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What is ecosystem multifunctionality?

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Preface

Recent years have seen a surge of interest in ecosystem multifunctionality, a concept that has developed in the largely separate fields of biodiversity-ecosystem function and land management research. Here we discuss the merit of the multifunctionality concept, the advances it has delivered, the challenges it faces, and solutions to these challenges. This involves the redefinition of multifunctionality as a property that exists at two levels: ecosystem function multifunctionality and ecosystem service multifunctionality. The framework presented provides a road map for the development of multifunctionality measures that are robust, quantifiable and relevant to both fundamental ecological science and ecosystem management.

Introduction

The idea of holistic 'whole ecosystem' properties and measures has a long history in ecology[1]. However, research into the ability of ecosystems to simultaneously provide multiple ecosystem functions and services (multifunctionality) has become increasingly common in recent years, as comprehensive datasets and model outputs from multidisciplinary, collaborative projects have become available[2-8]. Multifunctionality has been defined in several ways, including 'the overall functioning of an ecosystem[2], 'the simultaneous provision of several ecosystem processes'[9], the 'provision of multiple ecosystem functions and services at high or desired levels'[10], and 'the potential of landscapes to supply multiple benefits to society'[11], to name a few. However, underlying these seemingly simple definitions are complex and unresolved issues regarding the conceptualisation and measurement of multifunctionality[9-11,] and the overall utility of the multifunctionality concept in practice[12-15]. Research on multifunctionality has been carried out within two largely separate research fields: one that sought to understand how biotic attributes of ecological communities (mainly biodiversity) are related to overall ecosystem functioning (biodiversity-ecosystem functioning research), and the other which concerns how landscapes can be managed to deliver multiple, alternative land-use objectives (land management research). Accordingly, these two fields have defined and measured multifunctionality in very different ways.

In this article, we first discuss the potential benefits of the multifunctionality concept, and the advances it has enabled, before discussing the risks and drawbacks of current approaches to studying multifunctionality. We show how more explicit definitions of multifunctionality are required to overcome these hurdles and to answer both fundamental and applied research questions. In light of these challenges we propose a new general framework that defines multifunctionality at two levels. The first, *ecosystem function multifunctionality*, is most relevant to fundamental research into the drivers of ecosystem functioning, which we define as the array of biological, geochemical and physical processes that occur within an ecosystem. The second, *ecosystem service multifunctionality*, we define as the co-supply of multiple ecosystem services relative to their human demand, and is most relevant for applied research in which stakeholders have definable management objectives. These ideas are illustrated with worked examples from European forests. We conclude by showing how this framework can be extended to measure multifunctionality at the larger spatial and temporal scales where it is most relevant.

Benefits of the multifunctionality concept

Traditional studies of ecosystem functioning within the field of ecosystem ecology typically involve detailed investigations into how individual functions relate to their drivers. Moreover, by quantifying functions in a standardised way (e.g. soil carbon fluxes, biomass production) these measures can be compared amongst ecosystems and studies[15]. However, ecosystem functioning is inherently multidimensional and so multifunctionality measures can potentially complement this approach by summarising the ability of an ecosystem to deliver multiple functions or services simultaneously. Just as aggregated community-level properties such as species richness, evenness and functional diversity[16-17] have provided great insight into broad ecological patterns at a higher level of organisation, multifunctionality research could generate an integrative understanding of ecosystem functioning and ecosystem service provision.

The concept of ecosystem multifunctionality has recently gained traction with the publication of several studies that assessed the relationship between biodiversity and ecosystem functioning within experimental systems[2,3,18,19]. Overall conclusions from these studies have been largely consistent: the relationship between biodiversity and ecosystem functioning becomes stronger when multiple functions are considered. This has been attributed to different species promoting different functions[2,20,21], but recent work shows that such positive biodiversity-multifunctionality relationships can also be driven by the effect of diversity on individual functions and statistical averaging effects[22]. An increasing number of studies have also shown positive relationships, but of varying strength, between biodiversity and the multifunctionality of non-experimental 'real-world' (i.e. natural, semi-natural and human-dominated) ecosystems, where management and abiotic drivers additionally affect functioning[10,23-28].

The multifunctionality concept used in biodiversity-ecosystem functioning research overlaps with ideas developed in research fields related to landscape-level management of ecosystem services, where there is a long history of studying the drivers of 'multifunctional landscapes', although the term multifunctionality itself is not always used. The motivation for such work is that a growing and resource-hungry human population is placing increasing pressure on dwindling land resources[29] resulting in a need to design and manage landscapes that can reliably provide multiple ecosystem services simultaneously. For example, the concept of landscape multifunctionality permeates discussions over the design of landscapes in which food and bioenergy production, carbon storage, flood regulation and biodiversity conservation are all goals[7,8,30]. Landscape multifunctionality is also central to the 'land sparing' versus 'land sharing' debate, which focuses on the relative merits of managing for biodiversity and food production within the same or separated land areas[31,32].

Measurement of multifunctionality

To date there has been no single accepted definition of multifunctionality, nor any agreed means of measuring it. In biodiversity-ecosystem functioning studies the main methods for quantifying ecosystem-level multifunctionality are the 'averaging' (or sum) approach and the 'threshold' approach. The averaging approach takes the average, or sum, of the standardised values of each function[28,33]. In contrast, the threshold approach[9,18] counts the number of functions that have passed a threshold, or a range of thresholds, usually expressed as a percentage of the highest observed level of functioning in a study[9,18,23,27,34]. The conceptual and mathematical merits of these approaches have been discussed and reviewed from the viewpoint of biodiversity-ecosystem function research[9,22,35] but their relevance to other fields of fundamental ecological research, and to the management of 'real-world' ecosystems, has not.

