Received: 4 October 2017 | Revised: 27 March 2018 | Accepted: 31 May 2018
DOI: 10.1002/ldr.3066

SPECIAL ISSUE ARTICLE

WILEY

Managing soil functions for a sustainable bioeconomy—Assessment framework and state of the art

Katharina Helming[1,2] | Katrin Daedlow[3] | Carsten Paul[1] | Anja-Kristina Techen[1] | Stephan Bartke[4] | Bartosz Bartkowski[4] | David Kaiser[1] | Ute Wollschläger[5] | Hans-Jörg Vogel[5]

[1] Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany
[2] Faculty of Landscape Management and Nature Conservation, University for Sustainable Development (HNEE), Eberswalde, Germany
[3] Division Agriculture and Food Policy, Humboldt-Universität zu Berlin, Berlin, Germany
[4] Department of Economics, UFZ - Helmholtz Centre for Environmental Research, Leipzig, Germany
[5] Department Soil System Science, Helmholtz Centre for Environmental Research - UFZ, Halle (Saale), Germany

Correspondence
K. Helming, Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str 84, D-15374 Müncheberg, Germany.
Email: helming@zalf.de

Funding information
Bundesministerium für Bildung und Forschung (BMBF), Grant/Award Number: 031A608A, B

Abstract

Bioeconomy strategies have been adopted in many countries around the world. Their sustainable implementation requires a management of soils that maintains soil functions and avoids land degradation. Only then, ecosystem services can be maintained and resources used efficiently. We present an analytical framework for impact assessment that links policy and technology driving forces for soil management decisions to soil processes, soil functional changes, and their impacts on ecosystem services and resource use efficiency, both being targets that have been set by society and are anchored in bioeconomy policy strategies and sustainable development goals. Although the resource use efficiency concept has a long-term tradition, most studies of agricultural management do not address the role of soils in their efficiency assessment. The concept of ecosystem services has received increasing attention over the last years; however, its link to soil functions and soil management practices is still not well established. This study is the first to conceptually link the socioeconomic processes of external drivers for soil management with the natural processes of soil functions and connect them back to impacts on the social system. Application of the framework helps strengthen the science-policy interface and to systemically assess and compare the opportunities and threats of soil management practices from the perspective of goals set by society at different spatial and temporal scales. Insights gained in this way can be applied in stakeholder decision-making processes and used to inform the design of governance instruments aimed at sustainable soil management within a bioeconomy.

KEYWORDS

bioeconomy, ecosystem services, impact assessment, resource use efficiency, soil management practices, sustainable development goals

1 | INTRODUCTION

Soils functions are vital to food production, climate mitigation, and other ecosystem services. Agricultural management generally favors the production function over other soil functions, namely, water purification, carbon sequestration, habitat for biodiversity, and recycling of nutrients and (agro) chemicals (Schulte et al., 2014). Numerous drivers further stimulate this imbalance between soil functions, such as dietary changes and a globally increasing demand for food (Alexander et al., 2015) and, in many countries, a transition from fossil-based economies towards bioeconomies (Fund, El-Chichakli, Patermann, & Dieckhoff, 2015). Bioeconomy strategies strive for the agricultural production of more nonfood products, including energy and materials to substitute fossil resources, in addition to food products. However, ensuring a balanced system of soil functions and thereby avoiding soil degradation is important, not only to sustain soil fertility in the long term but also to meet other targets set by society, such as climate change mitigation and the support of regulating ecosystem services (flood control, cooling, buffering of weather extremes, and biodiversity) and cultural ecosystem services (recreation, heritage, and amenity; Dominati, Patterson, & Mackay, 2010). Additionally, biomass production needs to follow resource use efficiency considerations to avoid jeopardizing resource saving purposes inherent in the bioeconomy strategies (Scarlat, Dallemand, Monforti-Ferrario, & Nita, 2015). The term "sustainable intensification" (Garnett et al., 2013) was introduced to signify the challenge for agricultural management to increase production without increasing environmental pressures. This goal can only be achieved when agricultural resources are utilized efficiently and when ecological interactions are intensified to stimulate the inherent capacity of soil to produce biomass (Tittonell, 2014).

Operationalizing the concept of sustainable intensification from the perspective of soils requires improvements in at least two research fields: soil management–soil process interactions and impact assessment. Impact assessment is a means to synthesize scientific knowledge to inform policy and management (Carpenter, Bennett, & Peterson, 2006). It implies a linkage of the socioeconomic system of target setting and decision-making with the natural system of biological, physical, and chemical process interactions. It weaves an analytical thread from driving forces to management decisions to soil reactions, soil function changes, and their impacts on targets set by society. Such targets are usually defined in strategic policy documents such as the bioeconomy strategy and integrate across social, economic, and environmental targets. The knowledge gained by impact assessment supports stakeholders in making decisions in various contexts of decision-making, such as soil management (de Olde, Oudshoorn, Sørensen, Bokkers, & de Boer, 2016), governance and policy formulation (Podhora et al., 2013), or research design for sustainable development (Bond & Pope, 2012). To the best of our knowledge, no systematic, dynamic approach to an impact assessment of soil management and soil functions on targets set for a sustainable bioeconomy exists yet.

Although there is comprehensive, albeit not well systemized, evidence about the impacts of soil management on soil processes (Vogel et al., 2018), the linkage to targets set by society has only recently emerged in scientific and policy debate. Here, two partly interlinked assessment concepts stand out: ecosystem services and resource use efficiency. The concept of ecosystem services aims to demonstrate the value or contributions of nature to human societies (Costanza et al., 1997; Díaz et al., 2018; Haines-Young & Potschin, 2013; Millennium Ecosystem Assessment [MEA], 2005; The Economics of Ecosystems and Biodiversity [TEEB], 2010). The value can be seen as arising from the interaction of biotic and abiotic processes, and it specifically refers to the "final" outputs of ecological systems, that is, the goods and services directly consumed or used by people (Haines-Young & Potschin, 2013). Resource use efficiency is defined as the ratio of benefits generated by a product or process divided by the amount of resources used for that purpose (Di Maio, Rem, Baldé, & Polder, 2017). Both concepts are relevant to linking soil functions to bioeconomy targets and internationally acknowledged sustainable development goals (SDGs; General Assembly, 2015). Among the manifold linkages between soil functions and SDGs (Keesstra et al., 2016), three SDGs pertain most profoundly to soil functions from an ecosystem service perspective: SDG 2, target 2.4 (sustainable provision of food and regulating and maintenance services); SDG 13, target 13.2 (climate action—regulating services), strengthened by the "4 pour 1000"-initiative (Ministère de l'Agriculture, 2015); and SDG 15, target 15.3 (restoring degraded soils and achieving a land-degradation neutral world). One SDG pertains most profoundly to soil functions from a resource use efficiency perspective: SDG 12, target 12.2 (sustainable and efficient use of natural resources). A comprehensive assessment would therefore require a combination of the two concepts of ecosystem services and resource use efficiency.

The objective of this paper is to construct a robust analytical framework for an impact assessment of soil management and soil functions and to compile state-of-the-art knowledge of its analytical components, including a thorough discussion of opportunities and limits for the application of the framework.

The analytical framework combines the two concepts of resource use efficiency and ecosystem services into an assessment that links driving forces and management decisions to soil reactions, soil function changes, and their impacts on bioeconomy and sustainable development targets. We have developed this framework in the context of the National German research program BonaRes—"Soil as a Sustainable Resource for the Bioeconomy" (www.bonares.de).

2 | ANALYTICAL FRAMEWORK FOR IMPACT ASSESSMENT

The analytical framework combines the driver–pressure–state–impact–response (DPSIR) framework (Gabrielsen & Bosch, 2003) with the five steps of impact assessment (Helming, Diehl, Geneletti, & Wiggering, 2013). DPSIR was developed for the assessment of relations between human activities and the environment. The specific strength of the concept lies in its adaptability to various impact areas, objectives, and scales of analysis (Tscherning, Helming, Krippner, Sieber, & Paloma, 2012). For example, it has been proposed for soil system analysis by Bouma, de Vos, Sonneveld, Heuvelink, and Stoorvogel (2008) and Schjønning et al. (2015). Based on the DPSIR framework, we integrate the five steps of impact assessment (Figure 1): (1) analysis of future trends and driving forces for soil management; (2) definition of human activities exerting pressures on ecological systems, which in our case is soil management; (3) analysis of the effects of human activities on the state of ecological systems, which are soil processes and soil functions; here, this analytical step concerns the soil system, depicts how soil processes are affected by soil management, and describes how soil processes impact the ensemble of soil functions; (4) assessment and valuation of direct and indirect impacts in the context of social, economic, and environmental targets; here, we use the resource use efficiency and ecosystem service concepts; and (5) elaboration of governance instruments—making use of assessment results—to provoke responses that counteract

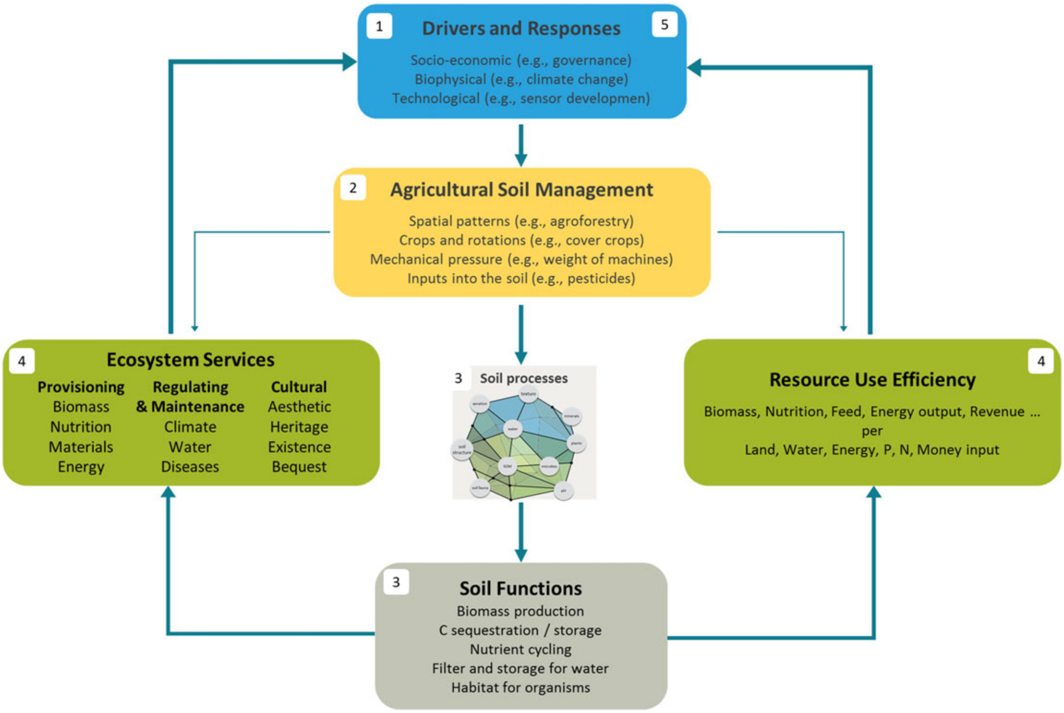

FIGURE 1 Analytical framework for impact assessment of agricultural soil management and soil functions. Numbers refer to the five steps of the DPSIR system: drivers (1), pressures (2), states (3), impacts (4), and responses (5) [Colour figure can be viewed at wileyonlinelibrary.com]

negative impacts and reinforce positive impacts. For example, (1) bioenergy policy (driver) can increase the demand for biomass and (2) motivate management change towards a higher share of maize in the crop rotation (pressure); (3) this narrower crop rotation affects the soil (e.g., changed and nutrient balance and altered composition of soil microbial communities) which in turn (4) has an impact on ecosystem services (increased nitrogen discharge, higher risk of water erosion) and resource use efficiency (yield per hectare, revenue per cost) with a consequence for the terrestrial ecosystem (SDG15). Based on an assessment of this causal chain, (5) policy makers may decide to revise the bioenergy policy (response). The five assessment steps are elaborated in subsequent sections, and state-of-the-art knowledge in the context of sustainable intensification is provided for each.

