., dominated dry sandy desert site of Karachi. *Pakistan Journal of Botany*, *32*(1), 171–210.

Kim, S., Kaplan, L. A., & Hatcher, P. G. (2006). Biodegradable dissolved organic matter in a temperate and a tropical stream determined from ultra-high resolution mass spectrometry. *Limnology and Oceanography*, *51*(2), 1054–1063. https://doi.org/10.4319/lo.2006.51.2.1054

Kirchman, D. L., Keel, R. G., Simon, M., & Welschmeyer, N. A. (1993). Biomass and production of heterotrophic bacterioplankton in the oceanic subarctic Pacific. *Deep Sea Research Part I: Oceanographic Research Papers*, *40*(5), 967–988. https://doi.org/10.1016/0967-0637(93)90084-G

Kitayama, K., & Aiba, S. (2002). Ecosystem structure and productivity of tropical rain forests along altitudinal gradients with contrasting soil phosphorus pools on Mount Kinabalu, Borneo. *Journal of Ecology*, *90*, 37–51. https://doi.org/0.1046/j.0022-0477.2001.00634.x

Kling, G. W., Kipphut, G. W., & Miller, M. C. (1991). Arctic lakes and streams as gas conduits to the atmosphere: implications for tundra carbon budgets. *Science*, *251*(4991), 298–301. https://doi.org/10.1126/science.251.4991.298

Kljun, N., Black, T. A., Griffis, T. J., Barr, A. G., Gaumont-Guay, D., Morgenstern, K., … Nesic, Z. (2007). Response of net ecosystem productivity of three boreal forest stands to drought. *Ecosystems*, *10*(6), 1039–1055. https://doi.org/DOI 10.1007/s10021-007-9088-x

Koch, M. S., & Madden, C. J. (2001). Patterns of primary production and nutrient availability in a Bahamas lagoon with fringing mangroves. *Marine Ecology Progress Series*, *219*(1998), 109–119. https://doi.org/10.3354/meps219109

Kolari, P., Pumpanen, J., Rannik, U., Ilvesniemi, H., Hari, P., Berninger, F., … Box, P. O. (2004). Carbon balance of different aged Scots pine forests in. *Global Change Biology*, *10*(7), 1106–1119. https://doi.org/10.1111/j.1365-2486.2004.00797.x

Koprivnjak, J.-F., & Moore, T. R. (1992). Sources, sinks, and fluxes of dissolved organic carbon in subarctic fen catchments. *Arctic and Alpine Research*, *24*(3), 204–210. https://doi.org/10.2307/1551658

Koschel, R. H., Gonsiorczyk, T., Krienitz, L., Padisák, J., & Scheffler, W. (2002). Primary production of phytoplankton and nutrient metabolism during and after thermal pollution in a deep , oligotrophic lowland lake (Lake Stechlin , Germany). *Internationale Vereinigung Für Theoretische Und Angewandte Limnologie: Verhandlungen*, *28*(2), 569–575. https://doi.org/10.1080/03680770.2001.11901781

Kosolapov, D. B., Kopylov, A. I., Kosolapova, N. G., & Mylnikova, Z. M. (2017). Structure and functioning of the microbial loop in a boreal reservoir. *Inland Water Biology*, *10*(1), 28–36. https://doi.org/10.1134/S1995082917010102

Kosugi, Y., Tanaka, H., Takanashi, S., Matsuo, N., Ohte, N., Shibata, S., & Tani, M. (2005). Three years of carbon and energy fluxes from Japanese evergreen broad-leaved forest. *Agricultural and Forest Meteorology*, *132*(3–4), 329–343. https://doi.org/10.1016/j.agrformet.2005.08.010

Koukoura, Z., Mamolos, A. P., & Kalburtji, K. L. (2003). Decomposition of dominant plant species litter in a semi-arid grassland. *Applied Soil Ecology*, *23*(1), 13–23. https://doi.org/10.1016/S0929-1393(03)00006-4

Kuhry, P., Mazhitova, G., Forest, P., Deneva, S., Virtanen, T., & Kultti, S. (2002). Upscaling soil organic carbon estimates for the Usa Basin (Northeast European Russia) using GIS-based landcover and soil classification schemes. *Geografisk Tidsskrift, Danish Journal of Geography*, *102*(1), 11–25. https://doi.org/10.1080/00167223.2002.10649462

Kumada, S., Kawanishi, T., Hayashi, Y., Ogomori, K., Kobayashi, Y., Takahashi, N., … Yamada, K. (2008). Litter carbon dynamics analysis in forests in an arid ecosystem with a model incorporating the physical removal of litter. *Ecological Modelling*, *215*(1–3), 190–199. https://doi.org/10.1016/j.ecolmodel.2008.02.022

Kurz, W. A., & Apps, M. J. (1999). A 70-year retrospective analysis of carbon fluxes in the Canadian Forest Sector. *Ecological Applications*, *9*(2), 526–547. https://doi.org/10.1890/1051-0761(1999)009[0526:AYRAOC]2.0.CO;2

Kutsch, W. L., Liu, C., Hörmann, G., & Herbst, M. (2005). Spatial heterogeneity of ecosystem carbon fluxes in a broadleaved forest in Northern Germany. *Global Change Biology*, *11*(1), 70–88. https://doi.org/10.1111/j.1365-2486.2004.00884.x

La Ferla, R., Azzaro, F., Azzaro, M., Caruso, G., Decembrini, F., Leonardi, M., … D’Alcalà, R. M. (2005). Microbial contribution to carbon biogeochemistry in the Central Mediterranean Sea: Variability of activities and biomass. *Journal of Marine Systems*, *57*(1–2), 146–166. https://doi.org/10.1016/j.jmarsys.2005.05.001

La Ferla, R., Azzaro, M., & Maimone, G. (2006). Microbial respiration and trophic regimes in the Northern Adriatic Sea (Mediterranean Sea). *Estuarine, Coastal and Shelf Science*, *69*(1–2), 196–204. https://doi.org/10.1016/j.ecss.2006.04.005

Laasonen, P., Muotka, T., & Kivijarvi, I. (1998). Recovery of macroinvertebrate communities from stream habitat restoration. *Aquatic Conservation-Marine and Freshwater Ecosystems*, *8*(1), 101–113. https://doi.org/10.1002/(sici)1099-0755(199801/02)8:1<101::aid-aqc251>3.0.co;2-4

Lamoureux, S. F., & Lafrenière, M. J. (2014). Seasonal fluxes and age of particulate organic carbon exported from Arctic catchments impacted by localized permafrost slope disturbances. *Environmental Research Letters*, *9*(4), 045002. https://doi.org/10.1088/1748-9326/9/4/045002

Lang, S. I., Cornelissen, J. H. C., Klahn, T., Van Logtestijn, R. S. P., Broekman, R., Schweikert, W., & Aerts, R. (2009). An experimental comparison of chemical traits and litter decomposition rates in a diverse range of subarctic bryophyte, lichen and vascular plant species. *Journal of Ecology*, *97*(5), 886–900. https://doi.org/10.1111/j.1365-2745.2009.01538.x

Larned, S. T., Eldridge, P. M., & Kinzie, R. A. (2008). Modeling C and N flows through a stream food web: an inverse approach. *Journal of the North American Benthological Society*, *27*(3), 674–689. https://doi.org/10.1899/07-134.1

Larouche, J. R. (2015). *Thermokarst and wildfire: Effects of disturbances related to climate change on the ecological characteristics and functions of arctic headwater streams*. University of Vermont.

Laubach, J., Hunt, J. E., Graham, S. L., Buxton, R. P., Rogers, G. N. D., Mudge, P. L., … Whitehead, D. (2019). Irrigation increases forage production of newly established lucerne but enhances net ecosystem carbon losses. *Science of the Total Environment*, *689*, 921–936. https://doi.org/10.1016/j.scitotenv.2019.06.407

Laudon, H., Berggren, M., Ågren, A., Buffam, I., Bishop, K., Grabs, T., … Köhler, S. (2011). Patterns and dynamics of Dissolved Organic Carbon (DOC) in boreal streams: The role of processes, connectivity, and scaling. *Ecosystems*, *14*(6), 880–893. https://doi.org/10.1007/s10021-011-9452-8

Lee, K. (2001). Global net community production estimated from the annual cycle of surface water total dissolved inorganic carbon. *Limnology and Oceanography*, *46*(6), 1287–1297. https://doi.org/10.4319/lo.2001.46.6.1287

LeRoy, C. J., & Marks, J. C. (2006). Litter quality, stream characteristics and litter diversity influence decomposition rates and macroinvertebrates. *Freshwater Biology*, *51*(4), 605–617. https://doi.org/10.1111/j.1365-2427.2006.01512.x

Li, X., Meixner, T., Sickman, J. O., Miller, A. M. Y. E., Schimel, J. P., & Melack, J. M. (2006). Decadal-scale dynamics of water, carbon and nitrogen in a California chaparral ecosystem : DAYCENT modeling results. *Biogeochemistry*, *77*(3), 217–245. https://doi.org/10.1007/s10533-005-1391-z

Lian, P. Y., Zeng, D. H., Liu, J. Y., Ding, F., & Wu, Z. W. (2011). Impact of Land-Use Change on Carbon Stocks in Meadow Steppe of Northeast China. *Applied Mechanics and Materials*, *108*, 262–268. https://doi.org/10.4028/www.scientific.net/AMM.108.262

Liboriussen, L., & Jeppesen, E. (2003). Temporal dynamics in epipelic, pelagic and epiphytic algal production in a clear and a turbid shallow lake. *Freshwater Biology*, *48*, 418–431. https://doi.org/10.1046/j.1365-2427.2003.01018.x

Limin, A., Shimizu, M., Mano, M., Ono, K., Miyata, A., Wada, H., … Hatano, R. (2015). Manure application has an effect on the carbon budget of a managed grassland in southern Hokkaido, Japan. *Soil Science and Plant Nutrition*, *61*(5), 856–872. https://doi.org/10.1080/00380768.2015.1051930

Lin, H.-J., Peng, T.-R., Cheng, I.-C., Chen, L.-W., Kuo, M.-H., Tzeng, C.-S., … Kao, S.-J. (2012). Trophic model of the subtropical headwater stream habitat of formosan landlocked salmon Oncorhynchus formosanus. *Aquatic Biology*, *17*(3), 269–283. https://doi.org/10.3354/ab00481

Lin, H., Shao, K., Hwang, J., Lo, W., Cheng, I., & Lee, L. (2004). A trophic model for

Kuosheng bay in northern Taiwan. *Journal of Marine Science and Technology*, *12*(5), 424–432.

Lin, H., Shao, K., Jan, R., Hsieh, H., Chen, C., Hsieh, L., & Hsiao, Y. (2007). A trophic model for the Danshuei River Estuary, a hypoxic estuary in northern Taiwan. *Marine Pollution Bulletin*, *54*, 1789–1800. https://doi.org/10.1016/j.marpolbul.2007.07.008

Lindeboom, H. J., & Sandee, A. J. J. (1989). Production and consumption of tropical seagrass fields in Eastern Indonesia measured with bell jars and microelectrodes. *Netherlands Journal of Sea Research*, *23*(2), 181–190. https://doi.org/10.1016/0077-7579(89)90012-4

Liu, R., Cieraad, E., Li, Y., & Ma, J. (2016). Precipitation Pattern Determines the Inter-annual Variation of Herbaceous Layer and Carbon Fluxes in a Phreatophyte-Dominated Desert Ecosystem. *Ecosystems*, *19*(4), 601–614. https://doi.org/10.1007/s10021-015-9954-x

Liu, R., Li, Y., Wang, Q., Xu, H., & Zheng, X. (2011). Seasonal and annual variations of carbon dioxide fluxes in desert ecosystem. *Journal of Desert Research*, *1*.

Logue, J. B., Robinson, C. T., Meier, C., & Van der Meer, J. R. (2004). Relationship between sediment organic matter, bacteria composition, and the ecosystem metabolism of alpine streams. *Limnology and Oceanography*, *49*(6), 2001–2010. https://doi.org/10.4319/lo.2004.49.6.2001

Long, S. P., Garcia Moya, E., Imbamba, S. K., Kamnalrut, A., Piedade, M. T. F., Scurlock, J. M. O., … Hall, D. O. (1989). Primary productivity of natural grass ecosystems of the tropics: A reappraisal. *Plant and Soil*, *115*(2), 155–166. https://doi.org/10.1007/BF02202584

Loranger, G., Ponge, J. F., Imbert, D., & Lavelle, P. (2002). Leaf decomposition in two semi-evergreen tropical forests: Influence of litter quality. *Biology and Fertility of Soils*, *35*(4), 247–252. https://doi.org/10.1007/s00374-002-0467-3

Lorion, C. M., & Kennedy, B. P. (2009). Riparian forest buffers mitigate the effects of deforestation on fish assemblages in tropical headwater streams. *Ecological Applications*, *19*(2), 468–479. https://doi.org/10.1890/08-0050.1

Lugthart, G. J., & Wallace, J. B. (1992). Effects of disturbance on benthic functional structure and production in mountain streams. *Journal of the North American Benthological Society*, *11*(2), 138–164. https://doi.org/10.2307/1467381

Lund, M., Falk, J. M., Friborg, T., Mbufong, H. N., Sigsgaard, C., Soegaard, H., & Tamstorf, M. P. (2012). Trends in CO2 exchange in a high Arctic tundra heath, 2000-2010. *Journal of Geophysical Research: Biogeosciences*, *117*(2), 2000–2010. https://doi.org/10.1029/2011JG001901

Luyssaert, S., Inglima, I., Jung, M., Richardson, A. D., Reichstein, M., Papale, D., … Janssens, I. A. (2007). CO2 balance of boreal, temperate, and tropical forests derived from a global database. *Global Change Biology*, *13*(12), 2509–2537. https://doi.org/10.1111/j.1365-2486.2007.01439.x CO2

Ma, A., He, N., Yu, G., Wen, D., & Peng, S. (2016). Carbon storage in Chinese grassland ecosystems: Influence of different integrative methods. *Scientific Reports*, *6*, 21378. https://doi.org/10.1038/srep21378

Ma, S., Baldocchi, D. D., Xu, L., & Hehn, T. (2007). Inter-annual variability in carbon dioxide exchange of an oak/grass savanna and open grassland in California. *Agricultural and Forest Meteorology*, *147*(3–4), 157–171. https://doi.org/10.1016/j.agrformet.2007.07.008

MacKenzie, R. A. (2008). Impacts of riparian forest removal on Palauan streams. *Biotropica*, *40*(6), 666–675. https://doi.org/10.1111/j.1744-7429.2008.00433.x

Madsen, J. D., & Adams, M. S. (1988). The seasonal biomass and productivity of the submerged macrophytes in a polluted Wisconsin stream. *Freshwater Biology*, *20*, 41–50. https://doi.org/10.1111/j.1365-2427.1988.tb01715.x

Malhi, Y., Aragão, L. E. O. C., Metcalfe, D. B., Paiva, R., Quesada, C. A., Almeida, S., … Teixeira, L. M. (2009). Comprehensive assessment of carbon productivity, allocation and storage in three Amazonian forests. *Global Change Biology*, *15*(5), 1255–1274. https://doi.org/10.1111/j.1365-2486.2008.01780.x

Malhi, Y., Farfán Amézquita, F., Doughty, C. E., Silva-Espejo, J. E., Girardin, C. A. J., Metcalfe, D. B., … Phillips, O. L. (2014). The productivity, metabolism and carbon cycle of two lowland tropical forest plots in south-western Amazonia, Peru. *Plant Ecology & Diversity*, *7*(1–2), 85–105. https://doi.org/10.1080/17550874.2013.820805

Malhi, Y., Girardin, A. J., Goldsmith, G. R., Doughty, C. E., Salinas, N., Metcalfe, D. B., … Silman, M. (2017). The variation of productivity and its allocation along a tropical elevation gradient : a whole carbon budget perspective. *New Phytologist*, *214*, 1019–1032. https://doi.org/10.1111/nph.14189

Manickchand-Heileman, S., Soto, L. A., & Escobar, E. (1998). A preliminary trophic model of the continental shelf, south- western Gulf of Mexico. *Estuarine Coastal and Shelf Science*, *46*(6), 885–899. https://doi.org/10.1006/ecss.1997.0324

Mannino, A., Signorini, S., Novak, M., Wilkin, J., Friedrichs, M. A. M., & Najjar, R. G. (2015). Dissolved Organic Carbon Fluxes in the Middle Atlantic Bight: An integrated approach based on satellite data and ocean model products. *Journal of Geophysical Research: Biogeosciences*, *121*, 1–25. https://doi.org/10.1002/2015JG003031

Mariash, H. L., Devlin, S. P., Forsström, L., Jones, R. I., & Rautio, M. (2014). Benthic mats offer a potential subsidy to pelagic consumers in tundra pond food webs. *Limnology and Oceanography*, *59*(3), 733–744. https://doi.org/10.4319/lo.2014.59.3.0733

Marra, J., & Heinemann, K. R. (1987). Primary production in the North Pacific Central Gyre: some new measurements based on 14C. *Deep Sea Research Part A. Oceanographic Research Papers*, *34*(11), 1821–1829. https://doi.org/10.1016/0198-0149(87)90056-2

Martens, H., Alphei, J., Schaefer, M., & Scheu, S. (2001). Millipedes and earthworms increase the decomposition rate of 15N-labelled winter rape litter in an arable field. *Isotopes in Environmental and Health Studies*, *37*(1), 43–51. https://doi.org/10.1080/10256010108033280

Martí, E., Fonollà, P., Von Schiller, D., Sabater, F., Argerich, A., Ribot, M., & Riera, J. L. (2009). Variation in stream C, N and P uptake along an altitudinal gradient: a space-for-time analogue to assess potential impacts of climate change. *Hydrology Research*, *40*(2–3), 123–137. https://doi.org/10.2166/nh.2009.090

Martin, D. B., & Arneson, R. D. (1978). Comparative limnology of a deep-discharge reservoir and a surface-discharge lake on the Madison River, Montana. *Freshwater Biology*, *8*(1), 33–42. https://doi.org/10.1111/j.1365-2427.1978.tb01423.x

Martínez-Yrízar, A., Núñez, S., & Búrquez, A. (2007). Leaf litter decomposition in a southern Sonoran Desert ecosystem, northwestern Mexico: Effects of habitat and litter quality. *Acta Oecologica*, *32*(3), 291–300. https://doi.org/10.1016/j.actao.2007.05.010

Martinsen, K. T., Andersen, M. R., Kragh, T., & Sand-Jensen, K. (2017). High rates and close diel coupling of primary production and ecosystem respiration in small , oligotrophic lakes. *Aquatic Sciences*, *79*(4), 995–1007. https://doi.org/10.1007/s00027-017-0550-3

Marxsen, J. (2006). Bacterial production in the carbon flow of a central European stream, the Breitenbach. *Freshwater Biology*, *51*(10), 1838–1861. https://doi.org/10.1111/j.1365-2427.2006.01620.x

Maselli, F., Vaccari, F. P., Chiesi, M., Romanelli, S., & Acqui, L. P. D. (2017). Modelling and analyzing the water and carbon dynamics of Mediterranean macchia by the use of ground and remote sensing data. *Ecological Modelling*, *351*, 1–13. https://doi.org/10.1016/j.ecolmodel.2017.02.012

Masese, F. O., Gretchen, J. S. S., Kenneth, M. G., & Mcclain, M. E. (2017). Influence of catchment land use and seasonality on dissolved organic matter composition and ecosystem metabolism in headwater streams of a Kenyan river. *Biogeochemistry*, *132*(1), 1–22. https://doi.org/10.1007/s10533-016-0269-6

Mathur, M., & Sundaramoorthy, S. (2016). Patterns of herbaceous species richness and productivity along gradients of soil moisture and nutrients in the Indian Thar Desert. *Journal of Arid Environments*, *125*, 80–87. https://doi.org/10.1016/j.jaridenv.2015.10.011

Mathuriau, C. C., & Chauvet, E. (2002). Breakdown of leaf litter in a neotropical stream. *Journal of the North American Benthological Society*, *21*(3), 384–396. https://doi.org/10.2307/1468477

Mathuriau, C., Thomas, A. G. B., & Chauvet, E. (2008). Seasonal dynamics of benthic detritus and associated macroinvertebrate communities in a neotropical stream. *Fundamental and Applied Limnology Archiv Für Hydrobiologie*, *171*(4), 323–333. https://doi.org/10.1127/1863-9135/2008/0171-0323

Matsuura, S., Miyata, A., Mano, M., Hojito, M., Mori, A., Kano, S., … Hatano, R. (2014). Seasonal carbon dynamics and the effects of manure application on carbon budget of a managed grassland in a temperate, humid region in Japan. *Grassland Science*, *60*(2), 76–91. https://doi.org/10.1111/grs.12042

Matteucci, M., Gruening, C., Ballarin, I. G., Seufert, G., Cescatti, A., Goded Ballarin, I., … Cescatti, A. (2015). Components, drivers and temporal dynamics of ecosystem respiration in a Mediterranean pine forest. *Soil Biology and Biochemistry*, *88*, 224–235. https://doi.org/10.1016/j.soilbio.2015.05.017

Mbaka, J. G., M'Erimba, C. M., & Mathooko, J. M. (2014). Impacts of benthic coarse particulate organic matter variations on macroinvertebrate density and diversity in the Njoro River, A Kenyan highland stream. *Journal of East African Natural History*, *103*(1), 39–48. https://doi.org/10.2982/028.103.0101

McCulley, R. L., Burke, I. C., Nelson, J. A., Lauenroth, W. K., Knapp, A. K., & Kelly, E. F. (2005). Regional patterns in carbon cycling across the Great Plains of North America. *Ecosystems*, *8*(1), 106–121. https://doi.org/10.1007/s10021-004-0117-8

McKinley, V. L., & Vestal, J. R. (1982). Effects of acid on plant litter decomposition in an arctic lake. *Applied and Environmental Microbiology*, *43*(5), 1188–1195.

McKnight, D. M., & Tate, C. M. (1997). Canada stream: a glacial meltwater stream in taylor valley, south victoria land, Antarctica. *Journal of the North American Benthological Society*, *16*(1), 14–17. https://doi.org/10.2307/1468224

McLaughlin, C., & Kaplan, L. A. (2013). Biological lability of dissolved organic carbon in stream water and contributing terrestrial sources. *Freshwater Science*, *32*(4), 1219–1230. https://doi.org/10.1899/12-202.1

Meirelles, M. L., Bracho, R., & Ferreira, E. A. B. (2015). Carbon dioxide exchange in a tropical wet grassland. *Wetlands Ecology and Management*, *23*(5), 817–826. https://doi.org/10.1007/s11273-015-9421-7

Mejia, F. H., Fremier, A. K., Benjamin, J. R., Bellmore, J. R., Grimm, A. Z., Watson, G. A., & Newsom, M. (2019). Stream metabolism increases with drainage area and peaks asynchronously across a stream network. *Aquatic Sciences*, *81*(1), 1–17. https://doi.org/10.1007/s00027-018-0606-z

Menéndez, M. (2009). Response of early Ruppia cirrhosa litter breakdown to nutrient addition in a coastal lagoon affected by agricultural runoff. *Estuarine, Coastal and Shelf Science*, *82*(4), 608–614. https://doi.org/10.1016/j.ecss.2009.02.029

Merritt, R. W., & Lawson, D. L. (1992). The role of leaf litter macroinvertebrates in stream-floodplain dynamics. *Hydrobiologia*, *248*(1), 65–77. https://doi.org/10.1007/BF00008886

Meyer, J. L., & Johnson, C. (1983). The influence of elevated nitrate concentration on rate of leaf decomposition in a stream. *Freshwater Biology*, *13*(2), 177–183. https://doi.org/10.1111/j.1365-2427.1983.tb00669.x

Meyers, P. A., & Eadie, B. J. (1993). Sources, degradation and recycling of organic matter associated with sinking particles in Lake Michigan. *Organic Geochemistry*, *20*(1), 47–56. https://doi.org/10.1016/0146-6380(93)90080-U

Mielnick, P. C., & Dugas, W. A. (2000). Soil CO2 flux in a tallgrass prairie. *Soil Biology & Biochemistry*, *32*(2), 221–228. https://doi.org/10.1016/S0038-0717(99)00150-9

Miller, S. D., Goulden, M. L., Menton, M. C., Rocha, H. R., Freitas, H. C. De, Michela, A., … Sousa, D. De. (2014). Biometric and Micrometeorological Measurements of Tropical Forest Carbon Balance. *Ecological Applications*, *14*(4), 114–126.

Mineau, M. M., Baxter, C. V., Marcarelli, A. M., Minshall, W. G., & G. Wayne Minshall. (2012). An invasive riparian tree reduces stream ecosystem efficiency via a recalcitrant organic matter subsidy. *Ecology*, *93*(7), 1501–1508. https://doi.org/10.1890/11-1700.1

Minshall, G. W. (1978). Autotrophy in Stream Ecosystems. *BioScience*, *28*(12), 767–771. https://doi.org/10.2307/1307250

Mitchell, S. R., Emanuel, R. E., & McGlynn, B. L. (2015). Land-atmosphere carbon and water flux relationships to vapor pressure deficit, soil moisture, and stream flow. *Agricultural and Forest Meteorology*, *208*, 108–117. https://doi.org/10.1016/j.agrformet.2015.04.003

Miyajima, T., Hori, M., Hamaguchi, M., Shimabukuro, H., Adachi, H., Yamano, H., & Nakaoka, M. (2015). Geographic variability in organic carbon stock and accumulation rate in sediments of East and Southeast Asian seagrass meadows. *Global Biogeochemical Cycles*, *29*, 379–415. https://doi.org/10.1002/2014GB004979

Miyajima, T., Koike, I., Yamano, H., & Iizumi, H. (1998). Accumulation and transport of seagrass-derived organic matter in reef flat sediment of Green Island, Great Barrier Reef. *Marine Ecology Progress Series*, *175*, 251–259. https://doi.org/10.3354/meps175251

Mlambo, D., & Nyathi, P. (2008). Litterfall and nutrient return in a semi-arid southern African savanna woodland dominated by Colophospermum mopane. *Plant Ecology*, *196*(1), 101–110. https://doi.org/10.1007/s11258-007-9337-2

Möller, A., Kaiser, K., & Guggenberger, G. (2005). Dissolved organic carbon and nitrogen in precipitation, throughfall, soil solution, and stream water of the tropical highlands in northern Thailand. *Journal of Plant Nutrition and Soil Science*, *168*(5), 649–659. https://doi.org/10.1002/jpln.200521804

Monaco, M. E., & Ulanowicz, R. E. (1997). Comparative ecosystem trophic structure of three US mid-Atlantic estuaries. *Marine Ecology Progress Series*, *161*, 239–254.

https://doi.org/10.3354/meps161239

Montero, P., Daneri, G., González, H. E., Iriarte, J. L., Tapia, F. J., Lizárraga, L., … Pizarro, O. (2011). Seasonal variability of primary production in a fjord ecosystem of the Chilean Patagonia: Implications for the transfer of carbon within pelagic food webs. *Continental Shelf Research*, *31*(3–4), 202–215. https://doi.org/10.1016/j.csr.2010.09.003

Moore, C. E., Beringer, J., Evans, B., Hutley, L. B., McHugh, I., & Tapper, N. J. (2016). The contribution of trees and grasses to productivity of an Australian tropical savanna. *Biogeosciences*, *13*(8), 2387–2403. https://doi.org/10.5194/bg-13-2387-2016

Morales-Zárate, M. V., Arreguín-Sánchez, F., López-Martínez, J., & Lluch-Cota, S. E. (2004). Ecosystem trophic structure and energy flux in the Northern Gulf of California, México. *Ecological Modelling*, *174*(4), 331–345. https://doi.org/10.1016/j.ecolmodel.2003.09.028

Morgner, E., Elberling, B., Strebel, D., & Cooper, E. J. (2010). The importance of winter in annual ecosystem respiration in the High Arctic: effects of snow depth in two vegetation types. *Polar Research*, *29*(1), 58–74. https://doi.org/10.1111/j.1751-8369.2010.00151.x

Mulholland, P. J. (1997). Organic matter dynamics in the west fork of Walker Branch, Tennessee, USA. *Journal of the North American Benthological Society*, *16*(1), 61–67. https://doi.org/10.2307/1468235

Mulholland, Patrick J. (1981). Organic carbon flow in a swamp-stream ecosystem.