Averaging- and threshold-multifunctionality measures are now being related to a wide range of other ecosystem drivers, including climate[25,28,34], soil conditions[36], habitat diversity[37], land cover changes[38], nitrogen enrichment[12,39], invasive species[40], and management actions, such as agricultural intensification[10], pasture and green roof planting schemes[41,42] and crop planting systems[39,43,44]. These advances have blurred the line between the multifunctionality concepts used in the biodiversity-functioning and land management research fields. In the latter, multifunctionality is defined more broadly than it is in biodiversity research, and it can even encompass social factors such as employment and benefits provided by human infrastructure (e.g. transport systems) in addition to ecosystem components[45,46]. Furthermore, multifunctionality is typically considered at much larger (landscape) scales than in most biodiversity research, and there is sometimes consideration of both the demand for ecosystem services (the level of service provision desired by people[47]) and their supply (the capacity of an ecosystem to provide a given ecosystem service[47]). Maps of multiple ecosystem service supplies are often overlain to assess trade-offs and synergies between them[48,49], to identify ecosystem service bundles, i.e. a set of services with a similar pattern of supply[50-52], or to find hotspots of multiple ecosystem services that can be prioritised for conservation[48,49]. These approaches could be extended to create more explicit measures of ecosystem-service multifunctionality that can inform a diverse range of ecosystem management decisions, with potential applications including the setting of restoration targets, invasive species management, forest planting and the design of agri-environment schemes. Multifunctionality measures can also indicate the overall benefit provided by an ecosystem to a range of stakeholder groups, thereby helping to minimise trade-offs and conflicts between them[10].

Multifunctionality risks

While the concept of multifunctionality can be useful in both fundamental and applied ecology, its measurement is extremely challenging. Any multifunctionality measure will always be comprised of a subset of all possible functions or services and so will only capture a fraction of "true" multifunctionality. Unfortunately, so far, few researchers have carefully defined what their subset of functions represents and what it omits. It is also clear that the definition of multifunctionality determines how it is measured, and vice versa. Hence, the different perspectives in biodiversity and land management research and the intermingling of these fields mean that a better conceptualisation of multifunctionality is required.

As with any aggregated measure, multifunctionality metrics simplify reality, and can obscure important information about variation in individual functions and their drivers[12]. Many drivers have contrasting effects on the component functions of a multifunctionality measure, meaning that trade-offs between ecosystem functions and services are common, and it is impossible to maximise all functions simultaneously. For example, promoting soil nutrient turnover often results in the release of carbon dioxide, thus boosting one ecosystem service (crop production) while diminishing another (carbon storage)[39]. Where such trade-offs exist, there is therefore uncertainty in how well measures of multifunctionality reflect mechanistic relationships[12-14]. A new method for measuring multifunctionality, the Multivariate Diversity-Interactions framework[35], overcomes some of these limitations by testing the relative importance of drivers across functions and identifying trade-offs between them. This provides considerable insight into the drivers of each function but the method does not provide a measure of overall multifunctionality and its complexity and reliance on detailed data may limit its widespread adoption.

Current standard practice in both averaging and threshold-based approaches is to include all available measures of ecosystem functions and services, to include a mix of state, rate and indicator variables, and to weight all variables equally[12,23,25-27,36]. It is also common for multiple closely related variables to be included in multifunctionality measures. This causes the up-weighting of certain aspects of ecosystem functioning or particular ecosystem services, biasing the multifunctionality measurement, especially if other important ecosystem functions are not measured. Furthermore, such measures assume that all functions are equally important, which may be a false assumption in many cases, as ecosystem managers typically prioritise certain functions or services in particular contexts. To address this issue, a recent study in European grasslands[10] weighted functions according to their presumed importance to different management objectives, such as agricultural production or tourism. This demonstrated that the identity and importance of the drivers of multifunctionality, such as land-use intensification and biodiversity, depended greatly on how multifunctionality was defined. To extend this approach, realistic measures of how different stakeholders value each ecosystem service are required.

It has been argued that the threshold approach is the most informative of the current approaches, especially when metrics are calculated for multiple thresholds[9]. A notable benefit of the threshold approach is that it avoids assumptions regarding the substitutability of functions and services that the averaging approach does not. However, it does not reflect the significance of particular functions or services, as it treats all functions passing an arbitrary threshold as equivalent. Furthermore, threshold-based metrics are highly sensitive to the means of standardisation and the number of functions included[22]. Specifically, the method of standardisation affects the mean and distribution of function values, and achieving 100% multifunctionality becomes increasingly unlikely as the number of functions increases[22]. Furthermore, different studies, using both averaging and threshold approaches, include different numbers and sets of ecosystem functions, which are standardised according to different local maxima[10,23,53]. This renders comparisons of multifunctionality measures across studies extremely challenging[22]. The mixing of functions and services also means that many multifunctionality measures are difficult to interpret from both a fundamental or applied perspective.

A final issue is that multifunctionality is rarely measured at the large spatial scales relevant to most management decisions: almost all multifunctionality measures have been calculated at the 'plot' scale (<1ha). In some cases, the delivery of multiple ecosystem services is required at these small scales, e.g. in smallholder subsistence farms, but landscape-level multifunctionality is often the priority for land managers, e.g. when managing watersheds[54]. Initial investigations into the drivers of landscape-level multifunctionality show that it is driven by factors other than those determining local-scale multifunctionality, such as the spatial turnover in species composition[53], and the variety and identity of different land uses and habitat types[37,55]. In land-management research there is a plethora of frameworks for assessing patterns in landscape multifunctionality, which frequently highlight the need to understand trade-offs and synergies between ecosystem services as key to maximising landscape multifunctionality[46,56]. Although earlier attempts to measure landscape multifunctionality (*sensu lato*) have been made[57], the frameworks of land-management research tend to lack explicit procedures for quantitatively measuring overall landscape multifunctionality[11]. For example, the delivery of multiple individual services is described[6,49], or hotspot approaches are used to identify locations where several services are at high supply, but not whether this supply exceeds or falls short of demand. It may be possible to represent multifunctionality as the total economic value of the ecosystem, but such approaches are demanding and typically fail to account for certain ecosystem values (e.g. those of cultural ecosystem services), or to represent the non-equivalence of ecosystem service values between stakeholder groups[58,59].