We particularly emphasize analytical Step 4, the impacts step. It evaluates the consequences of human activities on social and ecological systems from the perspective of targets set by society, thereby taking an anthropocentric viewpoint. In our framework, we focus on soil management practices as the human activities that trigger changes in soil functions, and the latter are understood to be the key linkages between ecological and societal systems. Depending on the system components of such linkages, impacts of human activities can be assessed by different value systems. Our framework has been developed to study the impacts of soil management practices in industrialized agricultural systems with low yield gaps and a low share of agriculture in the gross domestic product, as is the case in most industrialized countries. Targets set by society for such soil management systems are characterized by an ecosystem services perspective, that is, increasing biomass production while maintaining the contribution of soil functions to the other ecosystem services; and by resource use efficiency, that is, an increasing return from invested resources (Figure 1). The latter is rarely considered in recent studies on the value of soil functions for society (Schulte et al., 2014; Schwilch et al., 2016; Stavi, Bel, & Zaady, 2016), or it is not as explicit as the ecosystem service perspective (Keesstra et al., 2016). While both assessment concepts are at first sight motivated by environmental perspectives, the economic perspective is inherent in either of them. Embedded in the natural capital concept (Costanza et al., 1997), ecosystem services are understood as natural assets that can be evaluated in terms comparable to economic activities and manufactured capital. The resource use efficiency concept directly considers the economic dimension through indicators describing a benefit-cost ratio. Costs may be monetary or arise in the form of resources required. A high resource use efficiency is generally required to achieve competitive production. It is important to note that, for other agricultural systems (e.g., small holder farming in developing countries), additional and/or different assessment perspectives are appropriate, for example, motivated by targets such as nutrition, poverty alleviation, or rural development.

The proposed framework seeks to establish an analytical basis for the identification of indicators for impact assessment. The framework allows two modes of interaction between soil management (key pressure) and impacts: soil-borne interactions via changes in soil processes and soil functions (solid arrow in Figure 1) and management-induced interactions irrespective of changes in the soil system (thin arrows in Figure 1).

The definition of system boundaries, including the governance level and spatial and temporal scales, is essential for the assessment of management impacts. The chosen boundaries must reflect whether relevant impacts are expected at the respective spatial or temporal scale to avoid misleading results. Inclusion of effects up to a global scale may be required to account for spill-over effects, such as indirect land use changes, that is, the impacts of management decisions in one region emerging in other regions. The temporal scale must be sufficiently wide to account for an improvement or deterioration of soil functions and ecosystem services through management, which often only emerge after considerable time lags (Fremier et al., 2013). The challenges of assessing the impacts of these spill-over effects are discussed in Section 8.

3 | AGRICULTURAL SOIL MANAGEMENT AND ITS DRIVING FORCES

We use the term agricultural soil management for practices that affect soil processes and soil functions, and that are thus a pressure on soil in terms of the DPSIR framework. Agricultural soil management is driven by socioeconomic, biophysical, and technological drivers, such as policy subsidies, policy regulations, prices, information systems, climate change and advances in tillage technology, breeding, communication technology, and robotics. These drivers, in combination and with complex feedback mechanisms, constitute the background situation against which farmers make decisions on soil management and cropping practices; in turn, these decisions affect soil processes and soil functions. A categorization of management practices developed by Techen and Helming (2017) distinguishes between five main categories: (a) spatial patterns, (b) crops and rotations, (c) mechanical pressures, and (d) inputs into the soil (Figure 2). The categorization combines that of Haddaway et al. (2015) on the effects of agricultural management on soil organic carbon with that of Duru et al. (2015) on the effects of agricultural management on ecosystem services. Changes in soil management can occur either by changing the quantity of input factors, such as the amount of fertilizers and pesticides, or by qualitatively changing management, for example, by adding new crops to rotations or introducing different tillage practices. In the following, the management categories are illustrated with examples of practices and drivers.

Spatial patterns of cropping affect soils in multiple ways. For example, field transition zones and adaptations to landscape contours shorten overland flow lines and reduce erosion (Panagos et al., 2015). The same is true for the emerging practice of strip-tillage, which may also have potentially positive impacts on natural pest antagonists, microclimate and biological interactions (Williams et al., 2016). Intercropping and agroforestry form spatial cropping patterns that may gain relevance in temperate regions, for example, due to ongoing research and market developments for lignocellulosic products (Chum et al., 2015; Fagerholm, Torralba, Burgess, & Plieninger, 2016; Pelzer, Hombert, Jeuffroy, & Makowski, 2014; Yu, Stomph, Makowski, & van der Werf, 2015).

Crop species and varieties have different characteristics that are relevant to soil, such as root structure and effects on pest suppression. In Europe, approximately 60% of crop land is covered with cereals, half of which is wheat (Eurostat, 2016; Eurostat, 2017a). Recent trends, including emerging pesticide resistance and diversified consumer demand, may lead to increased diversity of crop rotations (DLG-Vorstand, 2017; Last, Buchmann, Gilgen, Grant, & Shreck, 2015); however, more narrow rotations are also possible in some regions, for example, due to climate change (Troost & Berger, 2015). New breeding technologies, such as CRISPR/cas9, may improve crop varieties but may also generate novel risks for ecosystems (Science for Environment Policy, 2016).

Mechanical pressures on soils mainly originate from machine use, including tillage and field traffic. For example, in the UK, France, and Germany, conservation tillage was practiced on approximately 40% of arable land in 2010, whereas in Scandinavian countries, it was practiced on 10–22% of arable land (Eurostat, 2017b). Cost saving is an established driver of reduced tillage (Flessa et al., 2012), whereas soil threats, particularly soil erosion (Techen, Ries, & Steinführer, 2015) and climate adaptation may drive its adoption in the future (Olesen et al., 2011). The weight of agricultural machines has increased for decades, leading to compaction and damage to soil structure (Schjønning et al., 2015). Emerging mitigation measures include decision-support systems that optimize field traffic corresponding to site characteristics (Han, Steward, & Tang, 2015) and smaller, autonomous

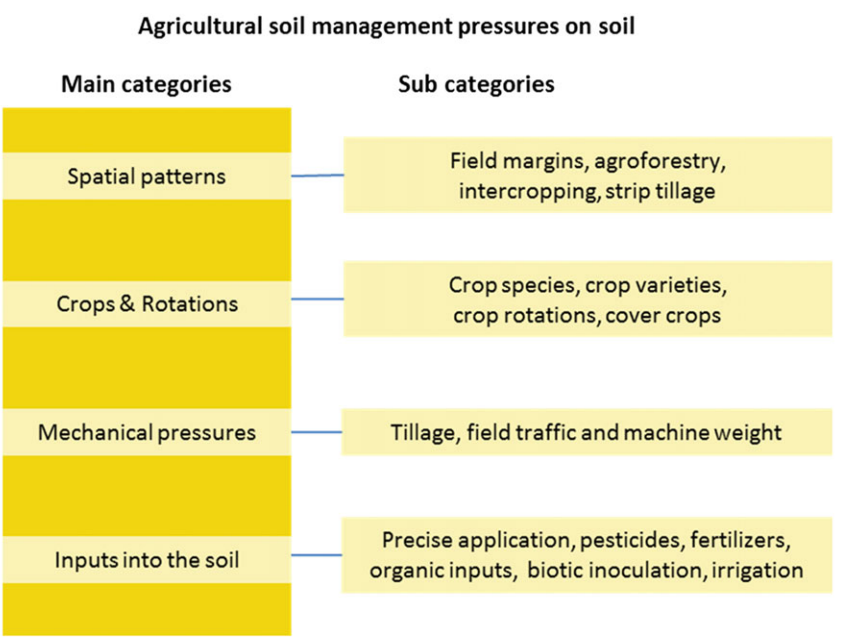

FIGURE 2 Categories of agricultural soil management practices affecting soil processes and soil functions (adapted from Techen & Helming, 2017) [Colour figure can be viewed at wileyonlinelibrary.com]

machines (e.g., Conesa-Muñoz, Gonzalez-de-Soto, Gonzalez-de-Santos, & Ribeiro, 2015; ecoRobotix Ltd., 2016); however, their future adoption is associated with numerous uncertainties.

The main inputs that farmers apply to soils are mineral fertilizers, organic material, pesticides and, in many countries, water. The pressures on soil in these categories differ by the applied quantity, spatial and temporal distribution and characteristics of the substance. Technological developments improve the site specificity and accuracy of application, leading to reduced inputs (especially for pesticides) and increased efficiency (especially for fertilizers; Flessa et al., 2012; Meuli, 2016). Pesticide application can also be reduced by promoting antagonists of pests, for example, by adding organic amendments or inoculating soil or seeds with beneficial organisms. The latter is still rare, but researchers see significant advances and potential for this technology (Johnson et al., 2016; Kergunteuil et al., 2016).

Opportunities for sustainable intensification especially lie in qualitative management changes (Garnett et al., 2013), which improve the inherent production capacity of the soil and thereby improve resource use efficiency and minimize adverse impacts on ecosystem services. However, new practices may in general also create novel threats to soil functions and ecosystem services, which must be better understood and assessed to support decision-making towards a sustainable bioeconomy.