Ecological Monographs, *51*(3), 307–322. https://doi.org/10.2307/2937276

Mulholland, Patrick J., Fellows, C. S., Tank, J. L., Grimm, N. B., Webster, J. R., Hamilton, S. K., … Peterson, B. J. (2001). Inter-biome comparison of factors controlling stream metabolism. *Freshwater Biology*, *46*, 1503–1517. https://doi.org/10.1017/CBO9781107415324.004

Mungai, N. W., & Motavalli, P. P. (2006). Litter quality effects on soil carbon and nitrogen dynamics in temperate alley cropping systems. *Applied Soil Ecology*, *31*(1–2), 32–42. https://doi.org/10.1016/j.apsoil.2005.04.009

Muto, E. A., Kreutzweiser, D. P., & Sibley, P. K. (2011). Over-winter decomposition and associated macroinvertebrate communities of three deciduous leaf species in forest streams on the Canadian boreal shield. *Hydrobiologia*, *658*(1), 111–126. https://doi.org/10.1007/s10750-010-0455-9

Myers-Pigg, A. N., Louchouarn, P., Amon, R. M. W., Prokushkin, A., Pierce, K., & Rubtsov, A. (2015). Labile pyrogenic dissolved organic carbon in major Siberian Arctic rivers: Implications for wildfire-stream metabolic linkages. *Geophysical Research Letters*, *42*(2), 377–385. https://doi.org/10.1002/2014GL062762

Naiman, R. J., & Link, G. L. (1997). Organic matter dynamics in 5 subarctic streams, Quebec, Canada. *Journal of the North American Benthological Society*, *16*(1), 33–39.

Naiman, R. J., Melillo, J. M., & Hobbie, J. E. (1986). Ecosystem alteration of boreal forest streams by beaver (Castor canadensis). *Ecology*, *67*(5), 1254–1269. https://doi.org/10.2307/1938681

Naiman, R. J., Melillo, J. M., Lock, M. A., Ford, T. E., & Reice, S. R. (1987). Longitudinal patterns of ecosystem processes and community structure in a subartic river continuum. *Ecology*, *68*(5), 1139–1156. https://doi.org/10.2307/1939199

Nakano, T., & Shinoda, M. (2015). Modeling gross primary production and ecosystem respiration in a semiarid grassland of Mongolia. *Soil Science and Plant Nutrition*, *61*(1), 106–115. https://doi.org/10.1080/00380768.2014.966043

Natali, S. M., Schuur, E. A. G., Webb, E. E., Pries, C. E. H., & Crummer, K. G. (2014). Permafrost degradation stimulates carbon loss from experimentally warmed tundra. *Ecology*, *95*(3), 602–608. https://doi.org/10.1890/13-0602.1

Naumann, M. S., Jantzen, C., Haas, A. F., Iglesias-Prieto, R., & Wild, C. (2013). Benthic primary production budget of a Caribbean reef lagoon (Puerto Morelos, Mexico). *PLoS ONE*, *8*(12), e82923. https://doi.org/10.1371/journal.pone.0082923

Naumann, M. S., Richter, C., Mott, C., El-Zibdah, M., Manasrah, R., & Wild, C. (2012). Budget of coral-derived organic carbon in a fringing coral reef of the Gulf of Aqaba, Red Sea. *Journal of Marine Systems*, *105–108*, 20–29. https://doi.org/10.1016/j.jmarsys.2012.05.007

Ndagurwa, H. G. T., Dube, J. S., & Mlambo, D. (2015). Decomposition and nutrient release patterns of mistletoe litters in a semi-arid savanna, southwest Zimbabwe. *Austral Ecology*, *40*(2), 178–185. https://doi.org/10.1111/aec.12191

Ng, B. J. L., Hutyra, L. R., Nguyen, H., Cobb, A. R., Kai, F. M., Harvey, C., & Gandois, L. (2015). Carbon fluxes from an urban tropical grassland. *Environmental Pollution*, *203*, 227–234. https://doi.org/10.1016/j.envpol.2014.06.009

Nõges, T., Luup, H., & Feldmann, T. (2010). Primary production of aquatic macrophytes and their epiphytes in two shallow lakes (Peipsi and Võrtsjärv) in Estonia. *Aquatic Ecology*, *44*(1), 83–92. https://doi.org/10.1007/s10452-009-9249-4

Nyirambangutse, B., Zibera, E., K. Uwizeye, F., Nsabimana, D., Bizuru, E., Pleijel, H., … Wallin, G. (2016). Carbon stocks and dynamics at different successional stages in an Afromontane tropical forest. *Biogeosciences Discussions*, *14*, 1285–1303. https://doi.org/10.5194/bg-14-1285-2017

O'Brien, J. M., Warburton, H. J., Graham, S. E., Franklin, H. M., Febria, C. M., Hogsden, K. L., … McIntosh, A. R. (2017). Leaf litter additions enhance stream metabolism, denitrification, and restoration prospects for agricultural catchments. *Ecosphere*, *8*(11), e02018. https://doi.org/10.1002/ecs2.2018

Obernborfer, R. Y., Mcarthur, J. V., Barnes, J. R., Dixon, J., & Oberndorfer, R. Y. (1984). The effect of invertebrate predators on leaf litter processing in an alpine stream. *Ecology*, *65*(4), 1325–1331. https://doi.org/10.2307/1938337

Oliver, R. L., & Merrick, C. J. (2006). Partitioning of river metabolism identifies phytoplankton as a major contributor in the regulated Murray River (Australia). *Freshwater Biology*, *51*, 1131–1148. https://doi.org/10.1111/j.1365-2427.2006.01562.x

Oñatibia, G. R., Aguiar, M. R., & Semmartin, M. (2015). Are there any trade-offs between forage provision and the ecosystem service of C and N storage in arid rangelands? *Ecological Engineering*, *77*, 26–32. https://doi.org/10.1016/j.ecoleng.2015.01.009

Ortiz-Zayas, J. R., Lewis, W. M., Saunders, J. F., McCutchan, J. H., & Scatena, F. N. (2005). Metabolism of a tropical rainforest stream. *Journal of the North American Benthological Society*, *24*(4), 769–783. https://doi.org/10.1899/03-094.1

Ortiz, M., Berrios, F., González, J., Rodríguez-Zaragoza, F., & Gómez, I. (2016). Macroscopic network properties and short-term dynamic simulations in coastal ecological systems at Fildes Bay (King George Island, Antarctica). *Ecological Complexity*, *28*, 145–157. https://doi.org/10.1016/j.ecocom.2016.06.003

Ostertag, R., Scatena, F. N., & Silver, W. L. (2003). Forest floor decomposition following hurricane litter inputs in several Puerto Rican forests. *Ecosystems*, *6*(3), 261–273. https://doi.org/10.1007/s10021-002-0203-8

Oswood, M. W., Irons III, J. G., & Schell, M. (1996). Dynamics of dissolved and particulate carbon in an arctic stream. In J. F. Reynolds & J. D. Tenhunen (Eds.), *Ecological Studies* (Vol. 120, pp. 275–289). Springer-Verlag, Berlin, Heidelberg.

Otieno, D., Ondier, J., Arnhold, S., Okach, D., Ruidisch, M., Lee, B., … Huwe, B. (2015). Patterns of CO2 exchange and productivity of the herbaceous vegetation and trees in a humid savanna in western Kenya. *Plant Ecology*, *216*(10), 1441–1456. https://doi.org/10.1007/s11258-015-0523-3

Owensby, C. E., Coyne, P. I., Ham, J. M., Auen, L. M., & Alan, K. (1993). Biomass production in a tallgrass prairie ecosystem exposed to ambient and elevated CO2. *Ecological Applications*, *3*(4), 644–653. https://doi.org/10.2307/1942097

Paar, M., De la Vega, C., Horn, S., Asmus, R., & Asmus, H. (2019). Kelp belt ecosystem response to a changing environment in Kongsfjorden (Spitsbergen). *Ocean and*

Coastal Management, *167*(1), 60–77. https://doi.org/10.1016/j.ocecoaman.2018.09.003

Park, J. H., Day, T. A., Strauss, S., & Ruhland, C. T. (2007). Biogeochemical pools and fluxes of carbon and nitrogen in a maritime tundra near penguin colonies along the Antarctic Peninsula. *Polar Biology*, *30*(2), 199–207. https://doi.org/10.1007/s00300-006-0173-y

Parmentier, F. J. W., Van Der Molen, M. K., Van Huissteden, J., Karsanaev, S. A., Kononov, A. V., Suzdalov, D. A., … Dolman, A. J. (2011). Longer growing seasons do not increase net carbon uptake in the northeastern Siberian tundra. *Journal of Geophysical Research: Biogeosciences*, *116*(4), 1–11. https://doi.org/10.1029/2011JG001653

Parsons, S. A., Congdon, R. A., Storlie, C. J., Shoo, L. P., & Williams, S. E. (2012). Regional patterns and controls of leaf decomposition in Australian tropical rainforests. *Austral Ecology*, *37*(7), 845–854. https://doi.org/10.1111/j.1442-9993.2011.02347.x

Pathak, K., Malhi, Y., Sileshi, G. W., Kumar Das, A., & Jyoti Nath, A. (2018). Net ecosystem productivity and carbon dynamics of the traditionally managed Imperata grasslands of North East India. *Science of the Total Environment*, *635*, 1124–1131. https://doi.org/10.1016/j.scitotenv.2018.04.230

Pavés, H. J., & González, H. E. (2008). Carbon fluxes within the pelagic food web in the coastal area off Antofagasta (23°S), Chile: The significance of the microbial versus classical food webs. *Ecological Modelling*, *212*(3–4), 218–232.

https://doi.org/10.1016/j.ecolmodel.2007.10.004

Peichl, M., Leahy, P., & Kiely, G. (2011). Six-year stable annual uptake of carbon dioxide in intensively managed humid temperate grassland. *Ecosystems*, *14*, 112–126. https://doi.org/10.1007/s10021-010-9398-2

Pellegrini, A. F. A., Hedin, L. O., Staver, A. C., Govender, N., & Henry, H. A. L. (2015). Fire alters ecosystem carbon and nutrients but not plant nutrient stoichiometry or composition in tropical savanna. *Ecology*, *96*(5), 1275–1285. https://doi.org/10.1890/14-1158.1.sm

Pellikan, G. C., & Nienhuis, P. H. (1988). Nutrient uptake and release during growth and decomposition of eelgrass, Zoostera Marina L., and its effects on the nutrient dynamics of Lake Grevelingen. *Aquatic Botany*, *30*(3), 189–214. https://doi.org/10.1016/0304-3770(88)90051-4

Peltomaa, E., & Ojala, A. (2016). Consequences for pelagic energy mobilisation of a sudden browning episode without a clear increase in DOC concentration: a case of a boreal pristine lake. *Aquatic Sciences*, *78*(4), 627–639. https://doi.org/10.1007/s00027-015-0452-1

Peng, Y., Gitelson, A. A., Keydan, G., Rundquist, D. C., & Moses, W. (2011). Remote estimation of gross primary production in maize and support for a new paradigm based on total crop chlorophyll content. *Remote Sensing of Environment*, *115*(4), 978–989. https://doi.org/10.1016/j.rse.2010.12.001

Perala, D. A., & Alban, D. H. (1982). Rates of forest floor and nutrient turnover in Aspen, Pine , and Spruce stands on two different soils. *St. Paul, MN: USDA Forest*

Service, North Central Forest Experiment Station., *6*.

Pereira Júnior, L. R., Andrade, E. M. de, Palácio, H. A. de Q., Raymer, P. C. L., Ribeiro Filho, J. C., & Pereira, F. J. S. (2016). Carbon stocks in a tropical dry forest in Brazil. *Revista Ciência Agronômica*, *47*(1), 32–40. https://doi.org/10.5935/1806-6690.20160004

Pessarrodona, A., Moore, P. J., Sayer, M. D. J., & Smale, D. A. (2018). Carbon assimilation and transfer through kelp forests in the NE Atlantic is diminished under a warmer ocean climate. *Global Change Biology*, *24*(9), 4386–4398. https://doi.org/10.1111/gcb.14303

Peterson, B., Hobbie, E., & Corliss, T. L. (1986). Carbon flow in a tundra stream ecosystem. *Canadian Journal of Fisheries and Aquatic Sciences*, *43*(1978), 1259–1270. https://doi.org/10.1139/f86-156

Petrie, M. D., Collins, S. L., Swann, A. M., Ford, P. L., & Litvak, M. E. (2015). Grassland to shrubland state transitions enhance carbon sequestration in the northern Chihuahuan Desert. *Global Change Biology*, *21*, 1226–1235. https://doi.org/10.1111/gcb.12743

Poffenbarger, H. J., Mirsky, S. B., Weil, R. R., Kramer, M., Spargo, J. T., & Cavigelli, M. A. (2015). Legume proportion, poultry litter, and tillage effects on cover crop decomposition. *Agronomy Journal*, *107*(6), 2083–2096. https://doi.org/10.2134/agronj15.0065

Post, W. M., Emanuel, W. R., Zinke, P. J., & Stangenberger, A. G. (1982). Soil carbon pools and world life zones. *Nature*, *298*(5870), 156–159.

https://doi.org/10.1038/298156a0

Premke, K., Fischer, P., Hempel, M., & Rothhaupt, K. O. (2010). Ecological studies on the decomposition rate of fish carcasses by benthic organisms in the littoral zone of Lake Constance, Germany. *Annales De Limnologie-International Journal of Limnology*, *46*(3), 157–168. https://doi.org/10.1051/limn/2010017

Propastin, P., & Kappas, M. (2009). Modeling Net Ecosystem Exchange for Grassland in Central Kazakhstan by Combining Remote Sensing and Field Data. *Remote Sensing*, *1*, 159–183. https://doi.org/10.3390/rs1030159

Pumpanen, J., A, L., Heli, M., Kolari, P., Ilvesniemi, H., Mammarella, I., … Vesala, T. (2014). Precipitation and net ecosystem exchange are the most important drivers of DOC flux in upland boreal catchments. *Journal of Geophysical Reserch: Biogeosciences*, *119*, 1861–1878. https://doi.org/10.1002/2014JG002705

Qasim, S. Z., & Bhattathiri, P. M. A. (1971). Primary production of a seagrass bed on Kavaratti Atoll (Laccadives). *Hydrobiologia*, *38*(1), 29–38. https://doi.org/10.1007/BF00036790

Qin, L., Lv, G. H., He, X. M., Yang, J. J., Wang, H. L., Zhang, X. N., & Ma, H. Y. (2015). Winter soil CO2 efflux and its contribution to annual soil respiration in different ecosystems of Ebinur Lake Area. *Eurasian Soil Science*, *48*(8), 871–880. https://doi.org/10.1134/S1064229315080050

Qiu, J., & Turner, M. G. (2016). Effects of non-native Asian earthworm invasion on temperate forest and prairie soils in the Midwestern US. *Biological Invasions*, *19*(1), 73–88. https://doi.org/10.1007/s10530-016-1264-5

Rabouille, C., Gaillard, J. F., Relexans, J. C., Tréguer, P., & Vincendeau, M. A. (1998). Recycling of organic matter in antarctic sediments: a transect through the polar front in the southern ocean (Indian Sector). *Limnology and Oceanography*, *43*(3), 420–432. https://doi.org/10.4319/lo.1998.43.3.0420

Rahman, M. M., & Tsukamoto, J. (2014). Opposing effects of substrate quality and site factors on forest floor turnover rates: An example from the tropics. *Forestry*, *88*(2), 190–199. https://doi.org/10.1093/forestry/cpu043

Rai, S. N., & Proctor, J. (1986). Ecological studies on four rainforests in Karnataka, India: I. Environment, structure, floristics and biomass. *Journal of Ecology*, *74*(2), 439–454. https://doi.org/10.2307/2260266

Ram, S. C., & Ramakrishnan, P. S. (1988). Litter decomposition patterns in seral grasslands at Cherrapunji in northeastern India. *Pedobiologia*, *32*(1–2), 65–76.

Ramírez, A., & Hernández-Cruz, L. R. (2004). Aquatic insect assemblages in shrimp-dominated tropical streams. *Biotropica*, *36*(2), 259–266.

Ramírez, A., & Pringle, C. M. (1998). Structure and Production of a Benthic Insect Assemblage in a Neotropical Stream. *Journal of North American Benthological Society*, *17*(4), 443–463. https://doi.org/10.2307/1468365

Ramlal, P. S., Hesslein, R. H., Hecky, R. E., Fee, E. J., Rudd, J. W. M., & Guilford, S. J. (1994). The organic carbon budget of a shallow Arctic tundra lake on the Tuktoyaktuk Peninsula, N.W.T., Canada. *Biogeochemistry*, *24*(3), 145–172. https://doi.org/10.1007/BF00003270

Rautio, M., Mariash, H., & Forsström, L. (2011). Seasonal shifts between autochthonous and allochthonous carbon contributions to zooplankton diets in a subarctic lake. *Limnology and Oceanography*, *56*(4), 1513–1524. https://doi.org/10.4319/lo.2011.56.4.1513

Rautio, M., & Vincent, W. F. (2006). Benthic and pelagic food resources for zooplankton in shallow high-latitude lakes and ponds. *Freshwater Biology*, *51*(6), 1038–1052. https://doi.org/10.1111/j.1365-2427.2006.01550.x

Recha, J. W., Lehmann, J., Walter, M. T., Pell, A., Verchot, L., & Johnson, M. (2013). Stream water nutrient and organic carbon exports from tropical headwater catchments at a soil degradation gradient. *Nutrient Cycling in Agroecosystems*, *95*(2), 145–158. https://doi.org/10.1007/s10705-013-9554-0

Reichstein, M., Tenhunen, J. D., Roupsard, O., Ourcival, J. M., Rambal, S., Dores, S., & Valentini, R. (2002). Ecosystem respiration in two Mediterranean evergreen Holm Oak forest:drought effect and decomposition dynamics. *Functional Ecology*, *16*, 27–39.

Reicosky, D. C., Dugas, W. A., Torbert, H. A., & Dugas Torbert, H.A., W. A. (1997). Tillage-induced soil carbon dioxide loss form different cropping systems. *Soil and Tillage Research*, *41*(1–2), 105–118. https://doi.org/10.1016/S0167-1987(96)01080-X

Reigstad, M., Carroll, J., Slagstad, D., Ellingsen, I., & Wassmann, P. (2011). Intra-regional comparison of productivity, carbon flux and ecosystem composition within the northern Barents Sea. *Progress in Oceanography*, *90*(1–4), 33–46. https://doi.org/10.1016/j.pocean.2011.02.005

Ren, H., Han, G., Ohm, M., Schönbach, P., Gierus, M., & Taube, F. (2015). Do sheep grazing patterns affect ecosystem functioning in steppe grassland ecosystems in Inner Mongolia? *Agriculture, Ecosystems and Environment*, *213*, 1–10. https://doi.org/10.1016/j.agee.2015.07.015

Ribas, A. C. de A., Tanaka, M. O., & De Souza, A. L. T. (2006). Evaluation of macrofaunal effects on leaf litter breakdown rates in aquatic and terrestrial habitats. *Austral Ecology*, *31*(6), 783–790. https://doi.org/10.1111/j.1442-9993.2006.01640.x

Rice, D. L., & Tenore, K. R. (1981). Dynamics of carbon and nitrogen during the decomposition of detritus derived from estuarine macrophytes. *Estuarine, Coastal and Shelf Science*, *13*(6), 681–690. https://doi.org/10.1016/S0302-3524(81)80049-7

Richardson, J. S. (1992). Coarse particulate detritus dynamics in small, montane streams of southwestern British Columbia. *Canadian Journal of Fisheries and Aquatic Sciences*, *49*(2), 337–346. https://doi.org/10.1139/f92-038

Riis, T., Christoffersen, K. S., & Baattrup-Pedersen, A. (2016). Mosses in high-arctic lakes: in situ measurements of annual primary production and decomposition. *Polar Biology*, *39*(3), 543–552. https://doi.org/10.1007/s00300-015-1806-9

Rivera Vázquez, R., Soto Pinto, L., Núñez Colín, C. A., De Jung, B., Hernández Rivera, M. G., & Ordóñes Diaz, J. A. B. (2013). Production and litter decomposition rate in Acahuales of deciduous tropical forest in Chiapas. *Revista Mexicana de Ciencias Forestales*, *4*(20), 20–30.

Roberts, B. J., Mulholland, P. J., & Hill, W. R. (2007). Multiple scales of temporal variability in ecosystem metabolism rates: Results from 2 years of continuous monitoring in a forested headwater stream. *Ecosystems*, *10*(4), 588–606. https://doi.org/10.1007/s10021-007-9059-2

Robinson, C. T., Tonolla, D., Imhof, B., Vukelic, R., & Uehlinger, U. (2016). Flow intermittency, physico-chemistry and function of headwater streams in an Alpine glacial catchment. *Aquatic Sciences*, *78*(2), 327–341. https://doi.org/10.1007/s00027-015-0434-3

Robinson, C T, & Jolidon, C. (2005). Leaf breakdown and the ecosystem functioning of alpine streams. *Journal of the North American Benthological Society*, *24*(3), 495–507. https://doi.org/10.1899/04-100.1

Robinson, Christopher T., Schmid, D., Svoboda, M., & Bernasconi, S. M. (2008). Functional measures and food webs of high elevation springs in the Swiss alps. *Aquatic Sciences*, *70*(4), 432–445. https://doi.org/10.1007/s00027-008-8125-y

Roden, E. E., & Tuttle, J. H. (1996). Carbon cycling in mesohaline Chesapeake Bay sediments .2. Kinetics of particulate and dissolved organic carbon turnover. *Journal of Marine Research*, *54*(2), 343–383. https://doi.org/10.1357/0022240963213349

Rodrigues, A., Pita, G., Mateus, J., Kurz-besson, C., Casquilho, M., Cerasoli, S., … Pereira, J. (2011). Eight years of continuous carbon fluxes measurements in a Portuguese eucalypt stand under two main events : Drought and felling. *Agricultural and Forest Meteorology*, *151*(4), 493–507. https://doi.org/10.1016/j.agrformet.2010.12.007

Röhr, M. E., Boström, C., Canal-Vergés, P., & Holmer, M. (2016). Blue carbon stocks in Baltic Sea eelgrass (Zostera marina) meadows. *Biogeosciences*, *13*(22), 6139–6153.

https://doi.org/10.5194/bg-13-6139-2016

Romano, C., Fanelli, E., D’Anna, G., Pipitone, C., Vizzini, S., Mazzola, A., & Badalamenti, F. (2016). Spatial variability of soft-bottom macrobenthic communities in northern Sicily (Western Mediterranean): Contrasting trawled vs. untrawled areas. *Marine Environmental Research*, *122*, 113–125. https://doi.org/10.1016/j.marenvres.2016.10.002

Romero, J., Pergent, G., Pergent-Martini, C., Mateo, M., & Regnier, C. (1992). The detritic compartment in a Posidonia oceanica meadow : litter features, decomposition rates, and mineral stocks. *Marine Ecology*, *13*(1), 69–83. https://doi.org/10.1111/j.1439-0485.1992.tb00341.x

Rong, Y., Johnson, D. A., Wang, Z., & Zhu, L. (2017). Grazing effects on ecosystem CO2 fluxes regulated by interannual climate fluctuation in a temperate grassland steppe in northern China. *Agriculture, Ecosystems and Environment*, *237*, 194–202. https://doi.org/10.1016/j.agee.2016.12.036

Rosemond, A. D., Pringle, C. M., & Ramírez, A. (1998). Macroconsumer effects on insect detritivores and detritus processing in a tropical stream. *Freshwater Biology*, *39*(3), 515–523. https://doi.org/10.1046/j.1365-2427.1998.00301.x

Rotenberg, E., & Yakir, D. (2010). Contribution of semi-arid forests to the climate system. *Science*, *327*(5964), 451–454. https://doi.org/10.1126/science.1179998

Rowe, G. (1991). “Total” sediment biomass and preliminary estimates of organic carbon residence time in deep-sea benthos. *Marine Ecology Progress Series*, *79*(1–2), 99–114. https://doi.org/10.3354/meps079099

Royer, T. V., & Minshall, W. G. (2001). Effects of nutrient enrichment and leaf quality on the breakdown of leaves in a hardwater stream. *Freshwater Biology*, *46*(5), 603–610. https://doi.org/10.1046/j.1365-2427.2001.00694.x

Ruehr, N. K., Law, B. E., Quandt, D., & Williams, M. (2014). Effects of heat and drought on carbon and water dynamics in a regenerating semi-arid pine forest: a combined experimental and modeling approach. *Biogeosciences*, *11*, 4139–4156. https://doi.org/10.5194/bg-11-4139-2014

Rybarczyk, H., Elkaim, B., Ochs, L., & Loquet, N. (2003). Analysis of the trophic network of a macrotidal ecosystem: The Bay of Somme (Eastern Channel). *Estuarine, Coastal and Shelf Science*, *58*(3), 405–421. https://doi.org/10.1016/S0272-7714(02)00294-9

Saccone, P., Morin, S., Baptist, F., Bonneville, J. M., Colace, M. P., Domine, F., … Clément, J. C. (2013). The effects of snowpack properties and plant strategies on litter decomposition during winter in subalpine meadows. *Plant and Soil*, *363*(1–2), 215–229. https://doi.org/10.1007/s11104-012-1307-3

Sadro, S., Melack, J. M., & MacIntyre, S. (2011). Spatial and temporal variability in the ecosystem metabolism of a high-elevation lake: Integrating benthic and pelagic habitats. *Ecosystems*, *14*(7), 1123–1140. https://doi.org/10.1007/s10021-011-9471-5

Saiz, G., Bird, M. I., Domingues, T., Schrodt, F., Schwarz, M., Feldpausch, T. R., … Lloyd, J. (2012). Variation in soil carbon stocks and their determinants across a precipitation gradient in West Africa. *Global Change Biology*, *18*(5), 1670–1683. https://doi.org/10.1111/j.1365-2486.2012.02657.x

Sakka, A., Legendre, L., Gosselin, M., Niquil, N., & Delesalle, B. (2002). Carbon budget of the planktonic food web in an atoll lagoon (Takapoto, French Polynesia). *Journal of Plankton Research*, *24*(4), 301–320. https://doi.org/10.1093/plankt/24.4.301

Salk, K. R., Ostrom, P. H., Biddanda, B. A., Weinke, A. D., Kendall, S. T., & Ostrom, N. E. (2016). Ecosystem metabolism and greenhouse gas production in a mesotrophic northern temperate lake experiencing seasonal hypoxia. *Biogeochemistry*, *131*(3), 1–17. https://doi.org/10.1007/s10533-016-0280-y

San José, J., Montes, R., Grace, J., & Nikonova, N. (2008). Land-use changes alter CO2 flux patterns of a tall-grass Andropogon field and a savanna – woodland continuum in the Orinoco lowlands. *Tree Physiology*, *28*(3), 437–450. https://doi.org/10.1093/treephys/28.3.437

Sanborn, P. T., & Brockley, R. P. (2009). Decomposition of pure and mixed foliage litter in a young lodgepole pine – Sitka alder stand in the central interior of British Columbia. *Canadian Journal of Forest Research*, *39*(11), 2257–2262. https://doi.org/10.1139/X09-122

Sand-Jensen, K., Riis, T., Markager, S., & Vincent, W. F. (1999). Slow growth and decomposition of mosses in Arctic lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, *56*(3), 388–393. https://doi.org/10.1139/f98-184

Sanjerehei, M. M. (2013). Annual gross primary production and absorbition of solar energy by artemisia sp. in arid and semiarid shrublands. *Applied Ecology and Environmental Research*, *11*(3), 355–370. https://doi.org/10.15666/aeer/1103

Sanzone, D. M., Meyer, J. L., Marti, E., Gardiner, E. P., Tank, J. L., & Grimm, N. B.