In summary, a lack of conceptual clarity in the definition of multifunctionality has led to multifunctionality measures that are subjective and difficult to interpret. Accordingly, the use of such measures could lead to erroneous conclusions about the drivers of ecosystem functioning and to poor management decisions.

Redefining multifunctionality

We propose that studies should clearly differentiate between 1) measures of multifunctionality including only ecosystem functions, which therefore constitute a metric of the overall performance of an ecosystem, which we term ecosystem-function multifunctionality (hereafter *EF-multifunctionality*), and 2) measures which include ecosystem services and where multifunctionality is defined and valued from a human perspective, which we term ecosystem-service multifunctionality (hereafter *ES-multifunctionality*). A key distinction between these measures is that EF-multifunctionality attempts to objectively represent overall ecosystem functioning without any value judgement regarding the desired level or types of functions, while ES-multifunctionality represents the supply of ecosystem services relative to human demand. These two multifunctionality types need to be calculated according to different procedures, which we outline below (see also Boxes 1 and 2). Throughout the process of measuring multifunctionality, we recommend the use of standardized definitions of ecosystem functions and services[60,61], which would increase comparability between studies.

Ecosystem-function multifunctionality

A standardised approach to defining and measuring multifunctionality is desirable in fundamental research on the drivers of ecosystem functioning, and for long-term monitoring of ecosystem conditions. In the following section, we describe calculation methods for calculating EF-multifunctionality that are designed to be as objective as possible and at the same time repeatable. The first barrier to achieving standardised and comparable measures is that there is little consensus on the definition of ecosystem functioning, and on what can be considered high levels of function[62]. A truly standardised and comparable measure of EF-multifunctionality is not likely to be possible until ecologists resolve long-running debates regarding the nature of ecosystem function, including whether states, rates and processes should all be considered functions. As a full discussion of this topic is outside the scope of this article, we work here from the basis that ecosystem functioning should ideally be defined solely on processes rates, i.e. those involving fluxes of energy and matter between trophic levels and the environment, with high functioning being defined by fast rates. High stocks of energy and matter (e.g. soil carbon stocks, algal biomass) can also be considered indicators of process rates over the long term, as they represent the net balance of inputs and outputs. However, care should be taken in interpreting them as they may either represent high rates of accumulation or low rates of biological activity, and it is important to clearly justify why a high or low stock indicates high or low functioning. Alternatives to this approach, in which ecosystem functioning or multifunctionality is defined relative to specific or desired levels, immediately take the measure outside of objective fundamental sciences and into the more subjective realm of ES-multifunctionality (see below). This approach suggested in this section avoids such value judgements.

The next step towards the development of standardised EF-multifunctionality measures is to assess which variables represent independent aspects of ecosystem functioning. To date, many multifunctionality metrics have attempted to represent overall ecosystem functioning by including as many different types of functions as possible[3,23,26,28,53,63]. However, ecosystem functions are numerous and interrelated via networks of interactions and shared drivers (e.g. those related to nutrient cycling and productivity). Accordingly, EF-multifunctionality measures should avoid bias caused by overweighting certain categories of function. As researchers will differ greatly in their definitions of these subsets, we suggest that these subsets are defined as objectively as possible, by applying a cluster analysis to all ecosystem function data, after first standardising the variables to make them comparable (Fig. 1a).

Once the clusters are identified they can be used to define weightings in threshold-based multifunctionality measures. In contrast to ES-multifunctionality measures (see below) there is no particular level of each function which is desired by people, so we consider threshold-based approaches[6] to be appropriate as long as each cluster is weighted equally in the EF-multifunctionality measure, irrespective of the number of functions within each cluster. This will prevent the overrepresentation of many similar functions. Prior to this analysis, a standardised maximum for each function should be defined (e.g. using existing data) and used to place the function data on a standardised scale, thus making studies comparable. As the indicator functions, and the means of measuring them, are likely to differ according to ecosystem types, standardisation should be performed at the level of major ecosystem types (e.g. grassland, forest, dryland, urban, cropland, wetland, lake, river, coastal, or open ocean), or relative to the likely maximum potential function given local conditions, if this can be determined. As certain clusters or functions may be of particular interest we also suggest that users report results for individual functions and clusters separately.

As the clustering method is sensitive to the identity of the functions used in the analysis, this process will produce system-specific measures for the time being. However, as studies accumulate, certain common groupings of functions are likely to become recognisable. This in turn, may allow us to identify standard indicators of multifunctionality in the future, for which rapid and standardised ecosystem assessments[64] can be developed. The identification of standard indicator functions and EF-multifunctionality measures would be greatly accelerated by the collation and analysis of ecosystem function data at a global level. To achieve a fully comprehensive and comparable measure of multifunctionality, we need to evaluate how many, and which, functions are necessary to measure to obtain a good representation of overall ecosystem functioning (i.e., the dimensionality of ecosystem functioning). In such an initiative the dimensionality of ecosystem functioning can be assessed by identifying associations between a fully comprehensive set of ecosystem functions (e.g. with principal components analysis), measured across a very wide range of conditions. Fundamental axes of ecosystem variation could then be identified and causes of variation along these will become better understood, in a process similar to what has been achieved for broad plant functional strategies, where fundamental axes of variation across plant species and communities are broadly accepted[65].

Delivering a set of accurate, comparable and easily measured indicators of ecosystem function, that have been validated across a wide range of conditions, is clearly a non-trivial task, yet it has the potential to provide significant insight into the drivers of ecosystem functioning and to help in identifying fundamental trade-offs and synergies between ecosystem functions. Such standardized measures are not without precedent as they are being used to monitor spatio-temporal changes in ecosystem functioning at continental scales worldwide[66], and they are roughly analogous to the use of indicator taxa in conservation monitoring, or to the measurement of a few plant traits to represent major axes of functional trait variation[65]. Furthermore, standard EF-multifunctionality indicator measures could be linked to related schemes to monitor climate and biodiversity change via 'essential variables'[67].

