

Towards a standardized Rapid Ecosystem Function Assessment (REFA)

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Quantifying ecosystem functioning is important for both fundamental and applied ecological research. However, there is currently a gap between the data available and the data needed to address topical questions, such as the drivers of functioning in different ecosystems under global change or the best management to sustain provisioning of ecosystem functions and services. Here, we identify a set of important functions and propose a Rapid Ecosystem Function Assessment (REFA). The proposed methods were specifically selected to be low-tech, easy to use, repeatable, and cost efficient. Thus, REFA enables standardized and comparable measurements of proxies for these functions that can be used at a large scale within and across studies. Adopting REFA can help to close the identified ecosystem functioning data gap.

An increasing interest in ecosystem functioning

The past few decades have seen an increasing interest in ecosystem functions (see [Glossary](#); [Box 1](#)), which has been fueled by at least three different sources: (i) biodiversity–ecosystem functioning research; (ii) ecological conservation and restoration; and (iii) the recognition of ecosystem services as a critical concept for biodiversity conservation and human well-being at the science–policy interface.

Classic biodiversity research aims to understand the abiotic and biotic drivers of the diversity of organisms in an ecosystem. The relatively young field of biodiversity–ecosystem functioning (BEF) research emerged around 1990, emphasizing that biodiversity itself can be a driver of ecosystem properties, and thereby allowing questions to be asked about the functional importance of biodiversity [1]. The main conclusion from BEF research over the past few decades is that low diversity in an assemblage is associated with a lowered mean (and an increase in the variance) in many of the ecosystem functions investigated [2–5]. Several meta-analyses support this conclusion (e.g., [6,7]).

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Ecological conservation and restoration is concerned with the amelioration and/or protection of habitats, and traditionally focuses on the species occurring within them. More recently, ecosystem functions have become an additional perspective of these research disciplines. For example, Aerts and Honnay [8] pointed out that the degradation of ecosystems also impacts ecosystem functions in addition to the alteration of the biotic composition. Consequently, restoring habitats could also restore functions. Likewise, the positive relationship between biodiversity and ecosystem functions found in BEF experiments has fostered the argument that species-rich or natural habitats need to be protected to maintain ecosystem functions ([9] but see also [10]).

Finally, publication of the Millennium Ecosystem Assessment [11] dramatically increased interest in ecosystem functions because these underlie the relationship between biodiversity and ecosystem services (e.g., food production and water availability [12]). The ecosystem service approach is prevalent in the 2020 target of the Convention of Biological Diversity [13,14] and has been integrated into national and supranational strategies for biodiversity conservation [15]. An understanding of the ecosystem functions underlying particular ecosystem services is necessary to make the ecosystem service approach amenable for political decision-making and ecosystem management [16–19].

The need for empirical data

In all three areas identified above, there is a lack of data quantifying ecosystem functions ([Box 2](#)). Existing data

Glossary

- **Consumer:** an organism that feeds on organic matter produced by, or available in, other living organisms.
- **Ecosystem compartment:** a unit in an ecosystem that can comprise either organic or inorganic material or living organisms. Ecosystem compartments are linked to each other by the flux of energy, matter, and/or information.
- **Ecosystem function:** the energy, matter, and information fluxes linking ecosystem compartments.
- **Ecosystem functioning:** following the definition by Jax [86], all individual ecosystem functions sustaining an ecosystem, such as element cycles and trophic interactions, can be summed under the name ‘ecosystem functioning’.
- **Ecosystem services:** those functions and products of an ecosystem that directly or indirectly benefit humans. Often ecosystem functions are considered a service when they can be attributed an economical value.
- **Rapid Ecosystem Function Assessment (REFA):** a suit of field methods to approximate ecosystem functions.

Box 1. Ecosystem functioning

Ecosystems are open systems and as such their persistence requires the continuous flow of energy and the recycling of matter (Figure 1, main text). They comprise different organisms that have adapted to each other and the abiotic conditions in their environment so that they form an overarching unit. All ecosystems contain four components: (i) primary producers (mostly green plants) that can live on inorganic compounds; (ii) accumulated dead organic matter; and (iii) decomposers that break down dead organisms and help to mineralize these (animals and microorganisms). Thereby, they replenish the (iv) inorganic nutrient pool, making the different elements again available to the primary producers [87]. These four components can be found even in the simplest ecosystem, such as cryptoendolithic lichen and cyanobacterial ecosystems in the Ross Desert in Antarctica [88]. In addition to nutrients, primary producers depend on the availability of water and light (Figure 1, main text). Interlinked with producers and decomposers into foodwebs are, in most ecosystems, a large number of consumers (Box 1, e.g. animals, fungi, and microorganisms). Consumers affect a plant community not only by feeding on plants, but also by a range of mutualistic interactions [87]. Prominent among these interactions between plants and animals are pollination and dispersal, which are essential in terrestrial systems for the regeneration of plants and, thus, the preservation of primary productivity over generations. Many of these ecosystem functions are also ecosystem services because they directly benefit humans or are indirectly linked to ecosystem services.

come from various sources and from a range of different methods, making integration difficult. In addition, the functions measured differ greatly between studies and ecosystems so that standardized measurements of the same function across different ecosystems are not available. Consequently, there is little hope that existing data can fill the ecosystem function data gap. Instead, new data need to be collected with the specific aim of measuring important functions with standardized methodology. We advocate that such methodology should not focus on measuring single ecosystem functions in technical detail, but rather span a range of functions to represent overall functioning. Therefore, we propose to establish a suite of

simple bioassays that we refer to as REFA, as a standardized approach to quantify ecosystem functions that will allow the collection of large and comparable data sets.