(2003). Carbon and nitrogen transfer from a desert stream to riparian predators. *Oecologia*, *134*(2), 238–250. https://doi.org/10.1007/s00442-002-1113-3

Scharler, U. M., & Baird, D. (2005). A comparison of selected ecosystem attributes of three South African estuaries with different freshwater inflow regimes, using network analysis. *Journal of Marine Systems*, *56*(3–4), 283–308. https://doi.org/10.1016/j.jmarsys.2004.12.003

Scheunemann, N., Maraun, M., Scheu, S., & Butenschoen, O. (2015). The role of shoot residues vs. crop species for soil arthropod diversity and abundance of arable systems. *Soil Biology and Biochemistry*, *81*, 81–88. https://doi.org/10.1016/j.soilbio.2014.11.006

Schindler, D. W., & Nighswander, J. E. (1970). Nutrient supply and primary production in Clear Lake, Eastern Ontario. *Journal of the Fisheries Research Board of Canada*, *27*(11), 2009–2036. https://doi.org/10.1139/f70-226

Scholes, R. J., & Walker, B. H. (1993). *An African savanna: Synthesis of the Nylsvley study*. *Cambridge Studies in Applied Ecology and Resource Management*. Cambridge University Press. https://doi.org/10.1017/CBO9780511565472

Schowalter, T. D., Fonte, S. J., Geaghan, J., & Wang, J. (2011). Effects of manipulated herbivore inputs on nutrient flux and decomposition in a tropical rainforest in Puerto Rico. *Oecologia*, *167*(4), 1141–1149. https://doi.org/10.1007/s00442-011-2056-3

Scott, R. L., Huxman, T. E., Williams, D. G., & Goodrich, D. C. (2006). Ecohydrological impacts of woody-plant encroachment: Seasonal patterns of water and carbon dioxide exchange within a semiarid riparian environment. *Global Change Biology*, *12*(2), 311–324. https://doi.org/10.1111/j.1365-2486.2005.01093.x

Scrimgeour, G. J., Tonn, W. M., & Jones, N. E. (2014). Quantifying effective restoration: reassessing the productive capacity of a constructed stream 14 years after construction. *Canadian Journal of Fisheries and Aquatic Sciences*, *71*(4), 589–601. https://doi.org/10.1139/cjfas-2013-0354

Seely, M. K., & Louw, G. N. (1980). First approximation of the effects of rainfall on the ecology and energetics of a Namib Desert dune ecosystem. *Journal of Arid Environments*, *3*, 25–54. https://doi.org/10.1016/S0140-1963(18)31673-2

Sfriso, A., Facca, C., & Ghetti, P. F. (2003). Temporal and spatial changes of macroalgae and phytoplankton in a Mediterranean coastal area: the Venice lagoon as a case study. *Marine Environmental Research*, *56*, 617–636. https://doi.org/10.1016/S0141-1136(03)00046-1

Shao, C., Chen, J., & Li, L. (2013). Grazing alters the biophysical regulation of carbon fluxes in a desert steppe. *Environmental Research Letters*, *8*, 025012. https://doi.org/10.1088/1748-9326/8/2/025012

Shaver, G. R. ., & Chapin III, F. . S. (1991). Production : Biomass relationships and element cycling in contrasting arctic vegetation types. *Ecological Monographs*, *61*(1), 1–31. https://doi.org/10.2307/1942997

Shilla, D., Asaeda, T., Fujino, T., & Sanderson, B. (2006). Decomposition of dominant submerged macrophytes: Implications for nutrient release in Myall Lake, NSW, Australia. *Wetlands Ecology and Management*, *14*(5), 427–433. https://doi.org/10.1007/s11273-006-6294-9

Shimizu, M., Limin, A., Desyatkin, A. R., Jin, T., Mano, M., Ono, K., … Hatano, R. (2015). Effect of manure application on seasonal carbon fluxes in a temperate managed grassland in Southern Hokkaido, Japan. *Catena*, *133*, 474–485. https://doi.org/10.1016/j.catena.2015.05.011

Shimizu, M., Marutani, S., Desyatkin, A. R., Jin, T., Hata, H., & Hatano, R. (2009). The effect of manure application on carbon dynamics and budgets in a managed grassland of Southern Hokkaido, Japan. *Agriculture Ecosystems & Environment*, *130*, 31–40. https://doi.org/10.1016/j.agee.2008.11.013

Singh, S. K., Sidhu, G. S., Choudhury, S. G., Pandey, C. B., Banerjee, T., & Sarkar, D. (2014). Soil organic carbon density in arable and non-arable lands under varied soil moisture and temperature regimes in cold arid to sub-tropical areas of Western Himalaya, India. *Arid Land Research and Management*, *28*(2), 169–185. https://doi.org/10.1080/15324982.2013.824930

Siokou-Frangou, I., Bianchi, M., Christaki, U., Christou, E. D., Giannakourou, A., Gotsis, O., … Zervakis, V. (2002). Carbon flow in the planktonic food web along a gradient of oligotrophy in the Aegean Sea (Mediterranean Sea). *Journal of Marine Systems*, *34*, 335–353. https://doi.org/10.1016/S0924-7963(02)00065-9

Sjögersten, S., van der Wal, R., & Woodin, S. J. (2012). Impacts of Grazing and Climate Warming on C Pools and Decomposition Rates in Arctic Environments. *Ecosystems*, *15*(3), 349–362. https://doi.org/10.1007/s10021-011-9514-y

Smale, D. A., Burrows, M., Evans, A., King, N., Sayer, M., Yunnie, A., & Moore, P. (2015). Linking environmental variables with regional-scale variability in ecological structure and standing stock of carbon within kelp forests in the United Kingdom. *Marine Ecology Progress Series*, *542*, 79–95. https://doi.org/10.3354/meps11544

Small, L., Landry, M., Eppley, R., Azam, F., & Carlucci, A. (1989). Role of plankton in the carbon and nitrogen budgets of Santa Monica Basin, California . *Marine Ecology Progress Series*, *56*, 57–74. https://doi.org/10.3354/meps056057

Sobek, S., Söderbäck, B., Karlsson, S., Andersson, E., Kristina, A., Karlsson, S., … Brunberg, A. K. (2006). A carbon budget of a small humic lake : An example of the importance of lakes for organic matter cycling in boreal catchments. *AMBIO: A Journal of the Human Environment*, *35*(8), 469–475. https://doi.org/10.1579/0044-7447(2006)35[469%3AACBOAS]2.0.CO%3B2

Søndergaard, M., Hansen, B., & Markager, S. (1995). Dynamics of dissolved organic carbon lability in a eutrophic lake. *Limnology and Oceanography*, *40*(l), 46–54. https://doi.org/10.4319/lo.1995.40.1.0046

Song, W., Chen, S., Zhou, Y., Wu, B., Zhu, Y., Lu, Q., & Lin, G. (2015). Contrasting diel hysteresis between soil autotrophic and heterotrophic respiration in a desert ecosystem under different rainfall scenarios. *Sci Rep*, *5*(June), 16779. https://doi.org/10.1038/srep16779

Souto, P. C., Souto, J. S., Dos Santos, R. V., Bakke, I. A., Sales, F. D. V., & De Souza, B. V. (2013). Rate of litter decomposition and microbial activity in an area of caatinga. *Cerne*, *19*(4), 559–565. https://doi.org/10.1590/S0104-77602013000400005

Staehr, P. A., Baastrup-Spohr, L., Sand-Jensen, K., & Stedmon, C. (2012). Lake metabolism scales with lake morphometry and catchment conditions. *Aquatic Sciences*, *74*(1), 155–169. https://doi.org/10.1007/s00027-011-0207-6

Stagliano, D. M., & Whiles, M. R. (2002). Macroinvertebrate production and trophic structure in a tallgrass prairie headwater stream. *Journal of the North American Benthological Society*, *21*(1), 97–113. https://doi.org/10.2307/1468303

Starovoytov, A., Gallagher, R. S., Jacobsen, K. L., Kaye, J. P., & Bradley, B. (2010). Management of small grain residues to retain legume-derived nitrogen in corn cropping systems. *Agronomy Journal*, *102*(3), 895–903. https://doi.org/10.2134/agronj2009.0402

Steinberg, D. K., Carlson, C. A., Bates, N. R., Johnson, R. J., Michaels, A. F., & Knap, A. H. (2001). Overview of the US JGOFS Bermuda Atlantic Time-series Study (BATS): A decade-scale look at ocean biology and biogeochemistry. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *48*(8–9), 1405–1447. https://doi.org/10.1016/S0967-0645(00)00148-X

Stephens, P. R., Kimberley, M. O., Beets, P. N., Paul, T. S. H., Searles, N., Bell, A., … Broadley, J. (2012). Airborne scanning LiDAR in a double sampling forest carbon inventory. *Remote Sensing of Environment*, *117*, 348–357. https://doi.org/10.1016/j.rse.2011.10.009

Stocker, Z. S. J., & Hynes, H. B. N. (1976). Studies on the tributaries of Char Lake, Cornwallis Island, Canada. *Hydrobiologia*, *49*(2), 97–102. https://doi.org/10.1007/BF00772678

Stone, J. P., & Steinberg, D. K. (2016). Salp contributions to vertical carbon flux in the

Sargasso Sea. *Deep-Sea Research Part I: Oceanographic Research Papers*, *113*, 90–100. https://doi.org/10.1016/j.dsr.2016.04.007

Stutes, J., Cebrian, J., Stutes, A. L., Hunter, A., & Corcoran, A. A. (2007). Benthic metabolism across a gradient of anthropogenic impact in three shallow coastal lagoons in NW Florida. *Marine Ecology Progress Series*, *348*, 55–70. https://doi.org/10.3354/meps07036

Sui, X., & Zhou, G. (2013). Carbon dynamics of temperate grassland ecosystems in China from 1951 to 2007: An analysis with a process-based biogeochemistry model. *Environmental Earth Sciences*, *68*(2), 521–533. https://doi.org/10.1007/s12665-012-1756-2

Sun, Q., Meyer, W. S., Koerber, G. R., & Marschner, P. (2016). A wildfire event influences ecosystem carbon fluxes but not soil respiration in a semi-arid woodland. *Agricultural and Forest Meteorology*, *226–227*, 57–66. https://doi.org/10.1016/j.agrformet.2016.05.019

Sundbäck, K., Nilsson, P., Nilsson, C., & Jönsson, B. (1996). Balance between autortophic and heterotrophic components and processes in microphytobenhtic communities of sandy sediments: a field study. *Estuarine, Coastal and Shelf Sciences*, *43*(6), 689–706. https://doi.org/10.1006/ecss.1996.0097

Suren, A. (1993). Bryophytes and associated invertebrates in first-order alpine streams of Arthur’s Pass , New Zealand. *New Zealand Journal of Marine and Freshwater Research*, *27*(September), 479–494. https://doi.org/10.1080/00288330.1993.9516589

Suseela, V., Tharayil, N., Xing, B., & Dukes, J. S. (2014). Warming alters potential enzyme activity but precipitation regulates chemical transformations in grass litter exposed to simulated climatic changes. *Soil Biology and Biochemistry*, *75*, 102–112. https://doi.org/10.1016/j.soilbio.2014.03.022

Szarek, S. R. (1979). Primary production in four North American deserts: indices of efficiency. *Journal of Arid Environments*, *2*(3), 187–209. https://doi.org/10.1016/S0140-1963(18)31771-3

Tagesson, T., Fensholt, R., Cropley, F., Guiro, I., Horion, S., Ehammer, A., & Ardö, J. (2015). Dynamics in carbon exchange fluxes for a grazed semi-arid savanna ecosystem in West Africa. *Agriculture, Ecosystems and Environment*, *205*, 15–24. https://doi.org/10.1016/j.agee.2015.02.017

Takanashi, S., Kosugi, Y., Tani, M., Matsuo, N., Mitani, T., & Nik, A. R. (2005). Characteristics of the gas exchange of a tropical rain forest in Peninsular Malaysia. *Phyton*, *45*(October 2015), 61–66.

Talmon, Y., Sternberg, M., & Grünzweig, J. M. (2011). Impact of rainfall manipulations and biotic controls on soil respiration in Mediterranean and desert ecosystems along an aridity gradient. *Global Change Biology*, *17*(2), 1108–1118. https://doi.org/10.1111/j.1365-2486.2010.02285.x

Tanner, E. V. J. (1980). Studies on the biomass and productivity in a series of montane rain forests in Jamaica. *The Journal of Ecology*, *68*(2), 573–588. https://doi.org/10.2307/2259423

Tewfik, A., Rasmussen, J. B., & Mccann, K. S. (2005). Anthropogenic enrichment alters a marine benthic food web. *Ecology*, *86*(10), 2726–2736.

Thokchom, A., & Yadava, P. S. (2016). Carbon dynamics in an *Imperata* grassland in Northeast India. *Tropical Grasslands - Forrajes Tropicales*, *4*(1), 19. https://doi.org/10.17138/TGFT(4)19-28

Throop, H. L., & Archer, S. R. (2007). Interrelationships among shrub encroachment, land management, and litter decomposition in a semidesert grassland. *Ecological Applications*, *17*(6), 1809–1823. https://doi.org/10.1890/06-0889.1

Thurow, L. T. (1989). Decomposition of grasses and forbs in coastal savanna of southern Somalia. *African Journal of Ecology*, *27*(3), 201–206. https://doi.org/10.1111/j.1365-2028.1989.tb01013.x

Titus, J. H., Nowak, R. S., & Smith, S. D. (2002). Soil resource heterogeneity in the Mojave Desert. *Journal of Arid Environments*, *52*(3), 269–292. https://doi.org/10.1006/jare.2002.1010

Trumbore, S., Davidson, E., Camargo, P., Nepstad, D., & Martinelli, L. (1995). Belowground cycling of carbon in forests and pastures of eastern Amazonia. *Global Biogeochemical Cycles*, *9*(4), 515–528. https://doi.org/10.1029/95GB02148

Turner, D. P., Ritts, W. D., Law, B. E., Cohen, W. B., Yang, Z., Hudiburg, T., … Duane, M. (2007). Scaling net ecosystem production and net biome production over a heterogeneous region in the western United States. *Biogeosciences*, *4*(2), 1093–1135. https://doi.org/10.5194/bgd-4-1093-2007

Turnewitsch, R., Dumont, M., Kiriakoulakis, K., Legg, S., Mohn, C., Peine, F., & Wolff, G. (2016). Tidal influence on particulate organic carbon export fluxes around a tall seamount. *Progress in Oceanography*, *149*, 189–213. https://doi.org/10.1016/j.pocean.2016.10.009

Uehlinger, U. (2006). Annual cycle and inter-annual variability of gross primary production and ecosystem respiration in a floodprone river during a 15-year period. *Freshwater Biology*, *51*(5), 938–950. https://doi.org/10.1111/j.1365-2427.2006.01551.x

Uehlinger, U., & Brock, J. T. (2005). Periphyton metabolism along a nutrient gradient in a desert river (Truckee River, Nevada, USA). *Aquatic Sciences*, *67*(4), 507–516. https://doi.org/10.1007/s00027-005-0788-z

Ulloa, E., Anderson, C. B., Ardon, M., Morcia, S., & Valenzuela, A. E. J. (2012). Organic matter characterization and decomposition dynamics in sub Antarctic streams impacted by invasive beavers. *Latin American Journal of Aquatic Research*, *40*(4), 881–892. https://doi.org/10.3856/vol40-issue4-fulltext-6

Ulseth, A. J., Bertuzzo, E., Singer, G. A., Schelker, J., & Battin, T. J. (2018). Climate-induced changes in spring snowmelt impact ecosystem metabolism and carbon fluxes in an alpine stream network. *Ecosystems*, *21*(2), 373–390. https://doi.org/10.1007/s10021-017-0155-7

Uri, V., Kukumägi, M., Aosaar, J., Varik, M., Becker, H., Aun, K., … Soosaar, K. (2019). The carbon balance of a six-year-old Scots pine (Pinus sylvestris L .) ecosystem estimated by different methods. *Forest Ecology and Management*, *433*, 248–262. https://doi.org/10.1016/j.foreco.2018.11.012

Vachon, D., Lapierre, J.-F., & del Giorgio, P. A. (2016). Seasonality of photochemical dissolved organic carbon mineralization and its relative contribution to pelagic CO_2 production in northern lakes. *Journal of Geophysical Research: Biogeosciences*, *121*(3), 864–878. https://doi.org/10.1002/2015JG003244

Vachon, D., Solomon, C., & del Giorgio, P. (2016). Reconstructing the seasonal dynamics and relative contribution of the major processes sustaining CO_2 emissions in northern lakes. *Limnology and Oceanography*, *In revisio*. https://doi.org/10.13140/RG.2.1.3702.8566

Vadstein, O., Harkjerr, B. O., Jensen, A., Olsen, Y., & Reinertsen, H. (1989). Cycling of organic-crbon in the photic zone of a eutrophic lake with special reference to the heterotrophic bacteria. *Limnology and Oceanography*, *34*(5), 840–855. https://doi.org/10.4319/lo.1989.34.5.0840

Van der Molen, M. K., van Huissteden, J. C., Parmentier, F. J. W. W., Petrescu, A. M. R. R., Dolman, A. J., Maximov, T. C., … Suzdalov, D. A. (2007). The growing season greenhouse gas balance of a continental tundra site in the Indigirka lowlands, NE Siberia. *Biogeosciences*, *4*(6), 985–1003. https://doi.org/10.5194/bg-4-985-2007

Van Hook, R. I. J. (1971). Energy and nutrient dynamics of spider and orthopteran populations in a grassland ecosystem. *Ecological Monographs*, *41*(1), 1–26.

Van Oevelen, D., Soetaert, K., Middelburg, J. J., Herman, P. M. J., Moodley, L., Hamels, I., … Heip, C. H. R. (2006). Carbon flows through a benthic food web: Integrating biomass, isotope and tracer data. *Journal of Marine Research*, *64*(3), 453–482. https://doi.org/10.1357/002224006778189581

Vankoughnett, M. R., & Grogan, P. (2016). Plant production and nitrogen accumulation above- and belowground in low and tall birch tundra communities: the influence of snow and litter. *Plant and Soil*, *408*(1–2), 195–210. https://doi.org/10.1007/s11104-016-2921-2

Vassiljevskaya, V. D., Ivanov, V. V., Bogatyrev, L. G., Popselova, E. B., Schalaeva, N. M., & Grishina, L. A. (1975). Agapa, USSR. In: Structure and function of tundra ecosystems. *Ecological Bulletins (Stockholm)*, *20*, 141–158.

Vávřová, P., Penttilä, T., & Laiho, R. (2009). Decomposition of Scots pine fine woody debris in boreal conditions: Implications for estimating carbon pools and fluxes. *Forest Ecology and Management*, *257*(2), 401–412. https://doi.org/10.1016/j.foreco.2008.09.017

Velasco, J., Millan, A., Suarez, M. L., Guerrero, C., & Ortega, M. (2003). Macrophytic, epipelic and epilithic primary production in a semiarid Mediterranean stream. *Freshwater Biology*, *48*, 1408–1420. https://doi.org/10.1046/j.1365-2427.2003.01099.x

Vesterinen, J., Devlin, S. P., Syväranta, J., & Jones, R. I. (2016). Accounting for littoral primary production by periphyton shifts a highly humic boreal lake towards net autotrophy. *Freshwater Biology*, *61*(3), 265–276. https://doi.org/10.1111/fwb.12700

Vézina, A. F., Savenkoff, C., Roy, S., Klein, B., Rivkin, R., Therriault, J. C., & Legendre, L. (2000). Export of biogenic carbon and structure and dynamics of the pelagic food web in the Gulf of St. Lawrence Part 2. Inverse analysis. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *47*(3–4), 609–635. https://doi.org/10.1016/S0967-0645(99)00120-4

Vitousek, P. M., Gosz, J. R., Grier, C. C., Melillo, J. M., & Reiners, W. A. (1982). A Comparative Analysis of Potential Nitrification and Nitrate Mobility in Forest Ecosystems. *Ecological Monographs*, *52*(2), 155. https://doi.org/10.2307/1942609

Von Schiller, D., Martí, E., Riera, J. L., Ribot, M., Marks, J. C., & Sabater, F. (2008). Influence of land use on stream ecosystem function in a Mediterranean catchment. *Freshwater Biology*, *53*(12), 2600–2612. https://doi.org/10.1111/j.1365-2427.2008.02059.x

Wallace, B. J., Eggert, S. L., Meyer, J. L., & Webster, J. R. (1999). Effects of resource limitation on a detrital-based ecosystem. *Ecological Monographs*, *69*(4), 409–442. https://doi.org/10.1890/0012-9615(1999)069[0409:EORLOA]2.0.CO;2

Wang, B. S., Tian, H., Liu, J., & Pan, S. (2003). Pattern and change of soil organic carbon storage in China : 1960s – 1980s. *Tellus*, *55B*(2), 416–427. https://doi.org/10.1034/j.1600-0889.2003.00039.x

Wang, D., Liu, Y., Shang, Z. H., Tian, F. P., Wu, G. L., Chang, X. F., & Warrington, D. (2015). Effects of grassland conversion from cropland on soil respiration on the semi-arid loess plateau, China. *Clean - Soil, Air, Water*, *43*(7), 1052–1057. https://doi.org/10.1002/clen.201300971

Wang, K., Deng, L., Ren, Z., Li, J., & Shangguan, Z. (2016). Grazing exclusion significantly improves grassland ecosystem C and N pools in a desert steppe of Northwest China. *Catena*, *137*, 441–448. https://doi.org/10.1016/j.catena.2015.10.018

Waring, B. G. (2012). A Meta-analysis of Climatic and Chemical Controls on Leaf Litter

Decay Rates in Tropical Forests. *Ecosystems*, *15*(6), 999–1009. https://doi.org/10.1007/s10021-012-9561-z

Weatherly, H. E., Zitzer, S. F., Coleman, J. S., Arnone III, J. A., & Arnone, J. A. (2003). In situ litter decomposition and litter quality in a Mojave Desert ecosystem: effects of elevated atmospheric CO2 and interannual climate variability. *Global Change Biology*, *9*(8), 1223–1233. https://doi.org/10.1046/j.1365-2486.2003.00653.x

Webb, W. L., Lauenroth, W. K., Szarek, S. R., & Kinerson, R. S. (1983). Primary production and abiotic controls in forests, grasslands, and desert ecosystems in the United States. *Ecology*, *64*(1), 134–151. https://doi.org/10.2307/1937336

Webster, J. R., & Meyer, J. L. (1997). Stream organic matter budgets-introduction. *Journal of the North American Benthological Society*, *16*(1), 3–13. https://doi.org/10.2307/1468223

Wefer, G., & Fischer, G. (1991). Annual primary production and export flux in the Southern Ocean from sediment trap data. *Marine Chemistry*, *35*(1–4), 597–613. https://doi.org/10.1016/S0304-4203(09)90045-7

Wein, R. W., & Bliss, L. C. (1974). Primary production in arctic cottongrass tussock tundra communities. *Arctic and Alpine Research*, *6*(3), 261–274. https://doi.org/10.2307/1550062

Welch, H. E., & Kalff, J. (1974). Benthic photosynthesis and respiration in Char Lake. *Journal of the Fisheries Research Board of Canada*, *31*(5), 609–620. https://doi.org/10.1139/f74-093

Welch, Harold E. (1974). Metabolic rates of arctic lakes. *Limnology and Oceanography*, *19*(1), 65–73. https://doi.org/10.4319/lo.1974.19.1.0065

Welch, Harold E., Legault, J. A., & Kling, H. J. (1989). Phytoplankton, Nutrients, and Primary Production in Fertilized and Natural Lakes at Saqvaqjuac, N.W.T. *Canadian Journal of Fisheries and Aquatic Sciences*, *46*(1), 90–107. https://doi.org/10.1139/f89-013

Welker, J. M., Fahnestock, J. T., Henry, G. H. R., O'Dea, K. W., & Chimner, R. A. (2004). CO2 exchange in three Canadian High Arctic ecosystems: Response to long-term experimental warming. *Global Change Biology*, *10*(12), 1981–1995. https://doi.org/10.1111/j.1365-2486.2004.00857.x

Whalen, S. C., Chalfant, B. A., & Fischer, E. N. (2008). Epipelic and pelagic primary production in Alaskan Arctic lakes of varying depth. *Hydrobiologia*, *614*(1), 243–257. https://doi.org/10.1007/s10750-008-9510-1

Wheeler, P. A., Gosselin, M., Sherr, E., Thibault, D., Kirchman, D. L., Benner, R., & Whitledge, T. E. (1996). Active cycling of organic carbon in the central Arctic Ocean. *Nature*, *380*(6576), 697–699. https://doi.org/10.1038/380697a0

Wiesmeier, M., Schad, P., von Lützow, M., Poeplau, C., Spörlein, P., Geuß, U., … Kögel-Knabner, I. (2014). Quantification of functional soil organic carbon pools for major soil units and land uses in southeast Germany (Bavaria). *Agriculture, Ecosystems and Environment*, *185*, 208–220. https://doi.org/10.1016/j.agee.2013.12.028

Williamson, P. (1976). Above-Ground Primary Production of Chalk Grassland Allowing for Leaf Death. *Journal of Ecology*, *64*(3), 1059–1075.

https://doi.org/10.2307/2258825

Wohlfahrt, G., Fenstermaker, L. F., & Arnone Iii, J. A. (2008). Large annual net ecosystem CO2 uptake of a Mojave Desert ecosystem. *Global Change Biology*, *14*(7), 1475–1487. https://doi.org/10.1111/j.1365-2486.2008.01593.x

Wolf, S., Eugster, W., Potvin, C., Turner, B. L., & Buchmann, N. (2011). Carbon sequestration potential of tropical pasture compared with afforestation in Panama. *Global Change Biology*, *17*, 2763–2780. https://doi.org/10.1111/j.1365-2486.2011.02460.x

Wright, M. S., & Covich, A. P. (2005). The effect of macroinvertebrate exclusion on leaf breakdown rates in a tropical headwater stream. *Biotropica*, *37*(3), 101–106. https://doi.org/10.1111/j.1744-7429.2005.00053.x

Wu, Z., Zhang, X., Lozano-Montes, H. M., & Loneragan, N. R. (2016). Trophic flows, kelp culture and fisheries in the marine ecosystem of an artificial reef zone in the Yellow Sea. *Estuarine, Coastal and Shelf Science*, *182*, 86–97. https://doi.org/10.1016/j.ecss.2016.08.021

Xiao, J., Sun, G., Chen, J., Chen, H., Chen, S., Dong, G., … Zhou, J. (2013). Carbon fluxes, evapotranspiration, and water use efficiency of terrestrial ecosystems in China. *Agricultural and Forest Meteorology*, *182–183*, 76–90. https://doi.org/10.1016/j.agrformet.2013.08.007

Xie, J., Jia, X., He, G., Zhou, C., Yu, H., Wu, Y., … Zha, T. (2015). Environmental control over seasonal variation in carbon fluxes of an urban temperate forest ecosystem. *Landscape and Urban Planning*, *142*, 63–70.

https://doi.org/10.1016/j.landurbplan.2015.04.011

Xie, J., Zha, T., Jia, X., Qian, D., Wu, B., Zhang, Y., … Peltola, H. (2015). Irregular precipitation events in control of seasonal variations in CO2 exchange in a cold desert-shrub ecosystem in northwest China. *Journal of Arid Environments*, *120*, 33–41. https://doi.org/10.1016/j.jaridenv.2015.04.009

Xu, L., & Baldocchi, D. D. (2004). Seasonal variation in carbon dioxide exchange over a Mediterranean annual grassland in California. *Agricultural and Forest Meteorology*, *123*(1–2), 79–96. https://doi.org/10.1016/j.agrformet.2003.10.004

Xu, M. Y., Xie, F., & Wang, K. (2014). Response of vegetation and soil carbon and nitrogen storage to grazing intensity in semi-arid grasslands in the agro-pastoral zone of northern china. *PLoS ONE*, *9*(5), e96604. https://doi.org/10.1371/journal.pone.0096604

Yan, J., Zhang, Y., Yu, G., Zhou, G., Zhang, L., Li, K., … Sha, L. (2013). Seasonal and inter-annual variations in net ecosystem exchange of two old-growth forests in southern China. *Agricultural and Forest Meteorology*, *182–183*, 257–265. https://doi.org/10.1016/j.agrformet.2013.03.002

Yang, F., & Zhou, G. (2013). Sensitivity of temperate desert steppe carbon exchange to seasonal droughts and precipitation variations in Inner Mongolia, China. *PLoS ONE*, *8*(2), e55418. https://doi.org/10.1371/journal.pone.0055418

Yonekura, Y., Ohta, S., Kiyono, Y., Aksa, D., Morisada, K., Tanaka, N., & Tayasu, I. (2013). Soil organic matter dynamics in density and particle-size fractions following destruction of tropical rainforest and the subsequent establishment of Imperata grassland in Indonesian Borneo using stable carbon isotopes. *Plant and Soil*, *372*(1–2), 683–699. https://doi.org/10.1007/s11104-013-1763-4

Young, R., & Huryn, A. (1997). Longitudinal patterns of organic matter transport and turnover along a New Zealand grassland river. *Freshwater Biology*, *38*, 93–107. https://doi.org/10.1046/j.1365-2427.1997.00196.x

Zeeman, M. J., Shupe, H., Baessler, C., & Ruehr, N. K. (2019). Productivity and vegetation structure of three differently managed temperate grasslands. *Agriculture, Ecosystems and Environment*, *270–271*(November 2018), 129–148. https://doi.org/10.1016/j.agee.2018.10.003

Zervoudaki, S., Frangoulis, C., Svensen, C., Christou, E. D., Tragou, E., Arashkevich, E. G., … Pagou, K. (2014). Vertical Carbon Flux of Biogenic Matter in a Coastal Area of the Aegean Sea: The Importance of Appendicularians. *Estuaries and Coasts*, *37*(4), 911–924. https://doi.org/10.1007/s12237-013-9723-z

Zhai, L., Gudmundsson, K., Miller, P., Peng, W., Gufinnsson, H., Debes, H., … Platt, T. (2012). Phytoplankton phenology and production around Iceland and Faroes. *Continental Shelf Research*, *37*, 15–25. https://doi.org/10.1016/j.csr.2012.01.013

Zhang, C., Lu, D., Chen, X., Zhang, Y., Maisupova, B., & Tao, Y. (2016). The spatiotemporal patterns of vegetation coverage and biomass of the temperate deserts in Central Asia and their relationships with climate controls. *Remote Sensing of Environment*, *175*, 271–281. https://doi.org/10.1016/j.rse.2016.01.002

Zhang, Lei, Sun, R., Xu, Z., Qiao, C., & Jiang, G. (2015). Diurnal and seasonal variations in carbon dioxide exchange in ecosystems in the Zhangye oasis Area, northwest

China. *PLoS ONE*, *10*(3), 1–16. https://doi.org/10.1371/journal.pone.0120660

Zhang, Li, Wylie, B. K., Ji, L., Gilmanov, T. G., Tieszen, L. L., & Howard, D. M. (2011). Upscaling carbon fluxes over the Great Plains grasslands: Sinks and sources. *Journal of Geophysical Research: Biogeosciences*, *116*(1), 1–13. https://doi.org/10.1029/2010JG001504

Zhang, N., Zhao, Y. S., & Yu, G. R. (2009). Simulated annual carbon fluxes of grassland ecosystems in extremely arid conditions. *Ecological Research*, *24*(1), 185–206. https://doi.org/10.1007/s11284-008-0497-x

Zhang, Yongyong, & Zhao, W. (2015). Vegetation and soil property response of short-time fencing in temperate desert of the Hexi Corridor, northwestern China. *Catena*, *133*, 43–51. https://doi.org/10.1016/j.catena.2015.04.019

Zhang, Yulong, Song, C., Zhang, K., Cheng, X., & Zhang, Q. (2014). Spatial-temporal variability of terrestrial vegetation productivity in the Yangtze River Basin during 2000-2009. *Journal of Plant Ecology*, *7*(1), 10–23. https://doi.org/10.1093/jpe/rtt025

Zhou, W. J., Zhang, Y. P., Schaefer, D. A., Sha, L. Q., Deng, Y., Deng, X. B., & Dai, K. J. (2013). The role of stream water carbon dynamics and export in the carbon balance of a tropical seasonal rainforest, Southwest China. *PLoS ONE*, *8*(2). https://doi.org/10.1371/journal.pone.0056646

Zhou, X., Wu, H., Li, G., & Chen, C. (2016). Short-term contributions of cover crop surface residue return to soil carbon and nitrogen contents in temperate Australia. *Environmental Science and Pollution Research*, *23*(22), 23175–23183. https://doi.org/10.1007/s11356-016-7549-5

Zhu, Z. Y., Wu, Y., Liu, S. M., Wenger, F., Hu, J., Zhang, J., & Zhang, R. F. (2016). Organic carbon flux and particulate organic matter composition in Arctic valley glaciers: Examples from the Bayelva River and adjacent Kongsfjorden. *Biogeosciences*, *13*(4), 975–987. https://doi.org/10.5194/bg-13-975-2016

Ziegler, S., & Benner, R. (1999). Nutrient cycling in the water column of a subtropical seagrass meadow. *Marine Ecology Progress Series*, *188*, 51–62. https://doi.org/10.3354/meps188051

Zwart, J. A., Craig, N., Kelly, P. T., Sebestyen, S. D., Solomon, C. T., Weidel, B. C., & Jones, S. E. (2016). Metabolic and physiochemical responses to a whole-lake experimental increase in dissolved organic carbon in a north-temperate lake. *Limnology and Oceanography*, *61*(2), 723–734. https://doi.org/10.1002/lno.10248

Global quantitative synthesis of ecosystem functioning across climatic zones and ecosystem types

Authors: Isabelle Gounand, Chelsea J. Little, Eric Harvey, and Florian Altermatt
Corresponding author: Isabelle Gounand – isabelle.gounand@sorbonne-universite.fr

Supporting Information

Content

Appendix S1 – Extended methods

This appendix provides details on the methods used in this study.

