Multifunctionality assessments – More than assessing multiple ecosystem functions and services? A quantitative literature review

Authors:
Lisanne Hölting*, Michael Beckmann, Martin Volk, Anna F. Cord

UFZ – Helmholtz Centre for Environmental Research, Department of Computational Landscape Ecology, Permoserstraße 15, 04318 Leipzig, Germany
*Corresponding author. E-mail: lisanne.hoelting@ufz.de

Highlights

- 101 studies were identified that assess multifunctionality using quantitative methods
- On average, studies investigated eight ecosystem functions and services
- Studies covered biophysical and integrated socio-ecological assessments
- 84% of the studies aggregated multifunctionality into a single metric
- The results elucidate different conceptualizations of multifunctionality

Abstract:

The capacity of a landscape or ecosystem to provide multiple socio-economic and ecological benefits to society is referred to as multifunctionality. While this topic is receiving growing attention in politics and research, the concept continues to lack implementation partly due to varying conceptualizations and assessments of multifunctionality. To analyze how multifunctionality is conceptualized, characterized and quantified in scientific publications, we reviewed 101 studies that used quantitative methods to assess landscape or ecosystem multifunctionality. On average, 7.9 ± 4.7 ecosystem functions and services were considered, covering Provisioning (19%), Regulating (30%), Cultural (16%) and Supporting (35%) service categories. The studies ranged from micro-scale experiments to global analyses. Different methods were used to aggregate multifunctionality into a single metric (e.g. the number of ecosystem functions and services above a certain threshold, the average value of ecosystem functions and services, the sum of ecosystem functions and services). The interpretation of multifunctionality and the way it is operationalized varied largely among the studies: 42 studies assessed ecological and socio-economic variables in equal shares and often integrated stakeholders (33%). 59 studies focused on ecological variables only and did not include stakeholders except for one study (1.7%). Based on these findings, we discuss the implications of the conceptual and methodological ambiguity within multifunctionality assessments. We present the strengths and limitations of current approaches and provide recommendations for future multifunctionality assessments.

Keywords:

Multifunctional landscapes; Environmental indicators; Socio-ecological assessments; Landscape management; Trade-offs; Stakeholders

Box 1. Definitions of the key concepts used in this article

Ecosystem functions: Properties and processes of an ecosystem, such as ecosystem matter and energy cycles, that have a specific function within the ecosystem and are essential for the capacity to provide goods and services (Costanza et al., 1997; de Groot, 1992).

Ecosystem services: Benefits people obtain from ecosystems. These include the following four service categories (MEA, 2005):

- **Provisioning Services:** Products obtained from ecosystems
- **Regulating Services:** Benefits obtained from regulation of ecosystem processes
- **Cultural Services:** Nonmaterial benefits obtained from ecosystems
- **Supporting Services:** Services necessary for the production of all other ecosystem services

Environmental indicator: A measure of environmentally relevant phenomena used to depict environmental conditions (Heink and Kowarik, 2010).

Landscape multifunctionality: The capacity of a landscape to provide socio-economic and ecological benefits to society, including potential trade-offs and synergies between individual ecosystem functions and services (based on this work, Mastrangelo et al., 2014, Stürck and Verburg, 2017).

1. Introduction

1.1. Multifunctionality as a policy aim

The intensification of agricultural production systems and the consumption of land for urban expansion have led to major changes in human-dominated landscapes and triggered a discussion on multifunctional land use (Brandt and Vejre (Eds), 2004; Haines-Young and Potschin, 2010; Holmes, 2006; Wiggering et al., 2003). In contrast to land-use systems that are maximized towards the supply of one or few ecosystem functions and services, multifunctional landscapes are characterized by a high diversity and abundance of different functions and services within the same spatial unit (Stürck and Verburg, 2017; Box 1). By avoiding a spatial segregation of ecosystem functions, multifunctional landscapes are expected to positively impact the conservation of biodiversity (Pasari et al., 2013) and the overall maintenance of ecosystem functions, such as soil fertility, pollination capacities or biomass production (Brandt and Vejre (Eds), 2004; Hector and Bagchi, 2007; Raudsepp-Hearne et al., 2010), thereby increasing ecological resilience (O'Farrell and Anderson, 2010).

Moreover, by accounting for a broad range of ecosystem services, multifunctional land use systems are capable of addressing multiple human needs (e.g. social, cultural, economic and ecological) (Brandt et al., 2014; Lovell and Johnston, 2009; Mander et al., 2007) and are thought to increase the overall benefits that societies can obtain from an ecosystem (Otte et al., 2007). Land use conflicts that arise from competing interests in a landscape are expected to be – at least partly – resolved in multifunctional land use systems (Brandt and Vejre (Eds), 2004).

Imbued with these ideas, multifunctionality (MF) has become a key concept within international legislation, such as the Common Agricultural Policy (CAP) of the European Union, and intergovernmental organizations, such as the Food and Agriculture Organization (FAO) and the Organization for Economic Cooperation and Development (OECD) (FAO, 2000; OECD, 2001; Otte et al., 2007; Wiggering et al., 2003). Policy support is being provided through agri-environmental measures and the production of non-commodity functions is regarded as a development option to sustain rural areas (Holmes, 2006; Wiggering et al., 2003).

1.2. Different understandings, conceptualizations and operationalizations of multifunctionality

While environmental planning towards increasing MF has become a policy aim, a lack of implementation has been pointed out (Hansen and Pauleit, 2014; O'Farrell and Anderson, 2010; Otte et al., 2007). This seems to be at least partly the result of different understandings and conceptualizations of MF (Brandt and Vejre (Eds), 2004; Mastrangelo et al., 2014; Stürck and Verburg, 2017). MF of landscapes is not a novel concept. It has originally been used as a land management concept with a strong focus on agricultural land use systems (Brandt and Vejre (Eds), 2004; Huang et al., 2015; Vos and Meekes, 1999). In Germany, for example, the work of Wolfgang Haber on differentiated soil and land use ('differenzierte Boden- und Landnutzung') in the early 1970s paved the way for the current understanding of interrelations between biodiversity, soil functions, conservation of rural landscapes and agricultural productivity (Haber, 2014). More recently, the works of Brandt and Vejre (2004), Holmes (2006) and Wiggering (2003) strongly promoted research on MF as a land management concept in the international arena. The aim of the original concept was to develop sustainable land use strategies that deliver multiple land-use objectives. The idea that people, who are well connected to the land and its resources, obtain more benefits from multifunctional land management has always been stressed in MF research (Huang et al., 2015). Consequently, when ecosystem services research emerged during the early 2000s, it was often implicitly linked with the MF concept (Huang et al., 2015).