A Rapid Ecosystem Function Assessment

REFA is designed as a suite of fast and easy-to-use methods to quantify essential ecosystem components and the functions interlinking them in terrestrial ecosystems (Box 1). Therefore, REFA cannot use detailed measurements of functions that have been reviewed elsewhere [20]. Rather, REFA quantifies easy-to-measure proxies for important functions that include assessments of pools, fluxes, and ecological interactions. In a comparable approach, field indicators for the status and functioning of rangelands have been proposed [21]. Keeping REFA feasible requires a trade-off between the number of functions measured and the coverage of functions in an ecosystem (Figure 1). As a starting point, we selected a total of 11 variables that together can serve as first descriptors of overall functioning (indicated in black in Figure 1), based on reviewing the literature and our own experience. Methods that quantify species interactions underlying ecosystem functioning are emphasized because these functions are often difficult to measure and, consequently, data on these functions are especially scarce. To select the minimum adequate subset of functions that best reflects overall ecosystem functioning, a targeted analysis of the interrelationships between all functions in an ecosystem studied in much detail would be needed. The resulting best subset of functions will overlap but, most likely, not be identical with the set of functions we identified here. Thus, for some functions, REFA methods still need to be developed in the future. We have identified suitable methods to provide measurements for the selected functions in the published literature and present them in Table 1. All methods proposed were specifically selected to be low-tech, easy to use, repeatable, and cost efficient. Thus, they enable standardized and, hence, comparable measurement

Box 2. The ecosystem function data gap

In biodiversity research

There is a great need for solid data on different ecosystem functions measured in sites varying in environmental conditions, anthropogenic disturbance, land-use intensity, and natural vegetation. These data are needed to answer pressing questions about the relation between biodiversity and ecosystem functioning: how general is the biodiversity effect on ecosystem functioning [5]? Are there trade-offs between different functions [89]? Does biodiversity affect ecosystem functioning also in natural and man-made ecosystems [90–92]? These questions are still pressing because only a few biodiversity experiments have measured ecosystem functions in much detail (e.g., The Jena Experiment [93]; Cedar Creek [94]), while many studies concentrate on a few functions, such as productivity. In particular, levels of functioning in natural systems are often not known. For progress in BEF research, a larger number of functions need to be measured in a standardized way, both in experiments and under natural conditions, to enable statistical comparisons.

In applied ecology

Improving or conserving ecosystem functioning have been invoked as reasons for ecological restoration and conservation. Yet, practical ecological conservation and restoration have rarely measured ecosystem functions [8]. Thus, it is not clear what functions are also maintained in disturbed habitats and which functions are sensitive to

disturbances and responsive to restoration. Knowledge of a range of functions is necessary to improve future management recommendations, and to evaluate the success of measures taken to increase functioning or ameliorate human impacts. Consequently, there is a need to monitor ecosystem functions following restoration and/or conservation efforts for both intact and degraded ecosystems.

At the science–policy interface

To integrate the concept of ecosystem services into management and policy guidelines, ecosystem services are mapped onto land-surface types [95]. This mapping requires quantification of associations between ecosystem service provision and certain habitats (e.g., forest) or attributes of habitats (e.g., level of diversity or proportion of natural area). Currently, the links between habitats and service provision have often little empirical basis or are derived from case studies with unclear dependence on local conditions [18] and mapping is constrained by data availability at all spatial scales [96]. Thus, there is a need for data linking habitats and land use to biodiversity and various ecosystem functions that allow researchers to derive, and empirically test, ecosystem service provisioning functions [95,96]. Resulting verified provisioning functions could then be used for modeling multiple ecosystem services [97], address trade-offs between the provisioning of different ecosystem services [98], and improve future management recommendations.

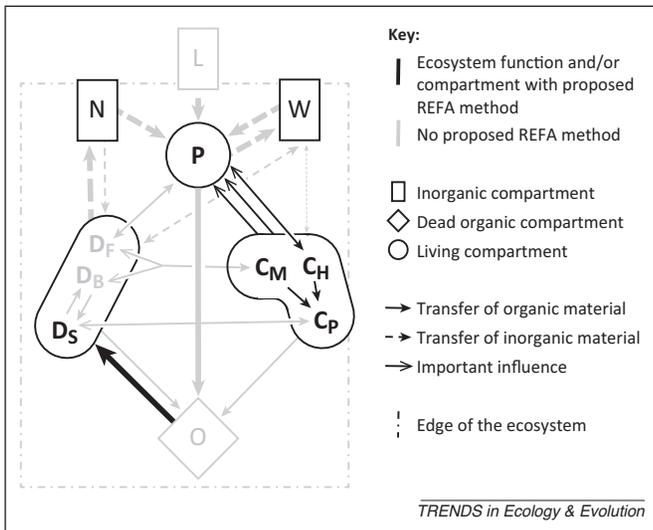


Figure 1. Schematic overview of a simplified ecosystem. Shown are important ecosystem compartments as symbols and the links between them as arrows. Letters indicate pools nested within compartments. These are (P) primary producers, mainly green plants; (O) dead organic matter; (D) decomposers, separated into (D_F) fungi, (D_B) bacteria, and (D_S) saprophagous fauna; (C) consumers, separated into (C_M) microbial feeders, (C_H) herbivores, and (C_P) predators and parasites; and the inorganic resources (N) nutrients, N, P, K, and others; (L) light; and (W) water. For details about the links between compartments, please see the main text. Respiration and leaching losses from the ecosystem are omitted for clarity. All ecosystem functions and/or compartments for which suitable Rapid Ecosystem Function Assessment (REFA) methods are proposed are shown in black. Figure modified from [87].

with a large number of replicates. To facilitate the integration of results from different climate zones and latitudes, measurements should be standardized relative to seasons, rather than sampling at fixed dates. We propose peak biomass as the seasonal fix point for all REFA methods.

