

Paul, C., Helming, K.

Leibniz Centre for Agricultural Landscape Research (ZALF)

Handbook of Soil-Related Impact Assessment

Second Edition (April 2025)

Title	Handbook of Soil-Related Impact Assessment
Authors	Paul, Carsten – Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg Helming, Katharina – Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg
Correspondence	paul@zalf.de
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Abstract	This handbook is designed to support researchers in conducting state-of-the-art assessments for evaluating impacts of agricultural soil management. Furthermore, it is addressed to a wider audience to aid understanding and interpretation of published impact assessments results. The handbook has been produced in response to a growing awareness of the fundamental role of soils and of the importance of sustainable soil management for coping with societal challenges such as food security, climate change or biodiversity loss. This is the second edition of a living document. In comparison to the first edition, this structure was further improved, and the content was expanded. The handbook is structured to follow the process of conducting impact assessments, starting with selecting impact areas and follows up with setting the system boundaries, choosing the indicators, dealing with factors that are difficult to assess, including future scenarios and giving more background information. Readers are welcome to either follow this process and go through the handbook from start to finish, or to browse and look up individual chapters that are relevant for them. The information presented in the handbook is also available online through the Impact Assessment Platform (www.sustainability.zalf.de). In the Information Hub, the Platform presents the latest updates and novel content of the information shown here.
Keywords	Soil Function, Resource Use Efficiency, Ecosystem Service, Guideline, BonaRes
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Contributions to individual chapters by:

Techen, Anja-Kristina (Soil Functions)

Barnickel, Sonja (Leakage Effects, Benchmarking)

Daedlow, Katrin (Ecosystem Services)

Robinson, James R. (Sustainable Development Goals, Multi-Criteria Analysis)

Stranzl, Laura (Soil Contamination and Human Health - including subchapters)

Eckhardt, Michelle (Additionality, Impact Area Selection)

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1. Welcome to the Handbook of Soil-Related Impact Assessment

This handbook provides a methodical guideline for structuring soil related impact assessments. It is designed to support researchers in conducting state-of-the-art assessments for evaluating impacts of agricultural soil management. Furthermore, it is addressed to a wider audience to aid understanding and interpretation of published impact assessments results. The handbook was originally developed as part of the BMBF funded research project “BonaRes - Soil as a sustainable resource for the bioeconomy”. The aim of BonaRes was to broaden the scientific understanding of soil ecosystems to improve soil functions and soil productivity. In this way, new strategies for the sustainable use of soil could be developed.

This is the second edition of a living document, and further editions will be published at irregular intervals to allow for updates, improvements and the inclusion of additional content¹. This handbook is structured to follow the process of conducting impact assessments. In comparison to the first edition, the structure was further improved, and the content was expanded. It details not only the processes and challenges of conducting soil-related impact assessments, but also provides a research tool, which guides the readers on how to conduct impact assessments by providing factsheets about different impact areas with brief descriptions of the respective topics. The structure starts with selecting impact areas and follows up with setting the system boundaries, choosing the indicators, dealing with factors that are difficult to assess, including future scenarios and giving more background information. Readers are welcome to either follow this process and go through the handbook from start to finish, or to browse and look up individual chapters that are relevant for them.

The length of the chapters is inhomogeneous, which to some degree is a reflection of project-related work schedules, but which is also partly on purpose. A strong emphasis is given to the structured selection of impact areas, because this is the stage with the highest risk of introducing bias. A second focus is on factors that are difficult to include in impact assessments and that are therefore often not considered by studies, such as leakage effects, rebound effects, and additionality. With regard to the latter, we were able to draw on new research findings generated within the BonaRes project. Finally, we put a focus on soil related ecosystem services within the European Environment Agency’s CICES

¹ The latest version of this handbook will be available as free download from:
www.sustainability.zalf.de/impact-assessment-platform

classification, because we perceive a lack of standardization in current research on ecosystem services to be an impairment to systematic reviews and to a transfer of research findings.