However, ‘multifunctionality’ is a very generic term that can be and has been used in many different contexts. In its literal meaning, MF simply describes the provision of multiple functions without referring to any specific spatial scale or land use type, nor to any human perspective (Byrnes et al., 2014; Huang et al., 2015). As a result, the concept has been applied to a wide array of research questions. In urban areas, for example, the MF of green roofs and green infrastructures has been assessed to portray the benefits obtained from such infrastructures by people (e.g. Lovell and Taylor, 2013; Meerow and Newell, 2017). Soil MF, defined as the capacity of a soil type to provide different ecosystem functions, has been assessed on small-scale to microscale plots (e.g. Delgado-Baquerizo et al., 2016; Liu et al., 2017; Wagg et al., 2014). And finally, MF has been assessed for a variety of different ecosystems, such as coastal areas (Allgeier et al., 2016), forests (van der Plas et al., 2016a) and water bodies (Peter et al., 2011).

In the last decade, an increasing number of studies on Biodiversity-Ecosystem-Functioning used MF assessments to elucidate the relationship between biodiversity and multiple ecosystem functions on various scales in different ecosystems (e.g. Byrnes et al., 2014; Hector and Bagchi, 2007; Lefcheck et al., 2015; Soliveres et al., 2016). In this sense, MF being equated with the supply of multiple *ecosystem functions* does not imply valuation from a human perspective and can therefore be assessed from a purely ecological perspective (O’Farrell and Anderson, 2010). Contrary to this, and largely in line with the ecosystem service concept (see Box 1), it is often assumed that MF studies present integrated socio-ecological analyses including some kind of normative dimension (Brandt and Vejre (Eds), 2004).

To disentangle this conceptual ambiguity, different approaches have been made to more clearly distinguish between MF concepts. Focusing on ‘landscape multifunctionality’, Brandt and Vejre (2004) suggested five different perspectives: 1) a purely ecological approach (biophysical assessments), 2) an anthropocentric approach (linking biophysical and social assessments), 3) a policy approach (focused on land use conflicts), 4) a cultural perspective (focused on aesthetics and cultural values), and 5) a holistic approach (including all perspectives from above). Another study, recently published by Manning et al. (2018) suggested a fundamental differentiation between ecosystem function multifunctionality (EF-MF) and ecosystem service multifunctionality (ES-MF). The separation between EF-MF and ES-MF here depends on what is being assessed (ecosystem functions or services), how it is being assessed (biophysical or integrated socio-ecological) and how the assessment is being used (e.g. Biodiversity-Ecosystem-Functioning research or integrated land management) (Manning et al., 2018).

1.3. Quantitative multifunctionality assessments

Today, a general consensus exists that the concept of MF should be “more than a policy-based initiative” (Lovell and Johnston, 2009). Different researchers have therefore developed methods to quantify MF. Such quantitative assessments should help to better understand processes within multifunctional landscapes. They should support decision-making processes (Holmes, 2006; Lovell and Johnston, 2009) and eventually lead to improved ways of managing our environment in a sustainable way (Andersen et al., 2013; Wiggering et al., 2003). While there is no unified approach for assessing and quantifying MF (Andersen et al., 2013; Hansen and Pauleit, 2014; Lovell and Johnston, 2009), most commonly, a set of ecosystem functions and services is aggregated into a single metric that estimates the level of MF (hereafter called 'MF indicator') (Byrnes et al., 2014; Gamfeldt et al., 2008; Maestre et al., 2012b; Rodríguez-Loinaz et al., 2015; see Stürck and Verburg (2017) for a recent comparison of MF indicators).

A large variety of MF indicators exists that give different weight to the importance of individual functions and services: Some MF indicators sum up or average all functions and services in the considered landscape (Byrnes et al., 2014; Mouillot et al., 2011). Other MF indicators only account for functions and services that are above a certain threshold, based on the assumption that only high supply levels contribute a value to the multifunctional environment (Byrnes et al., 2014; Gamfeldt et al., 2008). And finally, in contrast to the two previous examples which focus on the *number* of ecosystem functions and services, other researchers applied diversity indicators (e.g. Shannon index), which account for the *relative proportions* of ecosystem functions and services (Stürck and Verburg, 2017).

Environmental indicators, such as MF indicators, generally play an important role for the evaluation and communication of environmental conditions and changes as well as for setting environmental goals (Heink and Kowarik, 2010). Nevertheless, assessing MF via indicators in a quantitative way can be challenging, especially when focusing on ES-MF. Such indicators need to capture very complex socio-ecological systems, while being at the same time easily interpretable and technically feasible (Heink and Kowarik, 2010; Quero et al., 2013). The aggregation of ecosystem functions and services into single indicators has therefore led to some contradictions within MF research and researchers have called for more integrative assessment methods (Byrnes et al., 2014; Mastrangelo et al., 2014).

1.4. Scope of this review

Despite the increasing number of case studies on MF (Fig.1), there is a considerable knowledge gap about how MF has been conceptualized and typically assessed so far – from plot to global scale. Previous overview articles have focused on MF assessments in the context of Biodiversity-Ecosystem-Functioning only (Byrnes et al., 2014) or on studies that evaluate the joint supply of ecosystem services at specific spatial scales (Mastrangelo et al., 2014). We here focus on all quantitative assessments of landscape or ecosystem MF. By this, we aim to answer (1) how different conceptualizations of MF are operationalized in the literature and finally, (2) which are the major criteria that make MF assessments strong tools with high relevance for management and decision-making.

We used a systematic search strategy to identify the relevant studies and evaluated all identified publications regarding their research context, type of study as well as the selection and number of ecosystem functions and services considered. More specifically, focusing on quantitative MF assessments only, we analyzed the choice of MF indicator or other assessment methods, the spatial scale of the study region, the way of considering (or not) interactions among ecosystem functions or services (trade-offs, synergies, compatibilities), as well as the approaches used to involve stakeholders. We critically discuss the use of quantitative MF indicators in general and present the strengths and limitations of current approaches. To provide guidance for research on this topic, we highlight the implications of the conceptual and methodological ambiguity within MF assessments and conclude with recommendations for future studies.