Here, we review methods that could be used to estimate proxies of the ecosystem functions listed in Table 1. For each function, we propose a single REFA method. Often, established methods have resulted from the extensive work carried out in the wake of the International Biological Program (1964–1974) [22]. For other functions, potential REFA methods have only been used in case studies (Table 1) and need to be tested in more detail. Where we could not identify a clear best method, we review potential alternatives. Future work is needed to refine and calibrate the proposed methods and compare their performance to well-established, more-detailed measurements of the respective functions. Describing the practical details of the methods is beyond the scope of this review.

Plants and element cycles

Aboveground primary productivity

Photosynthesis by plants is the single most important energy input into terrestrial ecosystems. Net primary productivity (NPP) is defined as the total photosynthetic gain per unit ground area and time, including losses due to death and subsequent decomposition, herbivory, exudation/volatilization [23]. For herbaceous vegetation, methods to estimate productivity are well established. The simplest way that NPP can be approximated is by measuring standing peak biomass [24–26]. When vegetation contains woody plants, estimates of productivity require special methodologies because of the large standing (dead)

biomass and annual growth. Separating these two components is a major challenge, yet not impossible based on visual aids such as wood growth rings (in temperate climates) and bud-scale scars [27]. Stand biomass can be extrapolated via regressions between biomass of a subset of harvested individuals and nondestructive variables, such as height [24,28].

Belowground primary productivity

It is important that NPP comprises an above- and a belowground part. Yet, studies on plant productivity often focus only on aboveground peak standing biomass [23]. Belowground production of plants comprises the accumulated root biomass plus additional exudates and root litter, and can be a substantial fraction of total productivity (e.g., [29]). Equivalent to the measurements aboveground, the standing biomass of roots can be used as a measure for belowground NPP [25]. The use of an auger was identified as the most suitable method for taking volumetric soil-root samples [30]. After washing, roots are dried and weighed. Where belowground measurements are not available, it has been proposed to estimate belowground productivity from data on aboveground productivity via scaling models [31].

Soil fertility

Primary productivity critically depends on the availability of nutrients in the soil. Of all functions reviewed here, methods for the characterization of plant-available nutrients in soils are both among the best studied [32,33] but also the least applicable for REFA. Well-established methods for standardized soil analysis [32] are too detailed and labor intensive to be integrated into REFA without the support of a specialized laboratory. Most promising as a REFA method seems to be the use of commercial soil test kits [34] or to measure electrical conductivity of a soil suspension [35] with a hand-held electrode, given their expected future technical development, increased availability, and reduced cost. More targeted research is needed to establish a simple proxy of soil fertility suitable for REFA.

Water availability

A second important limiting factor for NPP is the availability of water. This depends on the climate at the site, which can be derived from global maps and climate diagrams, and the water-holding capacity of the local soil. Determining the water-holding capacity is labor intensive, but can be approximated by characterizing the soil texture [36]. Soil texture refers to the relative proportions of three differently sized fractions of particles: sand (0.05–2.0 mm), silt (0.002–0.05 mm), and clay (<0.002 mm). A rough characterization of soil texture can be obtained with a simple sedimentation assay [37].

Saprophagous foodweb

Decomposition

The quantity of accumulated dead organic matter depends on the rates at which new dead material is added and at which it decomposes, and also on human use (e.g., removal of wood from forests or hay from grasslands). Consequently, standing litter stocks are ambiguous to interpret and

Table 1. Collection of simple methods with a potential to be used as a REFA^a

Ecosystem function	Field sampling	Additional lab measurements	Status ^b	Time effort ^c	Refs
Plants and element cycles					
Aboveground primary productivity	Aboveground biomass of herbaceous vegetation is harvested; only current year growth from woody plants	Drying (70 °C) and weighing of biomass	E	L/L	[26]
Belowground primary productivity	Soil cores taken (20 cm diameter, 10 cm depth)	Determination of root dry mass (roots washed from soil cores, dried at 70 °C and weighted)	E	M/M	[30]
Soil fertility	Collection of soil sample	Electric conductivity or use of soil test kit	CS	L/L	[34,35]
Water availability	Collection of soil sample	Sedimentation assay to determine soil texture	CS	L/M	[37]
Saprophagous food-web					
Decomposition	Decomposition of standardized small wooden sticks as proxy; sticks are exposed within surface soil and collected after months	Measured as weight loss of dried sticks	CS	L*/M	[39]
Belowground secondary productivity	Samples taken as for belowground primary productivity	Extraction of soil fauna from soil cores by heat; determination of biomass by drying and weighting. Alternatively, fresh weight of invertebrates determined after storage in 70% ethanol and converted to dry weight via calibration curves	CS	M/H	[42]
Consumer–plant interactions					
Aboveground secondary productivity	Standardized suction sampling of invertebrates on a defined area (next to biomass plots)	Cleaned invertebrate sample dried and weighed or determination of fresh weight as for belowground fauna	C	M/H	[41]
Vertebrate herbivory	Fenced plots to exclude herbivores	Difference in biomass produced between fenced and unfenced plots	CS	H*/L	[48]
Invertebrate herbivory	Plant biomass sample (see above)	Scoring of all leaves or a subsample for herbivory damage (yes/no)	CS	L/M	[49]
Plant infection	Plant biomass sample (see above)	Scoring of all leaves or a subsample for pathogen infection (yes/no)	CS	L/M	[52]
Invertebrate predation	Predation rate of standardized prey items: aphids glued to plastic labels, exposed in field, and checked for disappearance in hourly intervals over sampling day	Calculation of removal rates	CS	M/L	[54,99]
	Attack rate on exposed artificial caterpillars made from plasticine; potential to identify different predator groups	Calculation of attack rates	CS	L/L	[58]
Pollination	Number of insects attracted to pan traps (yellow, blue, UV white), exposed on wooden sticks at maximum vegetation height in an undisturbed part of the site	Counting of caught individuals; determination of biomass as with aboveground invertebrates.	E	L/L	[100]
Seed dispersal	Removal of standard seeds; i.e., 25 wheat grains exposed in a regular grid spaced by 2 cm on plastic trays with positions marked by small wells; plates are checked in 1-h intervals over 1 day for the remaining number of grains to calculate instantaneous removal	Calculation of removal rates	CS	L/L	[75,76]

