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A closer look at the functions behind ecosystem multifunctionality: A review.

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Abstract

In recent years there has been an upsurge of studies on ecosystem multifunctionality (EMF), or the ability of ecosystems to simultaneously provide multiple functions and/or services. The concept of EMF itself, the analytical approaches used to calculate it, and its implications depending on the spatial scale and field of study have been discussed in detail. However, to date, there has been little dialogue concerning the basis of EMF studies- the functions themselves- nor what appropriate measures for ecosystem functions are. To begin this discussion, we performed an in-depth review of EMF studies across four major terrestrial ecosystems (agroecosystems, drylands, forests, and grasslands) by analysing 82 studies, which together have assessed 775 ecosystem functions from a variety of field and greenhouse experiments across the globe. The number of ecosystem functions analysed varied from two to 82 per study and we found large differences in the distribution of functions across ecosystem types. Furthermore, there was little explanation of why certain variables were included in the EMF calculation or how they relate to ecosystem functioning. Based on the literature analysis, we propose a general guideline for determining and measuring appropriate functions.

Introduction

The multiple threats posed by climate and land-use change, such as more frequent droughts, mega-fires, and loss of biodiversity (Costello *et al*. 2009; Bellard *et al*. 2012), have put a clear priority on the importance of maintaining our environment, while at the same time providing enough food, fuel and fibre to support the burgeoning population (United Nations 2015). Yet measuring and weighing trade-offs between different aspects of ecosystem services and functions is a complex and challenging task. Researchers and policy makers have attempted to accomplish this task using the well-known concept of ecosystem services, or the benefits provided to humans from ecosystem functions (Costanza *et al*. 1997; Fig. 1). This effort has led to influential reports and frameworks that have shaped environmental policy for decades (MEA 2005; Gómez-Baggethun *et al*. 2010; United Nations 2015). Although several different frameworks for conceptualizing and categorizing these functions and services exist (MEA 2005; Díaz et al., 2015; Díaz et al., 2018; TEEB, 2018), the majority are generally discussed in the framework of cultural, provisioning, regulating, and supporting ecosystem service categories (Fig. 1).

One of the key approaches to measure and appropriately manage ecosystems is to gain an understanding of how these functions and services are measured. In recent years, a relatively new practice to fulfil this goal has emerged in which researchers have begun to calculate a single measure to characterize the "overall functioning of an ecosystem" (Hector & Bagchi 2007; Gamfeldt et al., 2008) or the "ability of ecosystems to simultaneously provide multiple functions and services" (Manning *et al*. 2018) in a term commonly referred to as ecosystem multifunctionality (EMF). Here we define ecosystem functions as the biotic and abiotic processes that occur within an ecosystem and may contribute to ecosystem services either directly or indirectly (Fig. 1). While previous studies on key drivers of ecosystem functioning tended to assess single functions, more recent studies have focused on understanding the drivers of multiple ecosystem functions simultaneously (Maestre *et al*. 2012; Wagg *et al*. 2014; Lefcheck *et al*. 2015). This was an important progression for ecological research, since measuring only one ecosystem function does not consider the trade-offs between ecosystem functions, nor how changes in factors such as biodiversity and land management practices would affect these multiple functions overall (Allen et al., 2015).

The focus on EMF has brought new perspectives on the importance of biodiversity for ecosystem functioning (Meyer *et al*. 2018; Schuldt *et al.* 2018) and the impacts of global change drivers such as increases in temperature or the impact of wetting-drying cycles (Delgado-Baquerizo *et al*. 2017), to name a few. However, it has been much more challenging to transform the idea of EMF into a useful assessment tool for scientists and policy makers (Manning *et al*. 2018). In fact, the validity of the multifunctionality concept has been thoroughly debated in recent years (Bradford *et al*. 2014a,b; Manning *et al*. 2018; Table 1). Yet the main focus on EMF so far has been centered around the methodology and number of individual functions used to calculate it (Byrnes *et al*. 2014; Lefcheck *et al*. 2015; Gamfeldt & Rogers 2017; Meyer *et al*. 2018; Jing et al., 2020). In contrast, there is very little consideration of how the reported functions contribute to the overall ecosystem functioning or the provisioning of ecosystem services, and how the inclusion or exclusion of particular functions, in contrast to the number of functions (Allan *et al*. 2015; Gamfeldt & Rogers 2017; Meyer *et al*. 2018), affects the overall assessment of EMF. Moreover, in the EMF literature it is common to see ecosystem properties (i.e. soil pH, soil depth, water content, etc.), reported as functions, instead of drivers or regulators of such functions (Table S1). It is likely that these parameters are included in EMF calculations due to confusion amongst researchers regarding what an ecosystem function is and what an appropriate indicator of such functioning can be. Here we define indicator as a component or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions, as proposed by Heink and Kowarik (2010) (Fig. 1). For example, in a review linking soil functioning with ecosystem service provision, Bünemann *et al.* (2018) found that the word 'function' was used interchangeably as a process, function*ing*, role, and service. As a result, it is difficult to instinctively understand what is included in such an assessment, and how the term EMF actually relates to the overall functioning of an ecosystem.

Recent work has deepened our insights into the definition and development of EMF (Manning et al. 2018), its application to global change research (Gilling *et al*. 2018), and its differences in conceptualization across research fields (i.e. ecosystem multifunctionality compared to landscape multifunctionality) (Hölting *et al*., 2019). However, while Hölting et al. (2019) analysed 101 studies on the functions used across both ecosystem multifunctionality and landscape multifunctionality studies together, whether or not the specific functions or indicators were appropriate for such an assessment was not discussed. We propose that such an assessment is not only lacking, but also particularly necessary for several reasons. First, the value, robustness and strength of EMF assessments depends primarily on the functions used to calculate it. Second, a review of functions in the EMF literature can show us what types of functions have received the most attention in recent and past studies, how these differ between ecosystem types under study, and thus where research gaps remain. Lastly, it is important to reflect on whether or not the variables reported as functions in EMF assessments are indicative of actual functions. To address these aforementioned issues, we performed a literature review of EMF studies to analyse which functions are used to calculate EMF across four major ecosystem types (agroecosystems, drylands, forests, and grasslands). We then use these results to discuss how well the reported functions or indicators are linked to ecosystem functioning and service provision, as well as give recommendations for how to choose appropriate functions in order reduce ambiguity in the term EMF.