The content of the handbook is also provided online by the *Impact Assessment Platform* (www.sustainability.zalf.de/impact-assessment-platform, see QR-Code below). In the [Information Hub](#), the Platform presents the latest updates and novel content of the information shown here. The [Research Tool](#) includes factsheets about indicators that are used in literature for impact areas, which makes them useful for determining and quantifying relevant indicators for an assessment. For more information on the online version, please watch our [Impact Assessment Platform Introduction Video](#) (see QR Code below).

We hope you find this handbook and Impact Assessment Platform interesting and helpful, and we welcome any feedback that helps us to further improve them.

The Impact Assessment Platform:



Impact Assessment Platform

Designed for researchers.

THIS PLATFORM HELPS ASSESS THE IMPACT OF HOW SOILS AND THEIR FUNCTIONS ARE MANAGED, USING THE LATEST METHODS.

Why conducting a soil-related impact assessment?

In agriculture, sustainable management innovations are needed to meet the challenges of climate change mitigation, biodiversity preservation and food security. With a **soil-related impact assessment**, different management options can be analyzed by researchers to find the most sustainable choice. In this way, science can provide important information to farmers, policymakers, and other stakeholders to guide management decisions.

The Impact Assessment Platform

Our **Information Hub** provides detailed information on how to conduct a soil-related impact assessment, while the **Research Tool** allows you to select factsheets about indicators for your own impact assessment.

ABOUT THIS PLATFORM:

1. HANDBOOK

Handbook of Soil Science and Soil Management

Edited by: Paul C. A. Hengsdijk, K. J. Bonaldi Series

2019/4 | DOI: 10.2087/10101944.42019-5224

2. INTRODUCTION VIDEO:

Introduction Video

Impact Assessment Platform

Impact Assessment Platform

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Impact Assessment Platform

Introduction-Video of the Impact Assessment Platform (YouTube):



2. What do I want to assess? - Selecting Impact Areas



2. What do I want to assess? Selecting Impact Areas

2.1 Assessment Perspectives

Info-Box

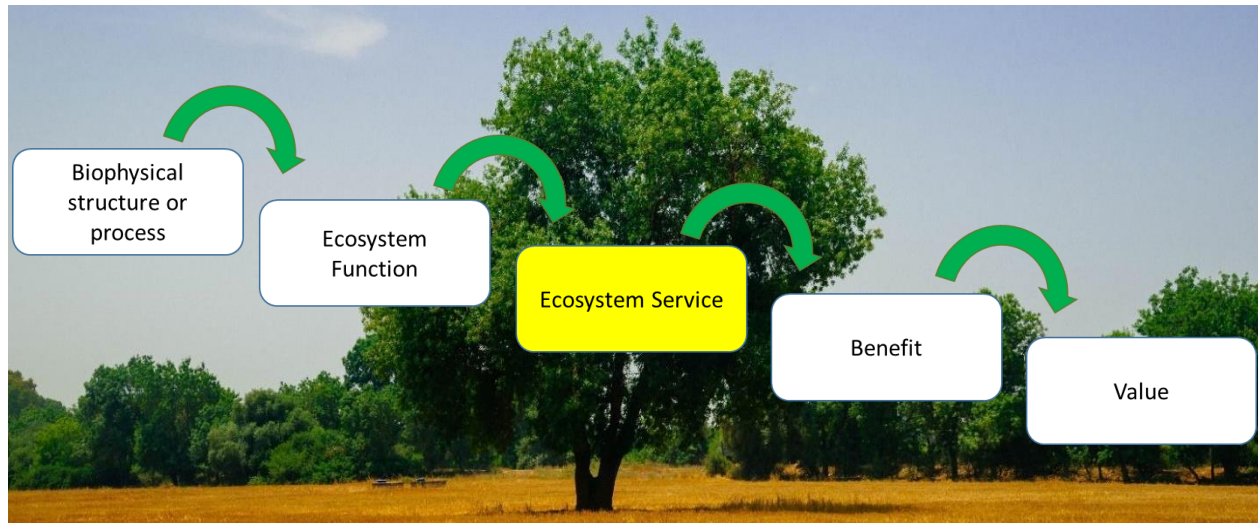
In impact assessments, effects of actions or policy options on societal targets are analysed. Because the number of societal targets and of potential impacts is too high to be investigated in a single assessment, some restriction or **focus** is required. **Assessment perspectives are a thematic focus** that can be used to make assessments operable. For example, assessments could choose to only analyse effects in relation to animal welfare or economic performance. More than one perspective may be chosen for an impact assessment, each with its own Impact Area.

