

Linking plant and ecosystem functional biogeography

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Classical biogeographical observations suggest that ecosystems are strongly shaped by climatic constraints in terms of their structure and function. On the other hand, vegetation function feeds back on the climate system via biosphere–atmosphere exchange of matter and energy. Ecosystem-level observations of this exchange reveal very large functional biogeographical variation of climate-relevant ecosystem functional properties related to carbon and water cycles. This variation is explained insufficiently by climate control and a classical plant functional type classification approach. For example, correlations between seasonal carbon-use efficiency and climate or environmental variables remain below 0.6, leaving almost 70% of variance unexplained. We suggest that a substantial part of this unexplained variation of ecosystem functional properties is related to variations in plant and microbial traits. Therefore, to progress with global functional biogeography, we should seek to understand the link between organismic traits and flux-derived ecosystem properties at ecosystem observation sites and the spatial variation of vegetation traits given geocological covariates. This understanding can be fostered by synergistic use of both data-driven and theory-driven ecological as well as biophysical approaches.

biogeochemistry | plant traits | carbon cycle | eddy covariance | FLUXNET

One of the long-term objectives in global ecology is to understand the multifaceted functions of terrestrial ecosystems in the Earth system. Of particular interest are the salient properties of terrestrial ecosystems as biogeochemical reactors in the Earth system and biogeophysical controls of land–surface atmosphere interactions (1). Limited comprehension and observational uncertainties in the ecosystem functions are hampering the representation of the dynamic interactions of climate and human intervention with the biosphere in current Earth-system models (2, 3). Clearly, the primary tools are models that compute fluxes across a variety of spatial levels (leaves, plants, ecosystems, landscapes, and biomes) and time scales (hours, days, seasons, years, decades, and centuries) (4–6). The implementation of terrestrial ecosystem models requires information on parameters of nonlinear algorithms that produce fluxes of carbon and water at the leaf level and integrate this information up to canopy and landscape scales. Therefore, a fundamental challenge in this context is to identify observations and observational patterns that allow us to parameterize the critical processes.

Today, global ecology is entering the new era of “big data” side-by-side with other areas of science (7). We are better equipped than ever before for exploring observations at a variety of time and space scales that can be integrated into process-based models. Large datasets on both ecosystem and organismic levels are opening new opportunities and allow us to explore challenges that have so far been left untouched. At the ecosystem level, observations of the fluxes of carbon, water, and energy between the biosphere and the atmosphere across a wide range of geocological conditions (FLUXNET) (8, 9) characterize ecosystem functions, as affected by vegetation, soil, and climate (10–13). By combining these fluxes with remote sensing information, it has become possible to scale-up, i.e., estimate the spatiotemporal variability of biosphere–atmosphere exchange at regional, continental, and global scales (14–17). At the organismic level, information on species occurrence and on plant traits has been assembled in large data bases and analyzed for functional tradeoffs (18–20).

One of today’s scientific challenges is to directly link the observations at organismic and ecosystem levels (21–23) to develop a profound understanding of biotic interactions with environmental constraints: i.e., hydrometeorological and nutritional preconditions. One fundamental question in this context is to what degree the local composition of morphological, anatomical, biochemical, or physiological features measurable at the individual plant (so-called “plant traits”) have an influence on the underlying process chains that may matter for the variation of ecosystem fluxes and properties (24). The future importance of biogeography for an integrated Earth-system science will crucially depend on its capacity to inform which plant traits (and their local composites) matter for the spatiotemporal variations of functions occurring at the ecosystem scale, in addition to, and independently of, climate and environmental factors. A biogeography of ecosystem functional properties has to explore multiple sources of information, from species-distribution maps and satellite remote-sensing data to local trait and flux observations, and foster the incorporation of biotic observations into process-based models (4, 25). An approach of this kind may allow us to scrutinize the emergent behavior of the local plant communities along with their (nonlinear) responses to, and collective feedbacks with, the environment.

In this contribution, we review recent advances of functional biogeography at the ecosystem level as achieved by the global network of biosphere–atmosphere observation and its integration with remote-sensing data and with physiological concepts. Both for assimilatory and dissimilatory functions and properties at ecosystem level, we see large global spatial and temporal variation. Climate or broad conventional vegetation types can explain only a fraction of the observed metabolic variations, indicating that we are confronted with an open scientific puzzle. We propose that trait-based biogeographical approaches will be instrumental for solving this riddle and hypothesize a number of links between vegetation (above- and below-ground) traits, with emphasis on processes that are important for the ecosystems’ carbon balance. However, we have to acknowledge that ecosystem functioning does not simply result from a linear combination of vegetation traits. Rather, we have to consider the nonlinear interactions between organisms and their traits that result in emergent behavior at the ecosystem level and apply appropriate biophysical and ecological, as well as statistical, modeling

Significance

This article defines ecosystem functional properties, which can be derived from long-term observations of gas and energy exchange between ecosystems and the atmosphere, and shows that variations of those cannot be easily explained by classical climatological or biogeographical approaches such as plant functional types. Instead, we argue that plant traits have the potential to explain this variation, and we call for a stronger integration of research communities dedicated to plant traits and to ecosystem–atmosphere exchange.

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approaches. Following ref. 26, we structure the text by identifying emergent behavior at the ecosystem level and then consider the underlying processes and traits at the organismic level, followed by a perspective on how the levels can be integrated.