Literature review

We conducted a literature search on 1 July 2018 which included all peer-reviewed publications in the Web of Science database published before this date. We conducted this review by first searching for 'multifunctionality' in the Web of Science database and refined by the research areas: ecology, environmental sciences, microbiology, environmental studies, biology, geography, agriculture multidisciplinary, soil science, multidisciplinary sciences, agronomy, plant sciences, agricultural economics policy, forestry, biodiversity conservation, and agricultural engineering. We then removed all publications that were listed twice, which resulted in a total of 1,029 references. Many of them were related to landscape management or multifunctional agriculture, which did not calculate a multifunctionality index using measured ecosystem functions, but instead discussed the impact of different landscapes or cropping systems on a variety of socio-economic and political issues, and therefore were beyond the scope of our study (e.g. see Hölting *et al*. (2019) where landscape multifunctionality is discussed). We then narrowed the search terms to 'multifunctionality and ecosystem' of terrestrial ecosystems, refined the search by the same research areas as stated above, and removed all duplicate publications, which resulted in a final list of 268 papers (Fig. S1).

We divided these 268 papers into those that: a) calculate EMF, b) measure a number of individual functions and discuss the overall results in terms of EMF, but do not calculate a final EMF value (i.e. mapping regions with more or less of a given number of functions), c) discuss EMF but do not measure it directly (i.e. reviews and discussion papers), and d) do not measure multiple functions, calculate an ecosystem EMF value, nor discuss it in detail. From this final list, 32%, or 86 papers, were redistributed to different individuals within the group of authors, who then applied the same search criteria and grouping categorizations. This was done as a quality assurance measure to make sure that all papers were being categorized similarly even when screened by different people, according to the protocol of Meissle *et al*. (2014). All papers were grouped into the same categories during this cross-check phase, thus supporting our categorization criteria.

Following the cross-check, we then chose all papers from categories a) and b) for further analyses since these measured multiple ecosystem functions and discussed them within the framework of EMF. Papers categorized into the final two categories (i.e. c and d, totalling 186 papers) were removed from our list. Using the data from categories a) and b), we compiled a table including information on the ecosystem type, number and type functions measured, and the methodology used to calculate EMF. The final list had a total of 82 papers, over half of which have been published since 2016, thus highlighting the steep increase in EMF studies in recent years (Fig. 2). From this final list of paper, we then compiled a table including information on the ecosystem type, number and type functions measured, and the methodology used to calculate EMF (see complete list in Table S1).

Are ecosystem functions necessarily linked with ecosystem service provision?

To effectively guide the advancement of research in the field of EMF, it is essential to understand a) if the various functions measured in EMF literature are currently being linked to ecosystem services, either directly or indirectly, and b) if so, how this is done. Although it is well-accepted that most biodiversity-ecosystem-functioning studies are assessed mainly from an ecological perspective (i.e. without human valuation) (i.e. Fig. 1b), we found still that many studies in our review discussed how certain measured functions contribute to ecosystem service provision (Fig. 1a). Therefore, we began by compiling a list of how each paper classified the measured functions according to the service it contributes to (Table 2). For those papers that specified why they chose to measure certain functions (i.e. see Maestre *et al*. 2012; Fanin *et al*. 2018), we found that some chose to assess functions across a wide range of ecosystem service categories (Schipanski *et al*. 2014; Allan *et al*. 2015), while others chose to look not at overall ecosystem functioning, but instead at specific aspects of functioning such as the role of different parameters on C, N and P cycling and/or storage (Lohbeck *et al*. 2016; Eldridge *et al*. 2016; Luo *et al*. 2017), or wild food production (Granath *et al*. 2018). Still others never explicitly state which functions were actually measured, but only discuss the final value of EMF without discussing the functions they considered (Lefcheck *et al*. 2015, Meyer *et al*. 2018). Given the large range of potential functions included in such studies, we feel that it is imperative that future studies make it clear which functions were included in their analysis and why, so that readers can appropriately interpret the overall EMF index within the context of each specific study.

Since direct information linking the measured functions with service provision was not available for all reviewed studies, we classified each of the measured functions into one of 24 functional categories dispersed among the four major ecosystem service categories identified by the Millennium Ecosystem Assessment (MEA 2005) (cultural, provisioning, regulating and supporting, Table 2). This was done not only to condense an otherwise unmanageably long list of individual functions (775 in total), but also to gain insight into how evenly the major ecosystem service categories are being represented in EMF literature. We believe that this classification scheme was an appropriate fit for the published functions, meaning that each ecosystem service was represented within the literature, and each published function could easily fit within one of these services. The decision of which ecosystem service category to place the functions was agreed upon by all co-authors during lengthy discussions in which the primary role of each individual function was discussed within the context of our definition of ecosystem function (i.e. as suggested by Jax, 2005). However, while we were able to place each published function in a single category, it is clear that in many cases a given function could potentially contribute to multiple functions or ecosystem services, which has been discussed previously (Constanza *et al*. 1997; Giling *et al*. 2018; Nilsson et al. 2017).

Distribution of functions across ecosystem types

In our assessment, we found that 30% of the papers were from grasslands, 23% from forests, 16% were from drylands, and 27% from agricultural systems (Table 3). These four main ecosystem types were not subdivided further (i.e. natural versus managed grasslands or primary versus secondary forests) because this type of ancillary information was not available for most studies. However, these broad categories are still useful for analysing differences in EMF assessment between major ecosystem types. For example, using these categories we were able to compare our results with the distribution of global land use types to get an idea of how well our focus on EMF aligns with global averages (Fig. 3). Overall, grassland and forest ecosystems were relatively evenly represented in relation to their global distribution (30% and 23% in EMF studies compared to 23% and 26% in global distribution, respectively). However, agricultural systems and drylands were over-represented, while the barren land and glaciers were under-represented compared to their global distribution.

In addition, there was also discontinuity between ecosystem categorizations. For example most studies were grouped by land-use type (i.e. grassland, forests, etc.) while others were grouped by environmental zones such as "drylands" (Maestre *et al*. 2012; Delgado-Baquerizo *et al*. 2016) or "peatlands" (Robroek *et al*. 2017). Most studies were conducted in a field setting, others were assessed using a greenhouse or soil incubation approach, and a minority did a meta-analysis of EMF studies investigating the role of a variety of modifying factors of EMF, such as differences in trophic levels (Lefcheck *et al*. 2015). Additionally, most of these studies assessed EMF at only one time point, while only one experimental study assessed how plant species diversity impacts EMF over several years (Meyer *et al*. 2018) (Table S1). The average number of functions per study in the different ecosystem types ranged from 5.6 to 10.6, showing great similarity to the median values (between 5 and 9) (Table 3). However, across all ecosystem types, the number of functions assessed per study ranged between 2 and 82, thus highlighting the wide variety between studies (Table 3). Our study complements the findings of Hölting et al. (2019) who found an average of 8 functions and services per study, although only 47% of the studies reviewed here overlapped with this study (Table S1).