4 | SOIL PROCESSES AND FUNCTIONS

From an anthropocentric viewpoint, soils have several functions, and Blum's classification (Blum, 1990) became very influential in policy (Baveye, Baveye, & Gowdy, 2016), for example, in the Soil Thematic Strategy of the European Union (European Commission, 2006). From the perspective of agricultural soil management that affects earth system functioning, five soil functions are critical to our study: biomass production, storing and filtering of water, storing and recycling of nutrients, habitat for organisms, and carbon storage. The performance of soils regarding these functions depends on inherent soil properties (e.g., texture, depth, mineralogy, and horizon sequence), geo-biophysical site conditions (e.g., relief, climate, and altitude), their management history, and actual soil processes as affected by soil management practices. Soil functions are considered to be integral properties that emerge from complex interactions between physical, chemical, and biological processes depending on these manifold factors. The quantification of soil functions is a prerequisite for any assessment, and it may lead to trade-offs but can also lead to potential complementarities (Reed et al., 2013). Every function can also be seen as providing a soil-related contribution to ecosystem services (Bouma, 2014; Keesstra et al., 2016). Thus, soil functions are the linkage from soil systems' processes to the valuation of performance or their services in the context of sustainable development.

All soil science disciplines have developed sophisticated methods to explore physical, chemical, and biological processes using a broad spectrum of observable soil attributes. However, it is not yet obvious how steadily improving insights can be synthesized into a better understanding of soil functioning (Kibblewhite, Ritz, & Swift, 2008). There is a need to identify soil functional characteristics that integrate systemic knowledge about the complex, nonlinear interactions between soil components and processes on various temporal and spatial scales on the one hand and to link them to soil management practices on the other hand. Soil functional characteristics emerge from the interactions between soil components (e.g., minerals, roots, and organisms) and soil processes (e.g., physical, chemical, and biological processes). They are sensitive to soil management and may change at a time scale of days to months. Examples are water capacity, aggregate stability, macropores, organic matter, and functional group diversity. The typical range of such functional characteristics depends on the soil type and the inherent soil properties that are considered to be stable at the time scale of decades (Vogel et al., 2018). They in turn influence state variables (e.g., water content, biological activity, and temperature) that change very quickly within days. The research challenge for soil sciences is an in-depth exploration of the spatial and temporal dynamics of soil functional characteristics being the basis to derive meaningful indicators for soil functions based on well-defined and observable soil properties. For a recent review on soil quality indicators, see also Bünemann et al. (2018), who make a plea for novel indicators that can account for the multifunctionality of soils.

5 | RESOURCE USE EFFICIENCY

In the context of soil management, we define resource use efficiency as ratio between benefits generated by agricultural production processes and the amount of resources used. Only resources for which there is competing demand are considered (Di Maio et al., 2017). Competition is context-specific and can be due to demand exceeding resource limitations or due to conflicts between resource use and other targets set by society (e.g., pesticide application conflicting with biodiversity preservation).

The concept of agricultural resource use efficiency is much older than the concept of soil functions, and few assessments documented in the literature explicitly address the role of soils. However, assessment results often implicitly reflect changes in soil functions due to the paramount role of soils for crop growth. Within the context of research for sustainable bioeconomies, it will be necessary to determine how soil functions affect resource use efficiencies and additionally, to what degree soil management can increase efficiencies.

The spatial and temporal scope must be clearly defined before efficiency assessments because system boundaries can have strong implications for the final results. Leakage, cascade, and rebound effects should be considered (Lambin & Meyfroidt, 2011). The use of multiyear averages and considering production over several years is necessary to account for interannual yield variability and crop rotation effects (Preissel, Reckling, Schläfke, & Zander, 2015; Zhang et al., 2017).

Farm- or field-level resource use efficiencies are of particular interest to practitioners, especially when they affect economic performance. Typical indicators are productivity (Alam, Humphreys, Sarkar, & Sudhir, 2017; Moreau et al., 2012; Zhang, Wang, Ma, Zhang, & Fu, 2016), water use efficiency (Pascual, Villar, & Rufat, 2016; Wei et al., 2016; Zhao et al., 2010), benefit-cost ratio (Alam et al., 2017; Moreau et al., 2012; Rehman, Farrukh Saleem, Safdar, Hussain, & Akhtar, 2011), nutrient use efficiency (nitrogen: Buckley, Wall, Moran, O'Neill, & Murphy, 2016; Gu, Ju, Chang, Ge, & Chang, 2017; and phosphorous: Gerber, Uwizeye, Schulte, Opio, & de Boer, 2014; Zhang et al., 2016), and energy use efficiency (Arodudu, Helming, Voinov, & Wiggering, 2017; Hill, Nelson, Tilman, Polasky, & Tiffany, 2006). Efficiency assessments with landscape or global implications are relevant to policy makers. Indicators include GHG emissions per yield (Khakbazan et al., 2017; Steyn, Franke, van der Waals, & Haverkort, 2016) or gross domestic product contribution per domestic material consumption (European Environment Agency, 2016; European Commission, 2011). Table 1 gives an overview on resource use efficiency indicator use in recent literature.

Indicators can be tailored to compare or monitor specific efficiencies. Examples are efficiencies for job provision (jobs generated per hectare of farmland by different biomass usages; BMEL, 2014) or economic risk efficiency (how does irrigation affect the amount of revenue that can be expected under a defined probability level; Meyer-Aurich, Gandorfer, Trost, Ellmer, & Baumecker, 2016).

In most cases, increased efficiency aligns with targets set by society or policy targets (e.g., European Commission, 2011; General Assembly, 2015). However, being too efficient is also possible. Reducing the labor required to produce an amount of biomass may have negative implications for job provision; nutrient use efficiencies greater than 100% are indicative of nutrient mining by harvest (Scholz & Wellmer, 2015) and maximizing the share of biomass harvested relative to net primary production conflicts with biodiversity targets (Mudgal et al., 2012).

Resource use efficiency indicators require the selection of specific benefits and resources. These choices should be guided by the intended function of a process and its main inputs and by the characteristics of production alternatives. However, agriculture is characterized by the production of multiple benefits while using multiple resources. For a comprehensive efficiency assessment, the appraisal of several indicators is therefore essential. The use of monetary indicators is an economic option that integrates the benefits of different products based on their explicit or implicit market value. However, the environmental and social consequences of resource use are often difficult to reflect in monetary terms and values attributed to nonmarketed goods vary strongly (Baveye et al., 2016). Several alternatives have been suggested to create integrated indicators. A parametric technique based on benchmarking is stochastic frontier analysis (Boshrabadi, Villano, & Fleming, 2008; Li, Feng, You, & Fan, 2013). A more common, nonparametric approach is data envelopment analysis (DEA; Table 1). Linear combinations of all enterprises or processes in a sample are used to calculate an *efficiency frontier* that represents combinations with the highest (positive) output and smallest resource use. Efficiencies are calculated as the distance to this frontier. Hoang and Alauddin (2012) used DEA to create efficiency scores for 30 Organisation for Economic Co-operation and Development countries based on agricultural production, costs, and fertilizer and energy use. Masuda (2016) used DEA to calculate eco-efficiency of Japanese wheat production based on global warming potential, aquatic eutrophication potential, and yield. Although integrated indicators allow for quick comparisons of efficiencies, the choice and weighing of efficiency categories that contribute to the indicator and final result interpretation are challenging.

Resource use efficiency is central to achieving highly productive agriculture while minimizing harmful externalities, including land degradation. However, although efficiency assessments are well suited to reflect performance, they can only cover a limited number of categories and are therefore unable to provide a holistic view of system interactions. In this regard, an assessment of ecosystem services provides an appropriate complementary measure.

6 | ECOSYSTEM SERVICES IMPACTS

The role of the soil system from the perspective of the ecosystem services concept was recently substantiated in a number of publications (Adhikari & Hartemink, 2016; Baveye et al., 2016; Bünemann et al., 2018; Keesstra et al., 2016; Schwilch et al., 2016; Stavi et al., 2016) in addition to earlier studies on distinct aspects (Bennett, Mele, Annett, & Kasel, 2010; Blum, 1993; Bouma, 2014; Breure et al., 2012; Daily, Matson, & Vitousek, 1997; Dominati et al., 2010; Pulleman et al., 2012; Robinson, Lebron, & Vereecken, 2009; Schulte et al., 2014). While each of the studies developed an individual perspective on assessing and valuating the contribution of soils to ecosystem services, a coherent analytical approach that applies the ecosystem service concept as a linkage to (a) soil management practices, (b) soil functions, and (c) other targets set by society, such as resource use efficiency, has not yet been developed. In the following paragraphs, we evaluate the suitability of the conceptual potential of existing studies to inform our analytical perspective of the impact assessment framework.

First, the importance of managing soil functions to support ecosystem services is widely acknowledged (Breure et al., 2012; Schulte et al., 2014). However, the operationalization of linkages between soil management, soil functions, and ecosystem services remains a challenge (Schwilch et al., 2016; Stavi et al., 2016). Our framework addresses this gap by linking soil management practices to soil functions and services in particular (Figure 1).

Second, the literature on ecosystem services has not yet found common ground on a conceptual delimitation of soil functions (Baveye et al., 2016; Bennett et al., 2010; Dominati et al., 2010; Robinson & Lebron, 2010; Schwilch et al., 2016; Stavi et al., 2016). This analytical disarray is aggravated by the fact that (a) researchers apply different, selective, and independently developed categories of classification systems for soil functions (Blum, 2005; FAO & ITPS, 2015; Stavi et al., 2016), and (b) different available ecosystem service classification systems exist (Haines-Young & Potschin, 2013; MEA, 2005; TEEB, 2010). Likewise, a conceptual study that directly connects soil function to services and that proposes a differentiation between both concepts is hard to find (an exception is,e.g., Pulleman et al., 2012, investigating soil biodiversity). For our study, we suggest application of the cascade model, which differentiates between structures, functions, services, benefits, and (economic) values of ecosystems along a so-called cascade chain (Braat & de Groot, 2012; Haines-Young &

TABLE 1 Indicators for measuring resource use efficiency in agriculture [Colour table can be viewed at wileyonlinelibrary.com]

Separate indicators					
Benefit →					
Resource ↓	Embodied energy	Embodied nitrogen	Revenue	Sequestered carbon	Yield
Agricultural land	Lin, Huber, Gerl, & Hülsbergen, 2017		Baumane, Celms, & Ratkevics, 2014; Li et al., 2013; Miklovicova & Miklovicova, 2012; Moreau et al., 2012; Rehman et al., 2011; Spicka, 2015		Moreau et al., 2012; Phengphaengsy & Okudaira, 2008; Rehman et al., 2011; Steyn et al., 2016; Zhao et al., 2010
Energy	Alluvione, Moretti, Sacco, & Grignani, 2011; Deike, Pallutt, & Christen, 2008a; Deike, Pallutt, Kustermann, & Christen, 2008b; Giambalvo et al., 2009; Khakbazan et al., 2017; Lin et al., 2017; Romanelli, Nardi, & Saad, 2012; Wasiak & Orynycz, 2014				Alluvione et al., 2011; Khakbazan et al., 2017
Fertilizer—N	Clark & Tilman, 2017	Buckley et al., 2016; Godinot, Carof, Vertès, & Leterme, 2014; Godinot, Leterme, Vertès, & Carof, 2016; Gu et al., 2017; Moreau et al., 2012; Rehman et al., 2011			Steyn et al., 2016; Rehman et al., 2011
Fertilizer—P					Korkmaz et al., 2009; Steyn et al., 2016
GHG emissions	Khakbazan et al., 2017				Khakbazan et al., 2017; Steyn et al., 2016
Human labor			Li et al., 2013		
Money (costs)			Li et al., 2013; Miklovicova & Miklovicova, 2012; Rehman et al., 2011	Khakbazan et al., 2017	
Pesticides			Van Lierde, Vandenberghe, Cools, De Backer, & Vergucht, 2009		
Water			Phengphaengsy & Okudaira, 2008		Pascual et al., 2016; Steyn et al., 2016; Wei et al., 2016; Zhao et al., 2010