Biogeography and Ecosystem Functional Properties

Biogeography has been defined as the science of documenting and understanding where organisms live, at what abundance, and why (27). This science has classically concentrated on individual species but extends to the study of communities and ecosystems, which emerge from the interaction of the communities with their abiotic environment. The variation of biological structure with space has a long research tradition and is often visually accessible, leading to broad classifications of organisms (such as lifeforms after Raunkiaer) (28) and at ecosystem level (e.g., shrublands, grasslands, forests). Living organisms exchange matter, energy, and information with their environment, which is an expression of their functioning. Ecosystems exchange these quantities with the atmosphere and adjacent ecosystems including rivers, lakes, groundwater, and the subsurface. Consequently, functional biogeography may be defined as the study of the spatial and temporal distribution of the functions of living organisms and of the resulting ecosystems. The emphasis on a functional perspective in biogeography is a comparatively recent development, possibly because “ecological functioning” is harder to observe than structure, in particular at the ecosystem level. However, it is the functioning of ecosystems and organisms therein that influences the environment (e.g., climate) and provides ecosystem services to humankind (23, 29). Therefore, it is of paramount interest to understand how organisms and environmental conditions coshape the variation of ecosystem functions in space and time.

Today considerable progress has been made to establish observing systems and databases to characterize the geographical variation of functioning at both organismic and ecosystem levels, as briefly described in *SI Appendix, Fig. S1* and related text. Ecosystem-level quantities are derived from flux and biometric observations, which allow a better characterization and understanding of the ecosystems. Often these quantities are analogous to ecophysiological leaf-level characteristics such as (intrinsic) water-use efficiency, leaf conductance, light-use efficiency, or light-saturated photosynthetic CO₂ uptake whereas others relate to physical and ecophysiological characteristics important for land surface–atmosphere interaction (e.g., aerodynamic and surface conductances, albedo, evaporative fraction) (30–32). In addition, and very important for the whole-ecosystem carbon balance, quantities are being explored that entail respiration fluxes and carbon pools (carbon-use efficiency, carbon-turnover times) (33). We define such “ecosystem functional properties” as quantities that characterize ecosystem processes and responses in an integrated and comparable manner.

As we will show here, the spatial and temporal variation of ecosystem functional properties is largely unexplained by classical approaches to vegetation (e.g., plant functional types) and remains a major functional biogeographical puzzle to solve, with a trait-based approach being a promising avenue.

Global Functional Biogeographical Knowledge and Questions from Ecosystem-Level Observations

Data-Driven Up-Scaling Approaches. Site-level measurements of ecosystem–atmosphere exchange, albeit covering footprints between $\sim 10^4$ to 10^6 m², essentially remain point measurements from a global Earth-system perspective. However, combining these flux observations with information from remote-sensing and gridded meteorological drivers via statistical machine-learning approaches (data-driven up-scaling) has allowed us to infer continental-to-global fields of ecosystem functions [gross primary production (GPP) and evapotranspiration (ET)] in recent years (11, 12, 16, 17, 34–36). The seasonal and spatial variation of quantities such as GPP, ET, and sensible heat flux (H) can be estimated with very good performance ($r^2 > 0.6$) as shown in cross-validation exercises (17). Therefore, these fields are used to evaluate whether global carbon-cycle models show the same global behavior as the up-scaled observations (4, 14).

Further research should analyze the functional properties of the ecosystems, which essentially govern the response of ecosystems to changing environmental conditions. Generating such functional properties from globally up-scaled flux fields yields very distinct spatial patterns (Fig. 1) even though these properties are simply derived from annual flux integrals and abstract from temporal variation. For example, the high water-use efficiency (carbon taken up per water transpired) in areas where closed-canopy forests dominate, in the boreal, temperate, and tropical biomes, is evident (Fig. 1A) and corresponds broadly with a high energy-use efficiency (fraction of solar energy converted to chemical energy in photosynthesis). However, within the biomes, the covariation between water and energy-use efficiency is less or even negative (e.g., compare Fig. 1A and B in the boreal zone). These subtle patterns are propagated to the evaporative fraction (fraction of energy passed to the atmosphere as latent heat) (compare *SI Appendix, Fig. S24*). These interrelated ecosystem functional properties can be derived only from the multiple synchronous biogeochemical and biophysical fluxes observed at, and up-scaled from, FLUXNET sites (10, 17) and provide multiple constraints, e.g., to Earth-system models. However, it remains an open question which ecoclimatic and organism-level functional biogeographical patterns underlie the variability of these ecosystem properties. Clearly, there are differences between vegetation types, but the within-vegetation type variability is notable (Fig. 1B and D and *SI Appendix, Fig. S2B*). To what extent species identity and