We found that there was a difference in the distribution of functions between ecosystem types (Table S2; Fig. 4). For example, studies conducted in drylands measured functions falling exclusively in the 'supporting' and 'regulating' ecosystem service categories, with 86% of measured functions falling within the 'supporting' category. In contrast, functions measured within the agricultural and forest ecosystems were much more evenly distributed across the four ecosystem service categories. Yet despite these general differences across ecosystem types, we found that the range of functions often differed greatly between studies of the same ecosystem type as well. For example, even within a forest ecosystem, some studies measured only 'supporting' functions (Bastida *et al*. 2016; Eldridge *et al*. 2016), others measured only 'provisioning' functions (Granath *et al*. 2018), and still others measured a relatively even distribution of all ecosystem service categories (van der Plas *et al*. 2016a,b). While some of these differences may be due to the success of certain research groups in publishing studies in a specific ecosystem type (i.e. drylands in the Maestre group), it is clear that the concept of EMF is in practice very ambiguous if different studies include such a range of functions. This requires the reader to carefully consider the particular functions included in the analysis to understand 1) the extent of multifunctionality that was in fact explored and 2) the constraints imposed to generalizations on EMF from each study design.

Measuring ecosystem functions

In addition to discussing which functions are being measured and whether or not they are linked with ecosystem services, one issue which must be addressed is the variability in how functions are being assessed (i.e. either by direct measurement or by the measurement of indicators) (Fig. 1). In contrast to reported ecosystem services, which were more straightforward to measure and require human valuation (i.e. via surveys or direct inventories), our review found that it was often unclear how a reported indicator was actually related to an ecosystem function. For example, we found that in addition to well-accepted ecosystem functions (i.e. rates of N_2O production, biomass production, etc.), in many cases several variables that do not reflect functions, including soil pH, soil water content, soil depth, soil slope, and cation exchange capacity were included in the EMF calculation as well (Table S1). From our perspective, these latter variables are neither ecosystem functions nor appropriate indicators of functions, but are instead a collection of inherent soil physicochemical properties that are driven primarily by long-term abiotic and biotic processes and should be considered drivers of ecosystem functioning, rather than direct measures of functions (Fig. 5).

We propose that much of this discrepancy is due to ambiguity in the definition of an ecosystem function. Although this topic has been discussed in detail (Jax, 2005; Farnsworth et al., 2017) it is clear that uncertainty remains. Much of this debate centers around whether or not ecosystem functions should include only process rates (i.e. enzyme activities, soil respiration rates, etc.), or if additional variables such as nutrient pools (i.e. soil C content, microbial biomass, etc.) or ecosystem properties (i.e. soil texture) (see Fig. 5 for definitions) can also be considered indicators of these functions. We agree with Jax (2005) and Manning *et al*. (2018) that a clear distinction must be made regarding what an appropriate indicator may be to overcome some of the confusion regarding ecosystem functioning. Recently, Manning *et al*. (2018) propose that process rates should be favoured over stocks of energy or matter when measuring ecosystem functions and EMF. However, they also admit that in certain cases, nutrient pools such as soil C stocks or biomass could be considered indicators of longer-term net process rates. Yet in our review we found that only three out of the 82 EMF papers reviewed consisted of functions based solely on process rates (Bradford *et al*. 2014; Eldridge *et al*. 2016; Luo *et al*. 2017). Most papers, instead, included a variety of properties, nutrient pools, and processes (Fig. 5; Table S1).

Similar to the conclusion of Farnsworth et al. (2017), we propose that ecosystem functions are comprised solely on processes, yet these can range from fast processes happening on an hourly or daily timescale (i.e. basal respiration, N_2O production, enzymatic activities, etc.) to slow processes taking months or even decades to assess (i.e. biomass production, changes in soil C accumulation, or habitat provision). Moreover, we propose that ecosystem functions should be assessed by measuring process rates directly, or if the process rates of interest are too slow to measure directly, then the measurement of certain nutrient pools can act as surrogates of these slower processes (Fig. 5). While there is no ideal definition, we feel that this viewpoint is inclusive enough to capture all possible measures of functionality, while also spanning multiple timescales and research foci.

Guidelines for choosing appropriate indicators of ecosystem functions

The selection of appropriate indicators for ecosystem functions is described conceptually in Figure 5. For the processes that can be measured directly (i.e. rates of decomposition, mineralization, enzyme activities, biomass production, etc.), these can be incorporated into EMF metrics, either linked to ecosystem services or not, without any issue (see additional examples given in green in Fig. 5). However, since in most cases it is not realistic to measure processes that require years or decades to assess, such as the build-up of soil fertility over time, it is logical to use specific nutrient pools as indicators to estimate such processes. For example, soil organic carbon and microbial biomass are often used as indicators of soil carbon sequestration and microbial activity, respectively (Table 2). Furthermore, in environments such as drylands, dynamic processes such as soil N transformation rates are strongly related to soil total N (Delgado-Baquerizo *et al*. 2013). As such, one commonly measured indicator for EMF studies is soil mineral N, which is an indicator of the bio-availability of nitrogen in a given system. However, soil mineral N is a) not a process rate, and b) is a very dynamic measure, and thus care must be taken when comparing its value across different times of year or even regions. Thus, while we agree with this approach and find that many nutrient pools are appropriate indicators of a variety of ecosystem functions, we also urge the inclusion of multiple measures over time whenever possible to get better grasp of how temporal changes affect EMF (Bradford *et al*. 2014). These changes could then be described as process rates directly, assuming an appropriate sampling scheme was utilized, and would in our opinion better fit the definition of an ecosystem function. Alternatively, after measuring multiple measures over time, an EMF index could be constructed for individual time points and compared to assess temporal changes. Furthermore, in managed ecosystems such as agricultural fields, where N fertilizers are applied annually, such measures cannot be used as indicators of functions related to N cycling. Instead, this variable should be interpreted as another driver of these functions, since the actual value depends on both the timing and quantity of fertilization application.