Data collection

Our systematic search covered four broad categories of terrestrial ecosystems (forest, grassland and shrubland, agroecosystem, and desert) and four of aquatic ecosystems (stream, lake, pelagic ocean, and benthic ocean). We considered all ecosystems (if available) in five major global climatic zones (arctic/alpine, boreal, temperate, tropical, and arid). Table S1.1 provides the definitions of ecosystem categories and climatic zones. For marine ecosystems, we grouped arctic, boreal, and temperate *versus* arid and tropical climates into Cold and Warm, respectively, to account for a lesser influence of climate on oceanic systems due to the buffering effect of large water volumes. For each relevant ecosystem x climatic zone combination, we collected data of carbon stocks (biomass, organic carbon, detritus), fluxes (gross primary production (GPP), ecosystem respiration (ER), and net ecosystem production (NEP)), and rates (uptake and decomposition rates) (see Fig. 1). We used all possible combinations of these categories and terms with similar meanings (see Table S1.1) in our systematic search. A first systematic search was conducted by using all possible combinations of the names of each ecosystem type, climatic zone and ecosystem variable of interest, with small variation when relevant (e.g. “decomposition OR decay” for decomposition flux and rates). The different terminologies used across various research fields to describe the same processes, and the fact that the data of interest were often located in different sections of the studies (Methods *versus* Results) limited the efficiency of standardized keyword search across the data types. We therefore complemented the dataset with multiple customized searches until we compiled a minimum number of ten independent values of each variable of interest (i.e. different stocks, fluxes, and decomposition rate) for each ecosystem x climatic zone combination. Figure S1.1 shows the flow of this recursive process and the associated decision tree to integrate studies in the data set. Our aim was not to be completely exhaustive but rather to provide representative ranges of variation for the different ecosystem variables. In total, we collected 4,479 values from 604 published studies (this count does not include the 512 GPP/ER ratios provided in the data table).

Calculations used for data extraction

When only one or two of three major fluxes (gross primary production, ecosystem respiration, and net ecosystem production (GPP, $\mathrm{R_e}$, and NEP, respectively) were reported, we estimated the unreported flux:

$$\mathrm{NEP} = \mathrm{GPP} - \mathrm{R_e} \qquad [1]$$

$$\mathrm{NEP} = \mathrm{NPP} - \mathrm{R_h} \qquad [2]$$

$$\mathrm{NPP} = \mathrm{GPP} - \mathrm{R_a} \qquad [3]$$

NPP is the net primary production, $\mathrm{R_h}$ the heterotrophic respiration, and R_a the autotrophic respiration. The ratio $\mathrm{GPP/R_e}$ was also calculated to compare with the NEP data (see Appendix S2.3).

Uptake rates were rarely reported as such. Some relative growth rates (RGR) were documented, but often at species and not community level only and as instantaneous maximal values (potential growth). Since we wanted to analyse uptake rates relevant at the ecosystem level and at yearly timescale, we thus looked at studies reporting both GPP and biomass of autotrophs, $\mathrm{B_a}$, at the same sites and calculated community uptake rates U:

$$\mathrm{U = GPP/B_a} \qquad [4]$$

As measures of decomposition rates, we collected values of k, the first order constant in the classical exponential decay model:

$$\mathrm{D_F = D_M(1 - e^{-kt})} \qquad [5]$$

with $\mathrm{D_F}$ the decomposition flux and $\mathrm{D_M}$ the detritus stock. When not directly provided, we derived k with one of the equations proposed by (Cebrian & Lartigue, 2004) depending on the data available in the study:

$$\mathrm{D_t = D_{t_0} e^{-k(t-t_0)}} \qquad [6]$$

$$\mathrm{D_F = (D_P - \mathit{E})(1 - e^{-kt})} \qquad [7]$$

In Equation [6], $\mathrm{D_t}$ is the detrital mass at time t and $\mathrm{D_{t_0}}$ the initial detrital mass. This equation was used when decomposition was estimated as the proportion of detrital mass loss $(1 - \mathrm{D_t/D_{t_0}})$ via a litter-bag experiment, a classical method in freshwater and terrestrial ecology. In equation [7], $\mathrm{D_F}$ is the (absolute) decomposition flux during the study period t, that is the flux from detritus stock to bacteria and other detritivores, $\mathrm{D_P}$ is the detritus production, and E the detritus export (e.g. sedimentation). In few cases of ocean pelagic data, we used the microbial loop of primary production *versus* bacterial production to parameterize $\mathrm{D_P}$ and $\mathrm{D_F}$, respectively. If not available, the export rate was set to 0, leading to k underestimation, which is conservative in our cross-ecosystem comparison given that k is already at the higher end of the range in these pelagic systems.

Unit conversions

Once collected, we standardized values by converting them all into areal carbon units, that is, gC m^{-2} for stocks, and gC m^{-2} yr^{-1} for fluxes, and g g^{-1} yr^{-1} for mass-specific uptake rates, and yr^{-1} for decomposition rates. Figure S2.2 details this data processing.

Carbon conversion: We used data in carbon units (gC) when it was directly provided in the study, or we calculated the values using carbon content when reported in the study (79% of data points). Alternatively, we converted the data into carbon units using the most specific conversion factor available depending on the level of detail about the material of interest (see Table S1.2 for conversion factors). For uptake rates, mass-normalization often made conversions unnecessary. Data were converted for calculations to homogenize units of GPP and autotrophic biomass when needed. For decomposition rates, we did not transform units into carbon. We made the most parsimonious assumption that carbon loss rate is identical to loss rate in the unit provided (generally dry weight or ash-free dry weight). While this is a simplification, we concluded that this best allowed us to keep measurements consistent across data sources, in the absence of more detailed information.

Time extrapolation: 65% of local fluxes or rates were already provided in yearly units. For the others, we extrapolated to the year by using the number of days in the growing season as reported in the study, or the ice-free period in cold climates. When growing season length (GSL) was not specified in the study we used averaged estimates detailed by Garonna et al. (2014) for the different climatic zones in Europe (Mücher, Klijn, Wascher, & Schaminée, 2010): 181 days for temperate climate (mean of "atlantic" and "continental"), 155 days for boreal, 116 days for arctic, and 163 days for arid systems (mean of "Mediterranean" and "steppic"). We assumed no strong seasonality in tropical climates (365 days of GSL). We did not apply any conversion if the value was measured on a study period longer than the above GSL for the corresponding climate.

Volume to area conversions and depth integration: Some data were given per unit of volume. For freshwater systems, we converted the data into area units by integrating them over the water column, using the mean depth of the river or lake. When not directly available in the study we calculated depth by dividing the volume per the area in lakes, or by estimating depth from discharge in rivers with the formula $\text{depth} = c \times Q^f$, with $c = 0.2$, $f = 0.4$ and Q the discharge in $m^3\ s^{-1}$ (see Rodriguez-Iturbe & Rinaldo (1997)). For small catchment areas, that is <1 km^2, we estimated the depth to be 5 cm based on known river scaling-properties (Rodriguez-Iturbe & Rinaldo, 1997). For marine data, notably production in the pelagic zone, studies generally provide a meaningful depth, which defines the euphotic zone such as the Secchi depth or the 1% light inflow depth. We integrated values in volume units over this depth, and to 100 m depth when only sampling depths were provided. For terrestrial and benthic marine ecosystems, carbon in soils or sediments was standardized by integrating it over the thirty first centimetres.

Statistical analyses

Firstly, we performed two-way analyses of variance (ANOVA) to determine the contribution of ecosystem type E and climatic zone C in explaining the variance within each ecosystem variable and within broad categories of variables, that is, stocks, fluxes and rates (see Methods in main text for details on broad categories, Fig.4, Tables S3.1, S3.2). The linear model used was y ~ C + E + C:E, with y being one of the seven ecosystem variables. Since variances were not homogenous, we performed non-parametric Kruskal-Wallis tests on ranks for multiple mean comparisons to test the mean differences among climatic zones (Table S3.3), among ecosystem types (Table S3.4), and climatic zone x ecosystem type combinations (Table S3.5). Results between parametric and non-parametric tests were identical. We analysed further climatic influence on GPP, ER and decomposition rate within each ecosystem type (excluding deserts and agro-ecosystems which are represented only in one climatic zone). We performed both one-way ANOVAs (Table S3.6) and non-parametric Kruskal-Wallis tests on ranks (Table S3.7), on those 18 ecosystem variables x ecosystem type combinations, with climatic zone as explanatory variable. For all the above analyses we used the initial five categories of climatic zones (i.e., arctic. boreal. temperate. tropical and arid), but we also performed the non-parametric tests adding the pooled categories "Warm" (i.e., tropical + arid) and "Cold" (i.e., arctic, boreal, temperate) for marine systems to provide the groups corresponding to the figure displaying the data (Fig. 3; Table S3.12). After each Kruskal-Wallis test, we performed a post-hoc test of multiple comparisons on rank sums to get the groups. For that we performed a Dunn's test using the dunn.test R-package (Dinno, 2017).

Secondly, we analysed the covariance between pairs of ecosystem variables across ecosystem types. We used a bootstrapping procedure to include the variance present in our data despite independent origins between ecosystem variables (see Methods in main text for more details on this procedure). We performed two-sided Pearson's correlation tests on the set of 10,000 bootstrapped data for each pair of ecosystem variables. We display the distributions of the 10,000 Pearson correlation coefficients, and provide the mean of these distributions and the percentage of significant correlations to assess the direction and strength of the relationships between ecosystem variable pairs. In addition, we visualize the variability by showing both the standard deviation of ecosystem variables' distributions (bars in Fig. 5, Fig. S4.1) and the 95% confidence interval (CI) derived from linear regressions made on the series of bootstrapped values (shaded areas). CIs were calculated for 1,000 values along the x-axis, for which we recorded the y-values predicted by each of the 10,000 linear regressions; the boundaries of the shaded area correspond to the 95% confidence interval of the y-values distributions along x-axis. Figures also show the 'mean' regression line defined by the mean slope and intercept (Fig. 5, Fig. S4.1). Note that we minimized the sum of orthogonal distances to the line rather than of residuals squares in these linear regressions to avoid side bias (we do not assume that one of the two variable explains the other one). Furthermore, we carried out a Principal Component Analysis (PCA) on median values of the variables in each E x C combination to examine the relative position of ecosystems in the space defined by all individual ecosystem variables (see Fig. S4.2). We corroborated our general findings by performing correlation tests on the subsets of data for which pairs of variables were available per site (see discussion in Appendix S2 section S2.4, Figs S2.10 and S2.11, and Table S3.13).

Thirdly, we analysed the correlations between ecosystem variables within each ecosystem type and latitude, using two-sided Pearson's correlation tests. In Table S3.8, we report the results of all these tests, along with slopes and intercepts of the corresponding linear regressions when the test was significant.

Software

We analysed the data and plotted the figures with the open source software R version 3.6.1(R Core Team, 2019) and different R-packages:

- Figure 1 (to show the map): *maps* (Becker & Wilks, 2018)
- Figures 5 and S4.1: *vioplot* (Adler, 2018) to show the distribution of correlation coefficients, *minpack.lm* (Elzhov, Mullen, Spiess, & Bolker, 2016) for the linear regression and, *ade4* (Dray & Dufour, 2007) to add a scatter plot;
- Figure 6: *plot3D* (Soetaert, 2017);

- Figure S4.2: *FactoMineR* for the PCA (Le, Josse, & Husson, 2008);
- Statistical tests: *pgirmess* (Giraudoux, 2018) (post-hoc tests of multiple mean comparison on rank sums), *dunn.test* (Dinno, 2017) (post-hoc test of multiple mean comparison on rank sums), *multcompView* (Graves, Piepho, Selzer, & with help from Dorai-Raj, 2015)(to find the groups);
- Figure S2.2: *RColorBrewer* (Neuwirth, 2014)for the colours.

Final artwork was realized with Illustrator CC 22.0.1.

Table S1.1 | Definitions of ecosystem and climate categories.

	Definition	Example ecosystems
Climatic zones		
Arctic	Extreme temperature limitation of growing season length, with abiotic conditions not supporting tree growth in arctic, subarctic, and alpine zones; OR high latitude oceans, generally above 66.5°	Tundra (grassland) Alpine grassland
Boreal	Strong temperature limitation of terrestrial growth, but environment supports tree growth. Covers northern parts of North America, Europe, and Russia from latitudes 50° to 55°; OR oceans between 50° and 66.5°	Taiga (forest) Sub-alpine forest
Temperate	Seasonal terrestrial growth with some temperature limitation. Covers latitudes between 23.5° and 50° to 55°, including oceans in this latitudinal range	Beech forest
Tropical	Warm terrestrial tropical, sub-tropical, equatorial systems not limited by drought between 0° to 23.5° latitude (including subtropical system), including oceans in this latitude range	Savanna (grassland), rainforest
Arid	Severely water-limited terrestrial systems at all latitudes, including arid, semi-arid, xeric, xerophytic, xeromorphic, Mediterranean systems, continental, warm or cold, and polar deserts	Garrigue (grassland), shrubland (grassland or forest, depending on the canopy), chaparral (grassland), steppe (grassland), caatinga (forest), cerrado
Ecosystems		
Forest	Complete vegetation cover with trees as dominant vegetation; tree canopy covers most of the surface	Rainforest, caatinga, woodland, some shrubland, cerrado
Grassland and shrubland	Complete vegetation cover. but with only very few or no trees; vegetation dynamics dominated by water limitation, fires, and grazing.	Steppe, savannah, meadow, prairie, tundra, old field, some shrublands, herbaceous rich-fen vegetation
Desert	Extreme growth limitation by water availability. with little vegetation distributed in remote patches	Sandy land
Agro-ecosystem	Ecosystems devoted to crop production or cattle grazing, often fertilized or irrigated to remove nutrient or water limitations for growth	Cropland, pasture, field, vineyard, orchard
Stream	Running freshwater and lotic systems of all sizes. including rivers	Creek, brook, river, stream
Lake	Standing (lentic) freshwater systems	Reservoir, lake, pond
Ocean	All salt water ecosystems with no emerged vegetation, including internal seas	Sea, ocean shelf, estuary, lagoon
Ocean pelagic	Ecosystems in the open water columns of oceans and seas	Upwelling system, open ocean
Ocean benthic	Ecosystems at the bottom of oceans and seas	Coral reef, sea grass bed, eelgrass meadow, kelp forest, deep-sea flour

Table S1.2 | Factors used for conversions into grams of carbon.

KJ = kilojoule; Kcal = kilocalorie; mol C = mole of carbon; g CO_2 = gram of carbon dioxide; g O_2 = gram of di-oxygen; mol O_2 = mole of di-oxygen; g WW = gram of wet weight; g DW = gram of dry weight; g AFDW = gram of ash-free dry weight. Values into brackets give the percentage of raw values converted using a given factor.

Type of material	KJ	Kcal	mol C	g CO_2	g O_2	mol O_2	g Chla	g WW	g DW	g AFDW
Organic Tissue [a]	0.02 (0.08%)	0.09 (0.10%)	12 (3.01%)	0.2727 (2.46%)				0.09 (0.94%)	0.45 (2.70%)	0.5 (4.39%)
Productivity, photosynthetic quotient = 1.2 [b]					0.3125 (3.33%)	10 (0.26%)				
Respiration, respiratory quotient = 1[ab]					0.375 (3.55%)	12 (0.26%)				
Non-woody primary producer terrestrial [c]									0.3* (3.11%)	
Algae, sea grasses [c]							50 (0.76%)	1/16.7 (0.12%)	1/2.92 (1.06%)	
Arthropods[d]									0.496 (0.22%)	

[a] from Table 1 p26 in Weathers, Strayer, & Likens (2013), and references therein.

[b] from supplementary references: Duarte et al., (2010); Huchette, Beveridge, Baird, & Ireland (2000); Irons III & Oswood (1997).

[c] from Table 2.5 p26 in Opitz (1996) for conversions factor from WW and DW; Conversion factor for Chl-a from Peterson, Hobbie, & Corliss (1986).

[d] from Small, Torres, Schweizer, Duff, & Pringle (2013).

* used general conversion factor 0.45 for DW in deserts and arid grasslands where the vegetation includes woody species.

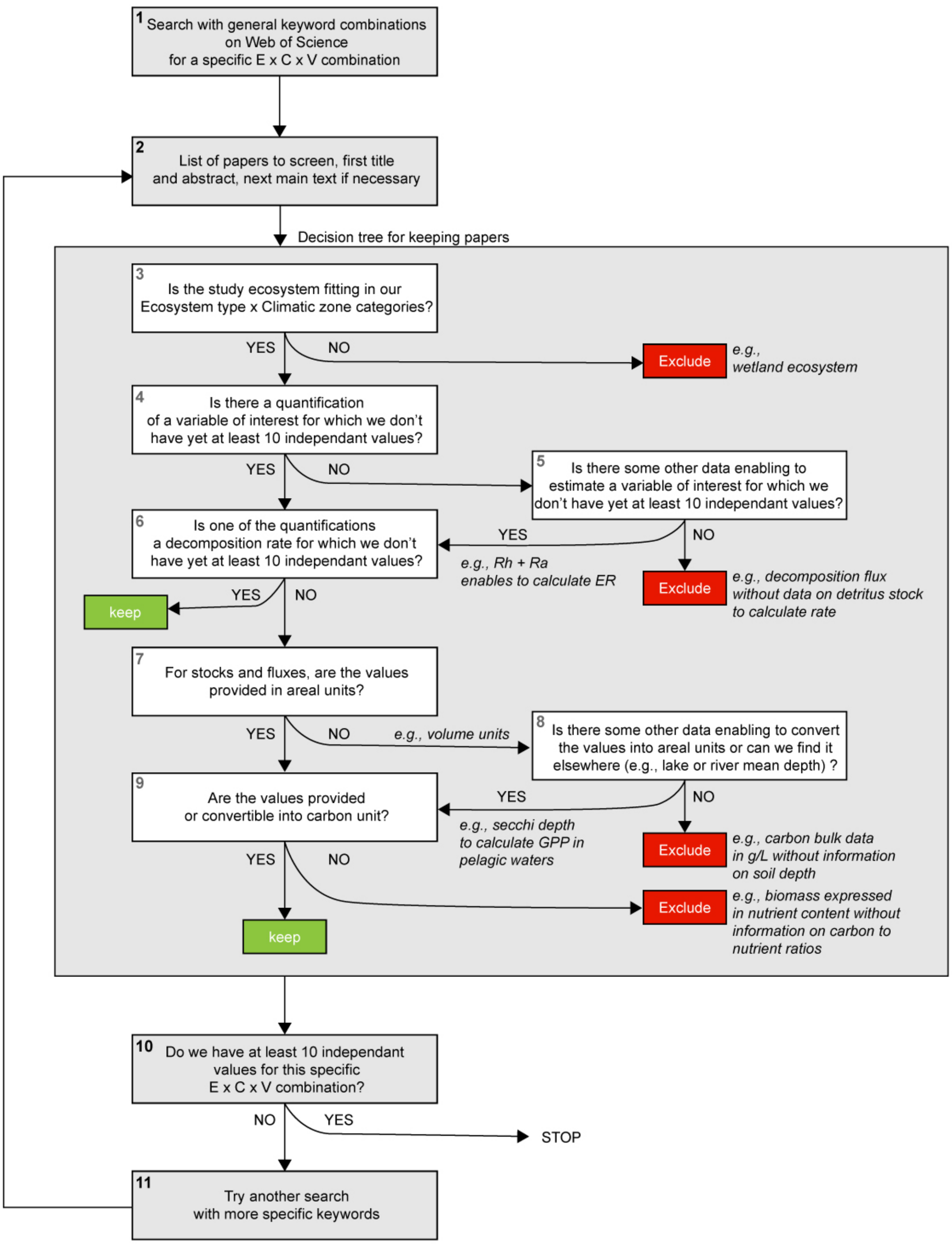

Figure S1.1 | Decision tree of the data collection process.

Steps 1, 2, 10, 12 describe the recursive steps of data search. Steps 3 to 9 describe the decision tree to include or not a paper in our collection.

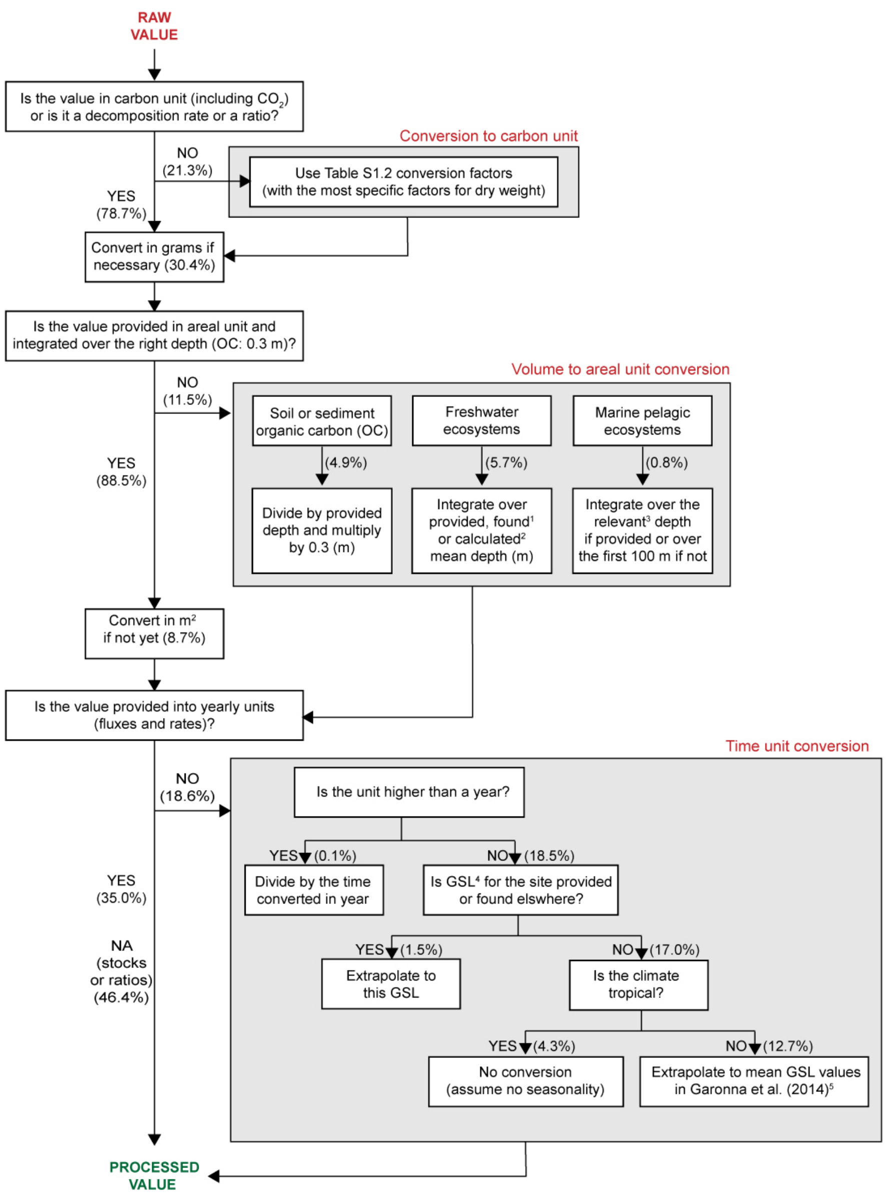

Figure S1.2 | Data treatment.

Conversions applied to raw value to homogenize units to g C m^{-2}, g C m^{-2} yr^{-1}, and yr^{-1}, for stocks, fluxes, and rates, respectively. Percentage refer always to the whole data set. Notes: [1] Some lake mean depths were found elsewhere when not provided in the study. [2] We estimated river mean depth with discharge and lake mean depth with area and volume when not directly provided. [3] Secchi or 1% light attenuation depths were used to integrate biological fluxes and stocks when provided. [4] GSL: Growing Season Length. [5] mean GSL values used to standardize: 116, 155, 163, and 181 days for arctic, boreal, arid, temperate climatic zones, respectively (see explanations and references in Appendix S1).

Appendix S2 – Data set presentation

This appendix presents the data set, relevant information on its content and on some identified possible sources of variability, to facilitate a nuanced interpretation of the observed patterns.

S2.1 Geographical location

Data are spread over the world (Fig. 2), with a typical under-representation of the southern hemisphere, notably for terrestrial and freshwater ecosystems. This tendency is illustrated by deserts, for instance, which are mainly represented by North American and Chinese deserts, and almost no data for African ones. Partitioning of individual variables shows no obvious geographical clustering (Fig. S2.1).