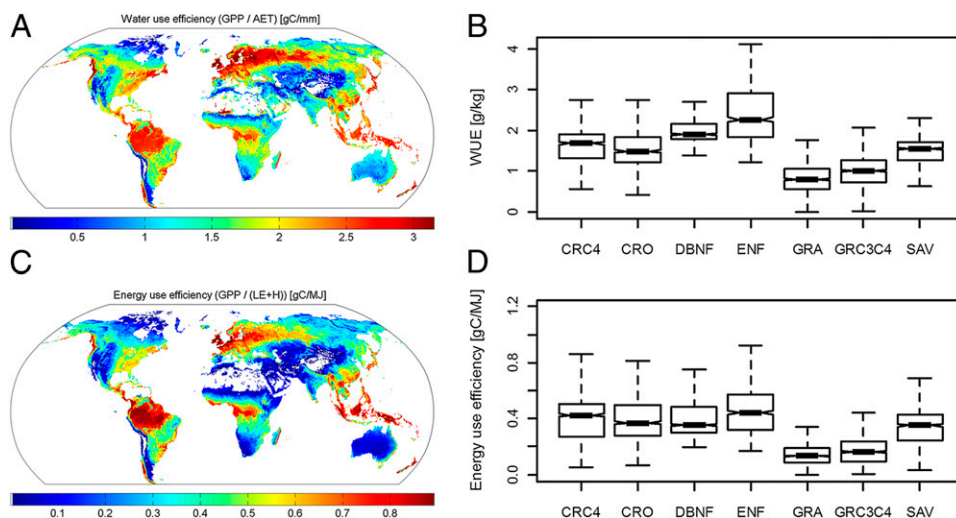


Fig. 1. Globally distributed ecosystem functional properties derived from integrating FLUXNET, remote sensing, and climate data (A and C) and their within- and between-vegetation type variation for selected vegetation types (B and D). The boxplots show minimum, 25th, 50th, and 75th percentiles, and maximum of the data. The notches approximate the 95% confidence interval for the median [(compare R documentation (87))]. CRO, cropland; CRC4, C4 crops; DBNF, deciduous broad-leaved and needle-leaved forests; ENF, evergreen needle-leaved forest; GRA, C3 grassland; GRC3C4, C3-C4 mixed grassland; SAV, savannah. Computed from Jung et al. (17).

plant traits contribute to explain this variability of ecosystem functional properties is an upcoming research topic in functional biogeography research, which will extend results emerging from existing studies on biodiversity–productivity relationships (37) and help their interpretation by integrating more physiological characterizations at the ecosystem level (Fig. 1).

Between-Site and Temporal Patterns of Ecosystem Functional Properties.

As mentioned in the introduction, the global network of ecosystem observations (FLUXNET) is able to characterize whole-ecosystem behavior or function in terms of their exchange of matter and energy with the atmosphere and its variation in space and time. Whole-ecosystem functional properties can be derived from FLUXNET data by fitting response curves to light, temperature, and vapor-pressure deficit (38–40). Light-saturated gross primary production per ground area (GPP_{sat}), for instance, can be seen as an analog to light-saturated photosynthesis (A_{max} , also per area) at leaf level (41, 42), which is recorded in trait databases. Ecosystem-level analysis of European FLUXNET data indicates that interannual variation of the net carbon balance (NEP) is significantly related to peak annual GPP_{sat} (Fig. 2A). This ecosystem physiological property correlates more strongly than any climate variable (and even more strongly than peak GPP flux) with annual NEP. This correlation emphasizes how important ecosystem-internal variation of physiology is for the variation

of ecosystem functions (here, net carbon fluxes). However, this whole-ecosystem physiological property in turn depends on ecosystem structure and (leaf-level) function because, at the ecosystem level, the light-saturated GPP depends on the fraction of light absorbed ($fAPAR$) and the efficiency with which the absorbed energy is converted to chemical energy (RUE). This dependency can be easily visualized with the conceptually simple radiation use-efficiency model

$$GPP = RUE \times fAPAR \times PAR, \quad [1]$$

where PAR is the photosynthetically active radiation. Also, more complex multilayer soil-vegetation-atmosphere transfer models, where GPP scales with photosynthetic carboxylation capacity (V_{cmax}) and leaf area index (LAI), show this behavior (43). Nevertheless, neither data-driven models nor process-based models that incorporate only ecosystem structural and climatic effects explain much of the interannual variability of carbon fluxes at ecosystem observation sites (17, 44), suggesting again that interannual variation of ecosystem physiology (for instance, carry-over effects of stress years) governs an important part of the variability (45–47).

By combining flux measurements with remotely sensed $fAPAR$ and a simple radiation-use efficiency model (as in Eq. 1) with a daily time step, one can infer the ecosystem parameter (RUE), which is independent of the ecosystem structure embedded in the $fAPAR$ observation (48, 49). Such an ecosystem-level parameter links more strongly to ecophysiological parameters in global Earth-system models (e.g., V_{cmax} and J_{max} in the Farquhar model) (50, 51). Classically, the ecophysiological parameters in global vegetation models are assumed constant per each plant functional type (PFT). These functional types are most often defined according to leaf habit (broadleaf, needle leaf), longevity (evergreen, deciduous), and life form (tree, shrub, grass, crop) and relate to vegetation type at the ecosystem level, which are defined based on the dominating PFTs (e.g., evergreen broadleaf forest). Parameterization strategies relying on FLUXNET data offer the chance to analyze the between- and within-vegetation type variability of the essential ecosystem parameters. Fig. 2B shows that there is considerable variation within vegetation types (here, evergreen needle leaf forest). It remains a challenge to explain this between-site variability. The within-vegetation type variability is partly, although not solely, dependent on species and should be able to be traced back to the traits of the dominant individuals of the ecosystem.

Obviously, the carbon balance of an ecosystem is determined not only by the variation of GPP but with the same importance by processes that determine the mean residence time of the assimilated carbon in the system: for instance, allocation and respiration of carbon, as well as disturbance events, such as fires, that lead to rapid release of carbon (52). Mahecha et al. (33) have found a convergence of the temperature sensitivity of ecosystem respiration. However, they found a considerable variation in the seasonal change of carbon respired versus carbon taken up: i.e., the seasonal carbon-use efficiency. In other words, some ecosystems respire a large proportion of the assimilated carbon within one season whereas others tend to store it. Fig. 3 shows that little of this variability can be explained by climate or conventional site characteristics. The question is whether the seasonal carbon-use efficiency belongs to a syndrome of ecosystem functional properties that might be underlying control by plant, faunal, and microbial traits.