2. Methods

2.1. Literature search

This review is based on a Scopus database search using the search string "(multifunctionality OR multi-functionality) AND (ecosystem* OR landscape*)". The search targeted article title, abstract and keywords of studies published until the 27th of April 2017, and resulted in 587 publications. We used the terms 'multifunctionality' and 'multi-functionality' without asterisk search modifiers (*), thereby excluding articles that used general terms, such as 'multifunctional'. In doing so, we expected to find a higher share of studies actually conducting MF assessments or discussing the definition of the concept. From the 587 articles found, 80 were excluded from this review due to the use of languages other than English (59) or formats other than research articles (21, e.g. Corrigenda, Editorials). The review process was carried out in three steps.

2.2. Step 1: All publications (507 studies)

At first, all 507 remaining articles were reviewed using a list of predefined assessment criteria (Table A1) in order to analyze the general understanding and application of MF research in the literature. We assessed the year of publication and the location where the study had been carried out. Each article was categorized after reviewing the title, abstract and keywords into six groups of research disciplines: 'Agricultural management', 'Landscape planning', 'Ecology and soil science', 'Urban and rural development', 'Forestry' and 'Other'. Based on the methods applied, studies were further grouped into seven categories: 'Reviews', 'Geospatial analyses' (spatial analysis, secondary data analysis), 'Experimental studies' (field or laboratory studies), 'Surveys', 'Models' (scenarios and simulations), 'Economic and policy analyses' (economic evaluations, Life Cycle Assessments (LCAs), policy evaluations, frameworks and concepts) and 'Other'.

2.3. Step 2: Only quantitative MF assessments (subset of 101 studies)

In the second step, we focused only on the studies that assessed MF in a quantitative way, i.e. that provide a metric indicating a specific level of MF for the studied ecosystem or landscape. 101 publications (hereafter, called 'MF assessments') fulfilled these criteria and serve as the basis for all subsequent analyses. These publications were reviewed using the following additional criteria (Table A1): First, we analyzed the choice of ecosystem functions, services or other variables (e.g.: landscape functions, ecosystem processes, etc.), which were used to quantify MF (hereafter summarized as 'ecosystem functions and services'). We noted the number of ecosystem functions and services considered and the terms used for these variables (Table A2). In addition, we classified them into 'ecological' and 'socio-economic' variables, indicating whether they mostly value ecological (e.g. 'litter decomposition' or 'habitat provision') or socio-economic aspects (e.g. 'outdoor recreation' or 'timber production') of MF. The ecosystem functions and services were further assigned to one of the four ecosystem service categories ('Provisioning', 'Regulating', 'Cultural' and 'Supporting') of the Millennium Ecosystem Assessment (MEA, 2005), which can be done for both ecosystem functions and services, as in Soliveres et al. (2016).

The data sources used to derive the ecosystem functions and services were classified as either 'primary data' (field experiments, lab experiments, questionnaires, remote sensing, and surveyed farm data) or 'secondary data' (administrative data, secondary spatial data, databases, expert knowledge, meta-analysis, and literature) (Seppelt et al., 2011; Table A3). We further identified six categories of assessment methods and classified all papers accordingly: 'Microscale experiments/samplings', ‘Plot/field observations’, ‘Municipality/farm scale observations’, ‘Regional observations (administrative units)’, ‘High resolution maps’, ‘Grid cells/land cover maps’ (Table A4).

We specifically analyzed the methodology used to quantify MF (e.g., averaging methods, threshold approaches), as well as the spatial scale at which the study had been carried out. For the categorization of the scale, we used upper political scales (national, EU, global) and lower political scales (local, regional), as in von Haaren and Albert (2011). We further added a landscape scale, since MF is increasingly viewed as a “property of the landscape level” that enables the integration of the biophysical and socio-economic context (Mastrangelo et al., 2014). The landscape scale is located between the local and regional scale (Haaren and Albert, 2011; Mastrangelo et al., 2014) and is defined to be below 100km² (Ayanu et al., 2012). In our analysis, local scale studies focus on forest stands, fields or city districts; landscape scale studies on sub-catchments or municipalities; and regional scale studies on hydrological catchments, mountain ranges or counties.

Furthermore, we examined whether interactions between the ecosystem functions or services considered had been analyzed via correlation analysis, descriptive methods or other methods (see Lee and Lautenbach, 2016 for a review of different methods). Following the classification proposed by Seppelt et al. (2011), we also assessed the type of stakeholder involvement as follows: none, selection of ecosystem functions and services, valuation of ecosystem functions and services, scenario planning. All data were analyzed using Microsoft Office Excel (2007) and R Studio (Version 3.3.1.).

2.4. Step 3: Conceptual categorization of quantitative MF assessments (subset of 101 studies)

As a third step of the analysis, we applied a hermeneutic analysis to classify the studies into two major groups (EF-MF and ES-MF studies) by scanning the title, abstract and the list of ecosystem functions and services assessed. This classification was not based on the terminology used in the specific papers (e.g. ‘ecosystem functions’ or ‘ecosystem services’), but on the definition of EF-MF and ES-MF in Manning et al. (2018). Taking also into account the categorization proposed by Brandt and Vejre (2004), the publications were sub-grouped as follows: EF-MF assessments a) of purely biophysical nature or b) including human perspectives; and ES-MF assessments focusing on a) land use issues, b) policy perspectives, c) cultural values, or d) other.

3. Results

3.1. Research context and study types

The number of papers using the term MF is increasing steadily (in particular since the year 2000, Fig.1), with the first article being published in 1972 and a total of 69 studies being published in 2016. More than two thirds of this research was conducted in Europe, with Italy, Germany, Spain and the UK together accounting for more than 25% of all studies (Table A5). The first quantitative MF assessments were conducted in 2007 and about 15 of such studies are currently published per year (Fig. 1).