Integrated indicators		
	Data envelopment analysis (DEA)	Stochastic frontier analysis (SFA)
Efficiency scores based on multiple inputs and outputs	Aldanondo-Ochoa, Casasnovas-Oliva, & Arandia-Miura, 2014; Azad & Ancev, 2014; Bojnec & Latruffe, 2011; Gomes et al., 2009; Hoang, 2011; Hoang & Alauddin, 2012; Lee & Park, 2017; Masuda, 2016; Pagotto & Halog, 2016; Sabiha, Salim, & Rahman, 2017; Spicka, 2014; Spicka & Smutka, 2014; Wang, Chen, Wu, & Li, 2015	Boshrabadi et al., 2008; Li et al., 2013

Note. Separate indicators are determined by the fraction of benefit divided by resource. Overview of studies published between 2008 and 2017 based on the Web of Science Core Collection by applying the search terms "efficiency" (title) and "agriculture," "indicator" (topic). Commonly applied indicators/methods are marked in red.

Potschin, 2009; Potschin-Young et al., 2017; TEEB, 2010) to assess the impacts of changing soil functions as a consequence of soil management. Here, soil functions represent ecosystem functions that are associated with soils. Together with the other ecosystem functions, soil functions contribute to ecosystem services.

The Common International Classification of Ecosystem Services (CICES) classification (Haines-Young & Potschin, 2013) is suitable for our framework because it currently provides the most complete and state-of-the-art classification developed based on TEEB (2010) and MEA (2005). In regard to services, CICES has a five-level hierarchical structure (section, division, group, class, and class type), which largely contributes to a standardization of ecosystem services and links to efforts to integrate them in national and European accounting systems (Edens & Hein, 2013). A first review of the CICES fourth-level classes (CICES V 4.3) suggests that most ecosystem services are primarily sensitive to soil functions, others are primarily sensitive to soil management, and some are affected by both (Table 2). However, indicator development and application are difficult due to manifold linkages between different services. Studies have mostly used unlinked, single indicators as proxies to assess the contribution of soil functions to ecosystem services (Grossman, 2015; Meylan et al., 2017; Schulte et al., 2014). It is important to clarify these analytical shortcomings to connect the insights and results from a large body of soil function literature to the ecosystem services concept.

Third, despite its very efficient approach to transferring environmental issues to science and society by streamlining social–ecological complexity to one dimension, that is, services for humans, the ecosystem services concept applied to soil management is limited because it does not consider other targets set by society or other valuation perspectives, such as resource use efficiency, equity, or health (Sandifer, Sutton-Grier, & Ward, 2015; Schröter et al., 2017). However, linkages to other valuation systems are possible, and the first studies have been conducted to discover these linkages, for example, as outlined by Bouma (2014) and Keesstra et al. (2016). Our framework addresses this conceptual gap by combining the ecosystem service approach with the resource use efficiency approach (Figure 1) that again can jointly inform governance of soil management and be considered in the design of particular policy instruments. More research is required to fully capture the link between valuation perspectives and governance as driver of soil management such as pioneered in a study by Öhlund, Hammer, and Björklund (2017).

TABLE 2 Common International Classification of Ecosystem Services (CICES) ecosystem service classes (V 4.3), adapted from Haines-Young & Potschin, 2013 [Colour table can be viewed at wileyonlinelibrary.com]

Provisioning services	Regulating & maintenance services	Cultural services
1. Cultivated crops	1. Bio-remediation by microorganisms, algae, plants, and animals	1. Experiential use of plants, animals, and land-/seascapes in different environmental settings
2. Reared animals and their outputs	2. Filtration/sequestration/storage/ accumulation by microorganisms, algae, plants, and animals	2. Physical use of land-/seascapes in different environmental settings
3. Wild plants, algae, and their outputs	3. Filtration/sequestration/storage/ accumulation by ecosystems	3. Scientific interactions
4. Wild animals and their outputs	4. Dilution by atmosphere, freshwater, and marine ecosystems	4. Educational interactions
5. Plants and algae from in situ aquaculture	5. Mediation of smell/noise/visual impacts	5. Heritage, cultural interactions
6. Animals from in situ aquaculture	6. Mass stabilization and control of erosion rates	6. Entertainment interactions
7. Surface water for drinking	7. Buffering and attenuation of mass flows	7. Aesthetic interactions
8. Ground water for drinking	8. Hydrological cycle and water flow maintenance	8. Symbolic interactions
9. Fibers and other materials from plants, algae, and animals for direct use or processing	9. Flood protection	9. Sacred and/or religious interactions
10. Materials from plants, algae, and animals for agricultural use	10. Storm protection	10. Existence
11. Genetic materials from all biota 12. Surface water for nondrinking purposes 13. Ground water for nondrinking purposes 14. Plant-based resources 15. Animal-based resources 16. Animal-based energy	11. Ventilation and transpiration 12. Pollination and seed dispersal 13. Maintaining nursery populations and habitats 14. Pest control 15. Disease control 16. Weathering processes 17. Decomposition and fixing processes 18. Chemical condition of freshwaters 19. Chemical condition of salt waters 20. Global climate regulation by reduction of greenhouse gas concentrations 21. Micro and regional climate regulation	11. Bequest

Note. Colors highlight services that we consider to be strongly affected by agricultural soil management: primarily via changes in soil functions (red), primarily nonsoil mediated (blue), and both via management and changes in soil functions (purple).

7 | RESPONSES AND GOVERNANCE FOR SUSTAINABLE SOIL MANAGEMENT

Multiple drivers influence the soil management decisions of farmers, and soil management decisions are also indirectly influenced via the decisions of other actors, particularly consumers. Their decision-making occurs in the context of governance structures, including obligatory, incentive-based and awareness-raising instruments (e.g., fertilizer regulation, agri-environmental measures and common agricultural policy subsidies, and persuasive campaigns). Of all the drivers of soil management, governance structures can be changed through policy, and thus, these instruments can be used to counteract or reinforce drivers in accordance with goals set by society. In this sense, governance is both a driver (current governance structures) and a means of response. Any governance structure is the result of societal processes of negotiation and deliberation among different actor and lobby groups (e.g., farmers, environmentalists, consumer groups, and industries).

The information generated through impact assessment is crucial to crafting appropriate responses; impact assessment informs the (re-)design of governance instruments and institutions that influence other drivers of soil management in such a way as to redirect pressures in line with goals set by society (Figure 1). Currently, soil-related governance is heavily understudied (Juerges & Hansjürgens, 2018); in the European Union, many different policies that influence soils exist, but because of failure to establish a Soil Framework Directive, they are not necessarily consistent with each other and only partially tackle the needs of sustainable soil management (Glæsner, Helming, & de Vries, 2014; Kutter et al., 2011; Paleari, 2017; Vrebos et al., 2017).

The challenge for sustainable soil governance is thus to align the use of soils with targets set by society, building on the results of impact assessments of different soil managements. In addition to the proper understanding of the sequence from soil management ➔soil processes ➔soil functions ➔human well-being (see Sections 5 and 6), governance needs to account for relevant future developments and drivers of soil management (Section 3) and the way that relevant actors behave and make their decisions—the latter is important for anticipating how actors, especially farmers, will respond to new governance structures and institutions. Monetary aspects of soil management are crucial for farmers acting as economic entities, albeit not the only factor. While a large amount of literature exists that deals with individual specific factors influencing farmers' decision-making (e.g., Lamarque, Meyfroidt, Nettier, & Lavorel, 2014; Lienhoop & Brouwer, 2015; Senger, Borges, & Machado, 2017), to be effective, governance has to be informed by the full suite of these factors. Much can be learned from the emerging field of behavioral environmental economics (Gsottbauer & van den Bergh, 2011). Furthermore, designing governance structures and institutions for sustainable soil management occurs in an existing institutional setting that needs to be adapted to new political goals. Future governance structures aimed at sustainable soil management should build upon the profound knowledge of existing structures and institutions in the status quo.

Based on the results of impact assessment on how well targets set by society are met under current management conditions, tailor-made governance instruments can then be identified and applied to steer soil management in favor of soil functioning.

8 | POTENTIAL AND LIMITATIONS

The assessment framework constructed here embeds the ecological sphere of soil process/soil function interactions within the socioeconomic spheres of soil management and its driving forces on the one side, and targets set by society on the other side, with governance linking the two sides. Its application enables a comparative analysis of alternative decision options and thereby supports decision-making towards sustainable implementation of bioeconomy strategies from a production perspective. However, the application of the framework is subject to an improved understanding of the causal chain relationships in each of its steps, including feedback loops, spatio-temporal variations, data needs, and modeling approaches. The particular asset is to use the framework for the design and setup of application studies, to identify the required expertise from different disciplinary backgrounds, and to facilitate their interdisciplinary cooperation. To deal with data limitations, applications would involve a combination of quantitative analysis and qualitative, expert based assessments, for example, through the use of Bayesian belief networks (Gonzalez, Luque, Poggio, Smith, & Gimona, 2016). Stakeholder engagement in the application would improve the adoption of assessment results by land managers and policy (Bünemann et al., 2018).

We constructed the assessment perspective by combining the concepts of ecosystem services with that of resource use efficiency to operationalize the term *sustainable intensification* in the context of bioeconomy strategies. Sustainable intensification aims for *increased production* while avoiding environmental damages (BMBF, 2010; BMEL, 2014). However, the term can also be understood as *increasing the sum of benefits from ecosystem services* (Buckwell et al., 2014; Garnett et al., 2013). This result may be achieved with constant or even lower production, especially in countries that already exhibit low yield gaps, for example, through higher shares of organic farming. Similar concepts are subsumed under the terms ecological intensification (Tittonell, 2014), agroecology (Duru et al., 2015), sustainable extensification (van Grinsven, Erisman, de Vries, & Westhoek, 2015), or smart intensification (Govers, Merckx, van Wesemael, & Van Oost, 2017). Additionally, consumption-side inefficiencies are at least as relevant as production-side inefficiencies. For example, reduction of wastage in food systems may significantly lower pressure on resources, including soils (Alexander et al., 2017). Sustainable intensification in the wider sense does therefore include the adoption of practices along the entire value chain of the food system (Rockström et al., 2017). Although these aspects have not been included in our framework, an extension in this direction is possible. Higher resource use efficiencies are often seen as a win–win solution for increasing economic competitiveness and reducing environmental burdens. However, most studies fail to include take-back or rebound effects. Rebound effects occur when higher resource use efficiencies lower production costs and product prices, resulting in changing patterns of production and consumption. This offsets part of the original resource saving and may in extreme cases lead to higher resource use than before. For example, higher irrigation efficiency can lower the price of irrigation, leading to a more widespread adoption of irrigation technologies and higher total water consumption (Pfeiffer & Lin, 2014). While more research is required to allow for quantifications of this effect, it must be considered in impact assessments. A strong collaboration of soil scientists with economists would be most beneficial in this respect.