In contrast to the above examples using processes and nutrient pools as indicators of ecosystem functions, we discourage the use of purely physicochemical properties as indicators of functions (see examples in red in Fig. 5). For example, we found several papers that included soil pH as an indicator for ecosystem functioning (Table S1). From our point of view, however, soil pH is not representative of a 'process that occurs within an ecosystem and may contribute to ecosystem services', but instead is a measure of a general chemical characteristic resulting from weathering of parent materials over long time periods. So, although pH at small scales (i.e. µm up to mm scales such as in the rhizosphere) can be influenced by root exudates and enzymes from plant and soil microbial communities (Hinsinger *et al*. 2003), at the plot- or ecosystem-scale on which most EMF studies focus, we consider soil pH not appropriate to include in an EMF calculation. We acknowledge that this variable is an important driver of soil microbial communities across a wide variety of terrestrial ecosystems (Fierer & Jackson 2006; Maestre *et al*. 2015; Delgado-Baquerizo *et al*. 2018), which in turn affects multiple functions related to nutrient cycling and plant productivity (e.g. Delgado-Baquerizo *et al*. 2016, Trivedi *et al*. 2016; Maron *et al*. 2018), but it cannot be considered as a function itself.

Similarly, other ecosystem properties that are less affected by biological processes and more inherent to a site (i.e. soil texture, slope) or a snapshot of a dynamic process (i.e. soil moisture) should not be included in an EMF index aiming to assess biological drivers on ecosystem functioning. In the case of soil moisture, we recommend instead measuring soil water holding capacity, as this is more indicative of the functional capacity of a soil to hold water, whereas soil moisture content largely depends on recent precipitation events and the time of the year the measurement is taken.

Finally, and regardless of which indicators are measured, we emphasize that it is important for researchers to explain why a particular indicator was used to assess a function, as well as what the impact of that measure is on ecosystem functioning overall. For example, we found that many EMF studies included at least one measure of soil N to represent N cycling, which we agree is very important to ecosystem functioning across all ecosystem types. However, since N cycling is such a broad term, there are many different indicators that fit this general description yet have very different impacts on overall ecosystem functioning (i.e. mineralization, denitrification, total soil N, nitrate, etc.). Without the specific rationale for why a certain measure was made is explicitly stated, the overall meaning and thus the interpretation of the resultant EMF index will be limited. Similarly, although it is clearly important to study and compare the overall values of EMF, we also recommend that researchers present the impact of these different factors on certain key functions individually as well (i.e. crop yield, C-sequestration, etc.) (Giling *et al*. 2018). Not only will this help with choosing meaningful indicators, but we think it will also aid in the understanding of how different functions are related to each other in terms of correlations or trade-offs (Meyer *et al*. 2018), and thus what are the main functions driving the overall trends in EMF.

Future Directions

Despite the usefulness of the EMF concept, it is clear that EMF is extremely broad and that authors conceptualize and thus measure EMF in many different ways. This resembles other popular ecological concepts such as 'keystone taxa' (Paine, 1969; Power et al., 1996; Cottee-Jones & Whittaker 2012; Banerjee et al., 2018) and 'sustainability' (Kuhlman & Farrington 2010) that are clear conceptually, but differ in both approach and application from study to study. To advance EMF research in the future, we believe that researchers must pay more attention to how they choose, measure, and interpret ecosystem functions (Table 3; Fig. 5). In contrast to creating a set of strict standardized variables for future EMF studies, as has been suggested previously (Meyer *et al*. 2015; Trogish *et al*. 2017), our recommendation is to create a general framework that includes a clear set of EMF definitions and appropriate indicators for ecosystem functions. However, this is by no means the only requirement to move this important concept forward. For example, while many EMF studies have made the link with ecosystem services based on the Millennium Ecosystem Assessment terminology and concepts (MEA 2005), there are many other ecosystem service assessment platforms that could be considered as well (see Carpenter *et al*. 2009; Maes *et al*. 2018). For example, there has recently been a call to incorporate more emphasis on the social and cultural aspects of ecosystems (Díaz *et al*. 2015, 2018). Based on this new outlook and understanding of the importance of assessing the cultural value of ecosystems, what we are referring to as 'ecosystem services' is now moving toward the terminology 'nature's contributions to people', which emphasizes the importance of a more balanced assessment of ecosystem functions and services by incorporating more measures of cultural services that are important for human societies (Díaz *et al*. 2018). However, even this suggestion has triggered much debate from the scientific community (Peterson *et al*. 2018). Furthermore, as we have shown in our review, the majority of EMF studies measure functions within the 'supporting' ecosystem service category, with 392 of the 775 published functions falling in this category (Table S1), and thus there remains no formal consensus on the appropriate terminology to use.

Similarly, while many researchers examine the influence of biodiversity as a driver of EMF (Hector & Bagchi 2007; Zavaleta *et al*. 2010; Lefcheck *et al*. 2014; Luo *et al*. 2017; Meyer *et al*. 2018), some authors consider high biodiversity as an ecosystem service itself (Smukler 2010; van der Plas *et al*. 2016a,b). This begs the question: can biodiversity be considered an ecosystem function or service, or only as a factor explaining EMF? While there are several different opinions on this topic (Maes *et al*. 2018; FAO 2019), which goes beyond the scope of our current objectives, we recommend further discussion on this point until a general agreement can be reached.

Regarding the distinction between EMF studies assessing ecosystem functions only, without a human valuation perspective, versus those in the framework of ecosystem service provision, a practical approach to resolve this issue was proposed by Manning *et al*. (2018). They suggest redefining multifunctionality overall, making a distinction between ecosystem *function* multifunctionality (EF-multifunctionality) and ecosystem *service* multifunctionality (ES-multifunctionality) (see Fig. 1). In line with this, we suggest that studies which measure a more narrowly focused niche of ecosystem functions (i.e. only soil enzyme activities or soil nutrient content), could reflect this emphasis in the title or terminology used (i.e. by studying the impact of drivers on ‘soil functioning’, ‘soil nutrient cycling’, or ‘soil quality’) (Schulte *et al*. 2015; Bünemann *et al*. 2018; Rabot *et al*. 2018). Such a change in terminology would not only make the research goals more obvious to readers, it would also help to reduce ambiguity with the term EMF. Fortunately, we have found that this change is already starting to occur, with terms such as ‘soil multifunctionality’ (Durán *et al*. 2018; Valencia *et al*. 2018), and is something we encourage others in the EMF to adopt.

Moreover, for studies aiming to assess ecosystem *service* multifunctionality (see Manning et al., 2018) we would like to stress the importance of measuring not only a large quantity of functions (i.e. Meyer *et al*. 2018), but also a broad and diverse set of functions and services that spans across multiple ecosystem service categories in order to give a representative measure of the overall ecosystem functioning. This will also allow a better comprehension of trade-offs between different services in a given system, which can not only help researchers, but land managers and policymakers as well. It is likely that in many cases such a task will require collaboration between researchers in multiple disciplines (i.e. ecologists and sociologists), or at least a transdisciplinary approach (Pohl 2011; Hoffman *et al*. 2017). Yet despite the extra effort that this may require for some researchers, the potential benefits that could be gained by producing a more holistic assessment of EMF would without doubt overcome the efforts involved in producing it.