^aReferences to studies that used the respective method are given.

^bIndicates how well established the method is. CS (case studies), single studies have used the method without explicit testing it; C (calibrated), the method has been tested against other methods and detailed measurements to establish its suitability; E (established), the method has been used by various studies and has been calibrated; S (standardized), the method is used frequently based on a standardized protocol.

^cGives a rough estimate of time needed for the method in the field and/or lab. Estimates are given per sample in the following categories: L (low), ≤15 min; M (medium) ≤1 h; H (high) > 1 h; * denotes that it is necessary to revisit the site to conclude the method. Waiting times (e.g., for drying of material) are not included in the estimates. For details on the methods and the selected ecosystem functions see the main text.

rates of decomposition are a better measure for carbon and nutrient dynamics in the soil. Decomposition of natural litter is variable, depending on the community of decomposers, environmental conditions, and the properties of the leaf litter. To standardize the assay and make results comparable, decomposition of a standardized substrate is used as a proxy. One well-established method is to expose stripes of cotton fabric in the soil, leave them to decay, and then to measure the loss of tensile strength [38]. More suitable for REFA, because it is easier to measure, is the weight loss of standardized material, such as wood [39] or straw [40]. All assays require revisiting the sites to collect the exposed samples. Given that the rate of decay is unknown a priori, a series of measurements after different time periods or exposing several materials with different decay rates is often necessary for valid results.

Decomposer abundance

Decomposition is accelerated by the physical breakdown of materials via feeding by soil fauna. The bulk biomass of soil fauna can be used to approximate the importance of the saprophagous foodweb in an ecosystem. Invertebrates are sampled quantitatively from a known area by taking a large (20-cm diameter, 10-cm depth) soil core [41,42]. Using a simple Berlese/Tullgren funnel with a light bulb on top, soil fauna are driven out of the soil core by heat and collected in a jar containing ethylene glycol [41,42]. After cleaning samples from contamination with soil particles, invertebrate biomass is determined after drying. Further analyses of samples for diversity by sorting and determining species or morphospecies is possible if the fresh weight of samples is determined after storage in 70% ethanol (to standardize water content). The dry weight biomass can then be calculated from calibrations.

Consumer–plant interactions

Aboveground secondary productivity

In most ecosystems, plants are linked to a large number of consumers both via trophic and nontrophic interactions. The bulk biomass of consumers can be used to approximate the importance of the phytophagous foodweb in an ecosystem. Separation into trophic groups would be informative, but is too labor intensive for REFA. Large (vertebrate) consumers might not occur at all sites because of restricted access or because of a combination of small sampling sites, patchy distributions, and low regional consumer densities. Various methods can be used to estimate the production of large herbivores [43], most of which are not easily amenable for REFA. By contrast, invertebrate consumers can be sampled quantitatively from a known area by suction sampling [41,44], which is preferred over simpler sweep netting because of the defined area sampled and reduced experimenter bias [44]. After cleaning the samples from plant material, invertebrate biomass is determined, as described for belowground fauna.

Herbivory

The consumption of living plant material by animals (i.e., herbivory) links primary producers and higher trophic levels. Herbivory sustains the consumer community and impacts vegetation structure, community composition, and

plant physiology ([45] and references therein; [46]). Herbivory by (large) vertebrates and by invertebrates has to be differentiated. Vertebrates have higher consumption rates that are commonly measured by exclusion of animals from plots via fencing and estimating the difference in plant biomass on fenced and unfenced plots [47,48]. While large herbivores might not occur on all sites, herbivory by invertebrates is omnipresent, albeit on lower levels than vertebrate herbivory [45]. To quantify invertebrate herbivory, a large random subset of leaves (in the order of hundreds) is scored as showing damage, 1, or being undamaged, 0. The proportion of leaves with damage [49] has been successfully used as an approximation of herbivore pressure, and methods estimating the removed leaf area [50] are too labor intensive for large-scale monitoring.

Plant–pathogen infection

Similar to herbivores, pathogens can have far-reaching consequences for individual plant fitness and plant community composition [51]. The same method used for herbivory can be used to estimate the proportion of leaves infected by plant pathogens. Scoring for both damage types can be done simultaneously to estimate co-occurrence [52]. Herbivory and pathogen damage can often be identified by comparison with reference pictures showing the different visual aspects included.

Predation

Consumers of higher orders feed on other animals transferring energy within the group of secondary producers (Figure 1). Thus, top-down control of the herbivores can be exerted, reducing the feeding pressure on plants [53]. The removal of experimentally exposed standardized prey (pea aphids glued to labels) was used to estimate predation risk by ground-dwelling invertebrate predators [54]. Mealworms (*Tenebrio molitor*) can be used as a commercially available replacement for aphids. Alternatively, exposing caterpillar dummies made from plasticine has been used in multiple studies both for invertebrate and vertebrate predators [55–57]. This method is well established [58] and has the additional advantage that predation marks left in plasticine dummies can be counted and attributed to different feeding types or even species [59].