The Potential of Plant Traits for Explaining Ecosystem Functional Properties

The role of plant traits as important determinants of ecosystem functioning was recognized early on (29). Ultimately, the concept of plant functional types is based on the observation that different trait syndromes result in distinct broad differences in ecosystem functioning. However, the large within-PFT variability of both biogeochemical processes (compare the previous section) and trait

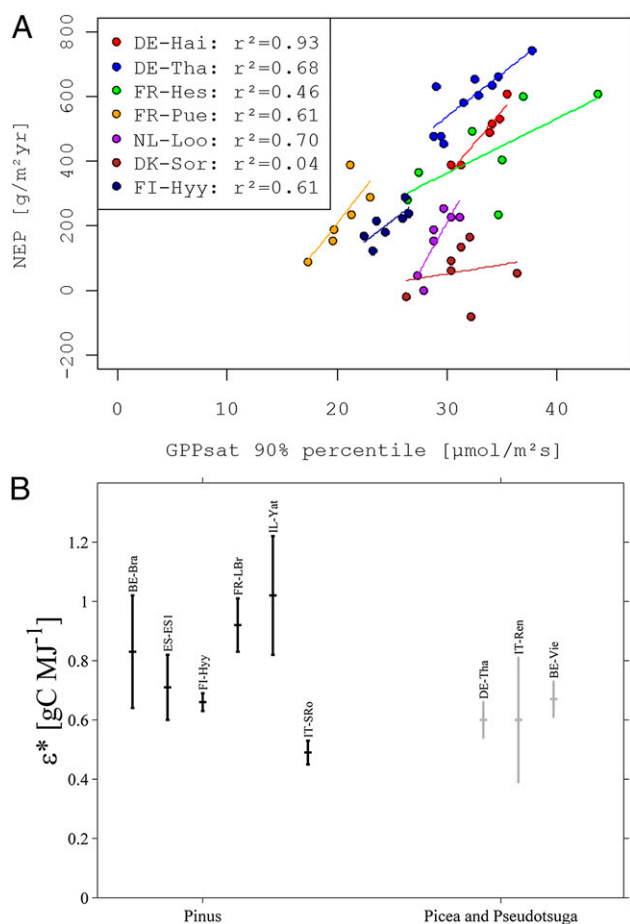


Fig. 2. (A) Covariation of net ecosystem production (NEP) with peak light-saturated GPP (90%ile) at seven European long-term observation sites [(data from Lasslop et al. (40)]. (B) Within- and between-species variation of the Carnegie–Ames–Stanford Approach (CASA) model parameter “maximum light-use efficiency” inferred with a model inversion approach [error bars indicate SEs; data from Carvalhais et al. (48)]. Compare *SI Appendix* for more details on analysis and sites.

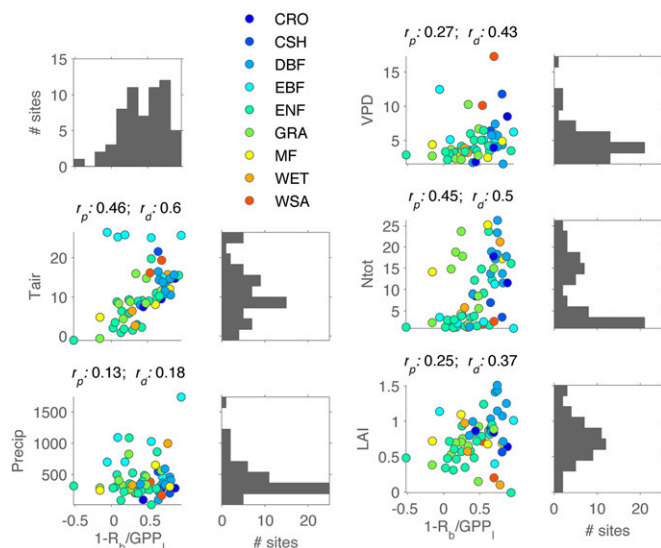


Fig. 3. Seasonal carbon-use efficiency after Mahecha et al. (see figure 3 and online supporting material in ref. 33) in relation to other ecosystem and climatic characteristics at FLUXNET sites. Shown are histograms of each variable across all sites and their relation with the seasonal carbon-use efficiency. On top of the panels, the (linear) Pearson correlation coefficient and the distance correlation coefficient are shown.

values (18) calls for exploring the joint patterns between these two sets of observation. It has been demonstrated that, across different PFTs and biomes, there is a convergence in the relationships of chemical, structural, and physiological leaf traits [the “leaf economics spectrum” (LES)] (20). While the LES includes some variation, partly explained by climate, it is robust in permitting the prediction of leaf physiological parameters based on leaf nitrogen concentrations and leaf mass per area (19, 53). Note, however, that leaf mass per area (LMA) has recently been suggested to reflect primarily its functional relationship with leaf lifespan and biases the correlation of leaf traits, which are functionally often area-proportional (54). Similarly, wood and root N concentrations (and root lifespans) are closely related to wood and root respiration rates (55, 56) although the slopes may differ between functional groups (e.g., grasses versus legumes) (57). Thus, ecosystem properties, such as GPP_{sat} and the autotrophic component of ecosystem respiration, can be in principle derived from plant traits (Fig. 4).

The heterotrophic component of ecosystem respiration is more difficult to approximate from plant traits. However, litter decomposition, which contributes substantially to heterotrophic respiration in many ecosystems, can be well-predicted from plant traits such as C, N, dry matter content, and lignin (58–60). Different organs (leaves, stems, roots) exhibit a different, although apparently coordinated, behavior (“plant economics spectrum”) (61). Under similar climates, wood decomposition is also well-correlated with nitrogen and phosphorus concentrations and C/N ratios, with gymnosperms decomposing more slowly than angiosperms (62). Through effects on litter quality, plant traits have also been suggested as important drivers for microbial community composition and shifts between more strongly saprophytic-based to more strongly symbiotic-based C cycling and thus soil organic carbon stabilization (63). Root traits, such as specific length, tissue density, and diameter, are important determinants of soil C turnover (64) and thus may contribute to the variation of carbon-use efficiency (Figs. 3 and 4). Root traits should thus also influence soil N turnover processes although this topic has so far received little attention. By changing tissue N concentrations and allocation patterns, changes in N availability will likely impact plant and ecosystem properties associated with the carbon cycle (compare to this section, above, and Fig. 4). An interesting trait reflecting long-term changes in N availability is

the stable N isotope ratio of plant tissues ($\delta^{15}N$) (65) as, e.g., obtained from wood samples or herbarium specimens of leaves (66, 67).