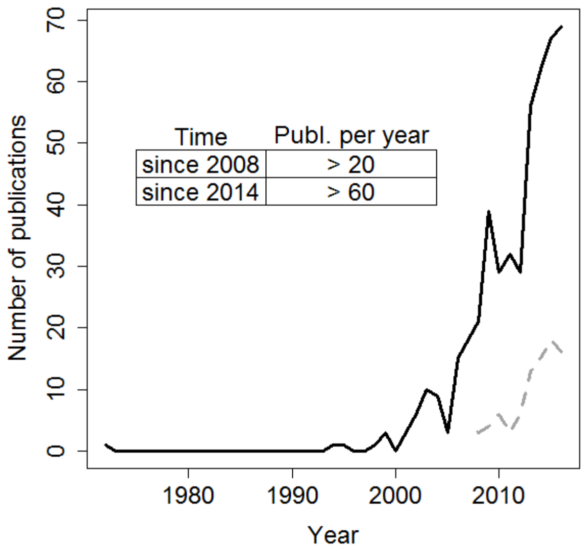

Fig. 1. Number of publications on multifunctionality per year. The table in the graph and the solid line represent all MF studies found (n = 507). The dashed line presents the subset of quantitative MF assessments (n = 101).

When analyzing all 507 MF studies, we found that most research on MF was conducted in the fields of 'Agricultural management' (27%) and 'Landscape planning' (22%), followed by 'Ecology and soil sciences' (19%), 'Urban and rural development' (14%), 'Forestry (9%) and 'Other' (9%) (Fig. 2a, Table A6). Conversely, almost half of the 101 quantitative MF assessments were conducted in the field of 'Ecology and soil sciences' (49%), while other research domains were represented far less often (Fig. 2a). The largest share of the 507 MF studies that we found were scientific reviews (27%), while the majority of the 101 quantitative MF assessments were experimental studies (42%), followed by geospatial analysis (28%) and model-based studies (22%) (Fig. 2b). The category 'Geospatial analyses' includes studies for which the data was not assessed via experimental field studies, surveys or models, but for which data originated from (re-analysis of) existing databases.

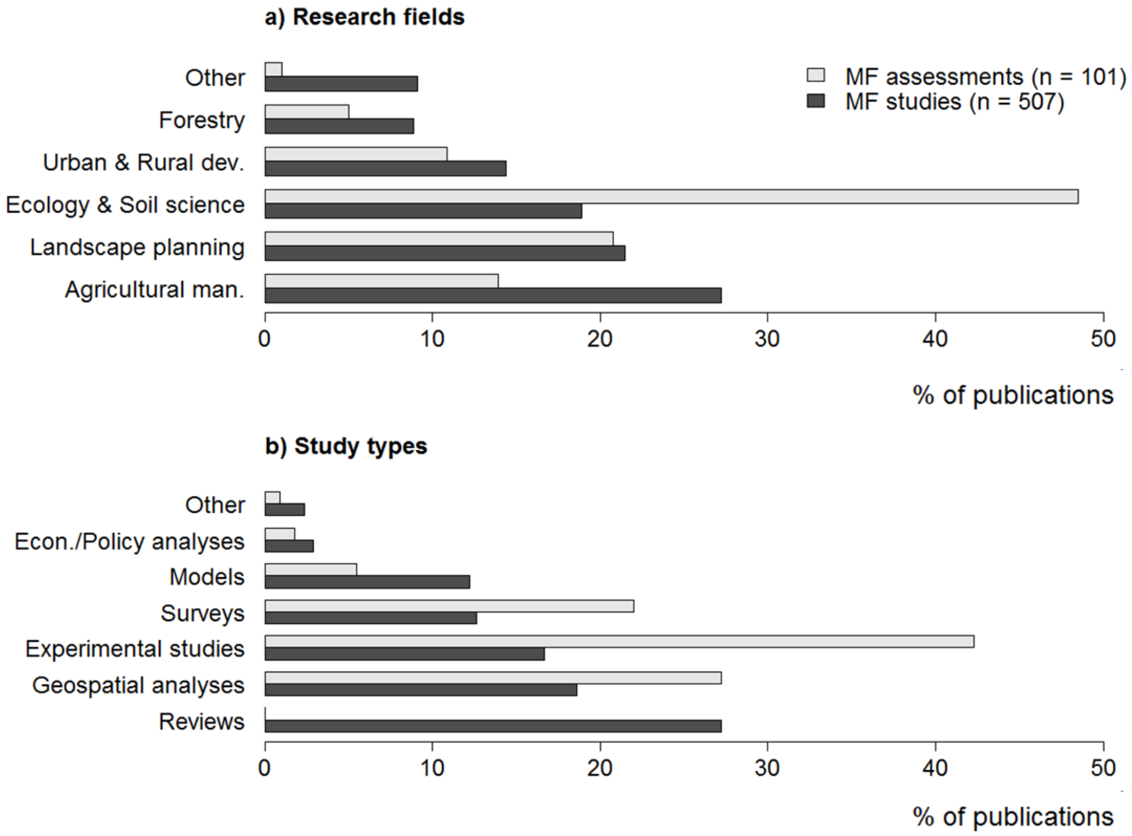

Fig. 2. Research fields and study types. a) Distribution of publications among six broad categories of research fields (for more information on the sub-categories of the six research fields see Table A6); b) distribution of publications among seven categories of study types. Black bars represent all MF studies found (n = 507). Grey bars represent only the quantitative MF assessments (n = 101).

3.2. The set of ecosystem functions and services: number, type and terms used

In total, we identified 20 different terms (Table A2) that were used to describe the underlying processes, functions or services considered in the MF assessments. The preferred terms were ‘ecosystem function’, which occurred in 35% of the MF assessments, followed by ‘ecosystem service’ that occurred in 25% of the MF assessments. Other phrases with the term ‘function’ (agricultural functions, landscape functions, etc.) were used in 20% of the MF assessments. For simplification, we here summarize all terms used under the term ‘ecosystem functions and services’. There was no obvious pattern of the use of different terms over time (Figure A1).