Although the targets set by society that form the basis of our impact assessment framework, that is, raising efficiencies and maintaining or enhancing environmental services, are well defined, there is no consensus on how to handle trade-offs. Normative decisions are required to derive comprehensive evaluations, and they should ideally be made in cooperative processes involving all relevant stakeholder groups. Participatory elements can be linked to the framework presented here to structure such a process (Bond, Morrison-Saunders, Gunn, Pope, & Retief, 2015). A different study context, for example, in developing countries, can also require different assessment perspectives and targets set by society that are not considered here, including risks to human health or equity issues between societal groups and/or generations. These issues would involve different indicator systems, but they could be implemented within the same assessment framework.

9 | CONCLUSIONS

Increasing demand for production from soils carries threats to soil functions and increases risk of land degradation. New agricultural management methods provide opportunities and threats for aligning production with soil function maintenance. Assessments are necessary to avoid threats and optimize benefits. The comprehensive framework presented here is well suited for this task. It helps to identify drivers for the adoption of different management methods and pressures that require an impact assessment. It connects management to soil functions. In addition, it offers a systematic approach to connecting changes in soil functions with targets set by society, which in this case were sustainable solutions for bioeconomy strategies. We have integrated the two most common assessment concepts for this context in countries with low yield gap agricultures, namely, ecosystem services and resource use efficiency. The framework can also be adapted to other assessment concepts. Although efficiency gains from improved management are usually enabled through soil processes and soil functions, this link is rarely made explicit in scientific studies. Efforts must be made to better understand the contribution of soil functions to resource use efficiencies. From bioeconomy perspective, resource use efficiency is highly relevant for decision-making. However, it does not necessarily lead to maintaining soil functions. Regarding ecosystem services, there is still no conceptual consensus among scientists on the links from soil management and functions to ecosystem services. More research is required to improve systematic assessments of the effects of soil functions on ecosystem services, systematically assess leakage and rebound effects, consider trade-offs between targets set by society and include other targets, such as human health or equity. All this requires interdisciplinary cooperation. The proposed assessment framework helps to structure this interdisciplinary research.

ACKNOWLEDGMENT

This research is funded by the German Federal Ministry of Education and Research (BMBF) in the framework of the funding measure "Soil as a Sustainable Resource for the Bioeconomy – BonaRes," project "BonaRes (Module B): BonaRes Centre for Soil Research, subproject A, B" (Grant 031A608A, B).

ORCID

Katharina Helming http://orcid.org/0000-0002-4379-7377

Anja-Kristina Techen http://orcid.org/0000-0001-9564-712X

REFERENCES

Adhikari, K., & Hartemink, A. E. (2016). Linking soils to ecosystem services—A global review. *Geoderma*, *262*, 101–111. https://doi.org/10.1016/j.geoderma.2015.08.009

Alam, M. J., Humphreys, E., Sarkar, M. A. R., & Sudhir, Y. (2017). Intensification and diversification increase land and water productivity and profitability of rice-based cropping systems on the High Ganges River Floodplain of Bangladesh. *Field Crops Research*, *209*, 10–26. https://doi.org/10.1016/j.fcr.2017.04.008

Aldanondo-Ochoa, A. M., Casasnovas-Oliva, V. L., & Arandia-Miura, A. (2014). Environmental efficiency and the impact of regulation in dryland organic vine production. *Land Use Policy*, *36*, 275–284. https://doi.org/10.1016/j.landusepol.2013.08.010

Alexander, P., Brown, C., Arneth, A., Finnigan, J., Moran, D., & Rounsevell, M. D. A. (2017). Losses, inefficiencies and waste in the global food system. *Agricultural Systems*, *153*, 190–200. https://doi.org/10.1016/j.agsy.2017.01.014

Alexander, P., Rounsevell, M. D. A., Dislich, C., Dodson, J. R., Engström, K., & Moran, D. (2015). Drivers for global agricultural land use change: The nexus of diet, population, yield and bioenergy. *Global Environmental Change*, *35*, 138–147. https://doi.org/10.1016/j.gloenvcha.2015.08.011

Alluvione, F., Moretti, B., Sacco, D., & Grignani, C. (2011). EUE (energy use efficiency) of cropping systems for a sustainable agriculture. *Energy*, *36*, 4468–4481. https://doi.org/10.1016/j.energy.2011.03.075

Arodudu, O. T., Helming, K., Voinov, A., & Wiggering, H. (2017). Integrating agronomic factors into energy efficiency assessment of agro-bioenergy production—A case study of ethanol and biogas production from maize feedstock. *Applied Energy*, *198*, 426–439. https://doi.org/10.1016/j.apenergy.2017.02.017

Azad, M. A. S., & Ancev, T. (2014). Measuring environmental efficiency of agricultural water use: A Luenberger environmental indicator. *Journal of Environmental Management*, *145*, 314–320. https://doi.org/10.1016/j.jenvman.2014.05.037

Baumane, V., Celms, A., & Ratkevics, A. (2014). Assessment for determination possibilities of land use economic efficiency. *13th International Scientific Conference on Engineering for Rural Development Book Series: Engineering for rural development*. (pp. 535–540). Jelgava, Latvia.

Baveye, P. C., Baveye, J., & Gowdy, J. (2016). Soil "ecosystem" services and natural capital: Critical appraisal of research on uncertain ground. *Frontiers in Environmental Science*, *4*. https://doi.org/10.3389/fenvs.2016.00041

Bennett, L. T., Mele, P. M., Annett, S., & Kasel, S. (2010). Examining links between soil management, soil health, and public benefits in agricultural landscapes: An Australian perspective. *Agriculture, Ecosystems & Environment*, *139*, 1–12. https://doi.org/10.1016/j.agee.2010.06.017

Blum, W. E. H. (1990). The challenge of soil protection in Europe. *Environmental Conservation*, *17*, 72–74. https://doi.org/10.1017/S037689290001732X

Blum, W. E. H. (1993). Soil protection concept of the Council of Europe and integrated soil research. In H. J. P. Eijsackers, & T. Hamers (Eds.), *Integrated soil and sediment research: A basis for proper protection:*

Selected proceedings of the first European conference on integrated research for soil and sediment protection and remediation (EUROSOL) (pp. 37–47). Dordrecht: Springer Netherlands.

Blum, W. E. H. (2005). Functions of soil for society and the environment. *Reviews in Environmental Science and Bio/Technology*, *4*, 75–79. https://doi.org/10.1007/s11157-005-2236-x

BMBF (2010). Nationale Forschungsstrategie BioÖkonomie 2030. In *Unser Weg zu einer bio-basierten Wirtschaft*. Berlin: Bundesministerium für Bildung Und Forschung (BMBF).

BMEL (German Federal Ministry of Food and Agriculture) (2014). *National policy strategy on bioeconomy: Renewable resources and biotechnological processes as a basis for food, industry and energy*. Berlin: German Federal Ministry of Food and Agriculture (BMEL).

Bojnec, S., & Latruffe, L. (2011). Farm size and efficiency during transition: insights from Slovenian farms. *Transformations in Business & Economics*, *10*, 104–116.

Bond, A., Morrison-Saunders, A., Gunn, J. A. E., Pope, J., & Retief, F. (2015). Managing uncertainty, ambiguity and ignorance in impact assessment by embedding evolutionary resilience, participatory modelling and adaptive management. *Journal of Environmental Management*, *151*, 97–104. https://doi.org/10.1016/j.jenvman.2014.12.030

Bond, A., & Pope, J. (2012). The state of the art of impact assessment in 2012. *Impact Assessment and Project Appraisal*, *30*, 1–4. https://doi.org/10.1080/14615517.2012.669140

Boshrabadi, H. M., Villano, R., & Fleming, E. (2008). Technical efficiency and environmental-technological gaps in wheat production in Kerman province of Iran. *Agricultural Economics*, *38*, 67–76. https://doi.org/10.1111/j.1574-0862.2007.00282.x

Bouma, J. (2014). Soil science contributions towards sustainable development goals and their implementation: Linking soil functions with ecosystem services. *Journal of Plant Nutrition and Soil Science*, *177*, 111–120. https://doi.org/10.1002/jpln.201300646

Bouma, J., de Vos, J. A., Sonneveld, M. P. W., Heuvelink, G. B. M., & Stoorvogel, J. J. (2008). The role of scientists in multiscale land use analysis: Lessons learned from dutch communities of practice. *Advances in Agronomy*, *97*, 175–237. https://doi.org/10.1016/S0065-2113(07)00005-3

Braat, L. C., & de Groot, R. (2012). The ecosystem services agenda: Bridging the worlds of natural science and economics, conservation and development, and public and private policy. *Ecosystem Services*, *1*, 4–15. https://doi.org/10.1016/j.ecoser.2012.07.011

Breure, A. M., De Deyn, G. B., Dominati, E., Eglin, T., Hedlund, K., Van Orshoven, J., & Posthuma, L. (2012). Ecosystem services: A useful concept for soil policy making! *Current Opinion in Environmental Sustainability*, *4*, 578–585. https://doi.org/10.1016/j.cosust.2012.10.010

Buckley, C., Wall, D. P., Moran, B., O'Neill, S., & Murphy, P. N. (2016). Farm gate level nitrogen balance and use efficiency changes post implementation of the EU Nitrates Directive. *Nutrient Cycling in Agroecosystems*, *104*, 1–13. https://doi.org/10.1007/s10705-015-9753-y

Buckwell, A., Nordang Uhre, A., Williams, A., Poláková, J., Blum, W., Schiefer, J., … Haber, W. (2014). *Sustainable intensification of European agriculture*. Brussels: RISE Foundation.