Pollination

The mutualistic transfer of pollen between flowers by (mostly) insects is often a prerequisite for seed set. Consequently, the loss of pollinators can cascade to the loss of plant species [60]. Realized pollination depends on traits of the respective plant (species), its surrounding plant community, the interacting pollinator community, and environmental conditions. Thus, its measurement is not feasible for REFA. Instead, abundance of insects caught in pan traps is the most effective proxy to assess pollinators in a standardized way [61,62]. Pan traps worked effectively for a wide range of pollinators [63] and have already been used extensively [64–68]. They should be used in three different colors (yellow, blue, and white) [63,69–71], mounted at standardized height relative to the vegetation [71,72], and should be spaced apart by at least 3–5 m for replication within sites [73].

Seed dispersal

A second mutualistic interaction that contributes to the successful regeneration of terrestrial plants is dispersal by animals [60] because it reduces density-dependent mortality [74]. Seed fate is routinely studied with removal experiments [75]. The removal of standardized seeds (e.g., cereal grains) quantifies the potential of seed dispersal to occur in a habitat, because up to half of the removed seeds are dispersed and germinate and are not preyed upon [76]. Rather than analyzing the proportion of grains removed after a fixed time period (which is extremely sensitive to the chosen time), the instant removal rate should be calculated by applying a survival analysis with the states present and removed recorded at several time steps.

Additional functions

The REFA methods proposed cover a large part of ecosystem functioning (Figure 1). Yet, this list cannot be exhaustive and additional functions might be of interest, such as storage of propagules in a seed or seedling bank, biomass of plants and animals separated into (functional) groups, or accumulation of dead organic material. Furthermore, estimates of additional rates in the element cycles are necessary to describe full ecosystem functioning. Among these, soil carbon stocks, microbial respiration (also fungal:bacterial ratios), and nutrient loss rates (nitrogen leaching) are probably the main ones of interest. The latter variables can be measured on a large number of samples, but established methods are more high tech and expensive compared with the REFA methods proposed here. Easy-to-measure proxies for these functions would be a valuable addition to a future REFA toolbox. Potentially, further functions can be included at low cost once non-invasive methods, such as hyperspectral imaging, are further developed [77].

Rapid biodiversity assessment

REFA can be combined with a fast assessment of biodiversity that has already been proposed to assess the state of biodiversity in an ecosystem (e.g., [78,79]). For example, the use of recognizable taxonomic units (e.g., [80–82]) or higher taxonomic levels, such as orders [83], rather than determining species or using genetic methods such as DNA barcoding [84] can reduce time and financial constraints. One particularly attractive approach would be to assess both the diversity of a particular taxon (e.g., birds) as well as a function affected by this taxon (e.g., predation as assessed by caterpillar dummies). Such a simultaneous application of a rapid biodiversity assessment and REFA would enable a direct evaluation of the relations between habitat conditions, biodiversity, and ecosystem functioning, and help to answer the research questions outlined in Box 2.

The way forward

In our view, the success of REFA in advancing understanding of the drivers of ecosystem functioning will depend on three conditions. Addressing these conditions requires further work.

Standardized protocols

To compile large data sets requires standardized methods to join data from different studies, sites, countries, and

continents. The methods proposed above can form the basis for a collection of detailed protocols setting the standards for the measurements of ecosystem functions. An essential next step is to validate results from the proposed REFA methods by comparing them to results from traditional, detailed, and more laborious methods. Thus, a series of method papers identifying the most suitable REFA method to approximate a particular function and presenting calibration data both by comparing results to other established methods and applying REFA in a range of conditions would be most valuable. Finalized protocols should be collected in a handbook of REFA methods, which would benefit from the contribution of specialists for particular functions. It has to be emphasized that REFA methods cannot replace laborious measurements in focused ecological studies. Yet, keeping the REFA protocols simple and the materials needed basic has considerable merits. It makes it possible to: (i) measure a large number of sites within a study; (ii) use the protocols also in areas with limited access to high technology; and (iii) opens the possibility for these methods to be applied by nonspecialists. Thus, some REFA methods could even be used in citizen science projects (e.g., <http://www.helsinki.fi/foodwebs/dummycaterpillars/index.htm>).

Common description of meta-data

Not only the data themselves need to be collected in a uniform way, but also the description of the data and important covariates should be standardized [85]. A unified meta-data framework that describes sites would also be helpful to integrate results of REFA with comparable efforts for rapid biodiversity estimates and habitat characterization. A minimum set of important meta-data should include: location, habitat, site conditions and season, time, data collector, and the exact protocol used.

Availability and storage of data

Finally, collected data need to be stored and made easily available. Journals increasingly require data deposition for papers published, so it is conceivable that the amount of data accessible will strongly increase in the near future. Yet, these individual solutions for access cause the data to be scattered throughout the Internet. A central storage holding the majority of the data for easy access would greatly increase their usability. The obvious solution for this would be an online repository and/or database linked to a web site that provides the up- and download capabilities and thereby ensures accessibility of the data. It would be desirable to extend current initiatives for the storage of biological- and especially biodiversity-related data to also include data on measured functions.

Concluding remarks

There is a need for data on ecosystem functioning in various areas of basic and applied research. This need can best be addressed by setting standards of easy-to-use methods so that future measuring efforts can gather data in the most useful and comparable way. We believe that there is a need for a suite of standardized methods that we refer to as REFA. With our suggestion of a collection of adequate methods, we hope to stimulate discussions within the research community and, ultimately, the

collection of data needed to answer questions about the factors driving levels of functioning in different ecosystems and how to manage ecosystems to protect their provision of functions.