Concluding remarks

Our goal with this review was to make a critical appraisal of the various functions included in EMF studies, thus shedding light on what is causing ambiguity of this term in order to avoid the degradation of its value and meaning. By summarizing the state of the field, we have shown that the number of ecosystem functions measured is highly variable, ranging from two to 82 per study. Moreover, in most EMF studies there was no clear link between the variables measured and the ecosystem services they contribute to, nor was there any consensus regarding what type of functional indicators are an appropriate measure of a given function. Therefore here we propose: 1) that process rates (ideally, in contrast to nutrient pools and ecosystem properties) should be considered as ecosystems functions; and 2) a set of standardized definitions for ecosystem functions and services, which is supported by examples and explanations for what appropriate indicators may be for such measures. To further improve the utility of EMF studies in the future, we emphasize the need for researchers to explain or justify why certain functions are measured in each study, and how they influence or contribute to ecosystem functioning.

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Tables and Figures

Table 1. Advantages and disadvantages of the use of EMF as a tool to assess and describe the ability of ecosystems to simultaneously provide multiple functions and services. References are given for each example.

	Main Point	References
Advantages	EMF provides a simple metric to assess the overall functioning of ecosystems, or treatments within a single ecosystem, by summarizing multiple variables into one value.	Manning *et al*. 2018
	EMF makes it possible to visualize trade-offs between different ecosystem functions when evaluating overall ecosystem performance.	Allan *et al*. 2015
Disadvantages	The number and type of ecosystem functions used to assess EMF varies greatly among studies, and thus EMF as a metric is not comparable across studies.	This review Hölting *et al*. 2019
	It is difficult to rank and weigh the importance of different ecosystem functions and services when assessing EMF, as this depends on the stakeholders involved (i.e. productivity versus environmental	Allan *et al*. 2015; Manning *et al*. 2015

performance for agro-ecosystems is weighed differently by farmers who wish to produce food compared to environmental biologists who wish to protect biodiversity).	
There are many methods available to calculate EMF (each method has its own strengths and weaknesses), which can significantly change outcome of results. Additionally, differences in calculation method can further limit the ability of researchers to compare EMF values.	Bradford et al. 2014; Byrnes et al. 2014; Lefcheck et al. 2015
In some cases, variables used to calculate EMF do not necessarily reflect ecosystem functions or services, but are instead considered ecosystem properties (e.g. pH, slope of soil).	This review
EMF is often measured at one single time point, and some functions used to calculate EMF are highly dynamic (e.g. soil mineral N, enzyme activities, etc.).	This review

Table 2: Ecosystem service and functional categories used to organize published functions into groups according to ecosystem service provision they can be linked with. Examples of functions and indicators are given for each category.

Ecosystem service category	**Ecosystem services/ Functional category**	**Functions/services**	**Indicators**
	1. Aesthetic values	Cover of flowers	Percentage of flower

			cover at given time
	2. Recreation and ecotourism	Space for recreation	Inventory of area devoted to hunting grounds; hiking
	3. Spiritual and religious values	Compatibility with local sociocultural values	Survey of community members' attitude toward ecosystem's role in spiritual practices
	4. Mental and physical health	Improving human health	Inventory of improved human health in a particular environment
	5. Habitat provision and biodiversity	Protected areas for habitat restoration	Inventory of environmental conservation areas
Nonmaterial benefits obtained from ecosystems		Biodiversity and richness of plant, animal, and microbial species	Species diversity or richness of beetles
Provisioning Products obtained from ecosystems	6. Food production	Food production	Crop yield
			Milk production
		Wild food provision	Wild berry production; wild mushroom production
	7. Raw materials	Timber production	Inventory of tree harvest in given area
		Bioenergy source	Yield of bioenergy substrate production
	8. Quality	Nutrient provision	Grain N concentration
		Palatability	Consumer surveys
		Food safety	Mycotoxin assessment

			rating
	9. Medicinal resources	Provision of medicinal products	Inventory of products used in medical manufacturing
	10. Fresh water	Providing a source of fresh water	Inventory of fresh water sources and quantities in a given area
	11. Employment	Providing a source of employment	Inventory of jobs created over a given time
	12. Income generation	Providing a source of income	Survey of net income
Regulating Benefits obtained from regulation of ecosystem processes	13. Air quality regulation	Reduction of air pollution	Concentration of NO_x, SO_2, and particulate matter
	14. Climate regulation	C sequestration	Change in soil organic C over time
		Shade provision	Percent cover of shade tree/plant species in given area
		Reduction of greenhouse gas emissions	N_2O, CH_4, CO_2 production
	15. Water regulation	Water conservation	Water infiltration rate
			Soil water holding capacity
	16. Erosion regulation	Soil structure	Comparison of soil aggregate stability
		Planting density	Total plant cover

	17. Water purification	Reducing nitrate leaching	Comparison of soil water nitrate concentration
	18. Disease and pest regulation	Reducing plant diseases or pest predation	Number and abundance of pest species
	19. Pollination	Plant pollination	Abundance of pollinator species
	20. Moderation of extreme events	Reduction of flooding events	Survey of flooded areas over given time period
		minimizing fire risk	Survey of area damaged by fire over given time period
Supporting Services necessary for the production of all other ecosystem services	21. Primary production	Biomass of understory vegetation	Aboveground biomass
			Root biomass
	22. Soil properties and fertility	Soil nutrient storage capacity	Soil phosphorus availability
			Change in total soil nitrogen over time
	23. Nutrient Cycling	Microbial activity	Microbial respiration rates
		Nitrogen cycling	Rates of nitrogen mineralization
		Enzyme activities	Rates of phosphatase activity
		Mycorrhizal associations	AMF root colonization
	24. Photosynthesis	Photosynthetic	Leaf area index

		capacity	

Table 3: Distribution of studies and range of ecosystem functions measured across ecosystem types.

	Ecosystem Type					
	Agroecosystems	Drylands	Forest	Grassland	Other	Overall
Total # studies	22	13	19	25	3	82
Total # individual functions	173	138	183	264	17	775
Avg # functions per study	7.8	10.6	9.8	10.5	5.6	8.9
Median	7	9	5	8	8	8
Range	2-21	5-15	2-28	2-82	4-8	2-82

Figure 1: Conceptual diagram showing that ecosystem multifunctionality (EMF) can be comprised of a) ecosystem functions and services or b) solely ecosystem functions, and that these functions can be measured either directly, or with the use of indicators (see Fig. 5 for guidelines on determining appropriate ecosystem functions and indicators).