Plant traits related to the water cycle include those affecting plant water uptake (rooting depth, root mass, and specific root length), transport (hydraulic properties), storage, and loss (stomatal and cuticular conductance, leaf size) and thus should strongly link to the spatial variation found in Fig. 1A. At the leaf, plant, and ecosystem scale, water-use efficiency (WUE) can be derived from the carbon-isotope signatures $\delta^{13}C$ of plant tissues (e.g., leaves, tree rings), which integrate WUE from daily to decadal timescales (68, 69). For trees, wood density has been found to be an important and well-documented integrative trait related to hydraulic conductivity, leaf traits (including photosynthetic ones), and patterns of water uptake and transpiration (70) and is thus potentially a good proxy for water use and its constraints on the carbon cycle (Fig. 4). Wood density has also been suggested as an indicator of drought resistance as it is positively related to cavitation resistance (71). However, a recent study indicated that, under an extreme drought, species compensated low wood density by drought deciduousness, higher sensitivity of stomata to leaf water potential, and possibly also greater rooting depth (72). Thus, wood density should not be used without considering other traits when predicting resistance and resilience to extreme drought. Similarly, whereas in all biomes trees typically operate at a narrow safety margin for vulnerability to drought (73), species may differ in their strategy of drought avoidance and their capacity of xylem refilling (74). This observation not only reinforces the notion that drought effects on the carbon cycle may be better captured by a combination of plant traits, but also suggests that, in multispecies forests, different species may respond at different thresholds and thus may potentially increase the resistance and resilience of ecosystem processes to extreme events.

Although it has been argued that functional diversity could be the most relevant measure for ecosystem productivity and stability (75), there is still very limited empirical evidence demonstrating the role of functional trait diversity (which could account for both inter- and intraspecific variation) (76, 77). Clearly, targeted studies are needed to explicitly test for such relationships, as well as the effect of species identity or keystone species. Different levels of phylogenetic and spatial integration should be addressed by including specific site-level information and data from trait databases (SI Appendix, Fig. S3).

The Ecosystem Is More than the Sum of Traits: Scale Emergent Properties at the Ecosystem Level

The advantage of investigating data-driven linkages between vegetation traits and ecosystem functional behavior is its directness. However, one should not always expect a simple relation between ecosystem functions and traits at the organismic level (such as the former being a simple linear combination of the latter) because ecosystems are complex dynamic and adaptive systems that may experience scale emergent properties when one transcends scales (78). For example, the reflectivity of a leaf is not the same as the albedo of a canopy (79). Forest canopies are effective at trapping light so they may appear much darker (at 400- to 800-nm wavelengths) than the reflectivity of individual leaves indicates. Nor is the light-use efficiency of a leaf the same as of a canopy (80, 81). The light-response curve of individual plant canopies ranges from being linear for well-watered crops that form a closed canopy and have high nitrogen inputs (82) to being curvilinear with open canopies and those limited in nitrogen resources (80). Similarly to leaves that interact regarding the transfer of radiation through the canopy in a way that needs explicit scaling, other ecosystem processes emerge from interactions between individuals given their specific traits. For example, how strongly physical traits such as leaf toughness will influence the mean-residence time (and thus long-term accumulation) of carbon will depend on the existence of a decomposer community that might be specialized to digest such material. Often in these contexts, biological symbioses are

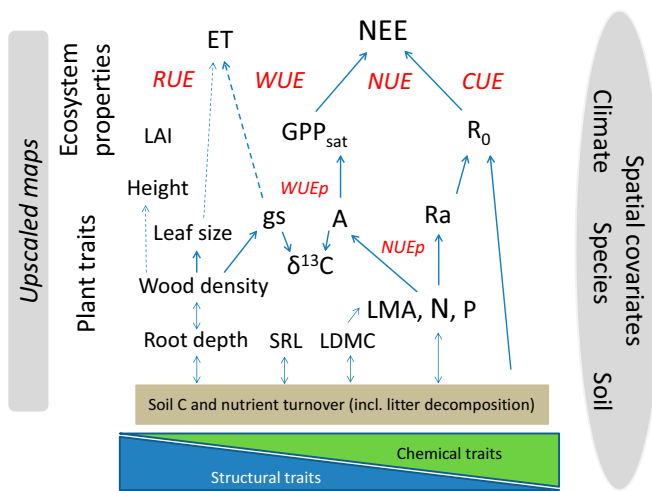


Fig. 4. Major relationships between plant structural and chemical–physiological traits and ecosystem functional properties related to carbon and water fluxes, embedded in an upscaling framework considering spatial covariates. Tradeoffs related to water-use (WUE), nitrogen-use (NUE), radiation-use (RUE), and carbon-use (CUE) efficiencies at plant (p) and ecosystem scale are printed in italics in red. Note that soil C and nutrient turnover processes are also important ecosystem properties affecting carbon fluxes directly via heterotrophic soil respiration and indirectly via effects of nutrient availability on plant functional traits and ecosystem structure. A, photosynthetic capacity; $\delta^{13}\text{C}$, stable carbon isotope ratio; ET, evapotranspiration; GPP_{sat} , gross primary productivity at saturating light; gs, maximum stomatal conductance; LAI, leaf area index; LDMC, leaf dry matter content; LMA, leaf mass per area; N, tissue nitrogen concentration; NEE, net ecosystem exchange of CO_2 ; P, tissue phosphorus concentration; R_0 , ecosystem respiration at reference temperature; Ra, plant respiration; SRL, specific root length.

crucially determining the cycling of elements. Examples include termite–microbial symbiosis, without which decomposition of lignin would be much retarded in tropical savannahs, or the influence of ruminant–microbial symbiosis for digesting lichens in high-latitude ecosystems. Similarly, a trait related to fast sprouting may be very important for ecosystem carbon dynamics in a frequently disturbed system, but not necessarily in a more stable environment. Therefore, traits are a necessary but not sufficient condition to understand the ecosystem carbon balance. It is needed to explicitly explore and model the interactions of individuals and to compare the emerging behavior against observed ecosystem functions varying in time and across sites. For an approach applicable at global scale, see ref. 83.