S2.2 Data set structuration among studies and sites

Half of the studies consider a single site, and less than 15% of the studies consider more than five sites (Fig. S2.2a, b). Similarly, most studies (46%) focus on a single ecosystem variable, while 34% of the studies consider two to three variables (Fig. S2.2c, d), which was often either several fluxes or several stocks; since a special collection effort was made on finding papers which provide both GPP and autotrophic biomass to estimate uptake rates, biomass is also recurrently found with flux data in our data set. The 15% studies considering more than four ecosystem variables are often studies on single sites, mostly aquatic ones, with a whole ecosystem budget perspective. This includes, for instance, studies on carbon budget in freshwater ecosystems, or studies gathering estimates to feed ECOPATH models in marine or lake ecosystems. Overall, we most often have only one ecosystem variable estimate per site (56%), which justified our bootstrapping approach to examine pairwise variable correlations (Figs. 5 and S4.1). For example, estimates of decomposition rates come mostly from decomposition experiments which do not provide any of the other focal variables we are considering here. By contrast, some variables are almost systematically measured together at the same site, such as GPP and ecosystem respiration (491 data points), biomass and detritus (213 data points), or biomass and GPP due to our search of uptake rate estimates (252 data points). Tables S3.13 and figures S2.10 and S2.11 display the significant correlations tests for available pairs of variables at the site-level (see also section S2.4 below).

S2.3 Data set composition and variance

Variance in our data set comes from both natural variation among and within the ecosystems looked at, and diversity and variability in what was measured and how (i.e. variation caused by the measurement and methods). These two levels of variation cannot be separated in our data set but we here discuss the individual components of our study (stocks, fluxes, and rates), their respective specificities with respect to data origin and specific possible biases. Coefficients of variation for each ecosystem variable are provided in Table S3.11.

Biomass

Biomass represents different components of the ecosystem depending on ecosystem type. Available estimates are most often representative for the organisms contributing the most to the biomass. In terrestrial ecosystems, or in benthic ecosystems such as dense seagrass beds or kelp forests, primary producers constitute most of the biomass (see Fig S2.3). In this case, methods are relatively standard (harvesting), but we gathered aboveground-only (A) and above+belowground (AB) estimates, which adds to natural variation (Fig S2.3b). Omitting roots necessarily underestimates biomass in terrestrial ecosystems, however, biomass increases significantly only in tropical forests when removing aboveground-only data (Fig. S2.4). In aquatic ecosystems, biomass also integrates heterotrophs (Fig S2.3b), especially when not dominated by macroalgae. In freshwater ecosystems, biomass measurements of the whole community are rare and estimates are often epilithon or macroinvertebrate-only data without fish. We thus acknowledge that at least half and a quarter of the data, for streams and lakes respectively, are obvious underestimations (Fig S2.3c). However, removing these partial data gives significantly higher mean biomass only in tropical streams (Fig S2.5). Overall, despite variability in the biomass estimates, we are confident that the strong among-ecosystem differences we observe are robust to those differences in documented biomass.

Organic carbon

Storage of decomposed organic carbon differs fundamentally in terrestrial-benthic versus freshwater-pelagic ecosystems. The estimates for the former are carbon stored in the first 30 cm of soils or sediments and reach areal amounts of magnitudes 1000–10,000 g m^{-2}. For the latter, estimates are organic carbon dissolved in the water column and range three to four orders of magnitude lower. Methods for both types of measurement are highly standardized and variance likely reflects the natural variation.

Detritus

Detritus is the ecosystem variable showing on average the highest coefficients of variation (Table S3.11). In terrestrial and macroalgae-dominated ecosystems detritus is most often the litter layer, sometimes also including dead standing stock. In freshwater ecosystems, detritus is not only autochthonous detritus but also detritus from terrestrial riparian systems in the form of fine or coarse particulate matter, and sometimes woody debris. Differences in adjacent terrestrial land use thus partly explain a high variance in freshwater detritus. In pelagic marine systems, detritus is particulate organic matter, which is either locally produced in the open ocean, or a combination of locally produced particulate organic matter and organic matter inflow from freshwater systems in estuaries. Sedimentation and fast decomposition through the microbial loop keep detritus stocks at low levels in the water column of these systems.

Ecosystem fluxes

The methods to measure ecosystem fluxes vary strongly among ecosystem types (Fig. S2.6). Notably, in terrestrial systems, CO_2 fluxes are mainly measured with the Eddy-covariance method from flux towers or chambers equipped with portable infrared gas analysers (73% of GPP estimates), but also satellite data (11% of GPP estimates; MODIS: MODerate Resolution Imaging Spectrometer) or more traditional methods involving the budget of biomass increment of plants (NPP) and autotrophic respiration (9%). In freshwater and benthic marine ecosystems, the dominant methods to estimate of photosynthesis and respiration are based on change of dissolved oxygen concentration in time or space (83% of GPP estimates), while in pelagic marine systems, incorporation of ^{14}C into the biomass is the preferred method to estimate primary production (62%). This last method, however, gives estimates that lie between GPP and NPP depending notably on incubation time (Codispoti et al., 2013). To assess that this was not affecting our conclusions, we identified data which were estimated from this method with an incubation time longer than 6H or unknown (to be conservative), and were likely to underestimate GPP. This concerns 47/687 estimates of GPP and 18/309 of uptake rates (calculated from local GPP and producer biomass). We applied a factor of 0.5 to these estimates, which is also very conservative according to some studies providing both NPP and GPP (e.g., factor of 0.88 in Carstensen, Conley, & Müller-Karulis (2003)), and re-run the analyses. This obviously has some quantitative effect, for instance lowering the strength of the relationship between latitude and GPP but increasing the one with uptake rates in pelagic marine systems, or increasing the strength of the correlations observed in Fig5b, 5d and 5e between pairs of ecosystem variables. Importantly, the general qualitative cross-ecosystem differences and the gradient of ecosystem functioning still hold (Figs. S2.7 and S2.8). Thus, while there are differences in the technical approaches how ecosystem fluxes are assessed, these differences do not change the qualitative relationships documented here.

NEP *versus* GPP/ER

NEP, shown in figure 3f, is a classical metric to assess ecosystem heterotrophy. However, differences in methodologies to measure GPP and ER can inflate errors when calculating NEP and might skew cross-ecosystem comparisons (Honti & Istvánovics, 2019). We therefore also examined the GPP/ER ratio, which removes such potential biases (Fig. S2.9). These latter ratios confirm the global trends in ecosystem heterotrophy with values generally above one in terrestrial and pelagic systems (78%) and often below one in freshwater and benthic ecosystems (78% also). Significant differences among climatic zones are identical for GPP/ER ratios and NEP (Table S3.3). GPP/RE also increases significantly with latitude in streams, while the weak negative correlation found for NEP in grasslands disappears (Table S3.8 and Figure S4.5). General differences among ecosystem types are also confirmed, although slightly weaker than for NEP (Table S3.4).

Carbon uptake rates

The vast majority of our carbon uptake rate estimates is calculated from studies where both GPP and autotrophic biomass was provided. In terrestrial ecosystems, uptake rates might be slightly overestimated when only aboveground biomass is considered, while in aquatic ecosystems potential overestimations due to methods to estimate primary production (see above) did not lead to significant differences in mean uptake rates (Fig. S2.7). Our results are thus conservative regarding the higher uptake rates in aquatic compared to terrestrial ecosystems.

Decomposition rates

Decomposition rates are most often obtained from litter bag experiments in terrestrial, freshwater and benthic ecosystems. In terrestrial and benthic ecosystems, the litter used comes from the same type of ecosystem, often comparing the local decomposition of different leaf species found regionally, while in freshwater ecosystems litter is of terrestrial origin. Thus, differences between terrestrial and freshwater decomposition rates reflects mostly differences in physical factors and decomposer communities. It's likely that decomposition of autochthonous production would increase estimate values in freshwater ecosystems because aquatic primary producers are way more labile than terrestrial ones (Elser et al., 2000). The observed differences are therefore conservative. Variations in decomposition rates among litter types of different species contribute a lot to within-ecosystem variations.

Estimates for pelagic marine ecosystems were not easy to find and the variability of our values also reflects strong methodological heterogeneity: Decomposition of local production was often estimated by the microbial loop, notably in the open ocean: that is the ratio of bacteria to phytoplankton production, in other words the production processed by bacteria (e.g., Cho & Azam, 1988; Ducklow, 1999; Kirchman, Keel, Simon, & Welschmeyer, 1993). Our data set integrates also estimates from measurements of remineralization rates of dissolved or particulate organic carbon (e.g., Gan, Wu, & Zhang, 2016), which gives lower values than the bacterial loop, or from a classical decomposition experiment on salp carcasses (an important component of zooplankton in some places), which gave us a high-value outlier (Stone & Steinberg, 2016).

S2.4 Correlations between pairs of ecosystem variable: bootstrap *versus* site-level data

To examine the relationships between ecosystem variables we adopted a bootstrapping strategy (see Methods and Appendix S1) due to the low number of per-site data for some pairs of variables. For instance, despite very extensive targeted literature searches, we only found ten sites across all ecosystem types which had data to document both uptake and decomposition rates. Nevertheless, we also tested pairwise-variable correlations on subsets of our data set when estimates for both variables were provided (thereafter called 'empirical' correlations; see Table S3.13 for all significant correlations and figures S2.10 and S2.11). These empirical correlations support all the findings obtained from bootstrapped values. They also quantify some significant cross-ecosystem relationships that are not indicated by our conservative bootstrap approach, for instance a negative relationship between detritus and decomposition, or positive relationships between ecosystem respiration and biomass or organic carbon (Table S3.13).

Additionally, correlation tests were performed within each ecosystem type for each ecosystem variable pair, which reveals whether relationships between variables emerge solely from cross-ecosystem differences or also from constraints operating at the ecosystem level. Notably, the positive relationship observed between biomass and organic carbon (Fig. 5a) clearly results from cross-ecosystem differences, with no within-ecosystem relationships detected (Fig. S2.10b), while the strong positive correlation between GPP and ER is also highly significant within each ecosystem type (Figs. 5b and S2.10d). This relationship is well-known and expected, notably in terrestrial ecosystems where ecosystem respiration is the sum of autotrophic respiration, which is causally connected with GPP, and heterotrophic respiration, which consists mostly in soil microbial respiration fed by plant detritus and exudates. Note, however, that this relationship is weaker and less systematically expected in aquatic ecosystems. In these ecosystems, respiration can result dominantly from the decomposition of allochthonous matter and be relatively disconnected from a low in-situ GPP (for example in rivers with high riparian cover or benthic ecosystems in deep or turbid water).

Interestingly, the strong negative relationship between ecosystem biomass and primary producer uptake rates holds both across and within ecosystem types (Fig. S2.10b). At cross-ecosystem level, the relationship likely emerges from contrasting differences among primary producers (e.g., size, composition in structural tissues), as discussed in the main text. Within ecosystems, the relationship can be interpreted as a result of both specific variation in producers and competition: higher biomass can result from more individuals which fix carbon at a lower rate due to mutual shading for instance.

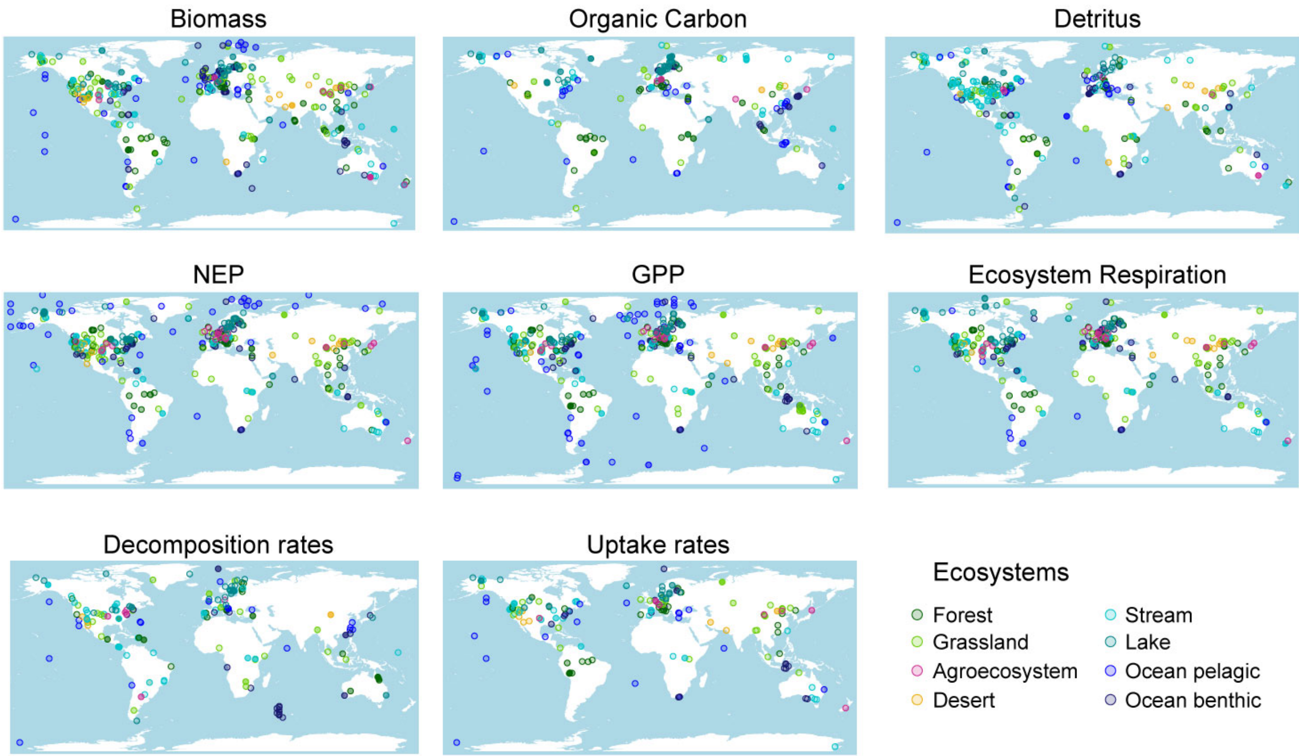

Figure S2.1 | Geographical distribution of data for each ecosystem variable.

Each dot shows the geographic location of sites from which we obtained data. Colours denote the different ecosystem types. For about 13% of the data either the coordinates are not provided or the geographical scale given is either too large or too coarse to be meaningfully reflected in the map. The map is made with Natural Earth. Free vector and raster map data @ naturalearthdata.com.

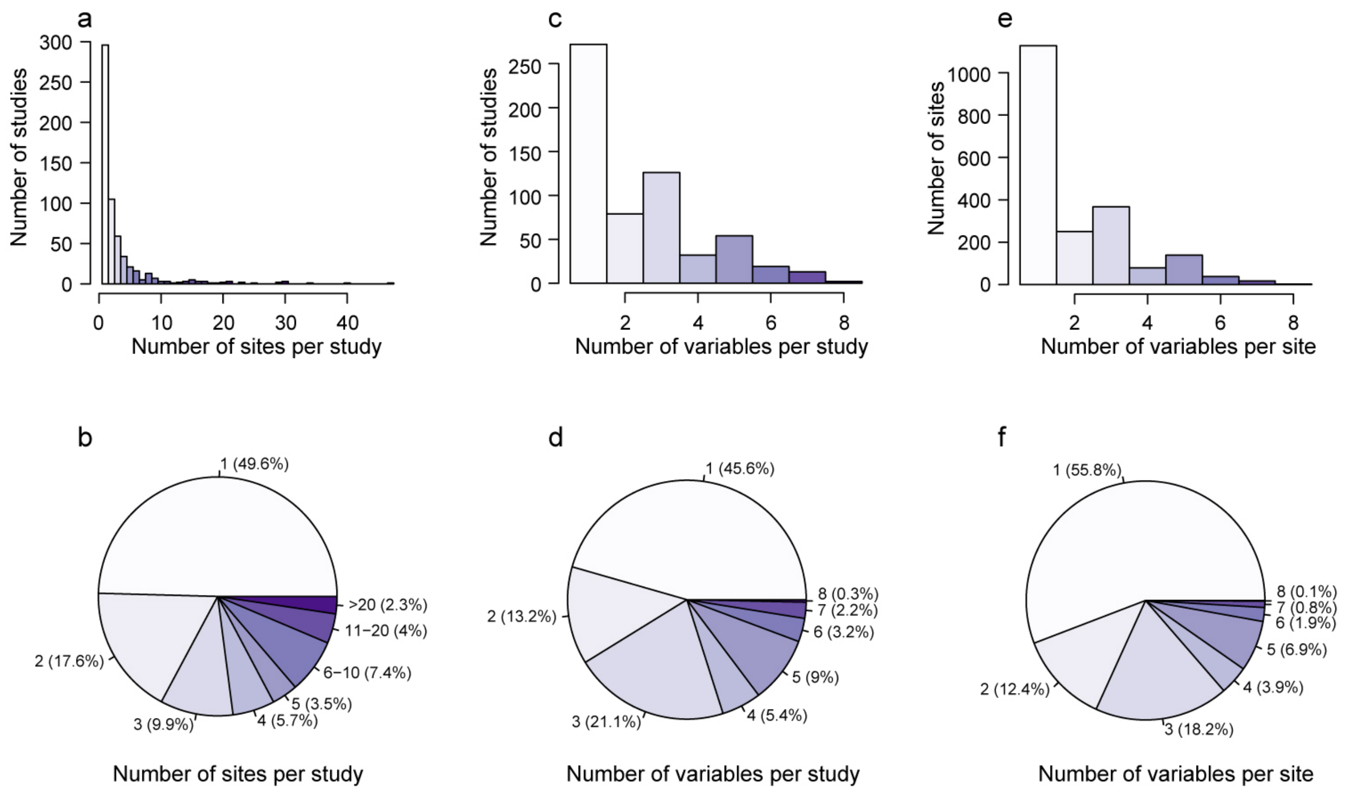

Figure S2.2 | Data distribution among studies, sites, and ecosystem variables.

Histograms (a, c, e) and pies (b, d, f) of (a, b) number of sites per study, (c, d) number of ecosystem variables per study and (e, f) number of ecosystem variables per site. The eight ecosystem variables considered here are: biomass, organic carbon, detritus stocks, gross primary production, ecosystem respiration, net ecosystem production, and uptake and decomposition rates. Some of the estimates were not directly provided but calculated from data provided in the studies (see Appendix S1). This analysis considers the data of 599 of the in total 604 studies in the complete synthesis; data from five studies had to be excluded as they provided only biome-scale estimates.

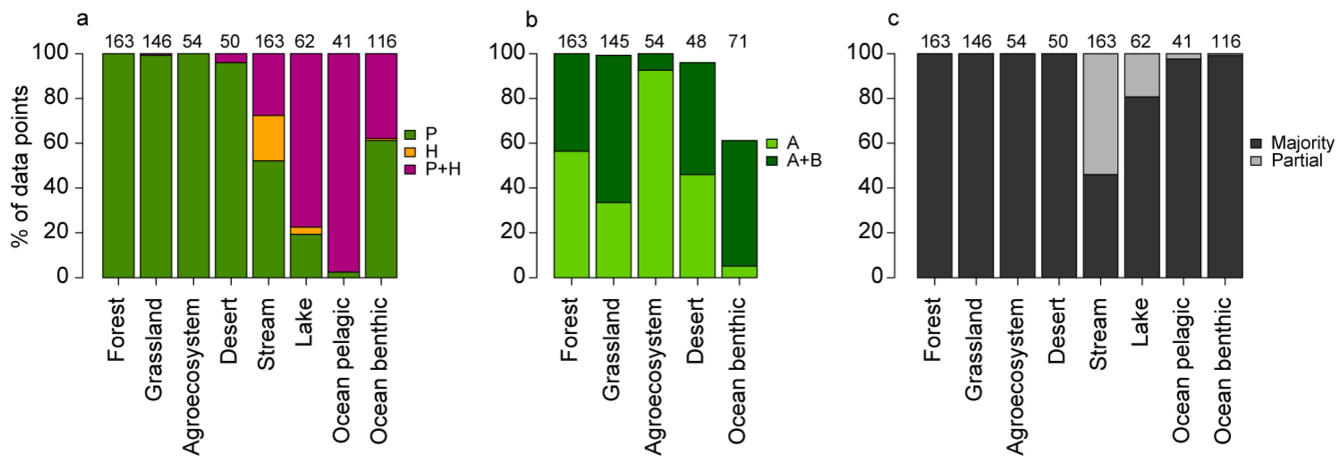

Figure S2.3 | Partitioning of biomass data.

Panel **a** shows the percentage of biomass estimates representing only primary producers (P), only heterotrophs (H) or both primary producers and heterotrophs (P+H). Panel **b** shows the percentage of estimates of primary producer biomass that include only aboveground (A) or both above and belowground biomass (A+B) in terrestrial and marine benthic ecosystems. Panel **c** shows the percentage of biomass estimates which are assumed to represent the majority of community biomass (in dark; e.g. trees in forests) or which are known to be only a partial estimate (in light grey). Estimates of complete communities were difficult to found in freshwater ecosystems. Numbers of data points are provided on the top of each panel.

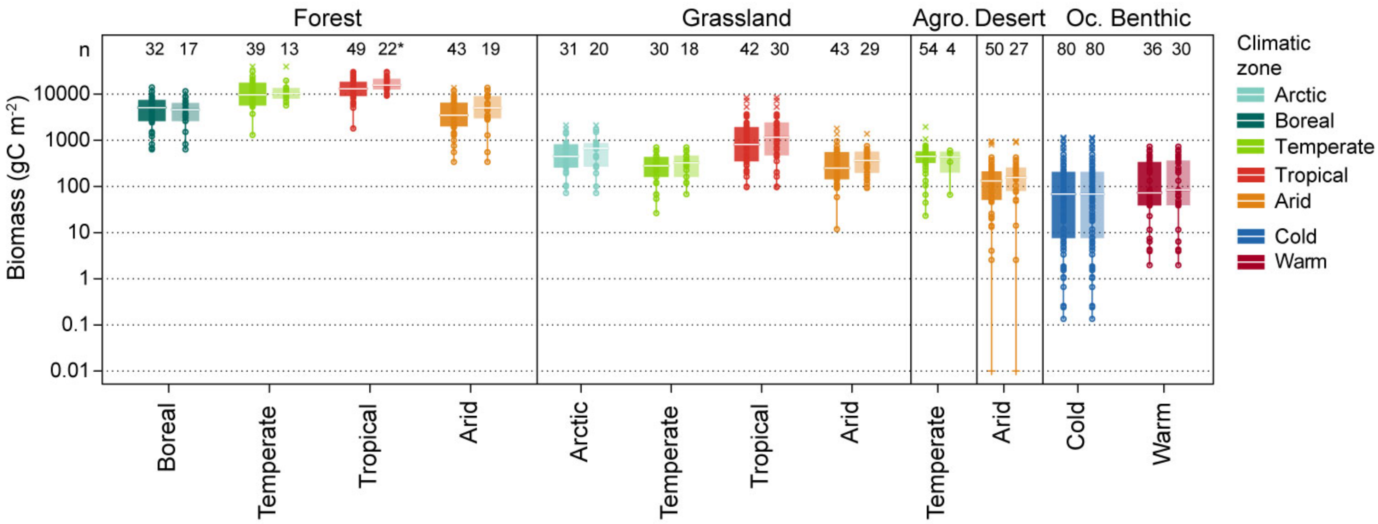

Figure S2.4 | Comparing data with or without aboveground-only biomass estimates.

Biomass data across different ecosystem types (left to right) and for different climatic zones (colours). Transparent colour boxes are for data from which we removed aboveground-only estimates of primary producer biomass while solid boxes are for the complete distribution. Points give values, with "x" denoting outliers. Zero values are replaced by 0.01 to be displayed despite log scales and are given as "+". Boxplots give median (white line), 25% and 75% percentiles (box), extended by 1.5* inter-quartile range (whiskers). Numbers of data points (n) are given on the panel top. Only tropical forests show a significant difference, denoted by an asterisk) between data with or without aboveground-only data (Wilcoxon test W=364; p-value = 0.03).

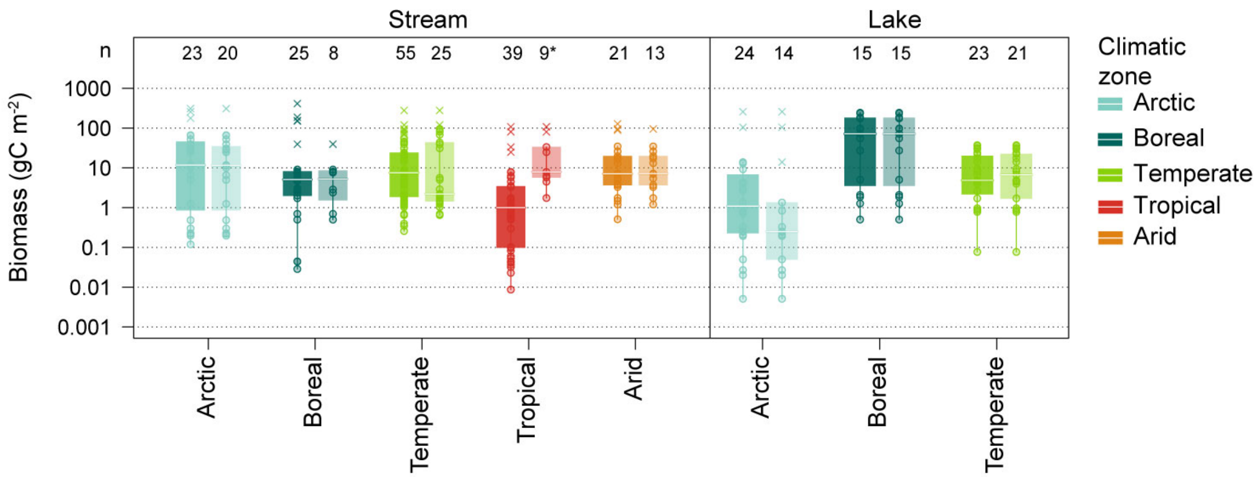

Figure S2.5 | Comparing freshwater data with or without partial biomass estimates.

Biomass data across different ecosystem types (left to right) and for different climatic zones (colours). Transparent colour boxes are for data from which we removed the data that clearly underestimate biomass (e.g., invertebrate-, fish-, periphyton- or epilithon-only data). Points give values, with “x” denoting outliers. Boxplots give median (white line), 25% and 75% percentiles (box), extended by 1.5* inter-quartile range (whiskers). Numbers of data points (n) are given on the panel top. Only tropical streams show a significant difference, denoted by an asterisk) between data with or without partial biomass estimates (Wilcoxon test W=46.5; p-value < 0.001).

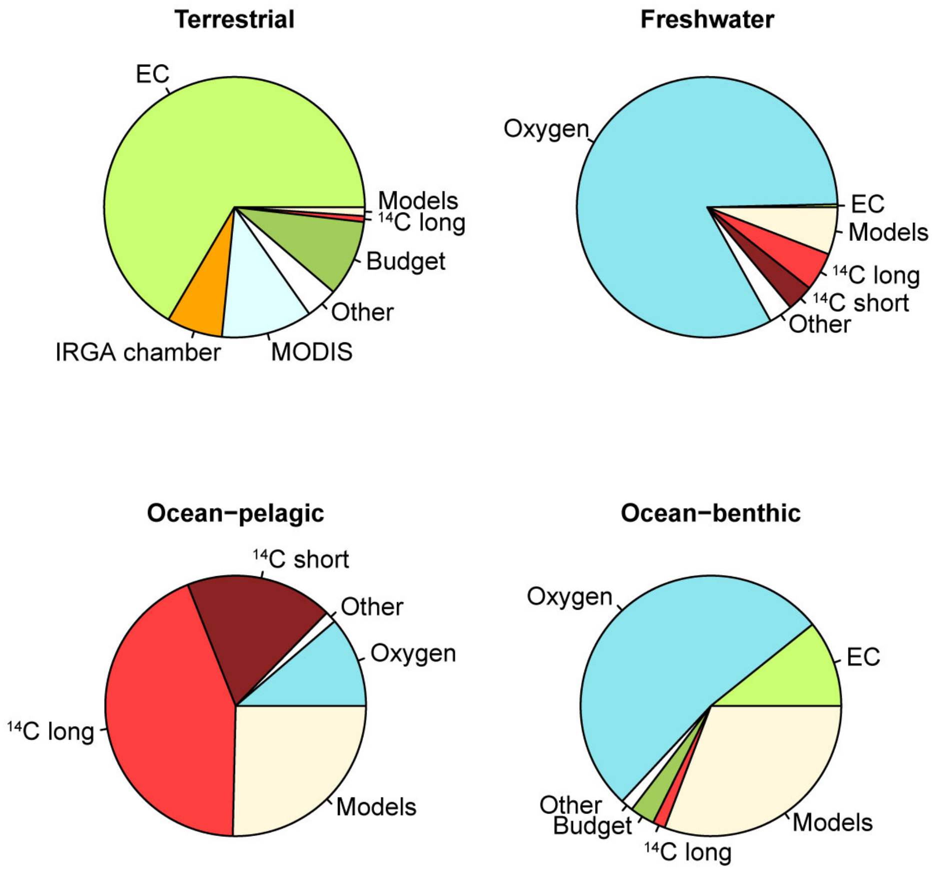

Figure S2.6 | Methods used to estimate GPP in our data set.