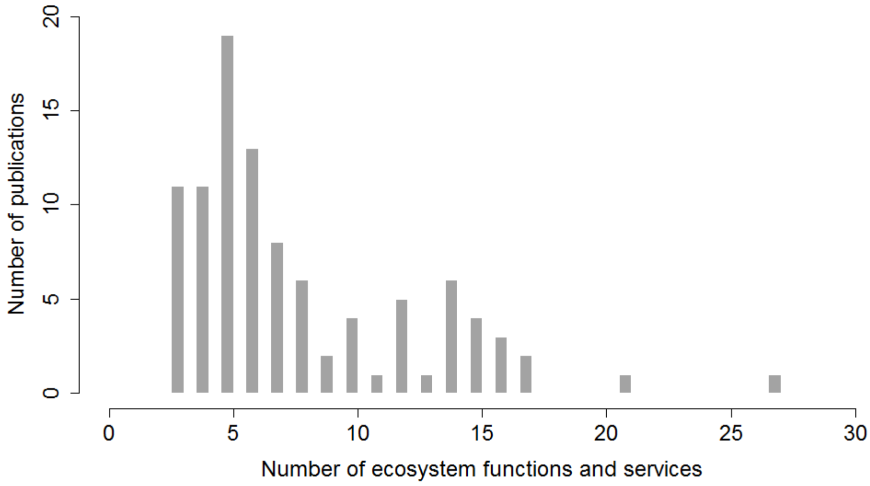

Fig. 3. Number of ecosystem functions and services assessed in each MF assessment (n = 101).

The number of ecosystem functions and services considered varied widely among the MF assessments, ranging from three to 27 with an average of eight (Fig. 3). Most MF assessments took into account five ecosystem functions or services. Looking into the type of ecosystem function or service considered we found that 55.4% of the MF assessments were focusing exclusively on ecological variables, 43.6% evaluated both ecological and socio-economic variables and the remaining 1.0% assessed only socio-economic variables.

Most MF assessments took into account ecosystem functions and services from the categories ‘Supporting’ and ‘Regulating’ (79% and 69%, respectively). Fewer studies included the categories ‘Provisioning’ and ‘Cultural’ (43% and 37%, respectively) (Fig. 4a). If the category ‘Provisioning’ was included, in most cases ‘Cultural’ functions and services were considered as well, the opposite was the case for the categories ‘Supporting’ and ‘Cultural’ (defined significance level of positive/negative correlations: $p < 0.05$) (Fig. 4b, Table A8). Moreover, 80.2% of the studies assessed variables from more than one category (Fig. 4c).

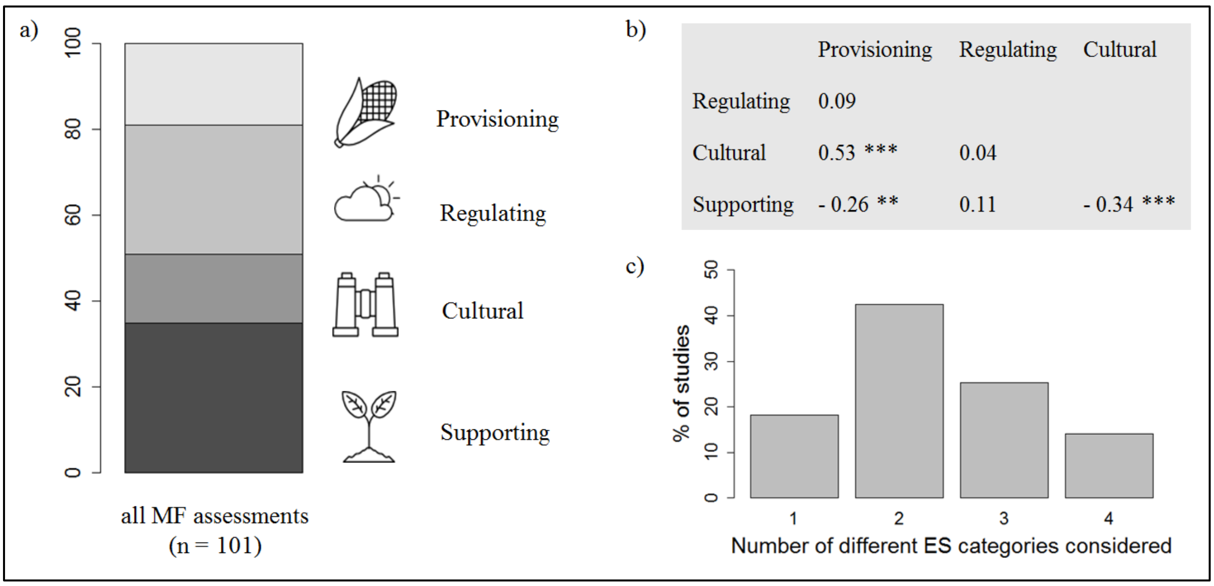

Fig. 4. a) Proportion of ecosystem service categories considered within MF assessments (n =101) (multiple categories are possible per study). ecosystem service categories are presented by a color gradient from light grey to dark grey in the following order: Provisioning, Regulating, Cultural and Supporting; b) Correlations between the different ecosystem service categories (***: $p < 0.005$, **: $p < 0.05$, see Table A8); c) Proportion of MF assessments that assessed ecosystem functions and services from 1, 2, 3 or 4 different ecosystem service categories.

3.3. Quantification of MF

3.3.1. MF indicators and other assessment methods

While many different approaches were used to quantify MF (Table 1), 84.0% of the studies used methods that aggregate MF into a single metric. Most commonly, the 'threshold' approach (32.8%) was employed, which calculates the number of ecosystem functions and services that simultaneously exceed one or multiple threshold value(s) (see Gamfeldt et al., 2008). Only ten of these threshold-focused studies applied a single threshold value, while most studies analyzed at least two or three discrete variables (Table A9). The remaining studies employed continuous thresholds, thereby covering a full range of thresholds between, for example, 1 and 99% of the values of ecosystem functions and services considered.

The second most widely used method was the 'averaging approach' (30.4%), which computes the average value of multiple standardized ecosystem functions and services (see Mouillot et al., 2011; Zavaleta et al., 2010) as a single MF metric. 14.4% of the studies estimated the level of MF by calculating the 'sum' of all standardized ecosystem function or services, and 6.4% studied MF by building other 'Indices' (Simpson's Index, Shannon Index etc.). The remaining 16% of studies used various other approaches for the assessment of MF without necessarily aiming at aggregating MF into a single metric. The category 'Other approaches' includes radar charts (3 studies), Principal Component Analysis (3), multi-objective optimization (2), the turnover approach (2), cluster analysis (2), the evaluation of stated preferences (2), etc. Notably, 16 of the 101 studies used more than one assessment method: Ten studies used two different approaches; four studies used three different approaches and two studies used four different approaches.

Table 1
Type of assessment method used to quantify multifunctionality.