In the short-term, we advise a cautious approach to the use of EF-multifunctionality measures, which should acknowledge the mathematical and conceptual sensitivity of these measures to the functions included, and which is transparent in reporting any biases in selecting variables. We also recommend reporting the degree of trade-off between functions (e.g. as a correlation matrix) and the maximum EF-multifunctionality present within a study. Ideally, this should be related to a theoretical or standardised maximum, so that cases where high EF-multifunctionality is impossible, e.g. due to strong trade-offs between functions, are identified. Regardless of the wider property that an EF-multifunctionality measure represents, it is imperative that researchers justify their choice of ecosystem function measures and understand the implications of these choices in driving their conclusions. We also recommend that EF-multifunctionality scores are compared to null expectations, given their sensitivity to the form of standardisation and number of contributing functions, and given that tools exist for their computation[22].

Ecosystem-service multifunctionality

As ecosystem services are defined in relation to human needs, the definition and measurement of ES-multifunctionality requires a different approach. The first step is to define which ecosystem services (including material, regulating and non-material relational values[68]) are desired, and the level and scale at which they are to be delivered. This requires consulting stakeholders[69,70]. As priorities differ depending on stakeholder identities, and local socio-economic and ecological factors, a single ES-multifunctionality measure would not be globally meaningful. Instead, bespoke ES-multifunctionality measures are needed to reflect the supply of ecosystem services relative to their demand with respect to various groups and organisations (Box 2, Fig. 2). This should be done in a two-stage process using social-science methodologies. First, the identity of important stakeholder groups and the services they value are identified qualitatively (e.g. via interview and discourse), before the weightings of these services are derived quantitatively (e.g. by deriving stated preferences from stakeholder questionnaires in which the importance of different ecosystem services are ranked on an ordinal scale[70]).

Once the main ecosystem services and their relative importance have been defined, the next step is to describe the functional relationship between the supply of each service and the benefit delivered in terms of a relevant measure of wellbeing (e.g. economic benefit, health, security or equity), which we term the supply-benefit relationship. The threshold approach[9,18] is a particular case of this relationship that assumes an abrupt shift from zero to full benefit at a particular level. Previous work on ecosystem services has found that such relationships can take a wide range of forms, e.g. threshold, asymptotic or linear. This emphasizes the need to construct ES-multifunctionality measures in which the supply-benefit relationship is derived for each service[71] (Box 2, Fig. 2). We suggest that many locally relevant, regulating services show a threshold relationship in which there are definable safe levels (e.g. a safe maximum threshold for nitrate in drinking water), while ecosystem services that operate at very large scales (e.g. climate regulation via carbon storage) can show a linear relationship with benefits at local scales. Ecosystem services with direct economic benefits, on the other hand, might show a 'threshold-plus' relationship, characterised by a break-even point, beyond which increasing levels of a service deliver increasing benefits (e.g. there is a minimum crop yield that will be profitable, beyond which further yields generate further profits, see Appendix S2 for further examples). The supply-benefit relationship can be defined using a range of techniques, many of which were developed in economics[69,71], and - where relevant - they may be defined separately for different stakeholder groups. Where it is difficult to determine the supply-benefit relationship, or it is uncertain, we suggest exploring the sensitivity of ES-multifunctionality metrics to a range of possible relationships (see Example 2, Appendix S1).

As a next step, ecosystem services need to be quantified. The services described by stakeholders will generally denote broad categories, so effort is required to convert these to quantifiable properties. In certain cases, they can be measured directly, e.g. carbon stocks[72]. However, many other services do not have generally applicable metrics, and so locally relevant indicators, ideally with direct links to the final service, need to be identified. Furthermore, multiple indicators may be required in cases where services have several components (Fig. 2, Example 2). Once identified and measured, indicator variables should then be transformed to service values using mathematical transfer functions that are appropriate for the function-service relationship[7,8] (see Example 2, Appendix S1). Then, the standardised values can be multiplied by the stakeholder-derived weightings (see Box 2) and finally be summed to generate ES-multifunctionality measures. With this method issues with substitutability[9], and with applying the same supply-benefit relationship (e.g. a 50% threshold) to all services, are largely avoided. Also, the preliminary assessment of stakeholder needs means that all important services for each area should be included, thus providing a comprehensive measure of ES-multifunctionality. This ensures that measures are comparable within a study, even where the number of services differs.

Once ES-multifunctionality measures have been calculated, their relationship to biotic (e.g. the presence of a keystone species) and abiotic (e.g. climate or land-use) drivers can be investigated for a range of stakeholder groups (Fig. 3) and the resulting knowledge can inform landscape management. For example, simulating changes in the most important drivers may allow for the prediction of future changes in ES-multifunctionality to different stakeholder groups, or the costs and benefits of different management actions. Such information is compatible with existing environmental decision-making frameworks, such as the Driving Forces-Pressures-States-Impacts-Responses (DPSIR) framework used by the European Environment Agency[73] or the Conceptual Framework of the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES)[74]. These recommended ES-multifunctionality measures advance upon existing approaches[50,51] by delivering an integrated measure of the supply of ecosystem services relative to their demand from a wide range of stakeholders, rather than simply indicating the supply of multiple ecosystem services[6], or coarsely estimating their total value[59]. In addition to ES-multifunctionality, the response of individual underlying services should also be reported for transparency and to allow individual practitioners to assess the data. This can be summarised concisely in the form of flower diagrams and radar charts[6],[51,75].