EC: Eddy-covariance methods; IRGA: Infrared Gas Analyser. MODIS: MODerate Resolution Imaging Spectrometer (satellite data); "Budget" refers to methods adding measures of autotrophic respiration and NPP estimates from biomass increment measures. "^{14}C short" refers to methods measuring the incorporation of ^{14}C into biomass with incubation times up to 6 hours. "^{14}C long" refers to methods measuring the incorporation of ^{14}C into biomass with incubation times higher than 6 hours, or when the incubation time is not specified (to be conservative). "Oxygen" refers to method based on change in dissolved oxygen concentration in time or space. "Models" refers to different empirical models (for instance involving the construction of chlorophyll-a – irradiance curves or outputs of ECOPATH models fed with empirical estimates). "Other" includes methods for instance measures of CO2 based on pH titration or measure of nutrient uptake.

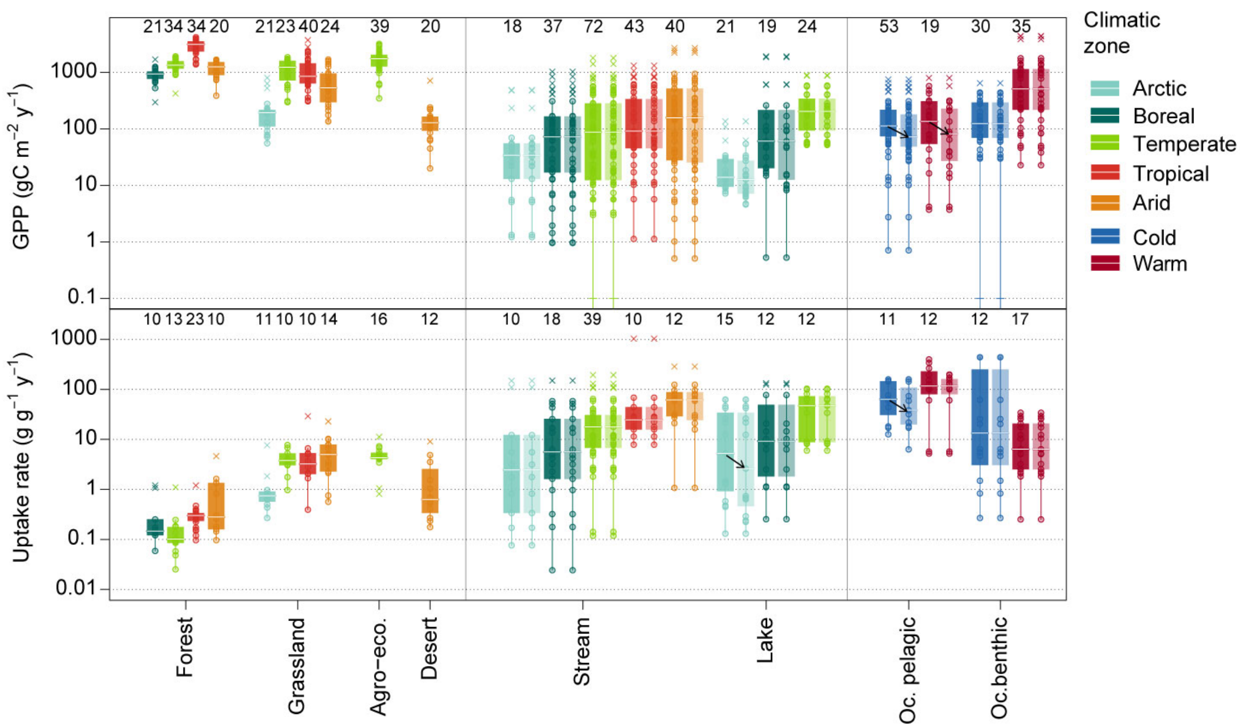

Figure S2.7 | Boxplots comparing data with or without correction of estimates from ^{14}C method.

GPP (top panel) and uptake rate data (bottom panel) across different ecosystem types (left to right) and for different climatic zones (colours). Transparent colour boxes are for data subsets in which estimates were divided by two when estimation involved the method of ^{14}C incorporation with a long incubation time because the primary production estimation is thought to be then closer to net than to gross primary production (Codispoti et al., 2013). This concerns 47/687 values of GPP and 18/309 of uptake rates, mainly in ocean pelagic and arctic lake ecosystems. Points give values, with "x" denoting outliers. Zero values are replaced by 0.1 to be displayed despite log scales and are given as "+". Boxplots give median (white line), 25% and 75% percentiles (box), extended by 1.5* inter-quartile range (whiskers). Numbers of data points (n) are given on the panel tops. Arrows highlight the decrease in median values. None of the Wilcoxon tests performed on pairs of corrected/not corrected data (individual pairs of solid and transparent boxplot) showed a significant mean difference, thus indicating that, overall, both qualitative and even quantitative differences due methodological differences in ecosystem flux measurement methods, have minor consequences on global patterns.

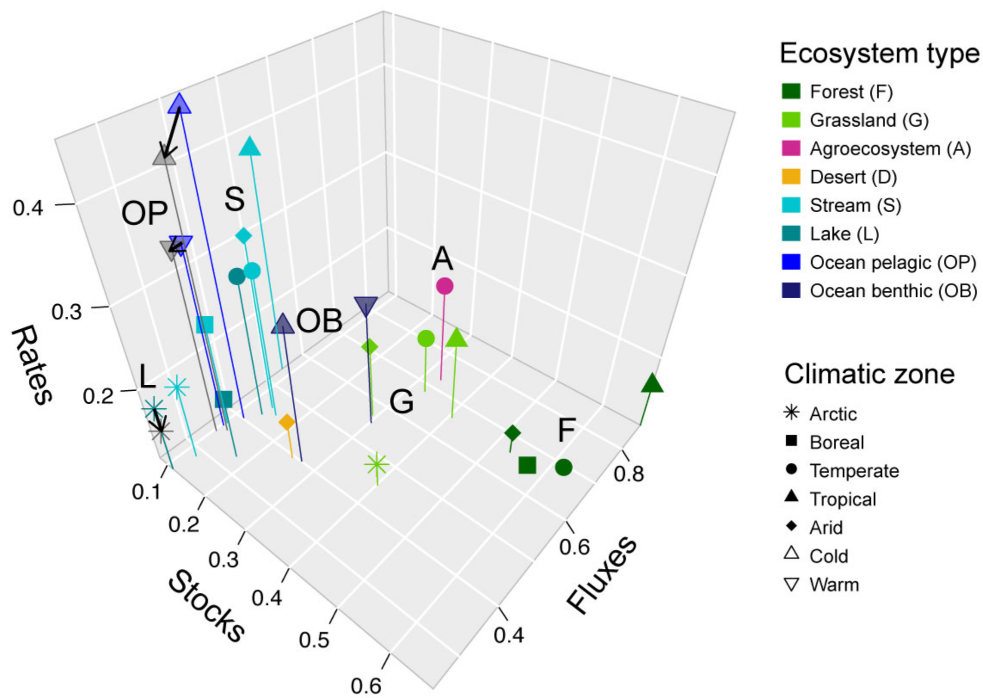

Figure S2.8 | Functioning type gradient including correction for ^{14}C method.

Relative positions of median ecosystem in the ecosystem functioning space: Ecosystem types (colours, labels) in each climatic zone (shapes) according to the medians of stocks (biomass, organic carbon, detritus), fluxes (gross primary production, ecosystem respiration), and rates (mass-specific uptake and decomposition rates). Values are scaled between 0 and 1 within each ecosystem variable before pooling them into broader categories (i.e., stocks, fluxes, and rates) to avoid biases resulting from different numbers of data points among ecosystem x climate x variable combinations. For purpose of clarity, scaled median values are double square root-transformed. Arrows and grey shapes show the new position of median ecosystems when a correction factor of 0.5 is applied on estimates of GPP and uptake rates which measurement involved the method of ^{14}C incorporation with a long incubation time. In this case, primary production estimation is thought to be then closer to net than to gross primary production (Codispoti et al., 2013).

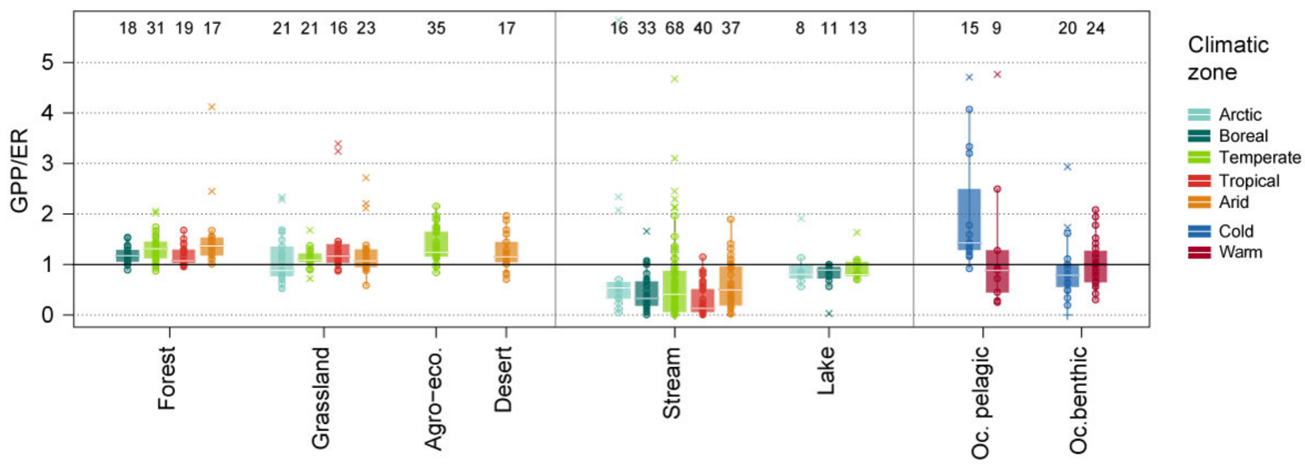

Figure S2.9 | GPP/ER ratios.

Ratios of gross primary production (GPP) to ecosystem respiration (ER) across different ecosystem types (left to right) and for different climatic zones (colours). Points give values, with “x” denoting outliers. Boxplots give median (white line), 25% and 75% percentiles (box), extended by 1.5* inter-quartile range (whiskers). Numbers of data points (n) are given on the panel top.

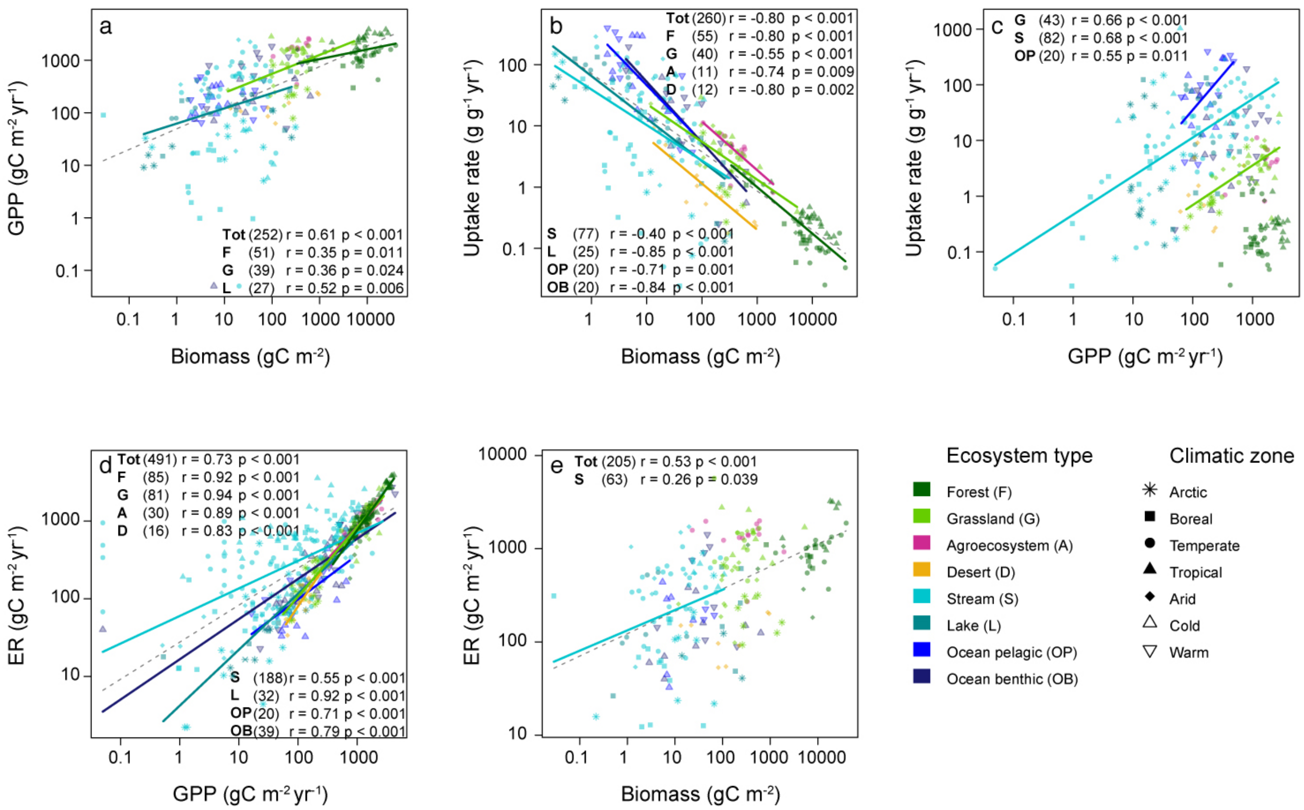

Figure S2.10 | Correlations among pairwise ecosystem variables (I –fluxes & rate).

Shapes show the data points in different climatic zones. Colours denote ecosystem types. Lines show regression lines for significant correlations between selected ecosystem variables in the different ecosystem types, based on two-sided Pearson's correlation tests. Pearson correlation coefficients and p-values are provided for these significant relationships, with the number of data points in brackets (see legend for abbreviations of ecosystem types). "ER" and "GPP" stands for ecosystem respiration and gross primary production, respectively. Uptake rates are GPP values divided by autotrophic biomass. Dotted lines show regression lines for significant correlation tests performed on all the points (all ecosystem types). "Tot" reports the corresponding statistics.

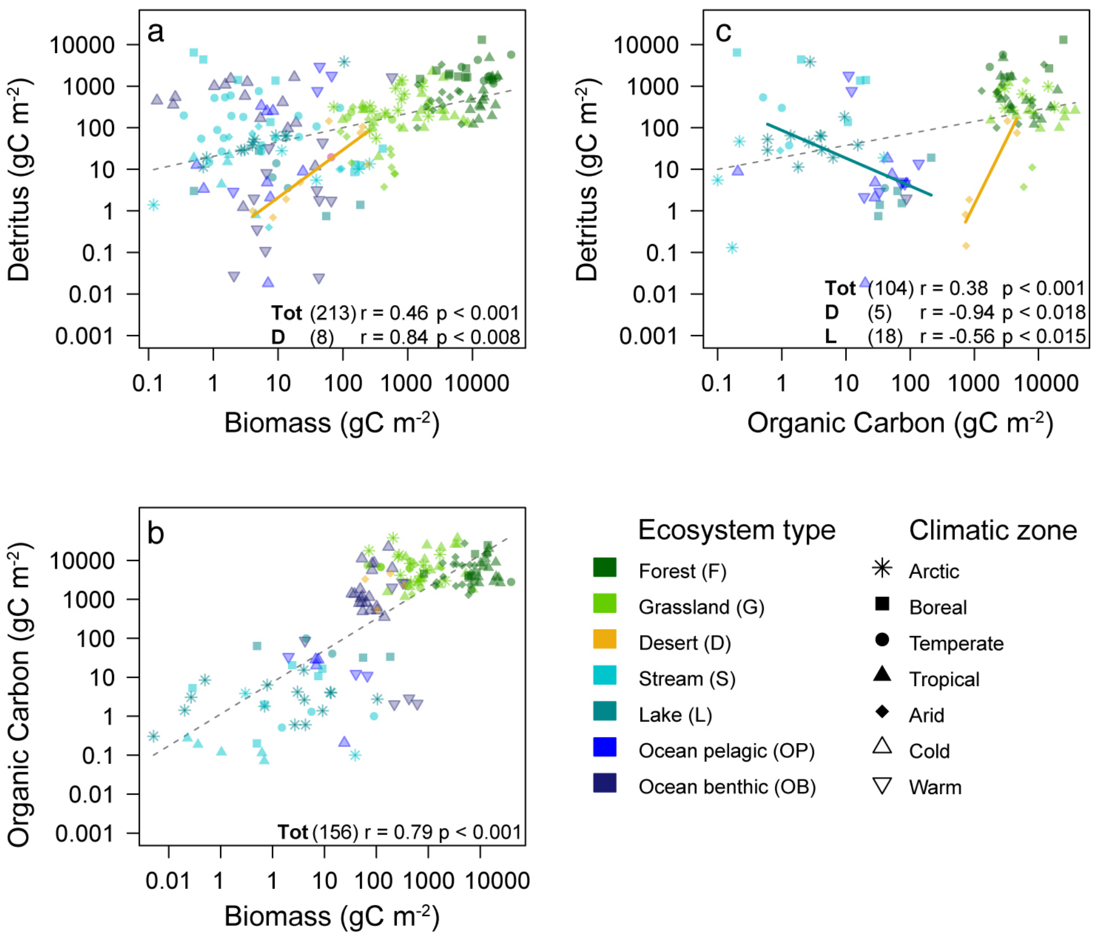

Figure S2.11 | Correlations among pairwise ecosystem variables (II – among stocks).

Shapes show the data points in different climatic zones. Colours denote ecosystem types. Lines show regression lines for significant correlations between selected ecosystem variables in the different ecosystem types, based on two-sided Pearson's correlation tests. Pearson correlation coefficients and p-values are provided for these significant relationships, with the number of data points in brackets (see legend for abbreviations of ecosystem types). Dotted lines show regression lines for significant correlation tests performed on all the points (all ecosystem types). "Tot" reports the corresponding statistics.

Appendix S3 – Statistical results

Table S3.1 | Two-way ANOVAs on ecosystem variables.

Results of seven analyses of variance (ANOVA) performed on ecosystem variables with climatic zone (C) and ecosystem type (E) as explanatory variables; model: y ~ C + E + C:E (statistics for Figure 4a). NEP, GPP, and ER stand for net ecosystem production, gross primary production, and ecosystem respiration, respectively. Degrees of freedom (DF), sum of squares (Sum Sq), F- and P-values of the significance tests, and proportion of variance explained, as well as of the explained variance for main and interaction effects are given.

Response Variable	Explanatory variable	DF	Sum Sq	% of variance explained	F-value	P-value	Sign.[1]	% of the explained variance
Biomass	C	4	425.1	5.23	45.73	<0.001	***	6.70
(log values)	E	7	5591.8	68.76	343.72	<0.001	***	88.03
	C:E	16	335.8	4.13	9.03	<0.001	***	5.29
	residuals	766	1780.2	21.89				
Organic	C	4	288.5	4.09	62.92	<0.001	***	4.46
Carbon	E	7	5990.8	84.85	746.56	<0.001	***	92.49
(log values)	C:E	14	197.9	2.80	12.33	<0.001	***	3.05
	residuals	509	583.5	8.26				
Detritus	C	4	164.68	5.23	12.95	<0.001	***	9.49
(log values)	E	7	1186.85	37.67	53.34	<0.001	***	68.37
	C:E	15	384.57	12.21	8.07	<0.001	***	22.16
	residuals	445	1414.46	44.90				
NEP	C	4	4004953	3.34	9.27	<0.001	***	8.51
	E	7	30288222	25.27	40.06	<0.001	***	64.38
	C:E	15	12742041	10.63	7.86	<0.001	***	27.08
	residuals	674	72804138	60.75				
GPP	C	4	382.52	16.85	63.69	<0.001	***	29.70
(log values)	E	7	844.34	37.19	80.33	<0.001	***	65.54
	C:E	16	61.19	2.70	2.55	<0.001	***	4.76
	residuals	654	982.01	43.26				
ER	C	4	400.22	31.45	107.33	<0.001	***	52.87
(log values)	E	7	319.26	25.09	48.93	<0.001	***	42.18
	C:E	15	37.50	2.95	2.68	<0.001	***	4.96
	residuals	553	515.60	40.51				
Uptake	C	4	52.95	3.34	6.60	<0.001	***	5.18
rate	E	7	887.84	55.96	63.24	<0.001	***	86.79
(log values)	C:E	16	82.12	5.18	2.56	0.001	**	8.03
	residuals	281	563.60	35.52				
Decomposition	C	4	246.2	17.79	47.76	<0.001	***	27.22
rate	E	7	571.85	41.33	63.39	<0.001	***	63.24
(log values)	C:E	15	86.13	6.23	4.46	<0.001	***	9.53
	residuals	372	479.38	34.65				

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Table S3.2 | Two-way ANOVAs on broad categories of ecosystem variables.

Results of three analyses of variance (ANOVA) performed on broad categories of ecosystem variables with climatic zone (C) and ecosystem type (E) as explanatory variables; model: y ~ C + E + C:E (statistics for Figure 4b). Stocks (biomass, organic carbon, detritus), fluxes (gross primary production and ecosystem respiration), and turnover rates (decomposition rate) are pooled within each of these categories after the ecosystem variables (log values) are individually scaled. Degrees of freedom (DF), sum of squares (Sum Sq), F- and P- values of the significance tests, and proportion of variance explained, as well as of the explained variance for main and interaction effects are given.

Response Variable	Explanatory variable	DF	Sum Sq	% of variance explained	F-value	P-value	Sign.[1]	% of the explained variance
Stocks	C	4	58.48	3.25	37.68	<0.001	***	5.26
	E	7	1005.89	55.94	370.32	<0.001	***	90.61
	C:E	16	45.65	2.54	7.35	<0.001	***	4.11
	residuals	1773	687.99	38.26				
Fluxes	C	4	285.71	22.68	151.07	<0.001	***	42.24
	E	7	355.86	28.24	107.52	<0.001	***	52.60
	C:E	16	34.98	2.78	4.62	<0.001	***	5.18
	residuals	1234	583.45	46.31				
Rates	C	4	50.22	7.11	28.79	<0.001	***	12.26
	E	7	324.25	45.93	106.21	<0.001	***	79.20
	C:E	16	34.97	4.95	5.01	<0.001	***	8.54
	residuals	680	296.56	42.01				

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Table S3.3 | Non-parametric tests for climatic effect on ecosystem variables.

Results of Kruskal-Wallis tests on ranks (light headers) and groups given by multiple mean comparison post-hoc tests on rank sums (dark headers) performed on each individual ecosystem variable and on broader categories of ecosystem variables (i.e., stocks, fluxes and rates) testing the effect of climatic zone (C); model: y ~ C. Stocks (biomass, organic carbon, detritus), fluxes (gross primary production and ecosystem respiration), and turnover rates (uptake and decomposition rates) were pooled within each of these categories after the ecosystem variables were individually scaled. See below the table for abbreviations. Degrees of freedom (DF), number of data points (n), Chi-squared and P- values of the Kruskal-Wallis tests are given. Significantly different groups have different letters.

Ecosystem Variable	Kruskal-Wallis test on ranks					Multiple mean comparison post-hoc tests				
	Chi-squared	DF	n	P-value	Sign.[1]	Arctic	Boreal	Temp.	Trop.	Arid
Biomass	39.04	4	795	<0.001	***	a	bc	b	c	bc
Organic carbon	22.10	4	535	<0.001	***	a	ab	c	bc	abc
Detritus	26.56	4	473	<0.001	***	a	ab	b	a	ab
GPP	121.78	4	687	<0.001	***	a	b	c	d	bc
ER	165.74	4	580	<0.001	***	a	b	c	d	b
NEP	21.29	4	701	<0.001	***	abc	c	a	bc	ab
GPP/ER	19.33	4	512	<0.001	***	abc	c	a	bc	ab
Uptake rate	10.76	4	309	0.030	*	a	a	a	a	a
Decomp. rate	69.51	4	399	<0.001	***	a	a	b	c	a
Stocks	76.74	4	1803	<0.001	***	a	c	b	b	b
Fluxes	284.71	4	1267	<0.001	***	a	b	c	d	b
Rates	26.16	4	708	<0.001	***	a	ab	bc	c	ab

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Abbreviations: GPP = gross primary production; ER = ecosystem respiration; NEP = net ecosystem production; Decomp. Rate = decomposition rate; Temp = temperate; Trop = tropical.

Table S3.4 | Non-parametric tests for ecosystem type effects on ecosystem variables.

Results of Kruskal-Wallis tests on ranks (light headers) and groups given by post-hoc tests on rank sums for multiple mean comparison (dark headers) performed on each individual ecosystem variable and on broader categories (i.e., stocks, fluxes and turnover rates) testing the effect of ecosystem type (E); models: y ~ E. Stocks (biomass, organic carbon, detritus), fluxes (gross primary production and ecosystem respiration), and turnover rates (decomposition rate) were pooled within each category after the ecosystem variables were individually scaled. Degrees of freedom (DF), number of data points (n), Chi-squared and P- values of the Kruskal-Wallis tests are given. Capital letters in dark headers are abbreviations for ecosystem types (see below the table). Significantly different groups have different letters.

Ecosystem Variable	Kruskal-Wallis test on ranks					Multiple mean comparison post-hoc tests							
	Chi-squared	DF	n	P-value	Sign.[1]	F	G	A	D	S	L	OP	OB
Biomass	619.29	7	795	<0.001	***	c	a	a	b	d	d	d	b
Organic carbon	432.98	7	535	<0.001	***	a	a	ab	abc	e	d	cd	b
Detritus	210.81	7	473	<0.001	***	d	b	ab	ac	ab	c	c	b
GPP	374.01	7	687	<0.001	***	a	d	a	bc	b	b	bc	c
ER	246.14	7	580	<0.001	***	a	e	a	bcd	d	b	bc	cd
NEP	337.09	7	701	<0.001	***	a	bc	a	bcd	e	d	c	bd
GPP/ER	222.84	7	512	<0.001	***	a	abc	a	abc	d	bd	ac	bc
Uptake rate	163.44	7	309	<0.001	***	c	a	ab	ac	b	b	d	ab
Decomp. rate	181.69	7	399	<0.001	***	a	a	ab	a	b	a	b	b
Stocks	1010.9	7	1803	<0.001	***	d	a	a	bc	c	e	ce	b
Fluxes	588.34	7	1267	<0.001	***	a	d	a	bc	c	b	bc	c
Rates	226.54	7	708	<0.001	***	a	a	ab	a	c	bc	d	c

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Abbreviations: GPP = gross primary production; ER = ecosystem respiration; NEP = net ecosystem production; Decomp. Rate = decomposition rate; F = forest; G = grassland; A = agroecosystem; D = desert; S = stream; L = lake; OP = ocean pelagic; OB = ocean benthic.

Table S3.5 | Non-parametric tests of mean differences among E x C combinations.
Results of Kruskal-Wallis tests on ranks (light row headers) and groups given by post-hoc tests on rank sums for multiple mean comparison (dark row headers) performed on each individual ecosystem variable testing the effect of ecosystem type (E) x climatic zone (C) combinations; models: y ~ EC. Number of data points (n), degrees of freedom (DF), Chi-squared and P- values of the Kruskal-Wallis tests are given. Significantly different groups have different letters. Note that for space reasons results are displayed in column (one Kruskal-Wallis test per column). Same tests but with clumped climatic variables, “Cold” and “Warm” for marine systems are shown in Table S3.12. See below the table for abbreviations.