Outlook

We have shown that, based on ecosystem-level observations, we detect large functional biogeographical variation of ecosystem

properties, which can only partially be explained by climate and classical vegetation approaches such as plant functional types. Although the gross carbon uptake by vegetation depends on the interactions between leaves generating the microclimate in the canopy, the processing of the photosynthetically fixed carbon depends even more on biological processes that are controlled by traits, including allocation, respiration and decomposition, and stabilization of carbon in the soil. Overall, in the biogeochemical Earth-system context, the challenge is to explore classical biogeographical questions from a functional perspective: The question how to explain spatial patterns of species distribution and diversity has to be rephrased as: What are the determinants and biogeochemical consequences of plant functional attribute and trait variation? How do the inter- and intraspecific variability of plant traits depend on environmental constraints and affect the derived ecosystem functional properties beyond productivity? How are response traits and effect traits coupled with ecosystem functional properties? Can a combined approach of up-scaled traits and down-scaled fluxes help quantifying emergent properties across vegetation types and biogeographic regions? Note that such emergent properties could comprise, e.g., nonadditive effects and/or effects induced by the canopy structure and related microclimatic conditions (76, 84). What is the role of functional diversity for ecosystem functional properties and their resistance and resilience to disturbance and long-term environmental changes?

To our mind, a crucial criterion for future progress in this direction will be whether a stronger integration of largely disjoint activities will be achieved. For example, hypotheses regarding the link between organismic traits and ecosystem flux-derived whole-ecosystem properties can be best tested if the respective observations are made at the same sites. Remote-sensing approaches that have been successful for characterizing ecosystem structural parameters (e.g., leaf area index) and their effect on ecosystem functions need to be extended to detecting plant traits and their diversity. It has recently been demonstrated that hyperspectral remote sensing can be a powerful tool for mapping trait syndromes, which could be used for monitoring functional shifts in ecosystems (85). Finally, trait-based modeling approaches should be linked to the observations via model–data fusion approaches, where the biosphere model parameters (i.e., traits) can be constrained from the ecosystem-level observation via model inversion and compared with observed organismic traits. Once the mechanistic scaling of trait effects on ecosystem functions and response to climate has been successful, such a model would go beyond the projection of species and trait maps under changing conditions and can inform dynamic Earth-system models to calculate effects of changing climate and land use on ecosystem–atmosphere carbon and energy exchange and related feedbacks (86).

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Supplementary online information for Reichstein et al.: On linking plant and ecosystem functional biogeography

Recent databases exploitable for functional biogeography from organismic to ecosystem level

Today considerable progress has been made to establish observing systems and databases to characterize the geographical variation of functioning at both organismic and ecosystem level. At the organismic level plant traits measurable at the individual plant (1), reflect the outcome of evolutionary processes in the context of abiotic and biotic environmental constraints. There have been initiatives to integrate and standardize different datasets, but these initiatives were focused on specific regions (e.g. LEDA, 2) or trait spectra (e.g. GLOPNET, 3), culminating in the TRY initiative (4) in 2007, aiming to develop a global database of plant traits for refining plant functional types (www.try-db.org). Based on the integration of 150 datasets the TRY database has achieved an unprecedented coverage of about 3 million trait entries for 721 different plant traits and about 70000 plant species at global scale (Figure S1).

The eddy covariance (EC) technique is the preferred method to measure flux densities of trace gases between the biosphere and the atmosphere (5). The method allows us to directly observe fluxes in situ, in a non-destructive manner without invasive artifacts at a spatial scale of hundreds of meters and on time scales spanning hours, days and years. Consequently the eddy covariance based ecosystem observation sites have been deployed since the mid-1990s almost in parallel in several regional to continental networks worldwide; it's strength and shortcomings are well-known, including the potential loss of fluxes, difficult application under complex terrain and the inability to monitor fast fluxes (e.g. from fire) (6). Hence, it is valuable to complement the eddy covariance method with other approaches, e.g. inventories. The current global network of sites includes more than 500 stations spanning from tropical to arctic climate regions and different ecosystems and disturbance levels. A series of efforts to

combine and synthesize the observations from the different regional networks participating in FLUXNET has resulted in a global standardized data set with more than 930 site-years from more than 250 sites (Figure S1). Released in 2007 (www.fluxdata.org), it forms an unprecedented basis for research on global ecosystem functioning, capturing most variation in climate and vegetation structure (measured at fraction of absorbed photosynthetically active radiation fAPAR).