Landscape-scale multifunctionality

In the previous sections we assumed that multifunctionality is measured at small spatial scales (often <1 ha). However, as mentioned earlier, high levels of ES-multifunctionality are often desired at much larger scales (often >1 ha), where factors such as beta diversity, connectivity, and landscape configuration may become important drivers of multifunctionality[37,53,76,77]. There have been previous attempts to measure landscape multifunctionality within biodiversity-ecosystem function research, where it has been quantified as the number of functions exceeding a threshold in at least one part of a landscape, and also as the average of standardised function measures across a landscape[53,78]. These previous studies measured multifunctionality by aggregating properties of plot-level measures, however, and thus were not able to consider spatial interactions between organisms and landscape features, which can strongly influence some ecosystem functions, particularly in heterogeneous and complex landscapes[45,76,75]. Where such interactions occur, simple extrapolation of existing knowledge of the drivers of local-scale multifunctionality to larger scales is not recommended as it is highly likely that whole landscape functioning is not equal to the sum of the functioning of small landscape units. In this section we suggest possible approaches to address this challenge and to quantify ES-multifunctionality at the landscape scale.

The first steps towards the measurement of landscape ES-multifunctionality are to ensure that the landscape is divided into analytically manageable units, e.g. even-sized grid cells, or patches undergoing uniform management, such as fields, which can then be used in upscaling calculations. Next, appropriate scaling functions should be applied to each ecosystem service of interest to calculate its overall level within the landscape (Fig. 5). For certain services, simple upscaling methods - in which the supply of a service is estimated from the properties of each landscape unit and then summed or averaged across the landscape - will be appropriate, e.g. carbon storage, which can be estimated from simple local measures or remote-sensing proxies[72]. However, many services and their underlying functions involve spatial exchanges of matter and organisms, e.g. nutrient leaching, pollination services or pest control[75,76,79]. These will be strongly influenced by surrounding features, making direct upscaling from local-level measures unreliable. Therefore, the quantification of such services will require spatially explicit algorithms in which the levels of an ecosystem service in each landscape unit are modified by features of the local environment. Finally, some important ecosystem services are not observable at local scales at all and so require landscape-level assessment, or estimation from the aggregated properties of smaller landscape units. Examples are landscape beauty, habitat suitability for organisms with large range sizes (e.g. many charismatic vertebrates) or landslip risk (Fig. 5). Ecosystem services can be attributed to these categories of upscaling method by combining expert knowledge with quantitative assessment of which local level services are influenced by surrounding features[75]. Such assessments could also provide the algorithms required to upscale each function or service (e.g. from spatially-explicit statistical models).

The next step in measuring landscape ES-multifunctionality is to define the supply-benefit relationship spatially, i.e. to define the location and level required for each service. Certain services may be required at very high levels, but only in certain locations (e.g. recreation, avalanche control), while for others only their overall landscape level is important (e.g. carbon storage). This spatial supply-benefit relationship should be defined by a range of stakeholders because they may differ in their spatial pattern of demand[80]. For example, a landscape formed of small subsistence farms requires multiple benefits in many landscape positions, while land belonging to a single owner (e.g. a large private company or conservation charity) may require larger scale ES-multifunctionality, with large areas dedicated to a small number of services. Once the spatial pattern of supply relative to demand is determined for each service, landscape level ES-multifunctionality can be quantified as described previously (Fig. 5).

Future avenues

Given the complexity and diversity of ecosystem functions and services, it is conceivable that the framework presented here may require adaptation for certain circumstances. It is also clear that several gaps in knowledge and data, e.g. the identity of the best indicators within clusters of related ecosystem functions, or the spatial patterns of ecosystem-service benefits, need to be addressed before EF- and ES-multifunctionality can be quantified with confidence. Temporal aspects also bring further complexity to the measurement of multifunctionality, which may explain the paucity of knowledge on this subject. Nevertheless, such aspects are essential for understanding the stability, resistance and resilience of overall ecosystem performance and its long-term benefits for human well-being. Time-series data give the potential to extend multifunctionality measures, e.g. by quantifying the number of years in which an ecosystem had high levels of multiple functions, thus merging measures of stability[77,81] and multifunctionality[9,18] to give measures of multifunctional stability. Future linkages between ecological and socio-economic systems are also encouraged, and are possible through the extension of the framework presented here, e.g. by quantifying ES-multifunctionality using monetary or life-satisfaction[82] units.

Conclusions

Multifunctionality is a simple but nebulous concept with many potential applications. It is increasingly studied in fundamental biodiversity and ecosystem science, whilst also becoming a common objective for ecosystem management and landscape-scale policy. There is therefore a pressing need to define it clearly and to provide useful multifunctionality metrics. With careful consideration of the issues raised here, multifunctionality metrics will become well founded, thus giving them the potential to provide important insights in ecosystem science and to support environmental decision-making. The recommendations made in this article often require greater resources and effort than current approaches, and it is still unlikely that all can be implemented within a single study. However, data-intensive methods are becoming increasingly possible thanks to large collaborative projects[2-8] and data-sharing, opening the possibility to identify general indicators of ecosystem functions and services, which may then be applied widely. By focusing research efforts on well-designed sampling protocols that include the most relevant and easy-to-measure functions and services, we can further accelerate this process. Even before such protocols are devised, increased awareness of the issues covered here will help to prevent inappropriate conclusions from being drawn from multifunctionality studies. Producing new and more reliable measures of EF- and ES-multifunctionality is not a trivial challenge, but a highly worthwhile one, given their great potential to provide insight into whole ecosystem functioning and to guide ecosystem management in an era in which dwindling natural resources are placed under increasing pressure.

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Author contributions

PM conceived the study and wrote the initial draft, which was developed and revised by all other authors. PM and FvdP designed and performed analyses.

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Box 1. Measurement of *ecosystem-function multifunctionality*

1. Using a cluster analysis of ecosystem function data, *n* clusters of closely related functions are identified and given equal weight.

2. EF-multifunctionality is then quantified according to the threshold method (see references 9 and 18 for details). Prior to this analysis function measures are standardised according to regionally standardised maxima for each ecosystem type.

3. Each cluster is then assigned equal weight in the threshold based measure (e.g. 1 one each) and functions within the cluster are weighted equally (e.g. 0.25 each if the cluster contains four functions). This avoids the overweighting of certain aspects of overall ecosystem functioning.