			Biom.	Org. C	Detritus	GPP	ER	NEP	Uptake	Dec.
Kruskal-Wallis test		**n**	795	535	473	687	580	701	309	399
		Chi-sq.	641.42	449.51	275.68	448.63	385.65	375.77	197.50	272.62
		DF	27	25	26	27	26	26	26	27
		P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		Sign.[1]	***	***	***	***	***	***	***	***
	Eco	**Clim**								
Post-hoc test of multiplemean comparison	**F**	**Boreal**	bg	a	bc	abghi	abfghijk	abd	abd	ab
		Temp	g	a	b	abg	ab	ad	a	abc
		Trop	g	abc	bcd	a	a	abd	ab	abcdefg
		Arid	bg	abc	bcd	abgh	abfghi	ad	abcd	ab
	G	**Arctic**	abc	a	bcdf	cdefi	cdel	bcefgh	abcde	a
		Temp	acde	ab	abcdefg	abgh	abg	abd	abcdef	abcdef
		Trop	bcg	abc	cdfg	abgh	abfg	abcd	abcdef	abcdefgh
		Arid	acd	abcd	adefg	bcdghi	bcfghijkl	abcdef	abcdef	abcdef
	A	**Temp**	abc	abc	abcdefg	ab	ab	a	abcdef	abcdefg
	D	**Arid**	adef	abcde	ae	cdef	cde	abcdef	abcde	abcdf
	S	**Arctic**	efhi	ef	a	ef	de	cefghi	abcdef	abcdefg
		Boreal	fhi	f	adefg	ef	cehjl	hi	cdef	defghi
		Temp	fhi	f	defg	ef	cehijkl	ghi	ef	efghi
		Trop	i	f	aefg	cef	bfgik	i	ef	i
		Arid	fhi	f	adefg	cef	cehijkl	eghi	f	ghi
	L	**Arctic**	hi	f	adefg	e	d	bcefgh	bcdef	abcdef
		Boreal	adefhi	def	aeg	cef	cde	cefghi	cef	abcd
		Temp	fhi	ef	a	cdefi	cdehijkl	eghi	f	defghi
	OP	**Arctic**	defhi	abcdef	aefg	ef	cdejkl	abcdf	bcdef	abcdefghi
		Boreal	abcdefghi	-	-	bcdefghi	-	-	abcdef	-
		Temp	fhi	cdef	adefg	cdfghi	cdefghijkl	abd	f	hi
		Trop	adefhi	def	a	cdefghi	bcdefghijkl	abcdefgh	f	ghi
		Arid	fhi	bcdef	aefg	cdefi	cdel	abcdefghi	f	abcdefghi
	OB	**Arctic**	acdefhi	-	abcdefg	abcdefghi	bcdefghijkl	abcdefgh	abcdef	bcdefghi
		Boreal	adefh	abcd	abcdefg	cdefi	cdel	abcdefghi	abcdef	defghi
		Temp	adefh	abcde	bcdefg	cdefi	cdehijkl	efghi	f	cdefghi
		Trop	acdefhi	abcde	aeg	abdghi	abfghijkl	abcdefg	cdef	eghi
		Arid	acdefh	abcdef	bcd	cdefhi	cdefhijkl	bcdefghi	abcdef	abcdefghi

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > ‘.’ ≥ 0.05 > ‘*’ ≥ 0.01 > ‘**’ ≥ 0.001 > ‘***’ ≥ 0.

Abbreviations: Eco = Ecosystem type; Clim = Climatic zone; F = forest; G = grassland; A = agro-ecosystem; D = desert; S = stream; L = lake; OB = ocean benthic; OP = ocean pelagic; Temp = temperate; Trop = tropical; Biom. = Biomass; Org. C = Organic carbon; GPP = gross primary production; ER = ecosystem respiration; NEP = net ecosystem production; Dec.= decomposition rate; Prod. = Productivity rate.

Table S3.6 | One-way ANOVAs on fluxes and rates of each ecosystem type.

Results of 18 analyses of variance (ANOVA) performed on gross primary production (GPP), ecosystem respiration (ER) and decomposition rate within each ecosystem type, with climatic zone (C) as explanatory variable; model: y ~ C (statistics for Figure 4c-e). Values were log-transformed and three zero values of GPP removed for that reason. Agro-ecosystem and desert ecosystems were removed because they are represented in only one climatic zone (temperate and arid, respectively). Degrees of freedom (DF), sum of squares (Sum Sq), F- and P- values of the significance tests, and proportion of variance explained are given.

Response variable		Explanatory variable	DF	Sum Sq	% of variance explained	F-value	P-value	Sign.[1]
GPP	Forest	C	3	21.61	66.38	69.12	<0.001	***
		residuals	105	10.94				
	Grassland	C	3	45.31	50.45	35.30	<0.001	***
		residuals	104	44.50				
	Stream	C	4	30.01	-	2.35	0.055	NS
		residuals	201	640.83				
	Lake	C	2	61.17	38.07	18.75	<0.001	***
		residuals	61	99.49				
	Ocean pelagic	C	4	26.82	20.73	4.38	0.003	**
		residuals	67	102.52				
	Ocean benthic	C	4	38.35	36.72	8.56	<0.001	***
		residuals	59	66.09				
ER	Forest	C	3	17.85	58.78	39.45	<0.001	***
		residuals	83	12.52				
	Grassland	C	3	48.41	56.08	37.88	<0.001	***
		residuals	89	37.91				
	Stream	C	4	138.61	30.64	22.64	<0.001	***
		residuals	205	313.83				
	Lake	C	2	35.63	45.36	21.17	<0.001	***
		residuals	51	42.92				
	Ocean pelagic	C	3	15.63	45.25	5.79	0.005	**
		residuals	21	18.91				
	Ocean benthic	C	4	33.69	30.05	5.37	0.001	**
		residuals	50	78.43				
Decomp. rate	Forest	C	3	51.97	41.78	17.7	<0.001	***
		residuals	74	72.43				
	Grassland	C	3	46.62	32.05	9.75	<0.001	***
		residuals	62	98.84				
	Stream	C	4	117.50	54.56	30.62	<0.001	***
		residuals	102	97.86				
	Lake	C	2	36.88	24.56	8.30	<0.001	***
		residuals	51	113.26				
	Ocean pelagic	C	3	52.52	50.86	9.32	<0.001	***
		residuals	27	50.74				
	Ocean benthic	C	4	15.44	33.36	4.00	0.010	**
		residuals	32	30.84				

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Table S3.7 | Non-parametric tests on fluxes and rates of each ecosystem type.

Results of Kruskal-Wallis tests on ranks (light headers) and groups given by multiple mean comparison post-hoc tests on rank sums (dark headers) performed on gross primary production, ecosystem respiration, and decomposition rate within each ecosystem type testing the effect of climatic zone (C); model: y ~ C. Agro-ecosystem and desert ecosystems were removed because they are represented in only one climatic zone (temperate and arid, respectively). Degrees of freedom (DF), number of data points (n), Chi-squared and P-values of the Kruskal-Wallis tests are given. Significantly different groups have different letters.

Eco	Eco	Kruskal-Wallis test on ranks					Multiple mean comparison post-hoc tests				
Var	Type	n	Chi-squared	DF	P-value	Sign.[1]	Arc.	Bor.	Temp.	Trop.	Arid
GPP	Forest	109	71.91	3	<0.001	***	-	a	b	c	ab
	Grassland	108	46.18	3	<0.001	***	a	-	c	bc	b
	Stream	210	9.51	4	0.05	.	a	a	a	a	a
	Lake	64	29.75	2	<0.001	***	a	b	b	-	-
	Oc. pelagic	72	17.60	4	0.001	**	a	ab	b	ab	a
	Oc. benthic	65	24.08	4	<0.001	***	ab	a	a	b	a
ER	Forest	87	42.33	3	<0.001	***	-	a	a	b	a
	Grassland	93	51.14	3	<0.001	***	a	-	c	c	b
	Stream	210	44.70	4	<0.001	***	a	ab	b	c	b
	Lake	54	26.91	2	<0.001	***	a	b	b	-	-
	Oc. pelagic	25	12.36	3	0.006	**	a	-	b	ab	a
	Oc. benthic	55	18.48	4	<0.001	***	ab	a	ab	b	ab
Dec.	Forest	78	38.32	3	<0.001	***	-	a	a	b	a
	Grassland	66	26.19	3	<0.001	***	a	-	b	b	ab
	Stream	107	61.97	4	<0.001	***	a	ab	ab	c	bc
	Lake	54	16.23	2	<0.001	***	a	a	b	-	-
	Oc. pelagic	31	16.48	3	<0.001	***	ab	-	b	b	a
	Oc. benthic	37	11.74	4	0.019	*	a	a	a	a	a

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Abbreviations: Eco Var = ecosystem variable; Eco Type = ecosystem type; GPP = gross primary production; ER = ecosystem respiration; Dec.= decomposition rate; Oc. = Ocean; Arc. = arctic; Bor. = boreal; Temp. = temperate; Trop. = tropical.

Table S3.8 | Correlations between ecosystem variables and latitude.

Results of Pearson's two-sided correlation tests between ecosystem variables within each ecosystem type and latitude (light headers) and slope and intercept of corresponding linear regression (dark headers) for significant correlations (P-value < 0.05) (statistics for Figs 7, S4.3, S4.4, and S4.5). Statistic t, degrees of freedom (DF), correlation coefficient (*r*), *r* squared, and P-values of the correlation tests are given.

Ecosystem Variable	Ecosystem type	Pearson's two-sided correlation test						Linear regression	
		t-stat.	DF	*r*	r^2	P-value	Sign.[1]	Slope	Intercept
Biomass	Forest	-2.48	114	-0.23	0.05	0.014	*	-84.27	13009
	Grassland	-0.97	111	-0.09	0.01	0.332	NS		
	Stream	1.57	125	0.14	0.02	0.118	NS		
	Lake	0.98	60	0.13	0.02	0.329	NS		
	Oc. pelagic	2.46	39	0.37	0.13	0.018	*	0.11	0.69
	Oc. benthic	-0.43	93	-0.04	0	0.668	NS		
Org. C	Forest	2.19	70	0.25	0.06	0.032	*	70.15	5134
	Grassland	-0.02	43	0	0	0.981	NS		
	Stream	2.33	90	0.24	0.06	0.022	*	0.30	-6.68
	Lake	-1.52	98	-0.15	0.02	0.131	NS		
	Oc. pelagic	1.55	28	0.28	0.08	0.132	NS		
	Oc. benthic	1.21	43	0.18	0.03	0.234	NS		
Detritus	Forest	1.90	92	0.19	0.04	0.06	NS		
	Grassland	-0.37	60	-0.05	0	0.709	NS		
	Stream	1.03	135	0.09	0.01	0.306	NS		
	Lake	1.62	41	0.25	0.06	0.113	NS		
	Oc. pelagic	0.42	32	0.07	0.01	0.678	NS		
	Oc. benthic	-0.40	44	-0.06	0	0.691	NS		
GPP	Forest	-12.92	95	-0.80	0.64	<0.001	***	-42.83	3280.4
	Grassland	-5.35	102	-0.47	0.22	<0.001	***	-15.59	1439.5
	Stream	-1.82	177	-0.14	0.02	0.07	.		
	Lake	-2.08	62	-0.26	0.07	0.042	*	-7.61	631.42
	Oc. pelagic	-3.94	68	-0.43	0.19	<0.001	***	-4.12	394.29
	Oc. benthic	-3.46	61	-0.41	0.16	0.001	**	-20.55	1347.5
ER	Forest	-10.51	77	-0.77	0.59	<0.001	***	-39.17	2844.2
	Grassland	-5.29	88	-0.49	0.24	<0.001	***	-20.57	1691.8
	Stream	-6.34	185	-0.42	0.18	<0.001	***	-14.86	1068.3
	Lake	-3.56	51	-0.45	0.20	0.001	**	-6.35	519.27
	Oc. pelagic	-0.7	21	-0.15	0.02	0.493	NS		
	Oc. benthic	-5.50	52	-0.61	0.37	<0.001	***	-18.57	1145.35
NEP	Forest	-1.34	97	-0.13	0.02	0.184	NS		
	Grassland	-2.01	96	-0.20	0.04	0.047	*	-3.07	242.25
	Stream	5.82	179	0.40	0.16	<0.001	***	11.77	-769.57
	Lake	1.83	87	0.19	0.04	0.071	NS		
	Oc. pelagic	-1.56	49	-0.22	0.05	0.126	NS		
	Oc. benthic	-1.38	53	-0.19	0.03	0.172	NS		
GPP/ER	Forest	0.96	75	0.11	0.01	0.340	NS		
	Grassland	-0.86	76	-0.10	0.01	0.39	NS		
	Stream	3.89	167	0.29	0.08	<0.001	***	0.01	0.08
	Lake	-0.52	30	-0.10	0.01	0.605	NS		
	Oc. pelagic	-0.39	20	-0.09	0.01	0.700	NS		
	Oc. benthic	0.72	41	0.11	0.01	0.478	NS		
Uptake rate (log values)	Forest	-0.65	46	-0.1	0.01	<0.001	NS		
	Grassland	-3.80	40	-0.51	0.27	<0.001	***	-0.03	2.42

	Stream	-2.56	59	-0.33	0.11	0.010	*	-0.04	3.82
	Lake	-3.88	37	-0.54	0.29	<0.001	***	-0.13	10.16
	Oc. pelagic	-2.39	21	-0.46	0.21	0.026	*	-0.04	5.56
	Oc. benthic	-1.03	27	-0.19	0.04	0.314	NS		
Dec. rate (log values)	Forest	-2.82	30	-0.46	0.21	0.008	**	-0.03	2.30
	Grassland	-6.13	38	-0.70	0.50	<0.001	***	-0.03	0.67
	Stream	-9.81	101	-0.70	0.49	<0.001	***	-0.05	3.13
	Lake	-3.04	47	-0.40	0.16	0.004	**	-0.06	2.77
	Oc. pelagic	-2.38	25	-0.43	0.19	0.025	*	-0.05	3.98
	Oc. benthic	-2.82	30	-0.46	0.21	0.008	**	-0.03	2.30

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Abbreviations: Org. C = organic carbon; NEP = net ecosystem production; GPP = gross primary production; ER = ecosystem respiration; Dec.= decomposition rate; Oc. = Ocean.

Table S3.9 | Non-parametric tests for climatic effect on NEP of each ecosystem type.

Results of Kruskal-Wallis tests on ranks (light headers) and groups given by multiple mean comparison post-hoc tests on rank sums (dark headers) performed on net primary production (NEP), within each ecosystem type testing the effect of climatic zone (C); model: y ~ C. Agro-ecosystem and desert ecosystems were removed because they are represented in only one climatic zone (temperate and arid, respectively). See below the table for abbreviations. Number of data points (n), degrees of freedom (DF), Chi-squared and P- values of the Kruskal-Wallis tests are given. Significantly different groups have different letters.

Ecosystem Type	Kruskal-Wallis test on ranks					Multiple mean comparison post-hoc tests						
	n	Chi-squared	DF	P-value	Sign.[1]	Arc.	Bor.	Temp.	Trop.	Arid	C	W
Forest	107	4.61	3	0.203	NS							
Grassland	102	12.54	3	0.006	**	a	-	b	b	ab	-	-
Stream	203	41.56	4	<0.001	***	a	a	a	b	a	-	-
Lake	99	29.28	2	<0.001	***	a	b	b	-	-	-	-
Oc. pelagic	73	5.32	1	0.021	*	-	-	-	-	-	a	b
Oc. benthic	58	1.29	1	0.256	NS							

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Abbreviations: Oc. = ocean; Arc. = arctic; Bor. = boreal; Temp. = temperate; Trop. = tropical; C = cold; w = warm.

Table S3.10 | Non-parametric tests for climatic effect within forests.

Results of Kruskal-Wallis tests on ranks (light headers) and groups given by multiple mean comparison post-hoc tests on rank sums (dark headers) performed on each ecosystem variable within forest ecosystems testing the effect of climatic zone (C); model: y ~ C (statistics for figure S4.5). See below the table for abbreviations. Number of data points (n), degrees of freedom (DF), Chi-squared and P- values of the Kruskal-Wallis tests are given. Significantly different groups have different letters.

Ecosystem variable	Kruskal-Wallis test on ranks					Multiple mean comparison post-hoc tests			
	n	Chi-squared	DF	P-value	Sign.[1]	Bor.	Temp.	Trop.	Arid
Biomass	163	65.06	3	<0.001	***	a	b	b	a
Organic Carbon	113	11.54	3	0.010	*	ab	b	ab	a
Detritus	99	25.37	3	<0.001	***	b	b	a	a
NEP	107	4.61	3	0.203	NS				
GPP	109	71.91	3	<0.001	***	a	b	c	ab
ER	87	42.33	3	<0.001	***	a	a	b	a
Uptake rate	56	15.31	3	0.002	**	ab	b	a	a
Decomposition	78	38.32	3	<0.001	***	a	a	b	a

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Abbreviations: NEP = net ecosystem production; GPP = gross primary production; ER = ecosystem respiration; Bor. = boreal; Temp. = temperate; Trop. = tropical.

Table S3.11 | Mean values, coefficients of variation and numbers of data points.
For each combination of ecosystem type, climatic zone and ecosystem variable, the mean value is in black, the coefficient of variation in grey and in brackets, the number of data points in red and in italics. See abbreviations below.

Ecosystem type	Climatic zone	Biom.	Org. C	Detritus	GPP	ER	NEP	Uptake	Dec.
Forest	Boreal	5250 (0.64) *32*	8381 (0.75) *21*	3807 (1.57) *22*	914.5 (0.31) *21*	832.7 (0.33) *18*	164.8 (0.83) *21*	0.34 (1.23) *10*	0.21 (0.79) *12*
	Temperate	12228 (0.66) *39*	8723 (0.72) *31*	2428 (1.16) *45*	1364 (0.23) *34*	1072 (0.27) *31*	303.6 (0.82) *38*	0.19 (1.49) *13*	0.31 (0.81) *12*
	Tropical	13797 (0.50) *49*	5689 (0.77) *30*	791.3 (1.48) *16*	2921 (0.27) *34*	2731 (0.32) *19*	355.9 (1.05) *21*	0.32 (0.67) *23*	1.17 (0.67) *36*
	Arid	4679 (0.72) *43*	5174 (0.96) *31*	693.1 (1.07) *16*	1200 (0.3) *20*	854.8 (0.40) *19*	271.8 (0.69) *27*	0.96 (1.46) *10*	0.3 (0.68) *18*
Grassland	Arctic	670.8 (0.89) *31*	9111 (0.83) *28*	457.7 (0.85) *14*	232.7 (0.82) *21*	218.9 (0.72) *23*	6.40 (12.49) *21*	1.39 (1.52) *11*	0.22 (0.97) *20*
	Temperate	302.8 (0.60) *30*	8134 (0.85) *28*	167.2 (0.44) *10*	1164 (0.42) *23*	1242 (0.80) *26*	120.1 (1.45) *34*	4.03 (0.52) *10*	0.85 (0.90) *22*
	Tropical	1535 (1.21) *42*	7714 (1.21) *31*	371.6 (1.38) *29*	1138 (0.66) *40*	1213 (0.58) *18*	270.5 (1.60) *17*	5.87 (1.43) *10*	1.6 (0.59) *12*
	Arid	373.2 (0.93) *43*	3057 (0.75) *15*	160.2 (2.09) *16*	697.3 (0.7) *24*	599.3 (0.67) *26*	95.17 (2.61) *30*	6.25 (0.92) *14*	0.61 (0.71) *12*
Agro-ecosystem	Temperate	462.2 (0.61) *54*	6866 (0.64) *17*	175.2 (0.52) *14*	1730 (0.38) *39*	1275 (0.31) *37*	439.7 (0.94) *36*	4.73 (0.51) *16*	1.35 (0.46) *14*
Desert	Arid	175.7 (1.17) *50*	1717 (0.76) *17*	51.80 (1.39) *16*	157.0 (0.91) *20*	113.3 (0.49) *19*	29.95 (1.56) *23*	1.91 (1.41) *12*	0.55 (0.70) *12*
Stream	Arctic	48.9 (1.72) *23*	28.12 (1.84) *20*	13.66 (1.26) *14*	90.55 (1.67) *18*	168.2 (1.69) *20*	-90.24 (-1.78) *20*	28.28 (1.92) *10*	1.48 (0.84) *14*
	Boreal	40.97 (2.29) *25*	4.23 (1.10) *27*	689.0 (2.41) *21*	170.7 (1.45) *37*	398.3 (1.18) *35*	-245.3 (-1.17) *35*	22.22 (1.66) *18*	2.74 (0.88) *19*
	Temperate	25.33 (1.76) *55*	1.31 (0.67) *15*	321.2 (1.14) *47*	213.2 (1.54) *72*	398.5 (0.69) *74*	-152.3 (-2.41) *66*	30.15 (1.35) *39*	3.48 (0.82) *23*
	Tropical	7.80 (2.78) *39*	0.12 (0.51) *16*	106.2 (1.86) *29*	247.3 (1.30) *43*	986.3 (0.92) *43*	-748.6 (-1.13) *41*	127.7 (2.50) *10*	30.86 (1.36) *39*
	Arid	23.15 (1.54) *21*	0.15 (1.57) *14*	336.3 (1.59) *30*	403.9 (1.61) *40*	459.0 (1.14) *38*	-113.5 (-2.80) *41*	74.74 (1.01) *12*	5.44 (0.49) *12*
Lake	Arctic	18.14 (3.05) *24*	14.14 (1.24) *38*	369.9 (2.96) *12*	28.15 (1.21) *21*	33.01 (0.85) *24*	-5.09 (-2.57) *38*	18.97 (1.23) *15*	0.81 (1.45) *10*
	Boreal	95.99 (0.99) *15*	59.15 (1.03) *34*	39.98 (2.42) *12*	316.1 (1.85) *19*	179.2 (1.29) *16*	-27.61 (-1.05) *25*	33.25 (1.48) *12*	4.81 (4.08) *22*
	Temperate	11.60 (1.06) *23*	35.80 (1.06) *39*	7.66 (1.58) *19*	269.3 (0.89) *24*	270.0 (1.11) *14*	-36.49 (-1.53) *36*	47.57 (0.75) *12*	3.45 (0.89) *22*
Ocean pelagic	Cold	7.15 (1.02) *26*	51.33 (0.68) *11*	57.26 (1.95) *16*	182.3 (0.98) *53*	201.4 (0.86) *15*	80.42 (1.19) *54*	81.64 (0.73) *11*	45.89 (1.64) *16*
	Warm	3.04 (0.51) *15*	55.09 (0.89) *20*	13.27 (2.09) *20*	208.6 (1.06) *19*	104.5 (1.03) *10*	29.31 (2.04) *19*	154.4 (0.80) *12*	65.45 (3.08) *15*
Ocean benthic	Cold	199.1 (1.52) *80*	3000 (1.39) *37*	472.5 (1.13) *20*	182.5 (0.86) *30*	202.0 (1.03) *31*	-35.73 (-3.29) *30*	120.3 (1.60) *12*	6.62 (1.10) *19*
	Warm	184.5 (1.11) *36*	2617 (1.00) *15*	723.7 (1.36) *35*	929.0 (1.23) *35*	701.4 (1.03) *24*	175.3 (3.37) *28*	12.04 (0.93) *17*	4.9 (1.50) *18*

Abbreviations: Biom. = biomass; Org. C = organic carbon; NEP = net ecosystem production; GPP = gross primary production; Dec. = decomposition rate; Uptake; = uptake rate.

Table S3.12 | Non-parametric tests of mean differences among E x C combinations.
Results of Kruskal-Wallis tests on ranks (light row headers) and groups given by post-hoc tests on rank sums for multiple mean comparison (dark row headers) performed on each individual ecosystem variable testing the effect of ecosystem type (E) x climatic zone (C) combinations; models: y ~ EC. Degrees of freedom (DF), number of data points (n), Chi-squared and P- values of the Kruskal-Wallis tests are given. Significantly different groups have different letters. Note that for space reasons results are displayed in column (one Kruskal-Wallis test per column). These are same the tests than in Table S3.6 but with clumped climatic variables, "Cold" and "Warm" for marine systems. It gives the significantly different groups per ecosystem variable in Fig. 3 (boxplots). See below the table for abbreviations.

			Biom.	Org. C	Detritus	GPP	ER	NEP	Uptake	Dec.
Kruskal-Wallis test		n	795	535	473	687	580	701	309	399
		DF	21	21	21	21	21	21	21	21
		Chi-sq.	640.40	448.47	250.97	435.45	347.75	369.12	187.86	261.24
		P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
		Sign.[1]	***	***	***	***	***	***	***	***
	Eco	Clim								
Post-hoc tests of multiple mean compa-risons	F	Boreal	bfg	a	bi	abef	abfgh	abc	abc	ab
		Temp	fg	a	i	abe	abf	ab	a	ab
		Trop	f	a	bdi	a	a	abc	ab	acde
		Arid	bfg	ac	bdi	abe	abfg	ab	abcd	ab
	G	Arctic	abc	a	bdgi	cdf	cde	cdefg	abcd	b
		Temp	acd	a	abcdefghi	abe	abf	abcd	abcde	abcd
		Trop	bcg	a	bdfg	abe	abf	abcd	abcde	abcdef
		Arid	acd	abc	acdefgh	bcef	cfgh	bcde	bcde	abcd
	A	Temp	abc	a	abcdefgh	ab	ab	a	abcde	abcde
	D	Arid	ade	abcde	ace	cd	cde	abcde	abcd	abcd
	S	Arctic	ehi	ef	ae	d	de	efgh	abcde	abcde
		Boreal	ehi	f	acdefgh	d	ceh	gh	cde	cdefg
		Temp	hi	f	dfgh	d	cegh	fgh	e	defg
		Trop	h	f	acefgh	d	bfg	h	e	g
		Arid	ehi	f	acdefgh	cd	cegh	efgh	e	efg
	L	Arctic	h	f	acdefgh	d	d	cdefg	cde	abcd
		Boreal	adehi	bdef	aceh	cd	cde	efgh	de	abc
		Temp	ehi	def	a	cdf	cdegh	efgh	e	cdef
	OP	Cold	hi	bcdef	acefh	d	cde	abc	e	fg
		Warm	ehi	bcdef	a	cd	cde	abcdef	e	cdefg
	OB	Cold	dei	ac	bcdfgh	cd	cde	defg	de	efg
		Warm	adei	abcd	cdefgh	cef	cfgh	cdef	de	cdefg

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Abbreviations: Eco = Ecosystem type; Clim = Climatic zone; F = forest; G = grassland; A = agro-ecosystem; D = desert; S = stream; L = lake; OB = ocean benthic; OP = ocean pelagic; Temp = temperate; Trop = tropical; Biom. = Biomass; Org. C = Organic carbon; GPP = gross primary production; ER = ecosystem respiration; NEP = net ecosystem production; Dec.= decomposition rate; Prod. = Productivity rate.

Table S3.13 | Empirical relationships between pairs of ecosystem variables.

Significant Pearson's two-sided correlation tests between pairs of ecosystem variables across and within ecosystem types (light headers) in a log-log space (null values were removed from the analysis), and slope and intercept of corresponding linear regression (dark headers) (includes statistics for figures S4.6 and S4.7). Statistic t, degrees of freedom (DF), correlation coefficient (*r*), *r* squared and P-values of the correlation tests are given.