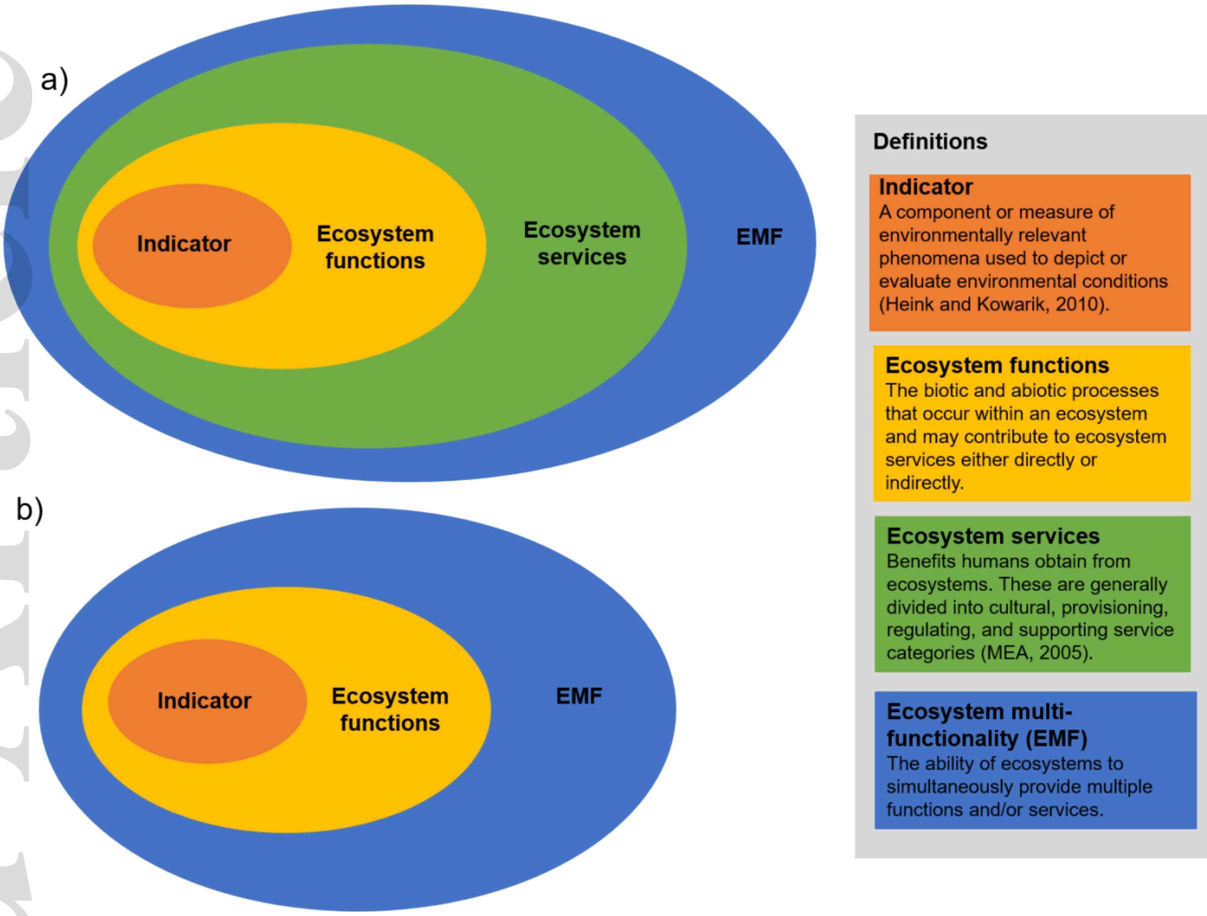

a)
Indicator
Ecosystem functions
Ecosystem services
EMF
b)
Indicator
Ecosystem functions
EMF
Definitions
Indicator
A component or measure of environmentally relevant phenomena used to depict or evaluate environmental conditions (Heink and Kowarik, 2010).
Ecosystem functions
The biotic and abiotic processes that occur within an ecosystem and may contribute to ecosystem services either directly or indirectly.
Ecosystem services
Benefits humans obtain from ecosystems. These are generally divided into cultural, provisioning, regulating, and supporting service categories (MEA, 2005).
Ecosystem multi-functionality (EMF)
The ability of ecosystems to simultaneously provide multiple functions and/or services.

Figure 2: Growth in the number of published EMF studies between 2006 and 2017 as determined by our literature review (details in Table S1).

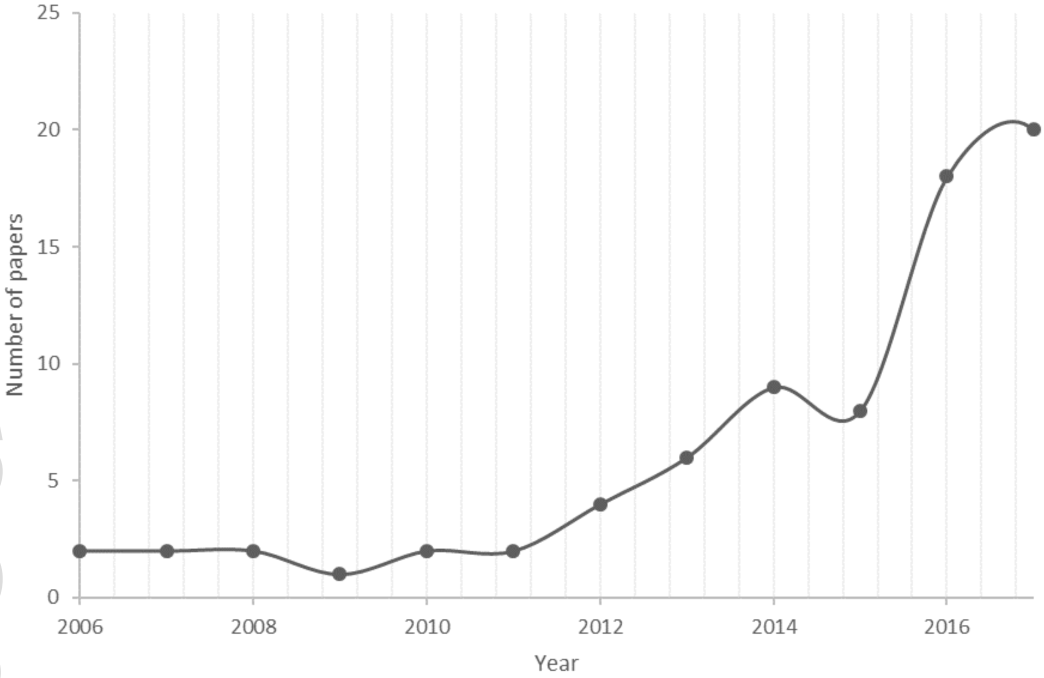


Figure 3: Discrepancy between measurements of EMF in each of the predominant ecosystem types compared to the actual global distribution. The ecosystem types represented in EMF studies are shown in the inner circle (data obtained by our literature review). The global distribution of land-use types is shown in the outer circle (data obtained by the Living Planet Report, WWF 2016). Barren land refers to those ecosystems in which less than one third of the area has vegetation or other cover. In general, barren land has thin soil, sand, or rocks and includes areas such as deserts, dry salt flats, beaches, sand dunes, exposed rock, strip mines, quaries, and gravel pits.