Method	Number of studies*	% of studies	Method description	References
Threshold approach	41	32.8%	Number of ecosystem functions and services that exceed…	
Single threshold	*10*	*8.0%*	*…a single threshold*	Gamfeldt et al., 2008
Discrete thresholds	*19*	*15.2%*	*…few multiple thresholds*	Zavaleta et al., 2010
Continuous thresholds	*12*	*9.6%*	*… a continuous range of thresholds*	Byrnes et al., 2014
Averaging approach	38	30.4%	Average value of all ecosystem functions and services	Maestre et al., 2012b
Sum	18	14.4%	Sum of all ecosystem functions and services	Andersen et al., 2013
Indices	8	6.4%	Richness and/or diversity of ecosystem functions and services	Brandt et al., 2014
Other approaches	20	16.0%	-	Queiroz et al., 2015

*The total number of MF assessments equals 125, as some studies used more than one method.

3.3.2. Accounting for trade-offs and synergies

In total, 59% of the 101 quantitative MF assessments accounted for interactions between ecosystem functions and services. There was no correlation between the number of ecosystem functions and services assessed and the testing for interactions. Most of the interactions were examined by correlation analysis (42%) and descriptive methods (14%) (Table A10). Descriptive methods for characterizing interactions between ecosystem functions and services, such as qualitative descriptions of ES relationships based on GIS analysis (e.g. Schulz and Schröder, 2017) or ecosystem service bundles (e.g. Mouchet et al., 2017), were mostly used in combination with the MF indicator ‘sum’ or ‘other approaches’ (Table A10). Among the different assessment methods the percentage of studies that tested interactions varied between 50% for studies that applied ‘continuous thresholds’, ‘indices’ or ‘averaging’, and 65% for studies that applied ‘other approaches’, ‘sum’, and ‘single or discrete threshold(s)’ (Table A10).

3.3.3. Spatial extent of the study region

MF was assessed on different spatial scales ranging from microscales to global scales (Table 2). In total, 71 studies were conducted on ‘lower political scales’ (local, landscape, regional) and 17 studies on ‘upper political scales’ (national, multinational, global). Additionally, 12 studies conducted MF assessments on a microscale (e.g. assessing bacterial or enzyme MF; e.g. Peter et al., 2011).

Table 2
Spatial extent of the MF assessments.

		Lower political scales			Upper political scales		
	Microscale	Local	Landscape	Regional	National	Multi-national	Global
MF assessments (n = 100)*	12	32	7	32	5	8	4

*Total = 100 MF assessments, as one study was conducted on two spatial scales and two studies were modeling studies without applicable extent.

3.3.4. Stakeholder involvement

We found that only 15 of the 101 quantitative MF assessments involved stakeholders. Stakeholders participated either through the selection of ecosystem functions and services (2 studies), the valuation of ecosystem functions and services (11) or both, selection and valuation (2). Notably, all of these 15 participatory studies assessed not only ecological, but also socio-economic variables. Furthermore, all but one of these studies took cultural ecosystem functions and services into account.

3.4. Conceptual differences

42 assessments fell into the group of ES-MF studies, having an anthropocentric perspective of MF (Fig. 5). The following terms were used in these studies: ecosystem services (20 studies), functions (8), landscape functions (6), farm/forest/agricultural functions (3), landscape services (2), etc. By sub-grouping the ES-MF studies according to the classification by Brandt and Vejre (2004), we found that five assessments looked at cultural aspects only; eight assessments had a strong policy focus; and

more than half of the studies (22) focused on multifunctional land use issues in general (e.g. land use conflicts, optimized land management practices, etc.) (Table A11). Overall, ES-MF studies were characterized by an equal proportion of ecological and socio-economic variables, as well as by a balanced representation of different ecosystem service categories (Figure 5; Table A7).

On the other hand, 59 assessments could be described as EF-MF studies. In these studies, the following terms were used to define multifunctionality: ecosystem functions (36 studies), ecosystem services (5), ecosystem/ecological processes (7), and soil variables/functions (3). While most studies (48) followed a purely ecological approach to assess MF, at least 11 EF-MF assessments included human perspectives and had a strong policy or management relevance (Table A11). A common feature of the EF-MF studies however was their strong focus on ecological variables; only 8% of the studies included socio-economic variables (Fig. 5, Table A7). Moreover, while the ES-MF studies did account for ecosystem functions and services of three ecosystem service categories on average and captured the different ecosystem service categories in a balanced way, the 59 EF-MF studies accounted for only two ecosystem service categories on average, with a strong focus on the categories 'Regulating' and 'Supporting' (Fig. 5). At the same time, stakeholder involvement was almost non-apparent in EF-MF studies (Fig. 5).