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References

- Schulze, E.-D. and Mooney, H.A., eds (1993) *Biodiversity and Ecosystem Function*, Springer
- Hooper, D.U. et al. (2005) Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecol. Monogr.* 75, 3–35
- Stachowicz, J.J. et al. (2008) Complementarity in marine biodiversity manipulations: reconciling divergent evidence from field and mesocosm experiments. *Proc. Natl. Acad. Sci. U.S.A.* 105, 18842–18847
- Scherber, C. et al. (2010) Bottom-up effects of plant diversity on multitrophic interactions in a biodiversity experiment. *Nature* 468, 553–556
- Allan, E. et al. (2013) A comparison of the strength of biodiversity effects across multiple functions. *Oecologia* 173, 223–237
- Balvanera, P. et al. (2006) Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecol. Lett.* 9, 1146–1156
- Cardinale, B.J. et al. (2006) Effects of biodiversity on the functioning of trophic groups and ecosystems. *Nature* 443, 989–992
- Aerts, R. and Honnay, O. (2011) Forest restoration, biodiversity and ecosystem functioning. *BMC Ecol.* 11, 29
- Hector, A. et al. (2001) Conservation implications of the link between biodiversity and ecosystem functioning. *Oecologia* 129, 624–628
- Srivastava, D.S. and Vellend, M. (2005) Biodiversity-ecosystem function research: is it relevant to conservation? *Annu. Rev. Ecol. Syst.* 36, 267–294
- Millennium Ecosystem Assessment (2005) *Millennium Ecosystem Assessment: Ecosystems and Human Well-being: Biodiversity Synthesis*, World Resources Institute
- Daily, G.C. (ed.) (1997) *Nature's Services: Societal Dependence on Natural Ecosystems*, Island Press
- Perrings, C. et al. (2010) Ecosystem services for 2020. *Science* 330, 323–324
- Perrings, C. et al. (2011) Ecosystem services, targets, and indicators for the conservation and sustainable use of biodiversity. *Front. Ecol. Environ.* 9, 512–520
- European Parliament (2012) *European Parliament Resolution – On Our Life Insurance, Our Natural Capital: an EU Biodiversity Strategy to 2020* (2011/2307(INI), European Parliament)
- Daily, G.C. et al. (2009) Ecosystem services in decision making: time to deliver. *Front. Ecol. Environ.* 7, 21–28
- Kareiva, P. et al. (2011) *Natural Capital – Theory and Practice of Mapping Ecosystem Services*, Oxford University Press
- Haines-Young, R. et al. (2012) Indicators of ecosystem service potential at European scales: mapping marginal changes and trade-offs. *Ecol. Ind.* 21, 39–53
- Koschke, L. et al. (2012) A multi-criteria approach for an integrated land-cover-based assessment of ecosystem services provision to support landscape planning. *Ecol. Ind.* 21, 54–66
- Sala, O.E. et al., eds (2000) *Methods in Ecosystem Science*, Springer
- Tongway, D. and Hindley, N. (2004) Landscape function analysis: a system for monitoring rangeland function. *Afr. J. Range Forage Sci.* 21, 109–113
- Worthington, E.B. (1975) *Evolution of IBP*, Cambridge University Press
- Scurlock, J.M.O. et al. (2002) Estimating net primary productivity from grassland biomass dynamics measurements. *Global Change Biol.* 8, 736–753
- Woodwell, G.M. and Bourdeau, P.F. (1965) Measurement of dry matter production of the plant cover. In *Methodology of Plant Eco-Physiology - Proceedings of the Montpellier Symposium* (Eckardt, F.E., ed.), pp. 519–527, UNESCO
- Ni, J. (2004) Estimating net primary productivity of grasslands from field biomass measurements in temperate northern China. *Plant Ecol.* 174, 217–234
- Singh, J.S. et al. (1975) Review and assessment of various techniques for estimating net aerial primary production in grasslands from harvest data. *Bot. Rev.* 41, 181–232
- Whittaker, R.H. (1961) Estimation of net primary production of forest and shrub communities. *Ecology* 42, 177–180
- Ovington, J.D. (1957) Dry-matter production by *Pinus sylvestris* L. *Ann. Bot. Lond.* 21, 287–314
- Ravenek, J.M. et al. (2014) Long-term study of root biomass in a biodiversity experiment reveals shifts in diversity effects over time. *Oikos* 123, 1528–1536
- Böhm, W. (1979) *Methods of Studying Root Systems*, Springer-Verlag
- Gill, R.A. et al. (2002) Using simple environmental variables to estimate below-ground productivity in grasslands. *Global Ecol. Biogeogr.* 11, 79–86
- Soil and Plant Analysis Council (1999) *Soil Analysis Handbook of Reference Methods*, CRC Press
- IUSS Working Group WRB (2014) *World Reference Base for Soil Resources 2014 – International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, FAO
- Malo, D.D. and Gelderman, R.H. (1984) Portable soil test laboratory results compared to standard soil test values. *Commun. Soil Sci. Plant Analysis* 15, 909–927
- Smith, J.L. and Doran, J.W. (1996) Measurement and use of pH and electrical conductivity for soil quality analysis. In *Methods for Assessing Soil Quality* (Doran, J.W. and Jones, A.J., eds), pp. 169–185, Soil Science Society of America
- Zacharias, S. and Wessolek, G. (2007) Excluding organic matter content from pedotransfer predictors of soil water retention. *Soil Sci. Soc. Am. J.* 71, 43–50
- Whiting, D. et al. (2014) Estimating soil texture: sand, silt or clayey? *CMG GardenNotes* 214
- Harrison, A.F. et al. (1988) *Cotton Strip Assay: An Index of Decomposition in Soils*, Institute of Terrestrial Ecology
- Reed, H.E. et al. (2005) Ecological consequences of C-4 grass invasion of a C-4 grassland: a dilemma for management. *Ecol. Appl.* 15, 1560–1569
- Vogel, A. et al. (2013) Plant diversity does not buffer drought effects on early-stage litter mass loss rates and microbial properties. *Global Change Biol.* 19, 2795–2803
- Southwood, T.R.E. and Henderson, P.A. (2009) *Ecological Methods*, John Wiley & Sons
- Edwards, C.A. (1991) The assessment of populations of soil-inhabiting invertebrates. *Agric. Ecosyst. Environ.* 34, 145–176
- Golley, F.B. and Buechner, H.K. (1968) *A Practical Guide to the Study of the Productivity of Large Herbivores*, Blackwell Science
- Brook, A.J. et al. (2008) Experimental verification of suction sampler capture efficiency in grasslands of differing vegetation height and structure. *J. Appl. Ecol.* 45, 1357–1363
- Weisser, W.W. and Siemann, E. et al. (2004) *Insects and Ecosystem Function*, Springer
- Hulme, P.E. (1996) Herbivory, plant regeneration, and species coexistence. *J. Ecol.* 84, 609–615
- Mcnaughton, S.J. et al. (1996) How can net primary productivity be measured in grazing ecosystems? *Ecology* 77, 974–977
- Borer, E.T. et al. (2014) Herbivores and nutrients control grassland plant diversity via light limitation. *Nature* 508, 517–520
- Souza, D.G. et al. (2013) Community-level patterns of insect herbivory in a fragmented Atlantic forest landscape. *Environ. Entomol.* 42, 430–437
- Loranger, H. et al. (2014) Invertebrate herbivory increases along an experimental gradient in grassland plant diversity. *Oecologia* 174, 183–193
- Dinoor, A. and Eshed, N. (1984) The role and importance of pathogens in natural plant communities. *Annu. Rev. Phytopathol.* 22, 443–466
- García-Guzmán, G. and Dirzo, R. (2001) Patterns of leaf-pathogen infection in the understory of a Mexican rain forest: incidence, spatiotemporal variation, and mechanisms of infection. *Am. J. Bot.* 88, 634–645
- Terborgh, J. et al. (2001) Ecological meltdown in predator-free forest fragments. *Science* 294, 1923–1926