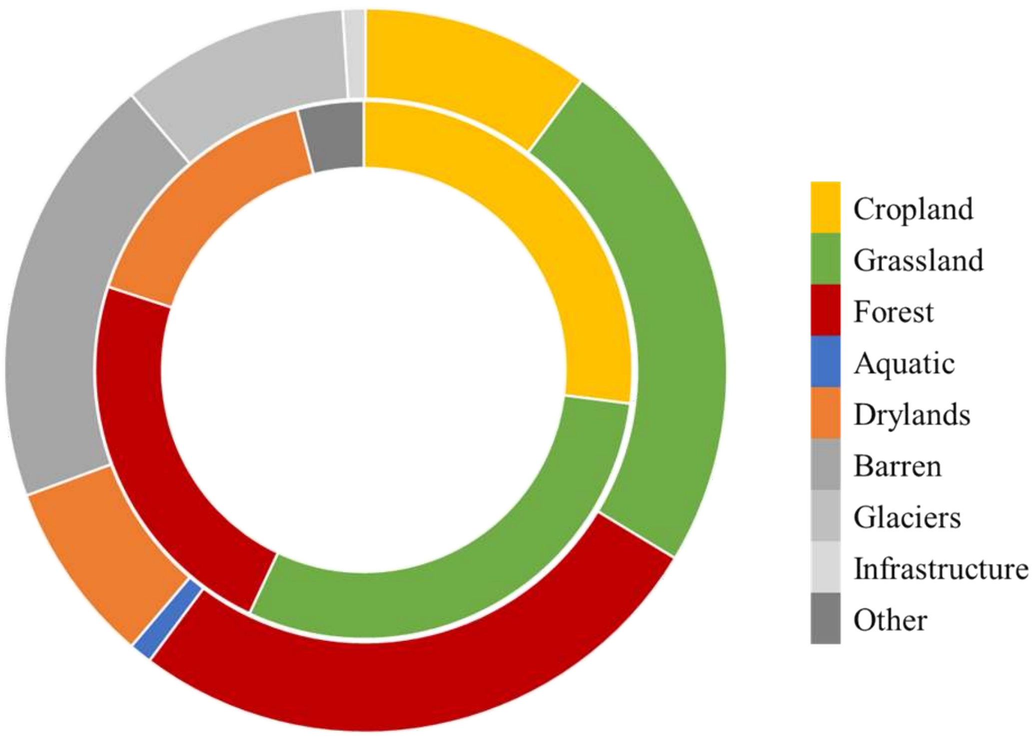

Cropland
Grassland
Forest
Aquatic
Drylands
Barren
Glaciers
Infrastructure
Other

Figure 4: Distribution of the number of measured functions within the different ecosystem service/functional categories across terrestrial ecosystems.