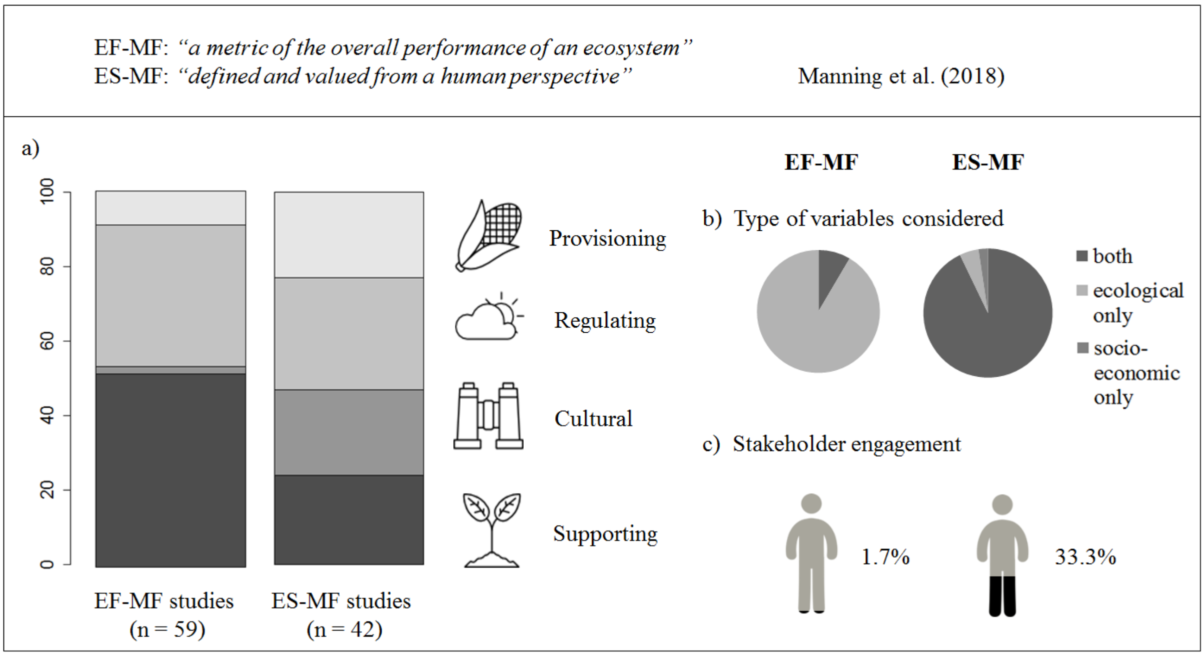

Fig. 5: a) Proportion of ecosystem service categories considered within EF-MF (n = 59) and ES-MF (n = 42) assessments. Ecosystem service categories are presented by a color gradient from light grey to dark grey in the following order: Provisioning, Regulating, Cultural and Supporting; b) Relative proportion of the type of variables considered in EF-MF and ES-MF assessments; c) Stakeholder involvement (proportion of studies) in EF-MF and ES-MF assessments.

EF-MF and ES-MF studies did not only show conceptual dissimilarities and different priorities, but also differed largely in the employed MF quantification methods. The dominating methods in EF-MF studies were the 'averaging' and 'threshold' approaches, together accounting for 86% of methods used. In contrast, taking the 'sum' was the method prevailing in ES-MF studies, followed by 'discrete thresholds' (38% and 20%, respectively, Table A7). ES-MF studies further used 'indices' much more than EF-MF studies (16% vs. 1.25%, Table A7). Interactions between ecosystem functions and services were more or less assessed in the same way. However, ES-MF studies made use of descriptive methods slightly more often than EF-MF studies, which mostly utilized correlation analysis (Table A7). Regarding the spatial extent of the analyses there were no striking differences, except for the regional scale which was addressed by 45% of the ES-MF studies, but only by 22% of the EF-MF studies. ES-MF studies were not conducted on microscales or global scales (Table A7).

4. Discussion

The results of this review have shown a variety of conceptualizations and assessments of MF. While it has been argued that this variety might limit the comparability among MF assessments (Queiroz et al., 2015), it also reflects the high interest in the topic and the broad field of potential applications (Brandt and Vejre (Eds), 2004; Manning et al., 2018). The two major questions that we here focused on are (1) how different conceptualizations of MF are operationalized (Section 4.1), and (2) which are the major criteria that make MF assessments strong tools with high relevance for management and decision-making (Section 4.2).

4.1. Different conceptualizations of MF

The choice of ecosystem functions and services considered in the reviewed studies reflects different conceptualizations of MF and represents the researchers' understanding of MF. As there is no common and unifying understanding of MF in the scientific community, each study needs to be interpreted individually in its study-specific context. With respect to future MF assessments, however, we found that a characterization of MF studies as recently suggested by Manning et al. (2018) is helpful. It is evident that this classification cannot be based on terminology only ('ecosystem functions' vs. 'ecosystem services'), as different ways of interpreting 'ecosystem services' and 'ecosystem functions' exist (Bennett et al., 2015; Huang et al., 2015). Assessments of multiple ecosystem functions, for example, often include aspects that go beyond a purely ecological dimension (e.g. information functions; de Groot et al., 2002). Assessments of multiple ecosystem services, on the other hand, are often based on biophysical indicators only (e.g. Lundholm, n.d.; Mitchell et al., 2014), being more easy to quantify (Seppelt et al., 2011). Such studies often lack a valuation by stakeholder and can therefore not directly be translated into the actual benefits that people derive from nature (Bennett et al., 2015).

While MF needs to be interpreted in the context of each individual study, a simple classification of MF assessments as conducted in this review allowed us to understand the implications of the different conceptualizations of MF for quantitative MF research. Depending on the individual conceptualization, we found different types of assessment approaches. First, MF assessments framed within a more anthropocentric understanding of MF (ES-MF studies) captured ecological and socio-economic values in a balanced way. They were capable of addressing multiple human needs, which is seen as a prerequisite for the management of sustainable and resilient land use systems (Lovell and Taylor, 2013; Mander et al., 2007; O'Farrell and Anderson, 2010). In line with other researchers (Hansen and Pauleit, 2014; Raudsepp-Hearne et al., 2010), we argue that such integrated and 'holistic' studies, considering human-environmental interactions, are much needed to support policies and decision-making towards increased MF. On the other hand, studies framed within a more ecological understanding of MF (EF-MF studies) largely focused on functions that regulate or support ecosystem processes. They ranged from fundamental research on ecosystem processes to more applied management-relevant issues. This again highlights that a separation of MF assessments into two concepts only is certainly a simplification. A large number of studies in this review were in fact capable of bridging ecological and social assessments (e.g. Allan et al., 2015; van der Plas et al., 2016b). Such inter- and transdisciplinary research is much needed to further develop concepts and methods in landscape ecology (Fischer et al., 2007; O'Farrell and Anderson, 2010).

4.2. Beyond the assessment of multiple ecosystem functions and services

Based on this review, we see three major criteria that make MF assessments strong tools with high relevance for management and decision-making: (1) the assessment of trade-offs and synergies, (2) the careful consideration of the underlying assumptions, strengths and weaknesses of the MF indicator(s) used, and (3) a sensible involvement of stakeholders for the study-specific definition and valuation of MF.

Trade-offs and synergies. Only an integrative analysis of trade-offs and synergies enables well-informed decisions towards or against certain land use and management practices (Cord et al., 2017; Willemen et al., 2010). Therefore, quantitative MF assessments should not only consider multiple ecosystem functions and services simultaneously, but also specifically assess interactions among them. Since many ecosystem functions and services are either directly interlinked or influenced by the same drivers (Bennett et al., 2009), the inability to account for trade-offs and synergies may be indeed one of the largest weaknesses of the common MF indicators (Dooley et al., 2015; Dusza et al., 2017). More than half of the MF assessments in this review were already complemented with an analysis of trade-offs and synergies (Table A10). We strongly recommend further expanding this field beyond the sole identification of interactions. As suggested in Cord et al. (2017), studies need to explore the drivers that shape ecosystem functions and services relationships, as well as the limits to MF, in order to support decisions towards increasing MF.