- 54 Geiger, F. *et al.* (2010) Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. *Basic Appl. Ecol.* 11, 97–105
- 55 Loiselle, B.A. and Farji-Brener, A.G. (2002) What's up? An experimental comparison of predation levels between canopy and understory in a tropical wet forest. *Biotropica* 34, 327–330
- 56 Koh, L.P. and Menge, D.N.L. (2006) Rapid assessment of Lepidoptera predation rates in neotropical forest fragments. *Biotropica* 38, 132–134
- 57 Ruiz-Guerra, B. *et al.* (2012) Consequences of fragmentation of tropical moist forest for birds and their role in predation of herbivorous insects. *Biotropica* 44, 228–236
- 58 Howe, A. *et al.* (2009) Dummy caterpillars as a simple method to assess predation rates on invertebrates in a tropical agroecosystem. *Entomol. Exp. Appl.* 131, 325–329
- 59 Low, P.A. *et al.* (2014) Determining predator identity from attack marks left in model caterpillars: guidelines for best practice. *Entomol. Exp. Appl.* 152, 120–126
- 60 Bond, W.J. (1994) Do mutualisms matter? Assessing the impact of pollinator and disperser disruption on plant extinction. *Philos. Trans. R. Soc. Lond. B: Biol. Sci.* 344, 83–90
- 61 Westphal, C. *et al.* (2008) Measuring bee diversity in different European habitats and biogeographical regions. *Ecol. Monogr.* 78, 653–671
- 62 Nielsen, A. *et al.* (2011) Assessing bee species richness in two Mediterranean communities: importance of habitat type and sampling techniques. *Ecol. Res.* 26, 969–983
- 63 Campbell, J.W. and Hanula, J.L. (2007) Efficiency of Malaise traps and colored pan traps for collecting flower visiting insects from three forested ecosystems. *J. Insect Conserv.* 11, 399–408
- 64 Carre, G. *et al.* (2009) Landscape context and habitat type as drivers of bee diversity in European annual crops. *Agric. Ecosyst. Environ.* 133, 40–47
- 65 Morandin, L.A. *et al.* (2007) Can pastureland increase wild bee abundance in agriculturally intense areas? *Basic Appl. Ecol.* 8, 117–124
- 66 Krewenka, K.M. *et al.* (2011) Landscape elements as potential barriers and corridors for bees, wasps and parasitoids. *Biol. Conserv.* 144, 1816–1825
- 67 Kovacs-Hostyanszki, A. *et al.* (2011) Set-aside promotes insect and plant diversity in a Central European country. *Agric. Ecosyst. Environ.* 141, 296–301
- 68 Romey, W.L. *et al.* (2007) Impacts of logging on midsummer diversity of native bees (Apoidea) in a northern hardwood forest. *J. Kansas Entomol. Soc.* 80, 327–338
- 69 Leong, J.M. and Thorp, R.W. (1999) Colour-coded sampling: the pan trap colour preferences of oligolectic and nonoligolectic bees associated with a vernal pool plant. *Ecol. Entomol.* 24, 329–335
- 70 Wilson, J.S. *et al.* (2008) Sampling bee communities (Hymenoptera: Apiformes) in a desert landscape: are pan traps sufficient? *J. Kansas Entomol. Soc.* 81, 288–300
- 71 Nuttman, C.V. *et al.* (2011) The utility of aerial pan-trapping for assessing insect pollinators across vertical strata. *J. Kansas Entomol. Soc.* 84, 260–270
- 72 Tuell, J.K. *et al.* (2009) Elevated pan traps for monitoring bees in crop canopies. *Entomol. Exp. Appl.* 131, 93–98
- 73 Droege, S. *et al.* (2010) Spatial patterns of bee captures in North American bowl trapping surveys. *Insect Conserv. Divers.* 3, 15–23
- 74 Harms, K.E. *et al.* (2000) Pervasive density-dependent recruitment enhances seedling diversity in a tropical forest. *Nature* 404, 493–495
- 75 Forget, P.M. and Wenny, D. (2004) How to elucidate seed fate? A review of methods used to study seed removal and secondary seed dispersal. In *Seed Fate: Predation, Dispersal and Seedling Establishment* (Forget, P.M. *et al.*, eds), pp. 379–394, CABI
- 76 Van der Wall, S.B. *et al.* (2005) Seed removal, seed predation, and secondary dispersal. *Ecology* 86, 801–806