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., … Brussard, L. (2018). Soil quality—A critical review. *Soil Biology and Biochemistry*, *120*, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Carpenter, S. R., Bennett, E. M., & Peterson, G. D. (2006). Editorial: Special feature on scenarios for ecosystem services. *Ecology and Society*, *11*. https://doi.org/10.5751/ES-01609-110232

Chum, H. L., Nigro, F. E. B., McCormicka, R., Beckhama, G. T., Seabrac, J. E. A., Saddlerd, J., … Overenda, R. P. (2015). Conversion technologies for biofuels and their use. In C. Mendes Souza, R. L. Victoria, C. A. Joly, & L. M. Verdade (Eds.), *Bioenergy and sustainability: Bridging the gaps*. SCOPE 72 (pp. 374–467). Paris: Scientific Committee on Problems of the Environment (SCOPE).

Clark, M., & Tilman, D. (2017). Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environmental Research Letters*, *12*. https://doi.org/10.1088/1748-9326/aa6cd5

Conesa-Muñoz, J., Gonzalez-de-Soto, M., Gonzalez-de-Santos, P., & Ribeiro, A. (2015). Distributed multi-level supervision to effectively monitor the operations of a fleet of autonomous vehicles in agricultural tasks. *Sensors*, *15*, 5402–5428. https://doi.org/10.3390/s150305402

Costanza, R., d'Arge, R., de Groot, R., Faber, S., Grasso, M., Hannon, B., … van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*(6630), 253–260. http://dx.doi.org/10.1038/387253a0

Daily, G. C., Matson, P. A., & Vitousek, P. M. (1997). Ecosystem services supplied by soil. In G. C. Daily (Ed.), *Nature's services: Societal dependence on natural ecosystems* (pp. 113–132). Washington DC: Island Press.

de Olde, E. M., Oudshoorn, F. W., Sørensen, C. A. G., Bokkers, E. A. M., & de Boer, I. J. M. (2016). Assessing sustainability at farm-level: Lessons learned from a comparison of tools in practice. *Ecological Indicators*, *66*, 391–404. https://doi.org/10.1016/j.ecolind.2016.01.047

Deike, S., Pallutt, B., & Christen, O. (2008a). Investigations on the energy efficiency of organic and integrated farming with specific emphasis on pesticide use intensity. *European Journal of Agronomy*, *28*, 461–470. https://doi.org/10.1016/j.eja.2007.11.009

Deike, S., Pallutt, B., Kustermann, B., & Christen, O. (2008b). Effects of herbicide application on energy use efficiency and carbon dioxide emissions of cereal cropping systems. *Journal of Plant Diseases and Protection*, 113–119.

Di Maio, F., Rem, P. C., Baldé, K., & Polder, M. (2017). Measuring resource efficiency and circular economy: A market value approach. *Resources, Conservation & Recycling*, *122*, 163–171. https://doi.org/10.1016/j.resconrec.2017.02.009

Díaz, S., Pacual, U., Stenseke, M., Martín-López, B., Watson, R. T., Molnár, Z., … Shirayama, Y. (2018). Assessing nature's contributions to people. *Science*, *359*(6373), 270–272. https://doi.org/10.1126/science.aap8826

DLG-Vorstand (2017). *Landwirtschaft 2030.10 Thesen*. Frankfurt/Main: DLG e.V.

Dominati, E., Patterson, M., & Mackay, A. (2010). A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecological Economics*, *69*, 1858–1868. https://doi.org/10.1016/j.ecolecon.2010.05.002

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.-A., Justes, E., … Sarthou, J. P. (2015). How to implement biodiversity-based agriculture to enhance ecosystem services: A review. *Agronomy for Sustainable Development*, *35*, 0–1281. https://doi.org/10.1007/s13593-015-0306-1

ecoRobotix Ltd. (2016). Project presentation. Yverdon-les-Bains: ecoRobotix Ltd.; http://www.ecorobotix.com/category/project/. Accessed 15 June 2016

Edens, B., & Hein, L. (2013). Towards a consistent approach for ecosystem accounting. *Ecological Economics*, *90*, 41–52. https://doi.org/10.1016/j.ecolecon.2013.03.003

EEA (European Environment Agency) (2016). *Environmental indicator report 2016—In support to the monitoring of the 7th Environment Action Programme*. Luxembourg: Publications Office of the European Union.

European Commission. (2006). Communication from the commission to the council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - *Thematic* Strategy *for Soil Protection* [SEC (2006)620] [SEC (2006)1165] /* COM/2006/0231 final */. Brussels: European Commission.

European Commission. (2011). Communication from the commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions. *Roadmap to a* Resource *Efficient Europe*/* COM/2011/0571 final */. Brussels: European Commission (European Commission).

Eurostat (2016). *Agriculture, forestry and fishery statistics 2016 edition*. Luxembourg: Publications Office of the European Union.

Eurostat. (2017a). Crop statistics (from 2000 onwards) [apro_acs_a] http://appsso. eurostat.ec. europa.eu/nui/setupDownloads.do. Accessed 04 August 2017

Eurostat. (2017b). online data code: ef_pmtilecs; http://ec.europa.eu/eurostat/Statistics-explained/images/4/4b/Fact_sheet_11.2.xls. Accessed 04 August 2017

Fagerholm, N., Torralba, M., Burgess, P. J., & Plieninger, T. (2016). A systematic map of ecosystem services assessments around European agroforestry. *Ecological Indicators*, *62*, 47–65. https://doi.org/10.1016/j.ecolind.2015.11.016

FAO, & ITPS (2015). *Status of the World's Soil Resources (SWSR)—Main report*. Rome: Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soil.

Flessa, H., Müller, D., Plassmann, K., Osterburg, B., Techen, A.-K., Nitsch, H., … Anspach, V. (2012). Studie zur Vorbereitung einer effizienten und gut abgestimmten Klimaschutzpolitik für den Agrarsektor. *Landbauforschung Sonderheft*, *361*, 1–472.

Fremier, A. K., DeClerck, F. A. J., Bosque-Pérez, N. A., Carmona, N. E., Hill, R., Joyal, T., … Wulfhorst, J. D. (2013). Understanding spatiotemporal lags in ecosystem services to improve incentives. *Bioscience*, *63*, 472–482. https://doi.org/10.1525/bio.2013.63.6.9

Fund, C., El-Chichakli, B., Patermann, C., & Dieckhoff, P. (2015). *A report from the German bioeconomy council: Bioeconomy policy (part II)—Synopsis of national strategies around the world*. Berlin: Bioökonomierat.

Gabrielsen, P., & Bosch, P. (2003). *Environmental indicators: Typology and use in reporting*. Copenhagen: European Environment Agency.

Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., … Godfray, H. C. J. (2013). Sustainable intensification in agriculture: Premises and policies. *Science*, *341*, 33–34. https://doi.org/10.1126/science.1234485

General Assembly. (2015). Transforming our world: The 2030 agenda for sustainable development, A/RES/70/1; http://www.un.org/en/ga/search/view_doc.asp? symbol=A/RES/70/1. Accessed 19 January 2016

Gerber, P., Uwizeye, A., Schulte, R., Opio, C., & de Boer, I. (2014). Nutrient use efficiency: A valuable approach to benchmark the sustainability of nutrient use in global livestock production? *Current Opinion in Environmental Sustainability*, *9-10*, 122–130. https://doi.org/10.1016/j.cosust.2014.09.007

Giambalvo, D., Alfieri, G., Amato, G., Salvatore Frenda, A., Iudicello, P., & Stringi, L. (2009). Energy use efficiency of livestock farms in a mountain area of Sicily. *Italian Journal of Animal Science*, *8*, 307–309. https://doi.org/10.4081/ijas.2009.s2.307

Glæsner, N., Helming, K., & de Vries, W. (2014). Do current European policies prevent soil threats and support soil functions? *Sustainability*, *6*, 9538–9563. https://doi.org/10.3390/su6129538

Godinot, O., Carof, M., Vertès, F., & Leterme, P. (2014). SyNE: An improved indicator to assess nitrogen efficiency of farming systems. *Agricultural Systems*, *127*, 41–52. https://doi.org/10.1016/j.agsy.2014.01.003

Godinot, O., Leterme, P., Vertès, F., & Carof, M. (2016). Indicators to evaluate agricultural nitrogen efficiency of the 27 member states of the European Union. *Ecological Indicators*, *66*, 612–622. https://doi.org/10.1016/j.ecolind.2016.02.007

Gomes, E. G., Soares de Mello, J. C. C. B., e Souza, G. S., Angulo Meza, L., & Mangabeira, J. A. C. (2009). Efficiency and sustainability assessment for a group of farmers in the Brazilian Amazon. *Annals of Operations Research*, *169*, 167–181. https://doi.org/10.1007/s10479-008-0390-6

Gonzalez, J., Luque, S., Poggio, L., Smith, R., & Gimona, A. (2016). Spatial Bayesian belief networks as a planning decision tool for mapping ecosystem services trade-offs on multifunctional forested landscapes. *Environmental Research*, *144*, 15–26. https://doi.org/10.1016/j.envres.2015.11.009

Govers, G., Merckx, R., van Wesemael, B., & Van Oost, K. (2017). Soil conservation in the 21st century: Why we need smart agricultural intensification. *The Soil*, *3*, 45–59. https://doi.org/10.5194/soil-3-45-2017

Grossman, J. J. (2015). Ecosystem service trade-offs and land use among smallholder farmers in eastern Paraguay. *Ecology and Society*, *20*. https://doi.org/10.5751/ES-06953-200119

Gsottbauer, E., & van den Bergh, J. C. J. M. (2011). Environmental policy theory given bounded rationality and other-regarding preferences. *Environmental and Resource Economics*, *49*, 263–304. https://doi.org/10.1007/s10640-010-9433-y

Gu, B., Ju, X., Chang, S. X., Ge, Y., & Chang, J. (2017). Nitrogen use efficiencies in Chinese agricultural systems and implications for food security and environmental protection. *Regional Environmental Change*, *17*, 1217–1227. https://doi.org/10.1007/s10113-016-1101-5

Haddaway, N. R., Hedlund, K., Jackson, L. E., Kätterer, T., Lugato, E., Thomsen, I. K., … Söderström, B. (2015). What are the effects of agricultural management on soil organic carbon in boreo-temperate systems? *Environmental Evidence*, *4*, 23. https://doi.org/10.1186/s13750-015-0049-0

Haines-Young, R., & Potschin, M. (2009). The links between biodiversity, ecosystem services and human well-being. In D. Raffaeli, & C. Frid (Eds.), *Ecosystem Ecology: A New Synthesis* ()*BES Ecological Reviews Series*. Cambridge: Cambridge University Press (CUP).

Haines-Young, R., & Potschin, M. (2013). Common international classification of ecosystem services (CICES): Consultation on Version 4, August-December 2012. EEA framework contract no EEA/IEA/09/003.

Han, S, Steward, BL, Tang, L. 2015. Intelligent agricultural machinery and field robots. In *Precision agriculture technology for crop farming*, Zhang, Q (ed). Boca Raton: CRC Press; 133–176.