Underlying assumptions of MF indicators. Methods used to quantify MF should be carefully selected by taking into account the underlying assumptions, strengths and weaknesses of different MF indicators. For example, the 'averaging' approach, originally introduced by Moulliot (2011), is a straightforward and simple technique (Byrnes et al., 2014) that produces a single metric by averaging the values of all standardized ecosystem functions and services. Individual functions or services are assumed to be substitutable by other functions or services in this approach. The same assumption applies to the 'sum' approach. These two methods estimate the supply of multiple ecosystem functions and services, without giving any insights on their identities or on underlying interactions (Byrnes et al., 2014; Gamfeldt et al., 2008; Maestre et al., 2012a). Such a representation of MF may be most suitable for the identification of hot- and coldspots of MF (e.g. Meerow and Newell, 2017; Willemen et al., 2010).

In contrast, the 'threshold' approach accounts for only those ecosystem functions and services that exceed a critical threshold. Low level ecosystem functions and services that may arise from strong trade-offs are not considered (Allan et al., 2015; Byrnes et al., 2014; Stürck and Verburg, 2017). This approach is particularly suitable if a specific threshold value exists (e.g. water purification: water quality has to meet certain standards for drinking water). However, the choice of the threshold value is critical and has a strong impact on the study outcome (Stürck and Verburg, 2017). The 'continuous thresholds' approach partly overcomes this drawback by exploring a continuous range of possible thresholds. Here, different MF metrics are being produced that allow a more nuanced interpretation of MF (see Byrnes et al., 2014). This, for example, allows exploring how the relationship between species richness and ecosystem functioning changes with the number of ecosystem functions considered (Gamfeldt and Roger, 2017). While the 'continuous thresholds' approach has often been used in Biodiversity-Ecosystem-Functioning studies (e.g. Lefcheck et al., 2015; van der Plas et al., 2016a), it has as of yet not been applied in ES-MF studies (Table A11).

Instead of focusing on the overall amount of ecosystem functions and services provided it has also been suggested to use diversity indices of ecosystem functions and services to provide an estimate of MF (e.g. Shannon's H, Plieninger et al., 2013; Simpson's reciprocal index, Raudsepp-Hearne et al., 2010). Using these indices, the supply of individual ecosystem functions and services is related to their total supply in an area (Stürck and Verburg, 2017). While richness-focused indicators of MF might be misleading, diversity-focused approaches allow evaluating whether functions and services are equally supplied or whether a few dominant ones exist (Plieninger et al., 2013; Stürck and Verburg, 2017). Some balancing among focal ecosystem functions and services can further be applied, as different diversity indices give more weight to either abundant (Simpson's reciprocal index) or rare (Shannon's H) functions and services. Such approaches to assess MF are particularly suitable in cases where in-depth analyses of MF composition are needed. Similarly, ecosystem service bundles, radar charts or flower diagrams have widely been used to elucidate ecosystem service diversity and to illustrate the composition or spatial clustering of multiple ecosystem services (Dittrich et al., 2017; Huang et al., 2015; Manning et al., 2018).

While there is no single best MF indicator, the choice of the quantification method needs to be based on the research question. The variety of available methods can also be used to highlight different aspects of MF (e.g. Früh-Müller et al., 2018), and to enable a sensitivity analysis of the results (Stürck and Verburg, 2017; Valencia et al., 2015).

Participatory approaches. The involvement of stakeholders within MF assessments and ecosystem service studies in general is small (Seppelt et al., 2011), which limits our understanding of the relationships between ecosystems and human well-being (Bennett et al., 2015). In order to better understand such relationships and to spur discussions on land use, the demand for individual ecosystem services and for overall MF needs to be integrated in socially-relevant studies (Cowling et al., 2008; O'Farrell and Anderson, 2010). In particular ES-MF assessments should therefore aim at a sensible involvement of stakeholders at different stages of the assessments: (i) conceptualization of MF; (ii) selection and valuation of ecosystem functions and services; and (iii) development of scenarios and planning for land use changes (Mastrangelo et al., 2014). A stronger focus on appropriate stakeholder involvement would significantly strengthen ES-MF assessments and enhance their policy relevance. We argue that MF indicators would then change from largely descriptive indicators to more normative ones.

5. Conclusions

While landscape MF has become a general policy aim and the number of papers published on MF increased rapidly since the 2000s, a lack of implementation of the concept in environmental management has been pointed out (Otte et al., 2007; Wiggering et al., 2003). This review of 101 publications using quantitative methods to assess ecosystem or landscape MF shows that these studies are associated with many different research fields. It also reflects on the variety of conceptualizations of MF and it summarizes the state-of-the-art of assessment methods. To provide guidance for priority setting and to spur the use of quantitative MF assessments in different research fields, we here conclude with recommendations towards improved MF assessments and their interpretations:

1) MF needs to be assessed differently, depending on the research context. The choice of ecosystem functions and services considered is therefore a critical first step in the study design and should not be driven by data availability only. Depending on the research question, MF can, for example, be assessed by focusing solely on ecological aspects or more on integrative socio-ecological perspectives.

2) The choice of the MF indicator used needs to take into account the underlying assumptions, strengths and weaknesses of each approach. A combination of multiple methods can be used to estimate the sensitivity of the results. MF studies should further include an integrative analysis of trade-offs and synergies among ecosystem functions and services.

3) MF assessments having a socio-ecological focus can be significantly strengthened by more (targeted) stakeholder involvement. This would enable their use as normative planning tools and would make assessments more relevant for decision-making processes.

Acknowledgements

We acknowledge funding from the Helmholtz Association (Research School ESCALATE, VH-KO-613, LH, MB) and from the 2013/2014 BiodivERsA/FACCE-JPI joint call, with the national funder BMBF - German Federal Ministry of Education and Research (Project "TALE - Towards multifunctional agricultural landscapes in Europe: Assessing and governing synergies between food production, biodiversity, and ecosystem services", grant 01 LC 1404 A). Special thanks to all reviewers for providing helpful and constructive feedback. Icons (Fig. 4, Fig. 5) made by Freepik from www.flaticon.com.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version. The Supplementary data includes the list of 101 MF assessments that were reviewed in this study (Table A11).

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