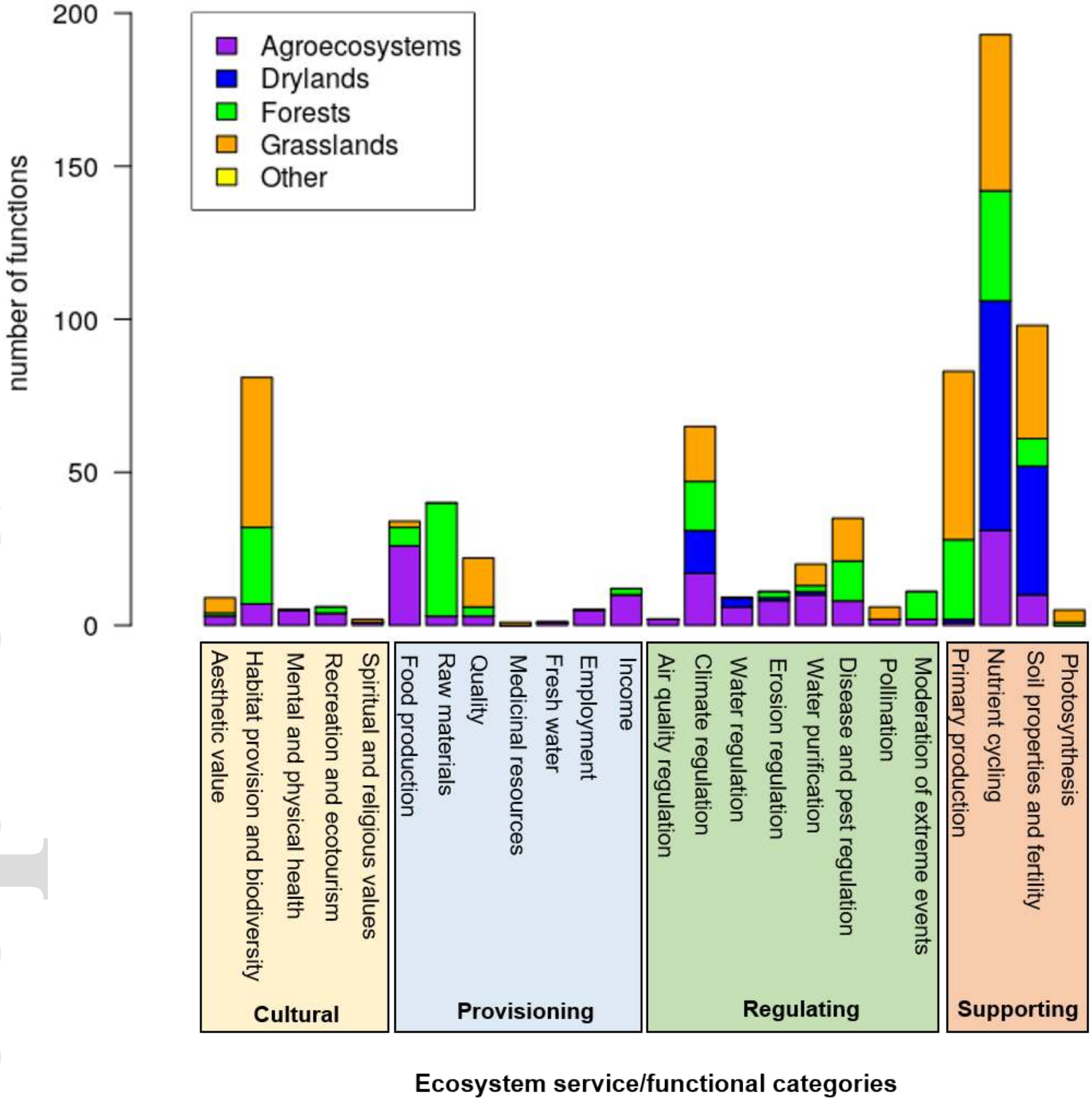
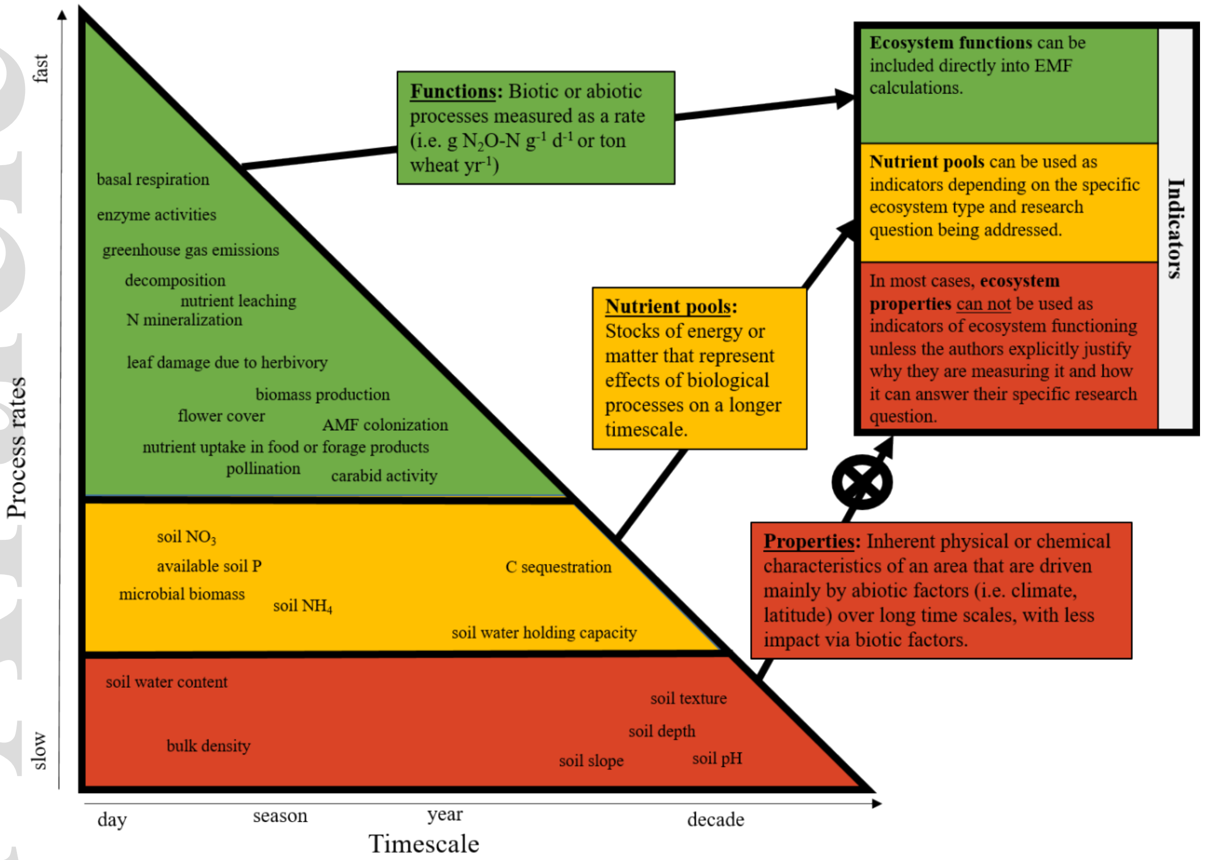


Figure 5: Conceptual diagram representing differences between ecosystem functions, nutrient pools, and properties and how they can be used as indicators for the calculation of EMF indices. All the variables shown here are examples of functions published in the EMF literature reviewed in this study. Direct measures of biotic or abiotic processes are considered ecosystem functions and can be included in the EMF calculation directly (green). On the other hand, processes that take place on slower timescales (i.e. soil C sequestration) or stocks of energy that are representative of slower biotic or abiotic processes (i.e. microbial biomass) can also be used as indicators of certain ecological functions (yellow). However, it is critical that the chosen indicator be appropriate for the specific research question addressed as well as the particular ecosystem type. In contrast, ecosystem properties (shown in red) are considered inherent physical or chemical characteristics of an ecosystem that are mainly driven by abiotic factors over very long timescales. In these cases, we caution against the use of ecosystem properties as indicators of ecosystem functions unless there is clear evidence given in the study that such variables can act as valid indicators of ecosystem functions. Once appropriate functions and/or indicators are determined for a given study, these can then be used to calculate EMF, either with or without the inclusion of ecosystem services (see Fig. 1).



Functions: Biotic or abiotic processes measured as a rate (i.e. g N_2O-N g^{-1} d^{-1} or ton wheat yr^{-1})
Ecosystem functions can be included directly into EMF calculations.
Nutrient pools can be used as indicators depending on the specific ecosystem type and research question being addressed.
In most cases, ecosystem properties can not be used as indicators of ecosystem functioning unless the authors explicitly justify why they are measuring it and how it can answer their specific research question.
Indicators
Nutrient pools: Stocks of energy or matter that represent effects of biological processes on a longer timescale.
Properties: Inherent physical or chemical characteristics of an area that are driven mainly by abiotic factors (i.e. climate, latitude) over long time scales, with less impact via biotic factors.
fast
slow
Process rates
basal respiration
enzyme activities
greenhouse gas emissions
decomposition
nutrient leaching
N mineralization
leaf damage due to herbivory
biomass production
flower cover
AMF colonization
nutrient uptake in food or forage products
pollination
carabid activity
soil NO_3
available soil P
microbial biomass
soil NH_4
C sequestration
soil water holding capacity
soil water content
bulk density
soil texture
soil depth
soil slope
soil pH
day
season
year
decade
Timescale