The Impact Assessment Platform currently supports the perspectives of **Ecosystem Services** and **Resource Use Efficiency** in its **Indicator Factsheets**. Both perspectives are largely complementary and highly relevant for agriculture in industrialised countries where yield gaps are low, and in particular for evaluating transformation processes from a fossil fuel based economy towards a bioeconomy based on renewable resources.

Additionally, the fields of **Sustainable Development Goals** and **Soil Contamination and Human Health** give different perspectives on the broader system in which agricultural actors are operating.

2. What do I want to assess? - Ecosystem Services

2.2 Ecosystem Services



Info-Box

The concept of ecosystem services aims at demonstrating the value of ecosystems for human societies. Multiple ecosystem services are based on soils. They are particularly relevant for targets of a sustainable bioeconomy and for the internationally agreed **Sustainable Development Goals (SDG)**. However, the operationalisation of linkages between soil management, soil functions and ecosystem services remains a challenge. The Impact Assessment Platform addresses this by supporting impact assessments from the perspective of soil related ecosystem services. It provides methods for designing assessments and offers guidance for selecting, applying and linking indicators related to ecosystem services.

What are soil related ecosystem services?

The concept of ecosystem services aims at demonstrating the value of nature for human societies (Costanza et al., 1997, 2017; MEA, 2005; Haines-Young & Potschin, 2013; Potschin-Young et al., 2017; TEEB 2010). Ecosystem services can be seen as arising from the interaction of biotic and abiotic processes, and refer specifically to the ‘final’ outputs of ecological systems, i.e., the goods and services directly consumed or used by people (Haines-Young & Potschin, 2013; Potschin-Young et al., 2017). According to the **cascade model**, first introduced by Haines-Young & Potschin (2010), ecosystem services are based on biophysical structures or processes and the functions they serve. From ecosystem services humans generate benefits and values. Figure 1 shows the full cascade, starting from a biophysical structure or process and leading to values for humans. Additionally, the figure provides a soil related example.