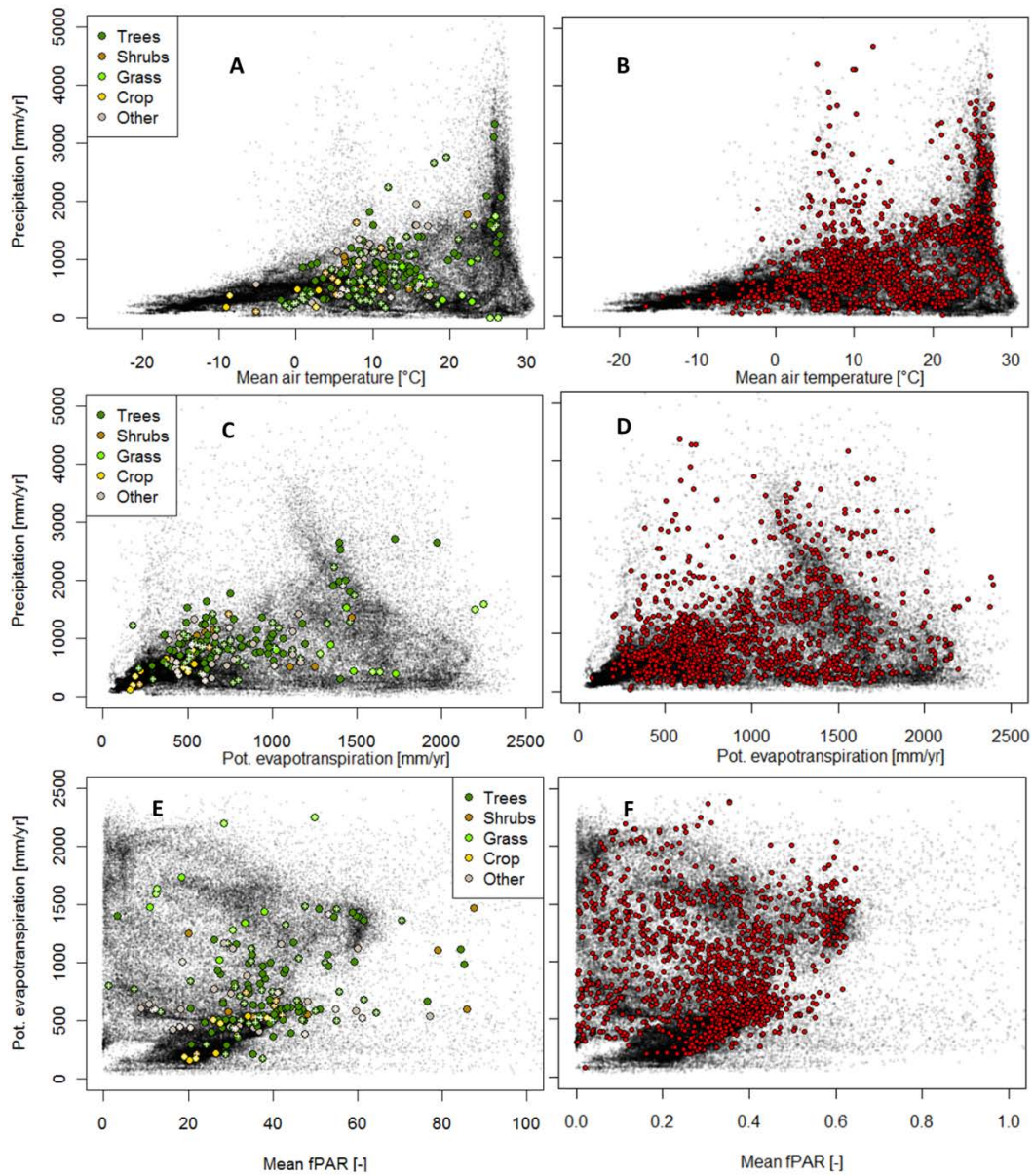


Figure S1: The distribution of FLUXNET (a,c,e) and TRY (b,d,f) observation sites in ecological spaces spanned by variable mean annual temperature and precipitation (a, b), potential evapotranspiration (PET) and precipitation (c, d) and fPAR and PET. The gray dots indicate all terrestrial landsurface pixels at 0.5°x0.5° and are derived from 7 for climate variables and 8 for fPAR.

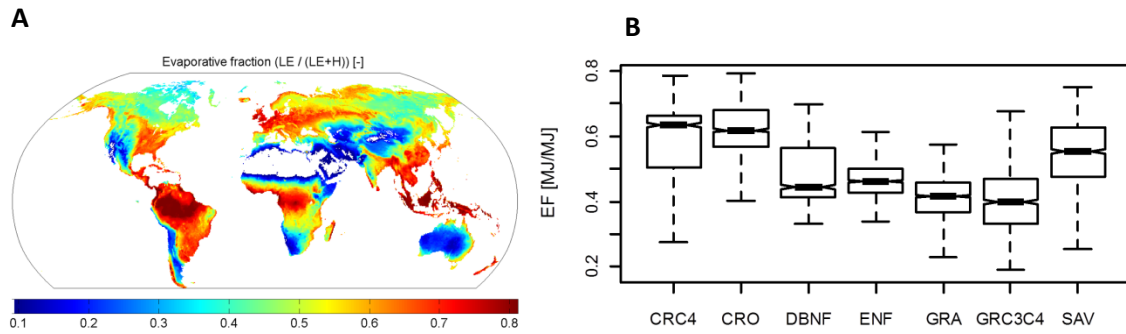


Figure S2: Global distribution of the ecosystem functional property evaporative fraction derived from integrating FLUXNET, remote sensing and climate data (A) and their within and between-vegetation type variation for selected vegetation types (B). Computed from Jung et al. (2011). CRO: Cropland, CRC4: C4 crops, DBNF: Deciduous broad leaved and needle leaved forests; ENF: Evergreen needle leaved forest, GRA: C3 grassland, GRC3C4: C3-C4 mixed grassland, SAV: savannah.