4. Alongside the overall measure of EF-multifunctionality, individual ecosystem function values, the response of individual clusters of interest, the maximum observed EF-multifunctionality and the degree of trade-off between functions should also be reported.

Example 1: Forest ecosystem function multifunctionality.

EF-multifunctionality was calculated using data collected in forests as part of the FunDivEUROPE project[51]. This dataset contains 21 ecosystem functions and services measured in 209 forest plots across six European countries. These plots were selected to differ in the diversity and composition of dominant tree species.

To calculate EF- multifunctionality from this data we first excluded variables which cannot be considered ecosystem functions (e.g. cultural service indicators such as bird diversity) and those which are not measures of the rates of ecosystem processes or major stocks of energy and matter (e.g. drought resistance). Next, we performed an agglomerative -cluster analysis of the remaining functions and found that four clusters was the appropriate number (see tutorial and Fig. 1a). The data were then scaled according to the maximum values observed across the whole dataset and EF-multifunctionality was calculated using a 50% threshold, where each cluster of ecosystem function had the same weight in the overall EF-multifunctionality measure. The resulting scores were then related to European region and the proportion of conifer trees (Fig. 1b). This showed that conifer cover promoted EF-multifunctionality (i.e. ecosystems with high levels of these four clusters of function in Fig. 1a) in some regions (e.g. Poland) but affected it negatively in others (e.g. Germany). The maximum and minimum values observed were 0.87 and 0 respectively, with a theoretical maximum of 1. See Appendix S1 for methodological details and a tutorial.

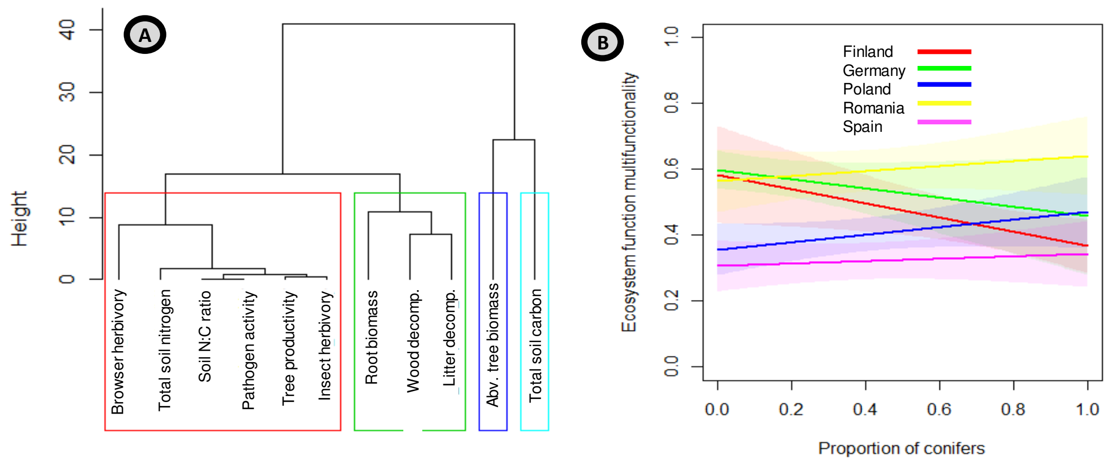

Figure 1. The quantification of EF multifunctionality in European Forests. (A) A dendrogram of ecosystem functions showing four main clusters, two related to fertility and turnover (red and green) and two related to the main stocks of energy and matter above- and belowground (blue and cyan) (B) The effect of forest region and conifer abundance on EF-multifunctionality. See Appendix S1 for details.

Box 2. Measurement of *ecosystem-service multifunctionality*

1. First, important ecosystem services can be identified and weighted according to their relative importance, via consultation of a representative range of stakeholder groups within the focal area, thus ensuring that a full range of perspectives are represented (Fig 2).

2. The relationship between supply levels of an ecosystem service and the benefit it provides to humans (supply-benefit relationship) is also defined, e.g. via expert knowledge, economic methods, or stakeholder consultation (Fig 2).

3. Next, the levels of each service are measured using indicators or direct measurements (e.g. Fig. 2)

4. Indicator measures are then standardised to the same scale using the supply-benefit relationship (Fig 3).

5. Finally, the scaled measures can be multiplied by their stakeholder weightings and summed to quantify ES-multifunctionality. Stakeholder weightings should sum to 1 so that ES-multifunctionality metrics are comparable.