2. What do I want to assess? - Ecosystem Services

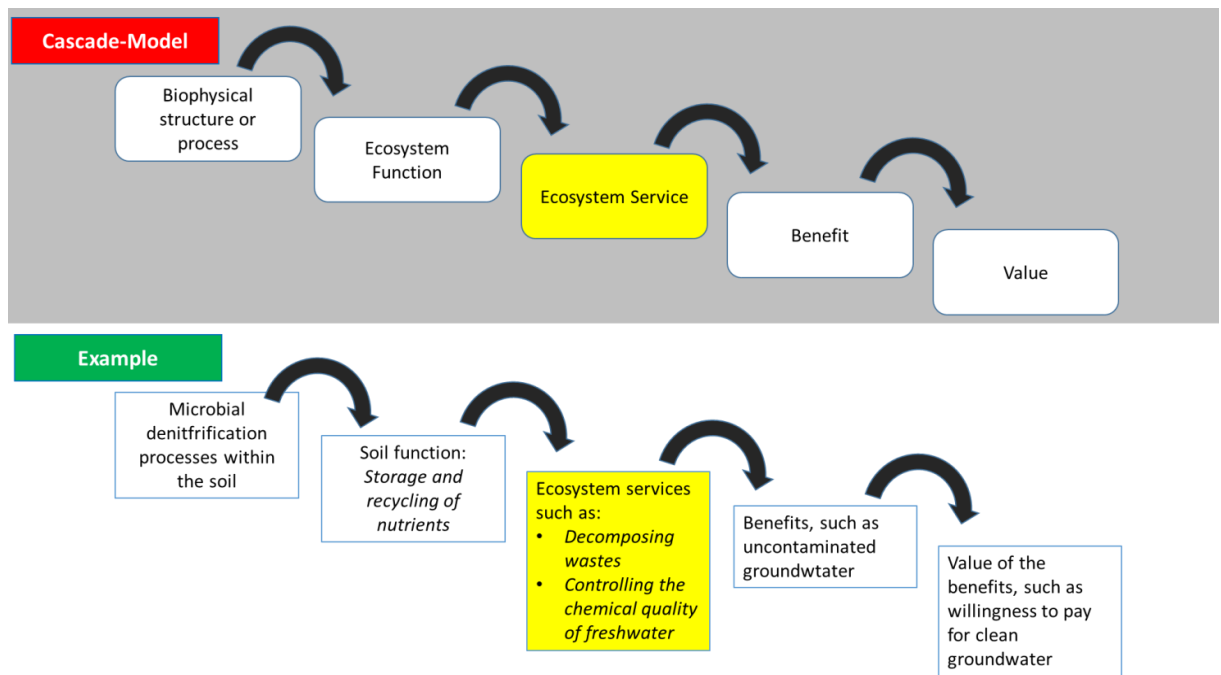


Figure 1: Ecosystem service cascade model and example for a soil related cascade. Own representation based on Potschin & Haines-Young (2011)

Defining which ecosystem services are provided by soils or to what degree soils contribute to specific ecosystem services is almost impossible, because most services are generated by the interaction of multiple ecosystem components. For example, soils allow cereals like wheat to grow and to produce food for humans. However, the wheat plant itself is not part of the soil, and neither are rainfall, sunlight or human inputs such as seedbed preparation and sowing. Only the combination of these factors creates the ecosystem service “provision of food”. For this reason, it is more practical to refer to **soil related ecosystem services**. In the context of impact assessments, we consider those ecosystem services to be soil related that are either **based exclusively** on soil functions, or where soil functions **make a significant contribution** to the final service. An example for services from the first category is the purification of water during its passage through the soil matrix, examples for services from the second category are the aboveground habitats created by plants growing in the soil. Both types of soil related ecosystem services have in common that they are affected by agricultural management.

The role of soils within the ecosystem services concept has been addressed in a number of recent publications (Stavi et al., 2016; Schwilch et al., 2016; Keesstra et al., 2016; Baveye et al., 2016; Adhikari & Hartemink, 2016; Helming et al., 2018) supplementing earlier studies on distinct aspects of soil functions and soil related ecosystem services (Blum, 1993; Daily et al., 1997; Robinson et al., 2009; Dominati et al., 2010; Bennett et al., 2010; Breure et al., 2012; Pulleman et al., 2012; Bouma, 2014; Schulte et al., 2014). The following figure illustrates how different categories of soil related ecosystem services are based on soil functions.