Helming, K., Diehl, K., Geneletti, D., & Wiggering, H. (2013). Mainstreaming ecosystem services in European policy impact assessment. *Environmental Impact Assessment Review*, *40*, 82–87. https://doi.org/10.1016/j.eiar.2013.01.004

Hill, J., Nelson, E., Tilman, D., Polasky, S., & Tiffany, D. (2006). Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *Proceedings of the National Academy of Sciences of the United States of America*, *103*, 11206–11210. https://doi.org/10.1073/pnas.0604600103

Hoang, V. N. (2011). Measuring and decomposing changes in agricultural productivity, nitrogen use efficiency and cumulative exergy efficiency: Application to OECD agriculture. *Ecological Modelling*, *222*, 164–175. https://doi.org/10.1016/j.ecolmodel.2010.09.032

Hoang, V.-N., & Alauddin, M. (2012). Input-orientated data envelopment analysis framework for measuring and decomposing economic, environmental and ecological efficiency: An application to OECD agriculture. *Environmental and Resource Economics*, *51*, 431–452. https://doi.org/10.1007/s10640-011-9506-6

Johnson, S. N., Benefer, C. M., Frew, A., Griffiths, B. S., Hartley, S. E., Karley, A. J., … Robert, C. A. M. (2016). New frontiers in belowground ecology for plant protection from root-feeding insects. *Applied Soil Ecology*, *108*, 96–107. https://doi.org/10.1016/j.apsoil.2016.07.017

Juerges, N., & Hansjürgens, B. (2018). Soil governance in the transition towards a sustainable bioeconomy—A review. *Journal of Cleaner Production*, *170C*, 1628–1639. https://doi.org/10.1016/j.jclepro.2016.10.143

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., … Fresco, L. O. (2016). The significance of soils and soil science towards realization of the United Nations sustainable development goals. *The Soil*, *2*, 111–128. https://doi.org/10.5194/soil-2-111-2016

Kergunteuil, A., Bakhtiari, M., Formenti, L., Xiao, Z., Defossez, E., & Rasmann, S. (2016). Biological control beneath the feet: A review of crop protection against insect root herbivores. *Insects*, *7*, 70. https://doi.org/10.3390/insects7040070

Khakbazan, M., Larney, F. J., Huang, J., Mohr, R., Pearson, D. C., & Blackshaw, R. E. (2017). Energy use efficiency of conventional versus conservation management practices for irrigated potato production in Southern Alberta. *American Journal of Potato Research*, *94*, 105–119. https://doi.org/10.1007/s12230-016-9551-3

Kibblewhite, M. G., Ritz, K., & Swift, M. J. (2008). Soil health in agricultural systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*, 685–701. https://doi.org/10.1098/rstb.2007.2178

Korkmaz, K., Ibrikci, H., Karnez, E., Buyuk, G., Ryan, J., Ulger, A. C., & Oguz, H. (2009). Phosphorus use efficiency of wheat genotypes grown in calcareous soils. *Journal of Plant Nutrition*, *32*, 2094–2106. https://doi.org/10.1080/01904160903308176

Kutter, T., Louwagie, G., Schuler, J., Zander, P., Helming, K., & Hecker, J. M. (2011). Policy measures for agricultural soil conservation in the European Union and its member states: Policy review and classification. *Land Degradation & Development*, *22*, 18–31. https://doi.org/10.1002/ldr.1015

Lamarque, P., Meyfroidt, P., Nettier, B., & Lavorel, S. (2014). How ecosystem services knowledge and values influence farmers' decision-making. *PLoS One*, *9*, e107572. https://doi.org/10.1371/journal.pone.0107572

Lambin, E. F., & Meyfroidt, P. (2011). *Global land use change, economic globalization, and the looming land scarcity* (Vol. 108). (pp. 3465–3472) Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.1100480108

Last, L., Buchmann, N., Gilgen, A. K., Grant, M., & Shreck, A. (2015). *Foresight study: Research for a sustainable Swiss food system*. Zürich: ETH Zürich.

Lee, P., & Park, Y.-J. (2017). Eco-efficiency evaluation considering environmental stringency. *Sustainability*, *9*. https://doi.org/10.3390/su9040661

Li, G. C., Feng, Z. C., You, L. Z., & Fan, L. X. (2013). Re-examining the inverse relationship between farm size and efficiency: The empirical evidence in China. *China Agricultural Economic Review*, *5*, 473–488. https://doi.org/10.1108/caer-09-2011-0108

Lienhoop, N., & Brouwer, R. (2015). Agri-environmental policy valuation: Farmers' contract design preferences for afforestation schemes. *Land Use Policy*, *42*, 568–577. https://doi.org/10.1016/j.landusepol.2014.09.017

Lin, H.-C., Huber, J. A., Gerl, G., & Hülsbergen, K.-J. (2017). Effects of changing farm management and farm structure on energy balance and energy-use efficiency—A case study of organic and conventional farming systems in southern Germany. *European Journal of Agronomy*, *82*, 242–253. https://doi.org/10.1016/j.eja.2016.06.003

Masuda, K. (2016). Measuring eco-efficiency of wheat production in Japan: A combined application of life cycle assessment and data envelopment analysis. *Journal of Cleaner Production*, *126*, 373–381. https://doi.org/10.1016/j.jclepro.2016.03.090

MEA (Millennium Ecosystem Assessment) (2005). *Ecosystems and human well-being: Synthesis*. Washington, DC: Island Press.

Meuli, K. (2016). EcoRobotix, Terranimo & Cie. In *Environnement* (pp. 24–26). Saint-Gall: NZZ Fachmedien AG.

Meyer-Aurich, A., Gandorfer, M., Trost, B., Ellmer, F., & Baumecker, M. (2016). Risk efficiency of irrigation to cereals in northeast Germany with respect to nitrogen fertilizer. *Agricultural Systems*, *149*, 132–138. https://doi.org/10.1016/j.agsy.2016.09.006

Meylan, L., Gary, C., Allinne, C., Ortiz, J., Jackson, L., & Rapidel, B. (2017). Evaluating the effect of shade trees on provision of ecosystem services in intensively managed coffee plantations. *Agriculture, Ecosystems & Environment*, *245*, 32–42. https://doi.org/10.1016/j.agee.2017.05.005

Miklovicova, J., & Miklovicova, S. (2012, 2012). The efficiency matrix as a tool for efficiency evaluation of farms in V4 countries. In T. Loster, & T. Pavelka (Eds.), *Conference proceedings of the 6th International Days of Statistics and Economics*, Prague, September 13–15 (pp. 794–803). Slany: MELANDRIUM.

Ministère de l'Agriculture de l'Agroalimentaire et de la Forêt. (2015/2016). 4 pour 1000. Partners; http://4p1000.org/partners. Accessed 16 February 2016

Moreau, P., Ruiz, L., Mabon, F., Raimbault, T., Durand, P., Delaby, L., … Vertès, F. (2012). Reconciling technical, economic and environmental efficiency of farming systems in vulnerable areas. *Agriculture, Ecosystems & Environment*, *147*, 89–99. https://doi.org/10.1016/j.agee.2011.06.005

Mudgal, S., Tan, A., Lockwood, S., Eisenmenger, N., Fischer, M., Giljumpappap, S., Brucker, M. (2012). Assessment of resource efficiency indicators and targets. Final report prepared for the European Commission, DG Environment. BIO Intelligence Service, Institute for Social Ecology and Sustainable Europe Research Institute.

Öhlund, E., Hammer, M., & Björklund, J. (2017). Managing conflicts goals in pig farming: Farmers' strategies and perspectives on sustainable pig farming in Sweden. *International Journal of Agricultural Sustainability*, *15*(6), 693–707. https://doi.org/10.1080/14735903.2017.1399514

Olesen, J. E., Trnka, M., Kersebaum, K. C., Skjelvåg, A. O., Seguin, B., Peltonen-Sainio, P., … Micale, F. (2011). Impacts and adaptation of European crop production systems to climate change. *European Journal of Agronomy*, *34*, 96–112. https://doi.org/10.1016/j.eja.2010.11.003

Pagotto, M., & Halog, A. (2016). Towards a circular economy in Australian agri-food industry. An application of input-output oriented approaches for analyzing resource efficiency and competitiveness potential. *Journal of Industrial Ecology*, *20*, 1176–1186. https://doi.org/10.1111/jiec.12373

Paleari, S. (2017). Is the European Union protecting soil? A critical analysis of community environmental policy and law. *Land Use Policy*, *64*, 163–173. https://doi.org/10.1016/j.landusepol.2017.02.007

Panagos, P., Borrelli, P., Meusburger, K., van der Zanden, E. H., Poesen, J., & Alewell, C. (2015). Modelling the effect of support practices (P-factor) on the reduction of soil erosion by water at European scale. *Environmental Science & Policy*, *51*, 23–34. https://doi.org/10.1016/j.envsci.2015.03.012

Pascual, M., Villar, J. M., & Rufat, J. (2016). Water use efficiency in peach trees over a four-years experiment on the effects of irrigation and nitrogen application. *Agricultural Water Management*, *164*, 253–266. https://doi.org/10.1016/j.agwat.2015.10.021

Pelzer, E., Hombert, N., Jeuffroy, M.-H., & Makowski, D. (2014). Meta-analysis of the effect of nitrogen fertilization on annual cereal–legume intercrop production. *Agronomy Journal*, *106*, 1775–1786. https://doi.org/10.2134/agronj13.0590

Pfeiffer, L., & Lin, C.-Y. C. (2014). Does efficient irrigation technology lead to reduced groundwater extraction? Empirical evidence. *Journal of Environmental Economics and Management*, *67*, 189–208. https://doi.org/10.1016/j.jeem.2013.12.002

Phengphaengsy, F., & Okudaira, H. (2008). Assessment of irrigation efficiencies and water productivity in paddy fields in the lower Mekong River Basin. *Paddy and Water Environment*, *6*, 105–114. https://doi.org/10.1007/s10333-008-0108-z

Podhora, A., Helming, K., Adenäuer, L., Heckelei, T., Kautto, P., Reidsma, P., … Jansen, J. (2013). The policy-relevancy of impact assessment tools: Evaluating nine years of European research funding. *Environmental Science & Policy*, *31*, 85–95. https://doi.org/10.1016/j.envsci.2013.03.002

Potschin-Young, M., Haines-Young, R., Görg, C., Heink, U., Jax, K., & Schleyer, C. (2017). Understanding the role of conceptual frameworks: Reading the ecosystem service cascade. *Ecosystem Services*, *29*, 428–440. https://doi.org/10.1016/j.ecoser.2017.05.015

Preissel, S., Reckling, M., Schläfke, N., & Zander, P. (2015). Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: A review. *Field Crops Research*, *175*, 64–79. https://doi.org/10.1016/j.fcr.2015.01.012

Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Pérès, G., & Rutgers, M. (2012). Soil biodiversity, biological indicators and soil ecosystem services—An overview of European approaches. *Current Opinion in Environmental Sustainability*, *4*, 529–538. https://doi.org/10.1016/j.cosust.2012.10.009

Reed, M. S., Hubacek, K., Bonn, A., Burt, T. P., Holden, J., Stringer, L. C., … Worrall, F. (2013). Anticipating and managing future trade-offs and complementarities between ecosystem services. *Ecology and Society*, *18*. https://doi.org/10.5751/ES-04924-180105

Rehman, A., Farrukh Saleem, M., Safdar, M. E., Hussain, S., & Akhtar, N. (2011). Grain quality, nutrient use efficiency, and bioeconomics of maize under different sowing methods and NPK levels. *Chilean Journal of Agricultural Research*, *71*, 586–593.