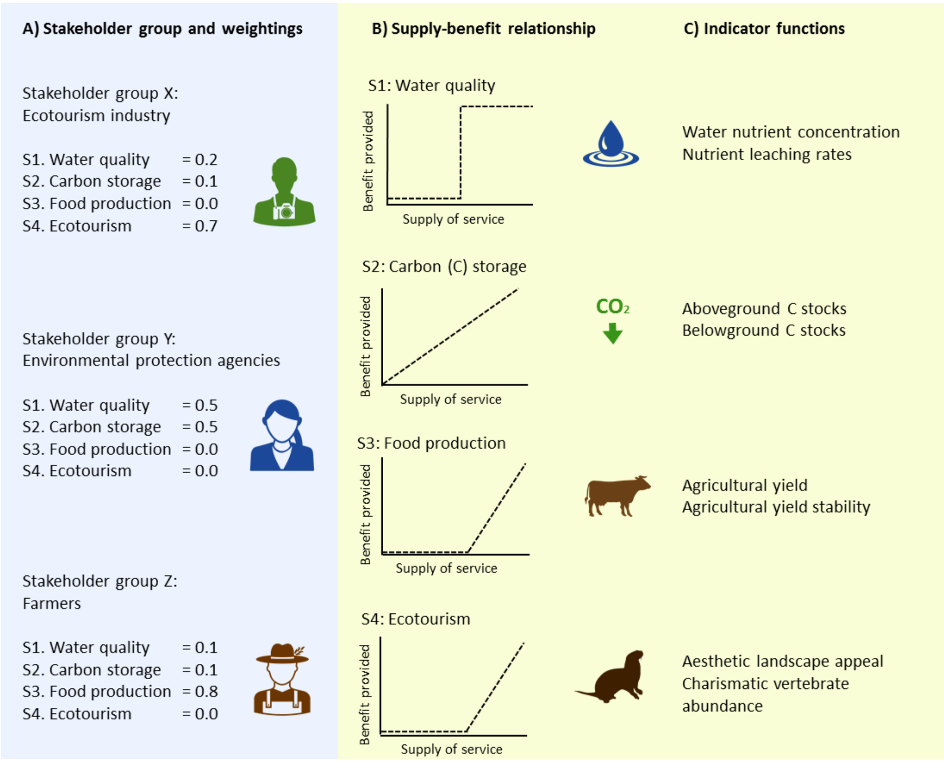

Figure. 2. Precursor stages to the measurement of ecosystem-service multifunctionality. Weighting of four example services according to different stakeholder perspectives (A). These services differ in the form of their supply-benefit relationships (B); for example, water is either legally safe to drink, or not; thus displaying threshold behaviour (S1), while at local level carbon storage has a linear relationship with global climate regulation. In contrast, a minimum amount of food production is required before agriculture becomes economically viable (S3), and ecosystems need to be in reasonable condition to attract tourists (S4). The values of these services increase linearly beyond these thresholds as greater profits are realised. Example indicator functions for each service are provided (C), and in for water quality these need to be transformed to a negative scale (i.e. high nutrient concentration is low water quality).

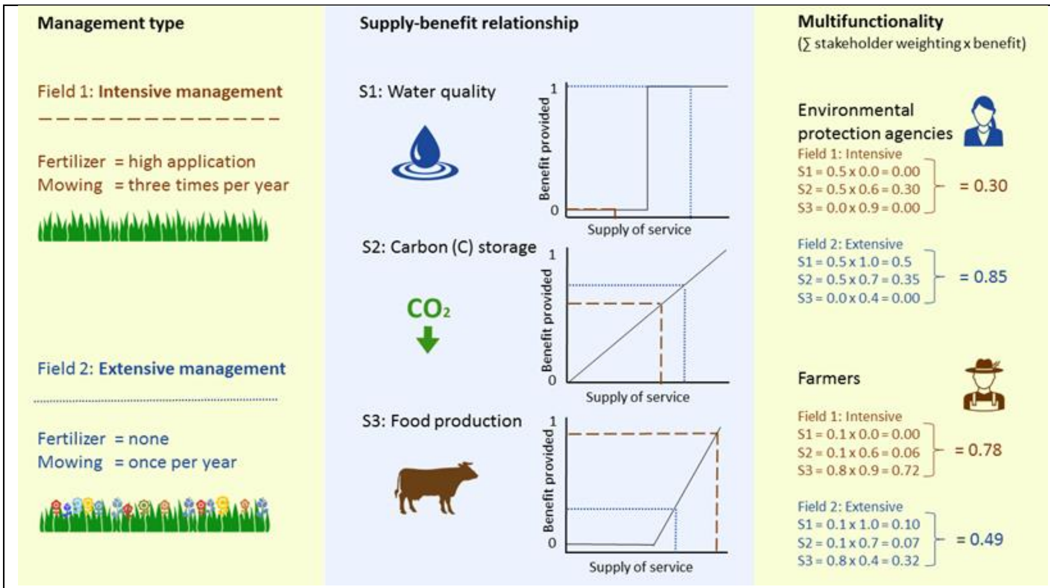

Figure 3. An example of how levels of ecosystem-service multifunctionality depend on stakeholder preferences and how they can be compared between ecosystems subject to differing management regimes.

Example 2. Ecosystem service multifunctionality of forest ecosystems

We demonstrate the calculation of ES-multifunctionality by using the FunDivEUROPE forest data (see Example 1)[53]. The first step was to obtain estimates of different ecosystem service values from stakeholders. As such data was not available for FunDivEUROPE, we took values from a stakeholder consultation conducted in Germany[83], where one of the FunDiv regions is located. Here, three stakeholder groups, managers of public owned forests (Public), managers of private owned forests (Private) and environmental organisations (Environmental group) stated differing priorities for four primary ecosystem services: timber production, biodiversity conservation, water supply and carbon sequestration. Timber production was given greater priority by the public and private groups. To represent these services with quantifiable measures we selected 1-3 indicator variables for each service from the 21 service and function variables available, and weighted them according to the stated stakeholder preferences. Each indicator variable was scaled relative to local or continental maximum and minimum values in a manner relevant to the demand of the ecosystem service (e.g. biodiversity relative to local maxima and carbon relative to continental maxima). As data for supply-benefit relationships were not available, we tested the sensitivity of ES-multifunctionality measures to a range of these relationships: linear, a 50% threshold, and 25, 50 and 75% threshold plus relationships. See Appendix S1 for details and a tutorial.

We found that a positive relationship between conifer abundance and ES-multifunctionality in German forests is broadly consistent across scenarios (Fig. 4). However, the slope of this relationship depended on stakeholder identity and the particular supply-benefit relationship. These differences are great enough to drive management decisions. For example, conifer planting would boost multifunctionality to public and private owners in the case of a 50% threshold-plus relationship, but would not promote multifunctionality from the perspective of the environmental organisations. This demonstrates the importance of using appropriate stakeholder weightings and supply-benefit relationships in ES-multifunctionality measures.