2. What do I want to assess? - Ecosystem Services

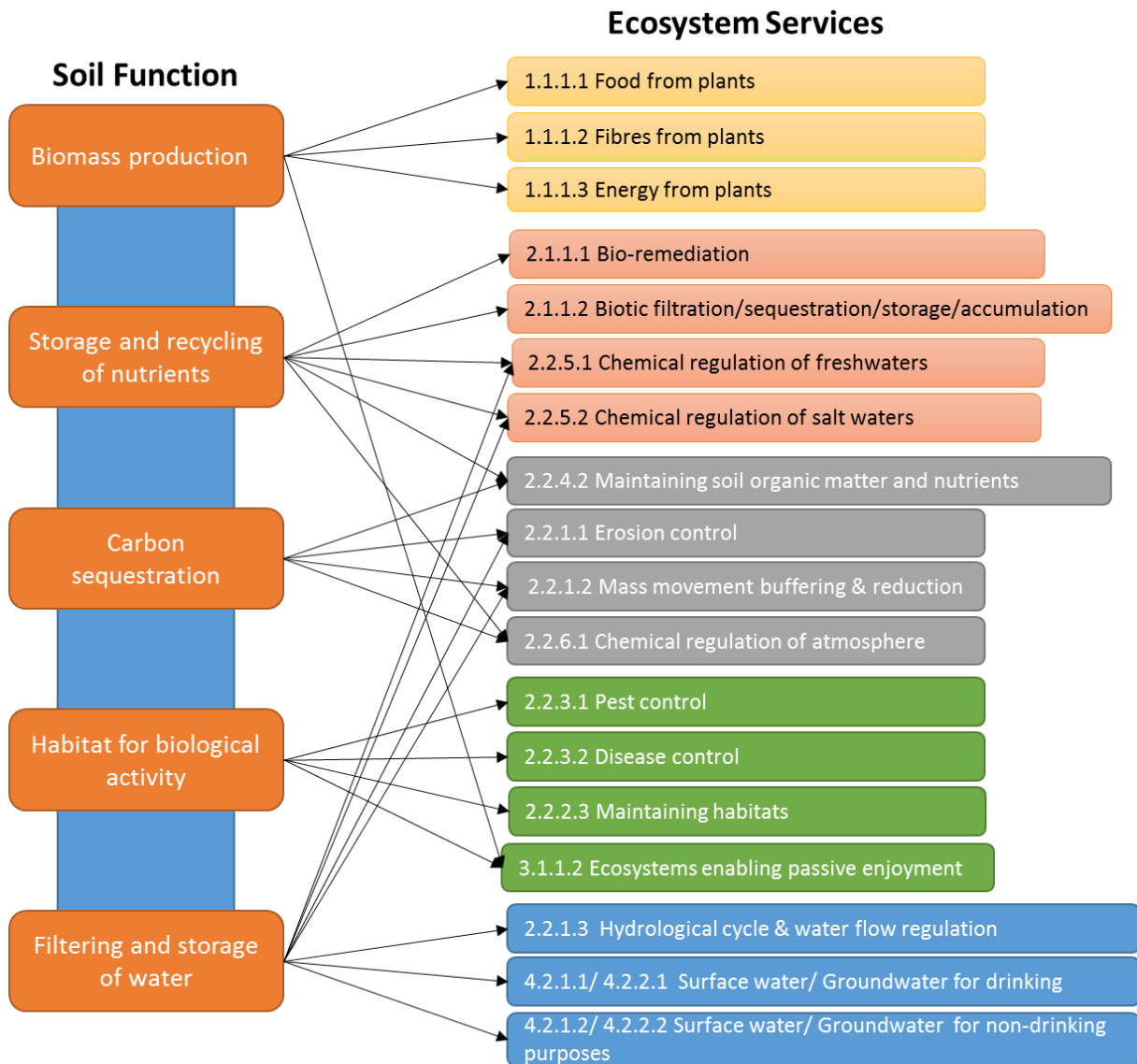


Figure 2: Connection between soil functions and selected soil related ecosystem services. Please note that all soil functions are connected to and influence each other.

Why are ecosystem services relevant for soil management?

The concept of ecosystem services has been proven very useful in policy support to demonstrate and assess human-environment interactions (Helming et al., 2013). Soil related ecosystem services are fundamental to achieving targets of a sustainable bioeconomy and of the internationally agreed Sustainable Development Goals (SDG (General Assembly, 2015)). For agricultural soils, management determines the degree by which different services are provided. **No management exists that can maximize all ecosystem services at the same time.** Farmers must make decisions on trade-offs between different services, wherein trade-offs between provisioning services (such as *provision of food, feed and fibre*) and regulating and maintenance services (such as *provision of habitats or chemical quality of freshwaters*) are the most typical. For example, intensive management with high applications of fertilizers and pesticides will maximize yields and the ecosystem service: *provision of food*. On the other hand, the ecosystem service: *provision of habitats for insects and birds* will be reduced and the

2. What do I want to assess? - Ecosystem Services

ecosystem service: *chemical quality of freshwaters (groundwater or rivers)* may be compromised by seepage.

How can ecosystem services be considered in assessments of soil management?

Impact assessments need to account for the fact that agricultural management always implies trade-offs between different ecosystem services. Each management option will enhance the provision of some ecosystem services while reducing the provision of others. **Where impact assessments only consider a selected number of services, this selection may therefore already determine the assessment results.** Depending on which ecosystem services are considered, assessments will find different policy options to have the most positive impacts. Sound research design is required to safeguard against such arbitrariness and potential for manipulation (see section on 3.3 *Impact Area Selection*), and to instead highlight the trade-offs between options.