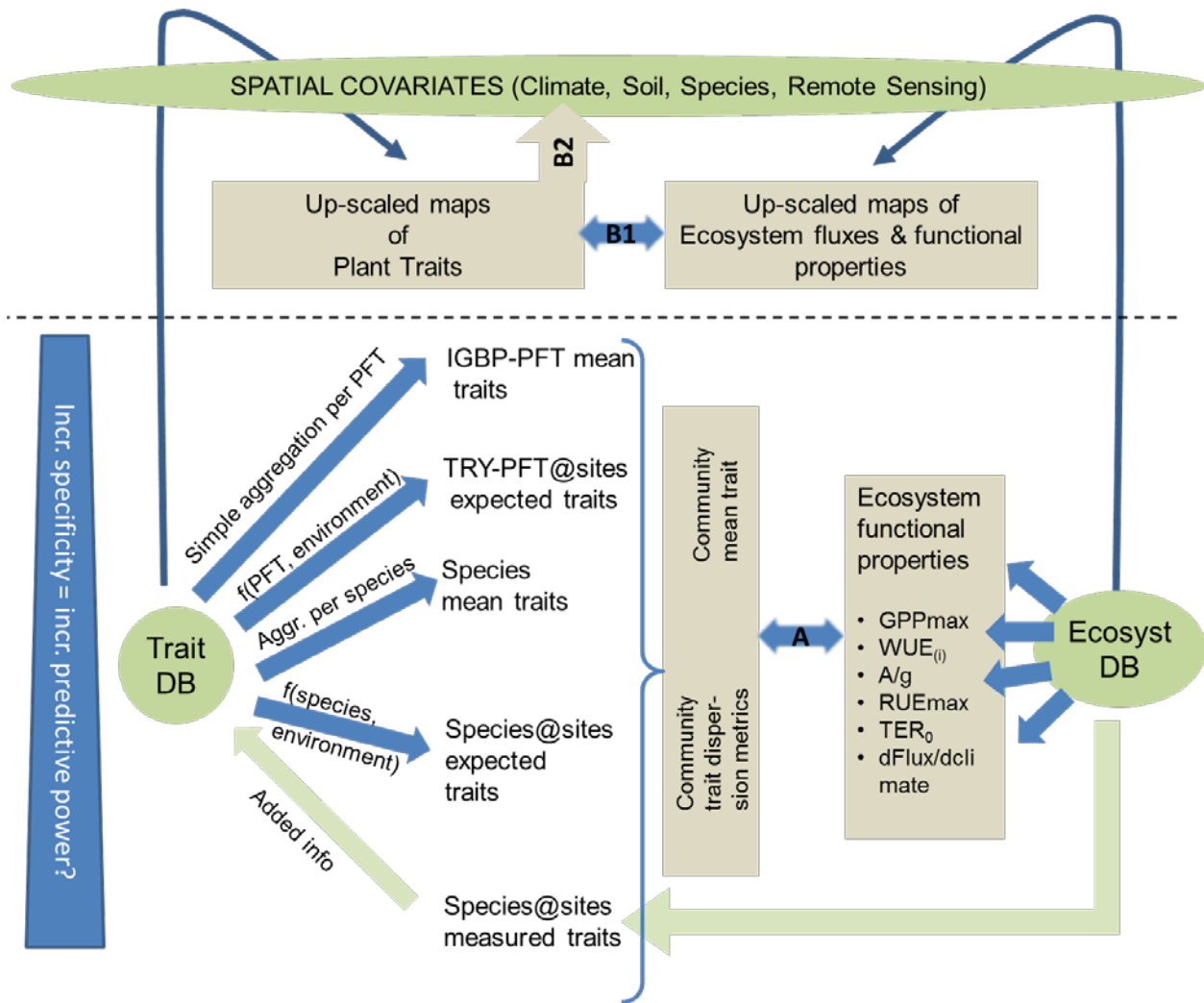


Figure S3: Conceptual scheme for linking trait and flux databases across different scales: A) Ecosystem scale (lower right part of the figure), B1) Continental to global scale (via comparing up-scaled fields of traits versus ecosystem properties), B2) By using up-scaled traits as spatial covariates to improve up-scaling (arrow).

Explanation of Figure 2a in main manuscript:

For Figure 2a, light response curve parameters from Lasslop et al. (2010) have been analysed. Lasslop et al. (2010) derive light-response parameters for consecutive 4-day periods, hence yielding a time series of parameters such as the light-saturated gross carbon uptake. For each year of the record the 90th percentile has been calculated (GPPsat_90) and plotted against the observed NEP for that year.

An ANCOVA reveals highly significant effects of GPPsat_90 on annual NEP and highly significant site effects, but no interaction between the two factors, indicating there is no significant difference in the NEP versus GPPsat_90 slopes between the site, but rather a general relation:

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
GPPsat_90.	1	602330	602330	116.6002	7.677e-13	***
SiteID	6	1366192	227699	44.0784	3.865e-15	***
GPPsat_90: SiteID	6	53065	8844	1.7121	0.1464	
Residuals	36	185968	5166			

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Analysis has been performed in R (9) with the “aov” function)

Table S1: Overview of the sites used in Figure 2a. The labels are the standardized FLUXNET labels as documented at www.fluxdata.org. More site-information can be found there.

Site label in Fig. 2	Site name	Vegetation type	Dominant species	Country of location
DE-Hai	Hainich	Temperate deciduous broadleaf forest	Fagus sylvatica L.	Germany
DE-Tha	Tharandt	Temperate evergreen needle-leaf forest	Picea abies L.	Germany
FR-Hes	Hesse	Temperate deciduous broadleaf forest	Fagus sylvatica L.	France
FR-Pue	Puéchabon	Mediterranean evergreen broadleaf forest	Quercus ilex L.	France
NL-Loo	Loobos	Temperate evergreen needle leaf forest	Pinus sylvestris L.	Netherlands
DK-Sor	Soroe	Temperate deciduous broadleaf forest	Fagus sylvatica L.	France
FI-Hyy	Hyytiälä	Boreal evergreen needle leaf forest	Pinus sylvestris L.	Finnland

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