- 77 Ustin, S.L. *et al.* (2004) Using imaging spectroscopy to study ecosystem processes and properties. *Bioscience* 54, 523–534
- 78 Duelli, P. and Obrist, M.K. (1998) In search of the best correlates for local organismal biodiversity in cultivated areas. *Biodivers. Conserv.* 7, 297–309
- 79 Coddington, J.A. *et al.* (1991) Designing and testing sampling protocols to estimate biodiversity in tropical ecosystems. In *The Unity of Evolutionary Biology: Proceedings of the Fourth International Congress of Systematic and Evolutionary Biology* (Dudley, E.C., ed.), pp. 44–60, Dioscorides Press
- 80 Obrist, M.K. and Duelli, P. (2010) Rapid biodiversity assessment of arthropods for monitoring average local species richness and related ecosystem services. *Biodivers. Conserv.* 19, 2201–2220
- 81 Oliver, I. and Beattie, A.J. (1996) Designing a cost-effective invertebrate survey: a test of methods for rapid assessment of biodiversity. *Ecol. Appl.* 6, 594–607
- 82 Oliver, I. and Beattie, A.J. (1993) A possible method for the rapid assessment of biodiversity. *Conserv. Biol.* 7, 562–568
- 83 Biaggini, M. *et al.* (2007) The taxonomic level order as a possible tool for rapid assessment of Arthropod diversity in agricultural landscapes. *Agric. Ecosyst. Environ.* 122, 183–191
- 84 Smith, M.A. and Fisher, B.L. (2009) Invasions, DNA barcodes, and rapid biodiversity assessment using ants of Mauritius. *Front. Zool.* 6, 31
- 85 Nadrowski, K. *et al.* (2013) Harmonizing, annotating and sharing data in biodiversity–ecosystem functioning research. *Methods Ecol. Evol.* 4, g201–g205
- 86 Jax, K. (2005) Function and ‘functioning’ in ecology: what does it mean? *Oikos* 111, 641–648
- 87 Ellenberg, H. *et al.*, eds (1986) *Ökosystemforschung - Ergebnisse des Sollingprojekts: 1966–1986*, Ulmer
- 88 Woodward, F.I. (1994) How many species are required for a functional ecosystem? In *Biodiversity and Ecosystem Function* (Schulze, E.D. and Mooney, H.A., eds), pp. 271–291, Springer-Verlag
- 89 Gamfeldt, L. *et al.* (2008) Multiple functions increase the importance of biodiversity for overall ecosystem functioning. *Ecology* 89, 1223–1231
- 90 Leps, J. (2004) What do the biodiversity experiments tell us about consequences of plant species loss in the real world? *Basic Appl. Ecol.* 5, 529–534
- 91 Duffy, J.E. (2008) Why biodiversity is important to the functioning of real-world ecosystems. *Front. Ecol. Environ.* 7, 437–444
- 92 Hillebrand, H. and Matthiessen, B. (2009) Biodiversity in a complex world: consolidation and progress in functional biodiversity research. *Ecol. Lett.* 12, 1405–1419
- 93 Roscher, C. *et al.* (2004) The role of biodiversity for element cycling and trophic interactions: an experimental approach in a grassland community. *Basic Appl. Ecol.* 5, 107–121
- 94 Tilman, D. *et al.* (2001) Diversity and productivity in a long-term grassland experiment. *Science* 294, 843–845
- 95 Maes, J. *et al.* (2011) *A European Assessment of the Provision of Ecosystem Services*, Institute for Environment and Sustainability, Joint Research Centre, European Commission
- 96 Naidoo, R. *et al.* (2008) Global mapping of ecosystem services and conservation priorities. *Proc. Natl. Acad. Sci. U.S.A.* 105, 9495–9500
- 97 Nelson, E. *et al.* (2009) Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Front. Ecol. Environ.* 7, 4–11
- 98 Kareiva, P. *et al.* (2007) Domesticated nature: shaping landscapes and ecosystems for human welfare. *Science* 316, 1866–1869
- 99 Östman, Ö. (2004) The relative effects of natural enemy abundance and alternative prey abundance on aphid predation rates. *Biol. Control* 30, 281–287
- 100 Aizen, M.A. and Feinsinger, P. (1994) Forest fragmentation, pollination, and plant reproduction in a Chaco dry forest, Argentina. *Ecology* 75, 330–351