For the assessment of ecosystem services, the Impact Assessment Platform uses the **Common International Classification of Ecosystem Services (CICES)** (Haines-Young & Potschin, 2018) which provides a complete and standardized classification scheme designed to support accounting of ecosystem services. It was developed in collaboration with the **European Environment Agency (EEA)** and builds on earlier classifications as part of *The Economics of Ecosystems and Biodiversity* (TEEB, 2010) and the *Millennium Ecosystem Assessment* (MEA, 2005). CICES makes a substantial contribution to a standardisation of ecosystem service assessments and links up with efforts to integrate ecosystem services into national and European accounting systems (Edens and Hein, 2013).

CICES has a strictly hierarchical, five-level structure, organized from bottom to top into: section, division, group, class and class type. Three sections provided by the biotic components of ecosystems are distinguished: **Provisioning, Regulation & Maintenance** and **Cultural**. In an extension introduced in 2018 with CICES version 5.1, abiotic sections for Provisioning, Regulation & Maintenance and Cultural services were added. Figure 3 shows how the production of cereals as food crops fits into the CICES hierarchy.

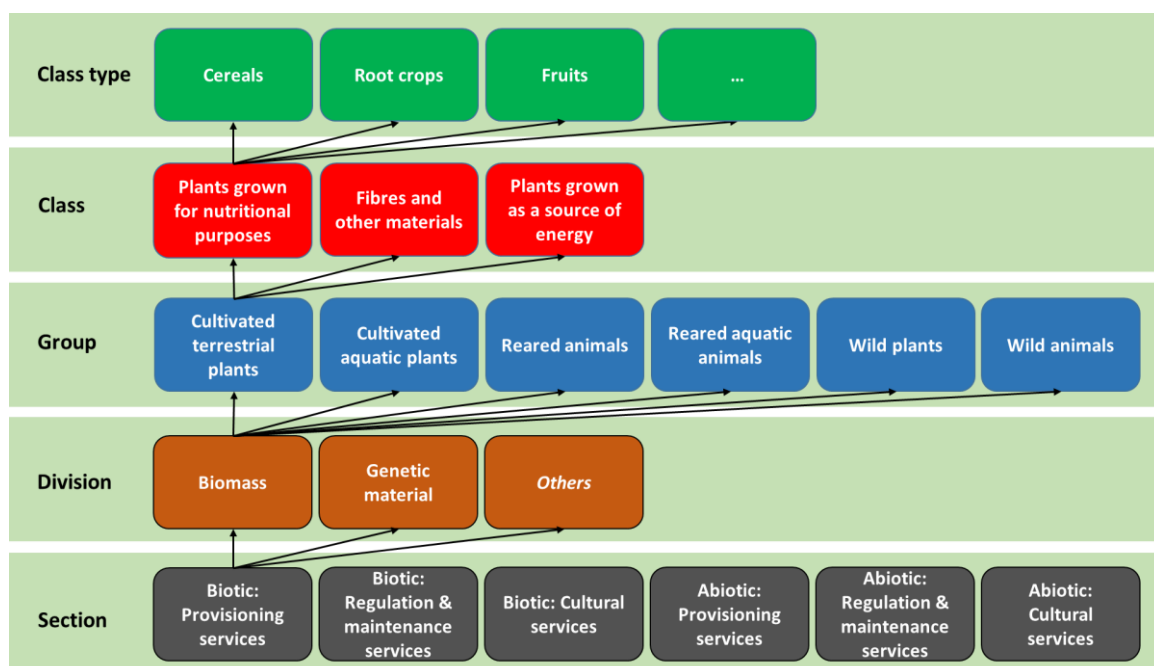


Figure 3: CICES 5.1 hierarchy from section to class type: Example of cereals produced as food crops.

2. What do I want to assess? - Ecosystem Services

The hierarchical structure is intended to facilitate ecosystem service accounting at different spatial scales. **The Impact Assessment Platform supports assessments at the class level**, because the higher hierarchical levels lack the detail usually required for meaningful investigations into the effects of agricultural management. However, where data availability is insufficient, users are encouraged to move to group level for individual categories. An example of such a strategy is provided by Maes et al. (2016).