Ecosystem Variables	Ecosystem type	Pearson's two-sided correlation test						Linear regression	
		t-stat.	DF	*r*	r^2	P-value	Sign.[1]	Slope	Intercept
GPP ~ Biomass	All ecosystems	13.25	248	0.64	0.41	<0.001	***	0.38	4.03
	Forest	2.63	49	0.35	0.12	0.011	*	0.18	5.68
	Grassland	2.35	37	0.36	0.13	0.024	*	0.36	4.65
	Lake	3.01	25	0.52	0.27	0.006	**	0.29	4.13
Uptake rate ~ Biomass	All ecosystems	-22.36	257	-0.81	0.66	<0.001	***	-0.64	4.30
	Forest	-9.82	53	-0.80	0.65	<0.001	***	-0.76	5.24
	Grassland	-4.06	38	-0.550	0.30	<0.001	***	-0.62	4.55
	Agroecosystem	-3.31	9	-0.74	0.55	0.009	**	-0.79	6.11
	Desert	-4.26	10	-0.80	0.64	0.002	**	-0.75	3.61
	Stream	-3.84	74	-0.41	0.17	<0.001	***	-0.56	3.69
	Lake	-7.62	23	-0.85	0.72	<0.001	***	-0.69	4.18
	Ocean pelagic	-4.23	18	-0.71	0.50	<0.001	***	-0.93	5.97
	Ocean benthic	-6.62	18	-0.84	0.71	<0.001	***	-0.99	6.24
Uptake rate ~ GPP	Grassland	5.58	41	0.66	0.43	<0.001	***	0.71	-3.65
	Stream	7.59	79	0.65	0.42	<0.001	***	0.69	-0.75
	Ocean pelagic	2.83	18	0.55	0.31	0.011	*	1.26	-2.24
ER ~ GPP	All ecosystems	27.80	484	0.78	0.61	<0.001	***	0.57	2.80
	Forest	21.76	83	0.92	0.85	<0.001	***	1.07	-0.73
	Grassland	24.37	79	0.94	0.88	<0.001	***	0.89	0.55
	Agroecosystem	10.14	28	0.89	0.79	<0.001	***	0.83	1.03
	Desert	5.56	14	0.83	0.69	<0.001	***	1.14	-0.85
	Stream	11.56	182	0.65	0.42	<0.001	***	0.48	3.49
	Lake	12.76	30	0.92	0.84	<0.001	***	0.72	1.43
	Ocean pelagic	4.29	18	0.71	0.51	<0.001	***	0.65	1.54
	Ocean benthic	13.66	36	0.92	0.84	<0.001	***	0.84	0.98
ER ~ Biomass	All ecosystems	8.9	203	0.53	0.28	<0.001	***	0.24	4.81
	Stream	2.11	61	0.26	0.07	0.039	*	0.22	4.89
Detritus ~ Biomass	All ecosystems	7.54	211	0.46	0.21	<0.001	***	0.34	3.02
	Desert	3.85	6	0.84	0.71	0.008	**	1.15	-1.90
Detritus ~ Org. C	All ecosystems	4.2	102	0.38	0.15	<0.001	***	0.29	2.96

	Desert	4.68	3	0.94	0.88	0.018	*	3.11	-21.13
	Lake	-2.72	16	-0.56	0.32	0.015	*	-0.67	4.46
Org. C ~ Biomass	All ecosystems	15.8	154	0.79	0.62	<0.001	***	0.82	2.01
Org. C ~ GPP	All ecosystems	7.51	78	0.65	0.42	<0.001	***	1.26	-2.47
	Grassland	-2.35	10	-0.6	0.35	0.041	*	-0.51	11.98
	Stream	2.46	18	0.5	0.25	0.024	*	0.43	-2.97
	Ocean benthic	-10.6	3	-0.99	0.97	0.002	**	-2.06	15.13
Detritus ~ GPP	All ecosystems	4.41	50	0.53	0.28	<0.001	***	1.15	-2.35
Org. C ~ ER	All ecosystems	5.17	82	0.5	0.25	<0.001	***	1.45	-4.04
	Grassland	-2.38	14	-0.54	0.29	0.032	*	-0.51	11.86
	Stream	5.27	25	0.73	0.53	<0.001	***	0.90	-5.81
Detritus ~ ER	All ecosystems	5.09	44	0.61	0.37	<0.001	***	1.37	-3.42
	Ocean pelagic	2.67	12	0.65	0.42	0.024	*	1.90	-5.28
Biomass ~ Decomposition rate	All ecosystems	-7.38	33	-0.79	0.62	<0.001	***	-1.04	5.70
	Grassland	-4.39	7	-0.86	0.73	0.003	**	-0.64	5.65
	Ocean pelagic	-3.76	7	-0.86	0.74	0.013	*	-0.47	2.94
Decomposition rate ~ Org. C	All ecosystems	-3.37	17	-0.63	0.40	0.004	**	-0.32	2.07
Decomposition rate ~ Detritus	All ecosystems	-4.22	37	-0.57	0.32	<0.001	***	-0.31	1.53
	Grassland	-2.73	13	-0.6	0.36	0.017	*	-0.74	3.77
Uptake rate ~ Org. C	All ecosystems	-6.44	46	-0.69	0.47	<0.001	***	-0.41	2.85
	Grassland	-2.69	9	-0.67	0.45	0.025	*	-0.68	6.22
Uptake rate ~ Detritus	All ecosystems	-2.71	42	-0.39	0.15	0.01	*	-0.31	3.30
Uptake rate ~ ER	Grassland	4.7	41	0.59	0.35	<0.001	***	0.69	-3.40
	Agroecosystem	2.33	9	0.61	0.38	0.045	*	0.89	-4.97
	Stream	5.27	67	0.54	0.29	<0.001	***	0.76	-1.65
	Ocean benthic	2.63	12	0.60	0.37	0.022	*	1.07	-3.89
Uptake rate ~ Decomposition	All ecosystems	3.2	10	0.71	0.51	0.009	**	0.62	1.86
	Ocean pelagic	3.76	4	0.88	0.78	0.02	*	0.94	1.21

[1] Significance code (Sign.): 1 ≥ NS > 0.1 > '.' ≥ 0.05 > '*' ≥ 0.01 > '**' ≥ 0.001 > '***' ≥ 0.

Abbreviations: Org. C = organic carbon; GPP = gross primary production; ER = ecosystem respiration; Dec.= decomposition rate; Oc. = Ocean.

Appendix S4 – Supplementary figures

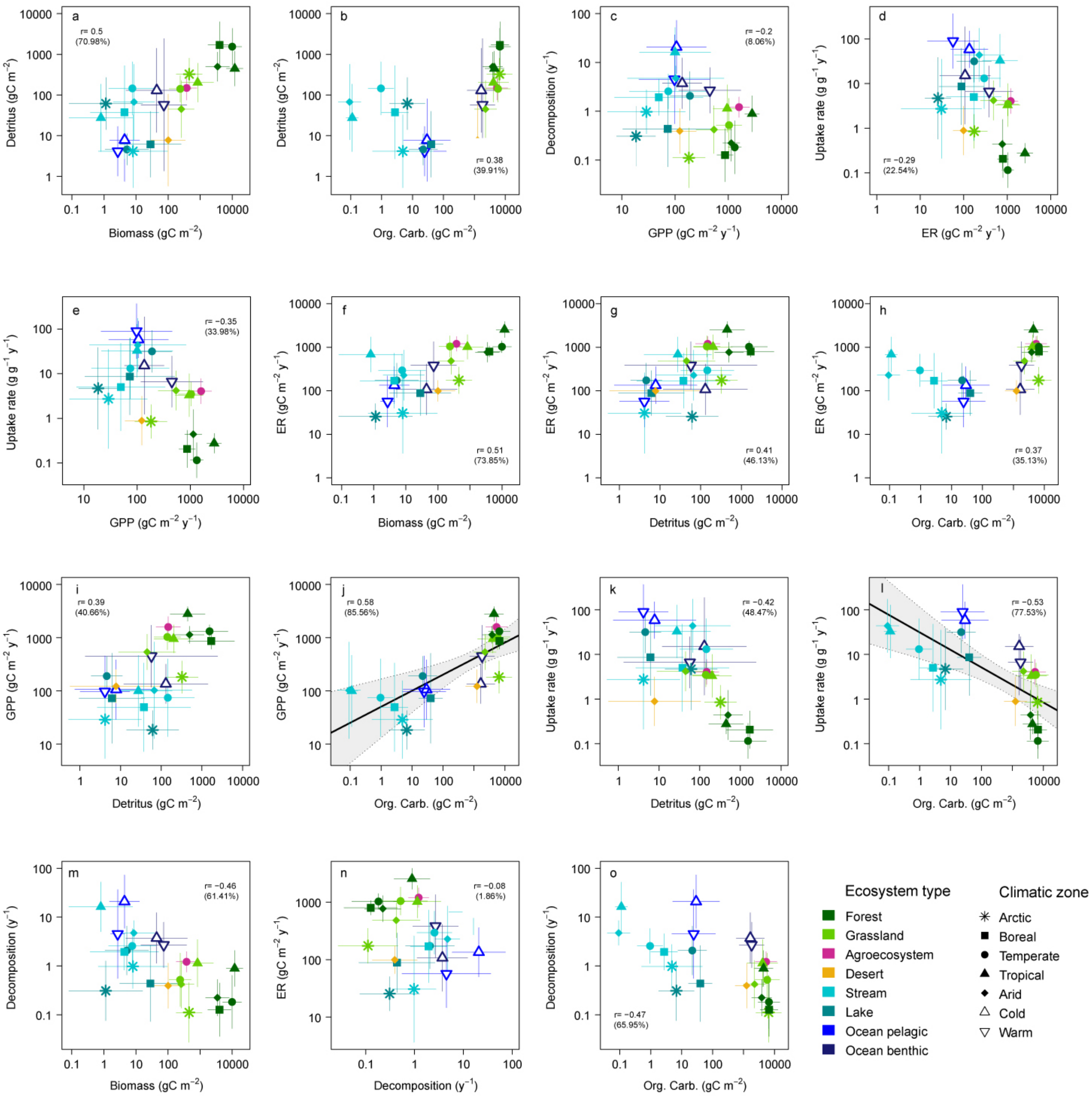

Figure S4.1 | Relationships between ecosystem variables.

Points and bars give median value and standard deviation respectively for the given ecosystem variables in each ecosystem type (colours) – climatic zone (shapes) combination. GPP and ER stand for gross primary production and ecosystem respiration, respectively, Black lines and grey areas give the median and the 95% confidence interval, respectively, of regressions realized in 10,000 iterations of bootstrapped values for each ecosystem x climatic zone combination (see methods). Text gives the median Pearson's correlation coefficient for these 10,000 series of bootstrapped values and the percentage of significant correlations into brackets. Median and quantile regressions are not displayed when less than 75% of the correlations are significant.

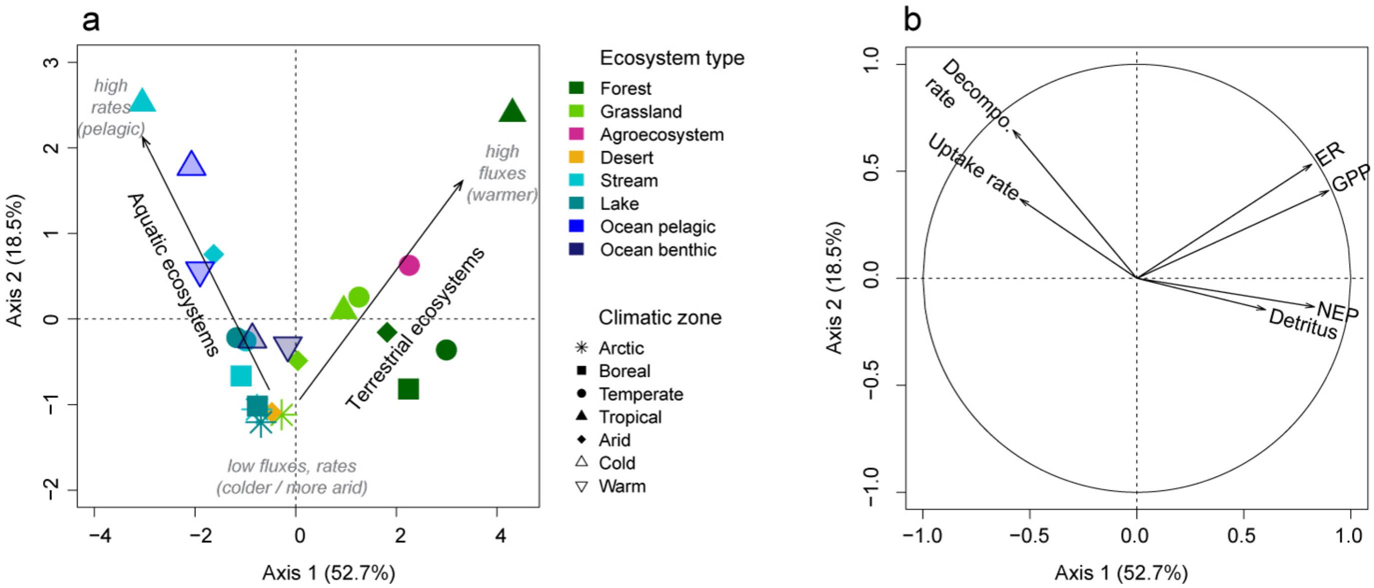

Figure S4.2 | Principal Component Analysis (PCA) on median ecosystems.

Quantitative variables included in the analysis are median values of biomass, organic carbon, detritus, gross primary production (GPP), ecosystem respiration (ER), net ecosystem production (NEP), decomposition rate (Decompo. rate), and uptake rate for each combination of ecosystem type (colours in panel a) and climatic zone (shapes in panel a). Panels a and b represent the median ecosystems and the map of active variables, respectively, in the two first dimensions of the PCA with the percentage of explained variance into brackets in axes' labels. In panel a, arrows highlight axes along which freshwater and terrestrial ecosystems are positioned according to changes in rates and fluxes from low to high, globally corresponding to colder or more arid to warmer climatic zones.

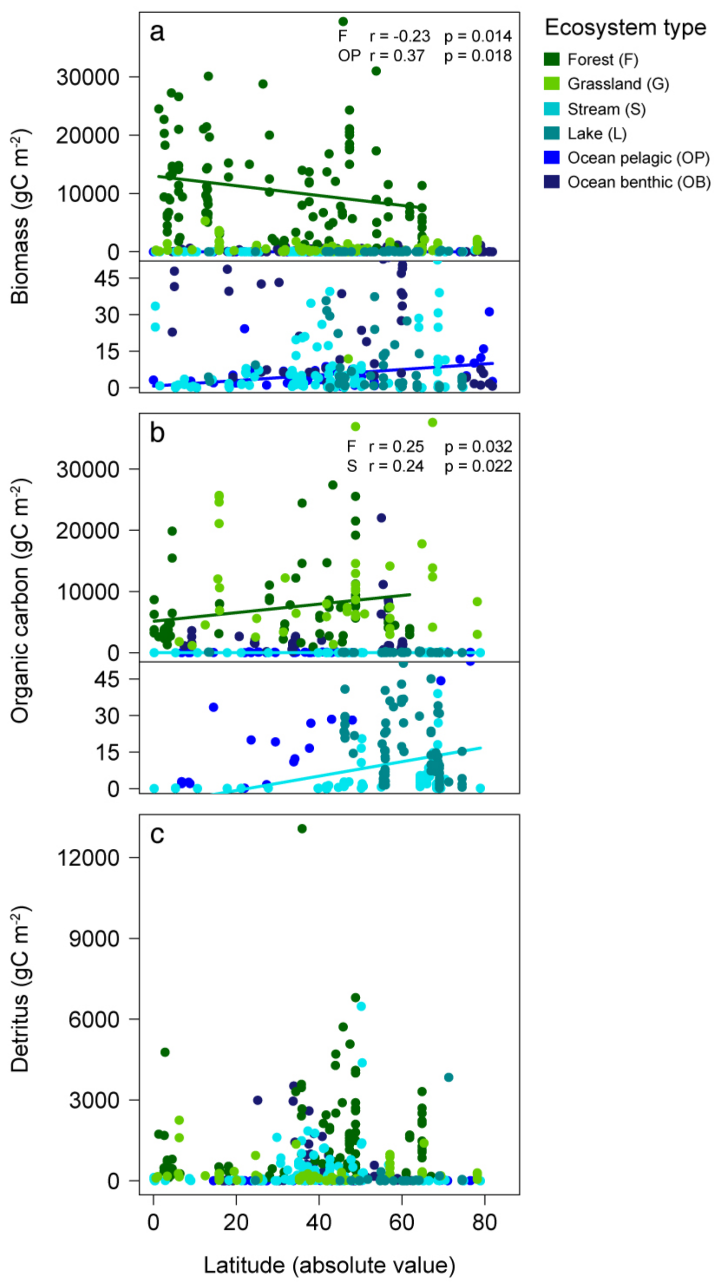

Figure S4.3 | Latitudinal trends in ecosystem stocks.

Solid circles show the data points. Colours denote ecosystem types. Lines show regression lines for significant correlations between latitude and stocks of **a** Biomass, **b** Organic carbon, or **c** Detritus, based on two-sided Pearson's correlation tests. Pearson correlation coefficients and p-values are provided for these significant relationships (see legend for abbreviations of ecosystem types). Bottom parts of panels are zooming in finer scales than the one of top parts.

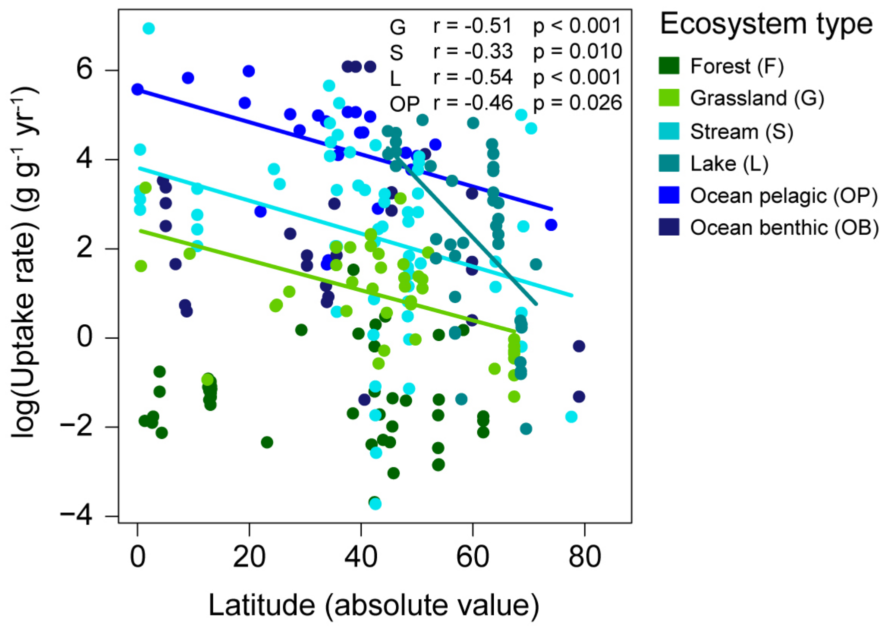

Figure S4.4 | Latitudinal trends in mass-specific uptake rates.

Solid circles show the data points. Colours denote ecosystem types. Lines show regression lines for significant correlations between latitude and uptake rates, based on two-sided Pearson's correlation tests. Pearson correlation coefficients and p-values are provided for these significant relationships (see legend for abbreviations of ecosystem types).

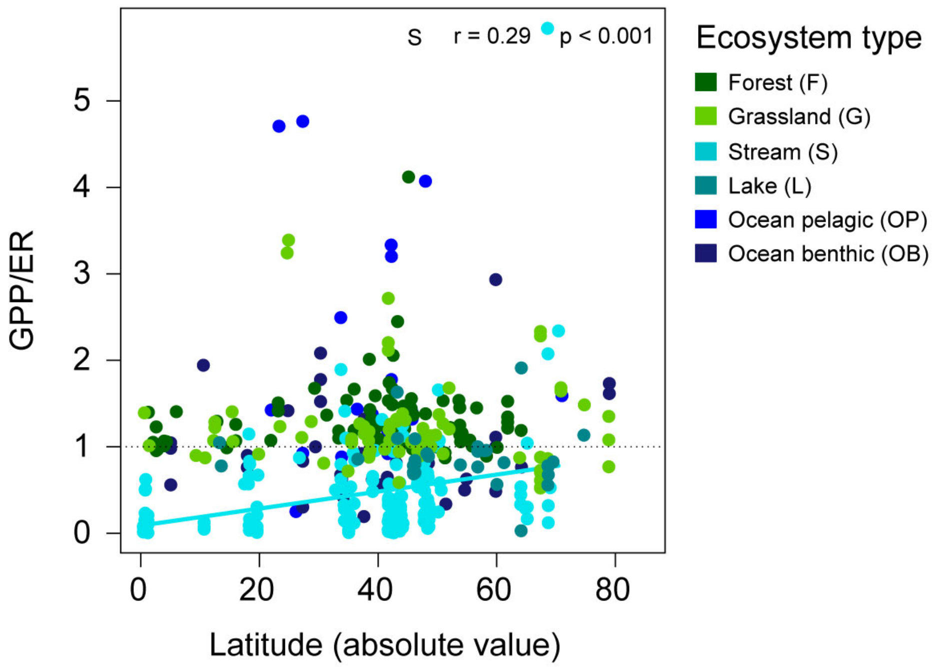

Figure S4.5 | Latitudinal trends in GPP/ER ratios.

Solid circles show the data points. Colours denote ecosystem types. Lines show regression lines for significant correlations between latitude and uptake rates, based on two-sided Pearson's correlation tests. Pearson correlation coefficients and p-values are provided for these significant relationships (see legend for abbreviations of ecosystem types). GPP and ER stand for gross primary production and ecosystem respiration, respectively.

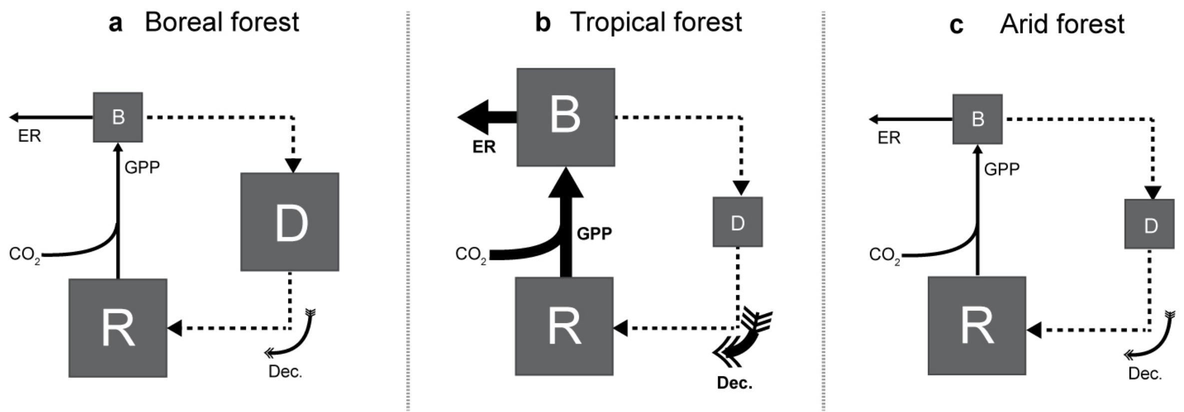

Figure S4.6 | Functioning shift of forests among climatic zones.

Diagrams of ecosystem functioning in **(a)** boreal, **(b)** tropical and **(c)** arid forests. Squares represent stocks of biomass (B), detritus (D), and organic carbon (R). Straight arrows represent fluxes of gross primary production (GPP) and ecosystem respiration (ER), and bent arrows decomposition rates. Significant differences among panels for the different ecosystem variables are highlighted by differences in size of boxes or arrows. For instance, biomass is higher in tropical than in boreal or arid forests, and not different between boreal and arid forest (see statistical tests in Table S3.10). Dotted arrows represent fluxes for which we have not collected data.

Appendix S5 – Supplementary references

Adler, D. (2018). vioplot: violin plot. *R Package Version 0.3.2*. Retrieved from https://github.com/TomKellyGenetics/vioplot

Becker, R. A., & Wilks, A. R. (original S. code). (2018). maps: Draw Geographical Maps. *R Version by Brownrigg, R. Enhancements by Minka, T. P. & Deckmyn, A., R Package Version 3.3.0.* Retrieved from https://cran.r-project.org/package=maps

Carstensen, J., Conley, D., & Müller-Karulis, B. (2003). Spatial and temporal resolution of carbon fluxes in a shallow coastal ecosystem, the Kattegat. *Marine Ecology Progress Series*, *252*, 35–50. https://doi.org/10.3354/meps252035

Cebrian, J., & Lartigue, J. (2004). Patterns of herbivory and decomposition in aquatic and terrestrial ecosystems. *Ecological Monographs*, *74*(2), 237–259. https://doi.org/10.1890/03-4019

Cho, B. C., & Azam, F. (1988). Major role of bacteria in biogeochemical fluxes in the ocean's interior. *Nature*, *332*, 441–443. https://doi.org/10.1038/332441a0

Codispoti, L. A., Kelly, V., Thessen, A., Matrai, P., Suttles, S., Hill, V., … Light, B. (2013). Synthesis of primary production in the Arctic Ocean: III. Nitrate and phosphate based estimates of net community production. *Progress in Oceanography*, *110*, 126–150. https://doi.org/10.1016/j.pocean.2012.11.006

Dinno, A. (2017). dunn.test: Dunn's Test of Multiple Comparisons Using Rank Sums. *R Package Version 1.3.5*. Retrieved from https://cran.r-project.org/package=dunn.test

Dray, S., & Dufour, A. (2007). The ade4 Package: Implementing the Duality Diagram for Ecologists. *Journal of Statistical Software*, *22*(4), 1–20. https://doi.org/10.18637/jss.v022.i04

Duarte, C. M., Marbà, N., Gacia, E., Fourqurean, J. W., Beggins, J., Barrón, C., & Apostolaki, E. T. (2010). Seagrass community metabolism: Assessing the carbon sink capacity of seagrass meadows. *Global Biogeochemical Cycles*, *24*(4), 1–8. https://doi.org/10.1029/2010GB003793

Ducklow, H. W. (1999). Minireview: The bacterial content of the oceanic euphotic zone. *FEMS Microbiology-Ecology*, *30*, 1–10. https://doi.org/10.1016/S0168-6496(99)00031-8

Elser, J. J., Fagan, W. F. F., Denno, R. F., Dobberfuhl, D. R., Folarin, A., Huberty, A., … Sterner, R. W. (2000). Nutritional constraints in terrestrial and freshwater food webs. *Nature*, *408*(6812), 578–580. https://doi.org/10.1038/35046058

Elzhov, T. V., Mullen, K. M., Spiess, A.-N., & Bolker, B. (2016). minpack.lm: R Interface to the Levenberg-Marquardt Nonlinear Least-Squares Algorithm Found in MINPACK, Plus Support for Bounds. *R Package Version 1.2-1*. Retrieved from https://cran.r-project.org/package=minpack.lm

Gan, S., Wu, Y., & Zhang, J. (2016). Bioavailability of dissolved organic carbon linked with the regional carbon cycle in the East China Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, *124*, 19–28. https://doi.org/10.1016/j.dsr2.2015.06.024

Garonna, I., de Jong, R., de Wit, A. J. W., Mücher, C. A., Schmid, B., & Schaepman, M. E. (2014). Strong contribution of autumn phenology to changes in satellite-derived growing season length estimates across Europe (1982-2011). *Global Change Biology*, *20*(11), 3457–3470. https://doi.org/10.1111/gcb.12625

Giraudoux, P. (2018). pgirmess: Spatial Analysis and Data Mining for Field Ecologists. *R Package Version 1.6.9*. Retrieved from https://cran.r-project.org/package=pgirmess

Graves, S., Piepho, H.-P., Selzer, L., & with help from Dorai-Raj, S. (2015). multcompView: Visualizations of Paired Comparisons. *R Package Version 0.1-7*. Retrieved from https://cran.r-project.org/package=multcompView

Honti, M., & Istvánovics, V. (2019). Error propagation during inverse modeling leads to spurious correlations and misinterpretation of lake metabolism. *Limnology and Oceanography: Methods*, *17*(1), 17–24. https://doi.org/10.1002/lom3.10293

Huchette, S. M. H. H., Beveridge, M. C. M. M., Baird, D. J., & Ireland, M. (2000). The impacts of grazing by tilapias (Oreochromis niloticus L.) on periphyton communities growing on artificial substrate in cages. *Aquaculture*, *186*(1–2), 45–60. https://doi.org/10.1016/S0044-8486(99)00365-8

Irons III, J. G., & Oswood, M. W. (1997). Organic matter dynamics in 3 subarctic streams of interior Alaska, USA. *Journal of the North American Benthological Society*, *16*(1), 23–28. https://doi.org/10.2307/1468226

Kirchman, D. L., Keel, R. G., Simon, M., & Welschmeyer, N. A. (1993). Biomass and production of heterotrophic bacterioplankton in the oceanic subarctic Pacific. *Deep Sea Research Part I: Oceanographic Research Papers*, *40*(5), 967–988. https://doi.org/10.1016/0967-0637(93)90084-G

Le, S., Josse, J., & Husson, F. (2008). FactoMineR: An R Package for Multivariate Analysis. *Journal of Statistical Software*, *25*(1), 1–18. https://doi.org/10.18637/jss.v025.i01

Mücher, C. A., Klijn, J. A., Wascher, D. M., & Schaminée, J. H. J. (2010). A new European Landscape Classification (LANMAP): A transparent, flexible and user-oriented methodology to distinguish landscapes. *Ecological Indicators*, *10*(1), 87–103. https://doi.org/10.1016/j.ecolind.2009.03.018

Neuwirth, E. (2014). RColorBrewer: ColorBrewer Palettes. *R Package Version 1.1-2*.

Opitz, S. (1996). *Trophic interactions in Caribbean coral reefs*. *Technical Reports* (Vol. 43). International Center for Living Aquatic Resources Management.

Peterson, B., Hobbie, E., & Corliss, T. L. (1986). Carbon flow in a tundra stream ecosystem. *Canadian Journal of Fisheries and Aquatic Sciences*, *43*(1978), 1259–1270. https://doi.org/10.1139/f86-156

R Core Team. (2019). R: A Language and Environment for Statistical Computing. Vienna, Austria. Retrieved from https://www.r-project.org/

Rodriguez-Iturbe, I., & Rinaldo, A. (1997). *Fractal river networks: chance and self-organization.* New York: Cambridge University Press.

Small, G. E., Torres, P. J., Schweizer, L. M., Duff, J. H., & Pringle, C. M. (2013). Importance of terrestrial arthropods as subsidies in lowland Neotropical rain forest stream ecosystems. *Biotropica*, *45(1)*(0), 80–87. https://doi.org/doi:10.1111/j.1744-7429.2012.00896.x

Soetaert, K. (2017). plot3D: Plotting Multi-Dimensional Data. *R Package Version 1.1.1*. Retrieved from https://cran.r-project.org/package=plot3D

Stone, J. P., & Steinberg, D. K. (2016). Salp contributions to vertical carbon flux in the Sargasso Sea. *Deep-Sea Research Part I: Oceanographic Research Papers*, *113*, 90–100. https://doi.org/10.1016/j.dsr.2016.04.007

Weathers, K. C., Strayer, D. L., & Likens, G. E. (2013). Section II. Ecological Energetics BT - Fundamentals of Ecosystem Science (pp. 25–26). Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-08-091680-4.00024-X