Robinson, D. A., & Lebron, I. (2010). On the natural capital and ecosystem services of soils. *Ecological Economics*, *70*, 137–138. https://doi.org/10.1016/j.ecolecon.2010.08.012

Robinson, D. A., Lebron, I., & Vereecken, H. (2009). On the definition of the natural capital of soils: A framework for description, evaluation, and monitoring. *Soil Science Society of America Journal*, *73*, 1904–1911. https://doi.org/10.2136/sssaj2008.0332

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., … Smith, J. (2017). Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio*, *46*, 4–17. https://doi.org/10.1007/s13280-016-0793-6

Romanelli, T. L., Nardi, H. S., & Saad, F. A. (2012). Material embodiment and energy flows as efficiency indicators of soybean (Glycine max) production in Brazil. *Engenharia Agrícola*, *32*, 261–270.

Sabiha, N. E., Salim, R., & Rahman, S. (2017). Eco-efficiency of high-yielding variety rice cultivation after accounting for on-farm environmental damage as an undesirable output: An empirical analysis from Bangladesh. *Australian Journal of Agricultural and Resource Economics*, *61*, 247–264. https://doi.org/10.1111/1467-8489.12197

Sandifer, P. A., Sutton-Grier, A. E., & Ward, B. P. (2015). Exploring connections among nature, biodiversity, ecosystem services, and human health and well-being: Opportunities to enhance health and biodiversity conservation. *Ecosystem Services*, 12: 1–12: 15. https://doi.org/10.1016/j.ecoser.2014.12.007

Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., & Nita, V. (2015). The role of biomass and bioenergy in a future bioeconomy: Policies and facts. *Environmental Development*, *15*, 3–34. https://doi.org/10.1016/j.envdev.2015.03.006

Schjønning, P., van den Akker, J. J. H., Keller, T., Greve, M. H., Lamandé, M., Simojoki, A., … Breuning-Madsen, H. (2015). Driver-pressure-state-impact-response (DPSIR) analysis and risk assessment for soil compaction—A European perspective. *Advances in Agronomy*, *133*, 183–237. https://doi.org/10.1016/bs.agron.2015.06.001

Scholz, R. W., & Wellmer, F.-W. (2015). Losses and use efficiencies along the phosphorus cycle—Part 2: Understanding the concept of efficiency. *Resources, Conservation and Recycling*, *105*, 259–274. https://doi.org/10.1016/j.resconrec.2015.10.003

Schröter, M., Stumpf, K. H., Loos, J., van Oudenhoven, A. P. E., Böhnke-Henrichs, A., & Abson, D. J. (2017). Refocusing ecosystem services towards sustainability. *Ecosystem Services*, *25*, 35–43. https://doi.org/10.1016/j.ecoser.2017.03.019

Schulte, R. P. O., Creamer, R. E., Donnellan, T., Farrelly, N., Fealy, R., O'Donoghue, C., & O'hUallachain, D. (2014). Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. *Environmental Science & Policy*, *38*, 45–58. https://doi.org/10.1016/j.envsci.2013.10.002

Schwilch, G., Bernet, L., Fleskens, L., Giannakis, E., Leventon, J., Marañón, T., … Verzandvoort, S. (2016). Operationalizing ecosystem services for the mitigation of soil threats: A proposed framework. *Ecological Indicators*, *67*, 586–597. https://doi.org/10.1016/j.ecolind.2016.03.016

Science for Environment Policy (2016). Synthetic biology and biodiversity. Future Brief 15. In *Produced for the European Commission DG environment by the Science Communication Unit*. Bristol: UWE.

Senger, I., Borges, J. A. R., & Machado, J. A. D. (2017). Using the theory of planned behavior to understand the intention of small farmers in diversifying their agricultural production. *Journal of Rural Studies*, *49*, 32–40. https://doi.org/10.1016/j.jrurstud.2016.10.006

Spicka, J. (2014). Production efficiency of mixed farming in the EU regions. *13th International Scientific Conference on Engineering for Rural Development*. *Book Series: Engineering for rural development* (pp. 31–39). Jelgava, Latvia.

Spicka, J. (2015). Changes in the energy efficiency of crop production in EU countries. In 7th International Scientific Conference Rural Development 2015: Towards the Transfer of Knowledge, Innovations and Social Progress. https://doi.org/10.15544/rd. 2015.099

Spicka, J., & Smutka, L. (2014). The technical efficiency of specialised milk farms: A regional view. *Scientific World Journal*. https://doi.org/10.1155/2014/985149

Stavi, I., Bel, G., & Zaady, E. (2016). Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems. A review. *Agronomy for Sustainable Development*, *36*, 32. https://doi.org/10.1007/s13593-016-0368-8

Steyn, J. M., Franke, A. C., van der Waals, J. E., & Haverkort, A. J. (2016). Resource use efficiencies as indicators of ecological sustainability in potato production: A South African case study. *Field Crops Research*, *199*, 136–149. https://doi.org/10.1016/j.fcr.2016.09.020

Techen, A.-K., & Helming, K. (2017). Pressures on soil functions from soil management in Germany. A foresight review. *Agronomy for Sustainable Development*, *37*(6). https://doi.org/10.1007/s13593-017-0473-3

Techen, A.-K., Ries, E., & Steinführer, A. (2015). *Evaluierung der Gewässerschutzberatung in Hessen im Kontext der EU-Wasserrahmenrichtlinie: Auswirkungen auf Wissen und Handeln von Landwirten*. Braunschweig: Johann Heinrich von Thünen-Institut.

TEEB (The Economics of Ecosystems and Biodiversity). (2010). Mainstreaming the economics of nature: A synthesis of the approach, conclusions and recommendations of TEEB.

Tittonell, P. (2014). Ecological intensification of agriculture—Sustainable by nature. *Current Opinion in Environmental Sustainability*, *8*, 53–61. https://doi.org/10.1016/j.cosust.2014.08.006

Troost, C., & Berger, T. (2015). Dealing with uncertainty in agent-based simulation: Farm-level modeling of adaptation to climate change in southwest Germany. *American Journal of Agricultural Economics*, *97*, 833–854. https://doi.org/10.1093/ajae/aau076

Tscherning, K., Helming, K., Krippner, B., Sieber, S., & Paloma, S. G. (2012). Does research applying the DPSIR framework support decision making? *Land Use Policy*, *29*, 102–110. https://doi.org/10.1016/j.landusepol.2011.05.009

van Grinsven, H., Erisman, J. W., de Vries, W., & Westhoek, H. (2015). Potential of extensification of European agriculture for a more sustainable food system, focusing on nitrogen. *Environmental Research Letters*, *10*(2), 025002. https://doi.org/10.1088/1748-9326/10/2/025002

Van Lierde, D., Vandenberghe, A., Cools, A. M., De Backer, E., & Vergucht, S. (2009). Economic efficiency of the use of plant protection products in Flemish horticulture. *Acta Horticulturae*, (817), 201–208. https://doi.org/10.17660/ActaHortic.2009.817.20

Vogel, H.-J., Bartke, S., Daedlow, K., Helming, K., Kögel-Knabner, I., Lang, B., … Wollschläger, U. (2018). A systemic approach for modelling soil functions. *SOIL*, *4*, 83–92. https://doi.org/10.5194/soil-4-83-2018

Vrebos, D., Bampa, F., Creamer, R., Gardi, C., Ghaley, B., Jones, A., … Meire, P. (2017). The impact of policy instruments on soil multifunctionality in the European Union. *Sustainability*, *9*, 407. https://doi.org/10.3390/su9030407

Wang, G. F., Chen, J. C., Wu, F., & Li, Z. H. (2015). An integrated analysis of agricultural water-use efficiency: A case study in the Heihe River Basin in Northwest China. *Physics and Chemistry of the Earth*, *89-90*, 3–9. https://doi.org/10.1016/j.pce.2015.10.009

Wasiak, A., & Orynycz, O. (2014). Formulation of a model for energetic efficiency of agricultural subsystem of biofuel production. In *2014 IEEE International Energy Conference (ENERGYCON)*; 1271–1275. https://doi.org/10.1109/ENERGYCON.2014.6850586

Wei, Z., Du, T., Zhang, J., Xu, S., Cambre, P. J., & Davies, W. J. (2016). Carbon isotope discrimination shows a higher water use efficiency under alternate partial root-zone irrigation of field-grown tomato. *Agricultural*

Water Management, *165*, 33–43. https://doi.org/10.1016/j.agwat.2015.11.009

Williams, A., Kane, D. A., Ewing, P. M., Atwood, L. W., Jilling, A., Li, M., … Jordan, N. R. (2016). Soil functional zone management: A vehicle for enhancing production and soil ecosystem services in row-crop agroecosystems. *Frontiers in Plant Science*, *7*. https://doi.org/10.3389/fpls.2016.00065

Yu, Y., Stomph, T. J., Makowski, D., & van der Werf, W. (2015). Temporal niche differentiation increases the land equivalent ratio of annual intercrops: A meta-analysis. *Field Crops Research*, *184*, 133–144. https://doi.org/10.1016/j.fcr.2015.09.010

Zhang, S. J., Wang, L., Ma, F., Zhang, X., & Fu, D. F. (2016). Arbuscular mycorrhiza improved phosphorus efficiency in paddy fields. *Ecological Engineering*, *95*, 64–72. https://doi.org/10.1016/j.ecoleng.2016.06.029

Zhang, Y., Wang, R., Wang, S., Wang, H., Xu, Z., Jia, G., … Li, J. (2017). Effects of different sub-soiling frequencies incorporated into no-tillage systems on soil properties and crop yield in dryland wheat-maize rotation system. *Field Crops Research*, *209*, 151–158. https://doi.org/10.1016/j.fcr.2017.05.002

Zhao, L., Wu, L., Li, Y., Animesh, S., Zhu, D., & Uphoff, N. (2010). Comparisons of yield, water use efficiency, and soil microbial biomass as affected by the system of rice intensification. *Communications in Soil Science and Plant Analysis*, *41*, 1–12. https://doi.org/10.1080/00103620903360247

How to cite this article: Helming K, Daedlow K, Paul C, et al. Managing soil functions for a sustainable bioeconomy—Assessment framework and state of the art. *Land Degrad Dev*. 2018;29:3112–3126. https://doi.org/10.1002/ldr.3066