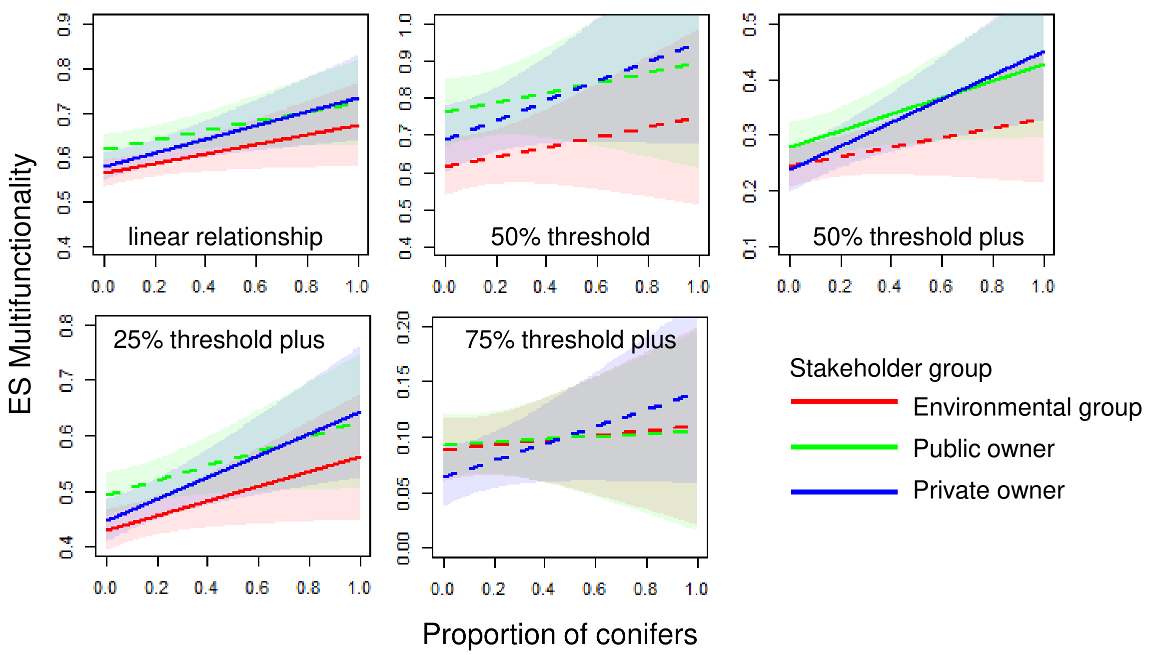

Figure 4. Dependency of ecosystem service multifunctionality on the supply-benefit relationship**,** stakeholder preferences and conifer abundance in German forests. Dashed lines indicate non-significant slopes (*p*>0.05) and solid lines significant slopes (*p*<0.05). Note the wide range in absolute ES multifunctionality values between the different supply-benefit relationships.

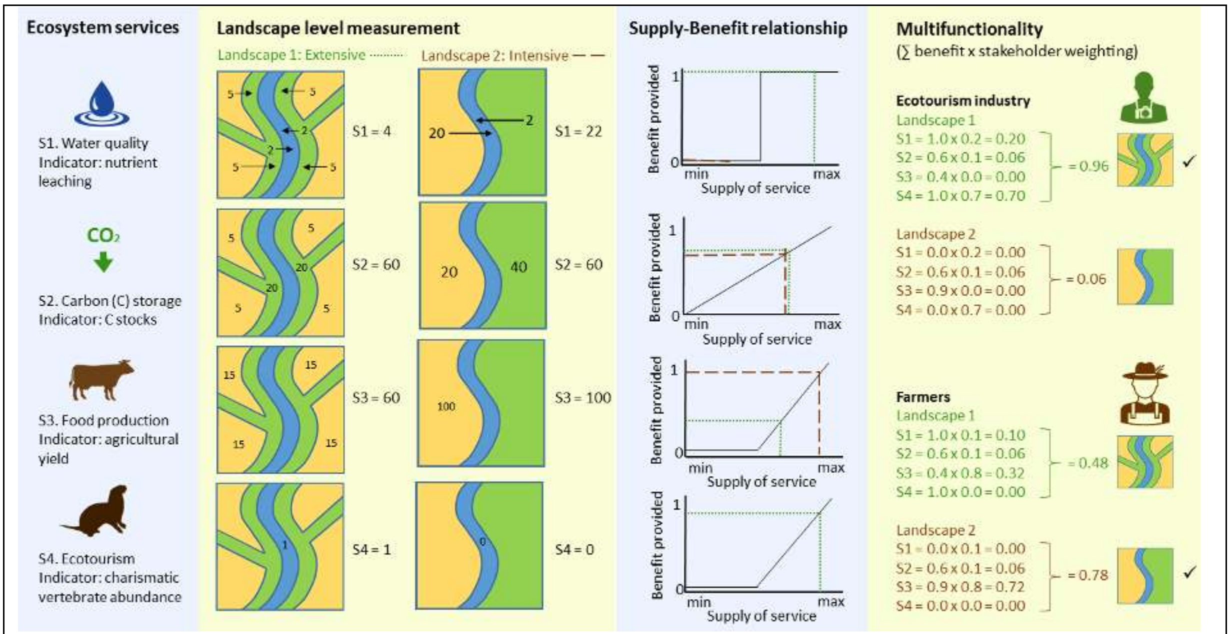

Figure 5. An example of the measurement of landscape scale ecosystem service multifunctionality. Two hypothetical landscapes possess the same proportion of two habitat types, pasture (yellow) and forest (green), but differ in their spatial configuration. Different ecosystem services require different upscaling functions. Carbon storage (S2) can be estimated simply from the area of crop and forest, while nutrient leaching into water bodies, which reduces water quality, (S1) is buffered by forest, thus requiring spatially-explicit consideration, as does food production, which is affected here by the proximity of livestock to water (S3). The charismatic vertebrate (S4) responds to landscape structure and requires a connected habitat, requiring measurements of habitat suitability to be made at the landscape scale. The preferred landscape structure differs between two stakeholder groups: the ecotourism industry, and farmers, although trade-offs between these two groups are notably weaker in the extensive landscape. Note that nutrient leaching, the indicator of water quality, is inverted to represent a lack of leaching, a positive service, in the supply-benefit relationship.