In total, there are 84 ecosystem service classes in CICES. In a preliminary assessment conducted by the author, half of them (42) were considered to be related to agricultural soils and their management (Tables 1 and 2). These service classes are mainly from the biotic regulating and maintenance section. In the context of the Impact Assessment Platform, soil related ecosystem service classes are considered potential **impact areas**. For each of them, a description, lists of indicators, information on strength and weaknesses associated with their measurement, and references to examples in published research are provided. Additionally, the platform offers guidelines for selecting impact areas suited to requirements of specific assessment. Though multiple correlations exist between ecosystem services, these correlations are very difficult to account for in the design of measurements. Published studies generally assess ecosystem services individually and only address correlations between them as part of their results and discussion. This approach is also followed in the methods presented on the Impact Assessment Platform.

The CICES classes are not an ideal fit for the context of soil related impact assessments. Some classes are very broad (e.g., *maintaining soil organic matter and nutrients*), some are very specific (e.g., *biomass for food & feed*, *biomass for material use*, *biomass for energy*) some overlap (e.g., *bio-remediation of wastes*, *maintaining soil organic matter and nutrients*, *chemical regulation of freshwaters*) and some important soil physical categories such as aggregate stability or resistance against compression are not accounted for. However, CICES offers a comprehensive standard for ecosystem services assessment, thereby increasing policy relevance and comparability of study results. In spite of these shortcomings in the current CICES version, the Impact Assessment Platform therefore builds on the CICES classification and aims at facilitating its use in soil related assessments.

Please note: As is the case for all assessment perspectives, the ecosystem services concept only addresses a limited set of societal targets while ignoring targets from other valuation systems, such as resource use efficiency, equity or health (Sandifer et al., 2015; Schröter et al., 2017; Helming et al., 2018). Using more than one perspective will provide a more comprehensive picture of (potential) impacts. Though still uncommon, a number of soil related studies have recently shown how linkages to other valuation systems are possible, e.g., as outlined by Bouma (2014) and Keesstra et al. (2016). For this reason, the Impact Assessment Platform also supports the two complementary perspectives of **Ecosystem Services** and **Resource Use Efficiency** and encourages researchers to use them both.

Table 1: Soil management-related ecosystem services. Twenty-five services are typically affected by agricultural soil management (white background) and comprise a short list that should be considered in any impact assessment of soil management. Fifteen services (grey background) are only relevant within specific contexts

2. What do I want to assess? - Ecosystem Services

(e.g., geographic peculiarities or special land uses). Common International Classification of Ecosystem Services (CICES) class names were simplified to aid intuitive understanding.

CICES code	Biotic provisioning services	CICES code	Biotic regulation & maintenance services
1.1.1.1	Cultivated terrestrial plants for nutrition	2.1.1.1	Biotic remediation of waste
1.1.1.2	Cultivated terrestrial plants for materials	2.1.1.2	Biotic filtration, sequestration and storage of waste
1.1.1.3	Cultivated terrestrial plants for energy	2.2.1.1	Erosion control
1.2.1.1	Genetic material from plants to maintain populations	2.2.1.3	Hydrological cycle and flood control
1.2.1.2	Genetic material from plants for breeding	2.2.2.1	Pollination
	Abiotic provisioning services	2.2.2.3	Nursery populations and habitats
4.2.1.1	Surface water for drinking	2.2.3.1	Pest control (including invasive species)
4.2.1.2	Surface water for non-drinking purposes	2.2.3.2	Disease control
4.2.2.1	Groundwater for drinking	2.2.4.2	Soil quality by decomposition and fixing processes
4.2.2.2	Groundwater for non-drinking purposes	2.2.5.1	Chemical condition of freshwaters
		2.2.6.1	Chemical composition of atmosphere and oceans
		2.2.6.2	Local regulation of air temperature and humidity
CICES code	Biotic cultural services		
3.1.1.1	Recreation through activities in nature	2.1.2.3	Visual screening
3.1.1.2	Recreation through observation of nature	2.2.1.2	Mass movement control
3.1.2.3	Culture or heritage from interactions with nature	2.2.1.4	Wind protection
3.1.2.4	Aesthetics from interactions with nature	2.2.1.5	Fire protection
3.1.2.1	Scientific interactions with nature	2.2.2.2	Seed dispersal
3.1.2.2	Education and training interactions with nature	2.2.5.2	Chemical condition of salt waters
3.2.1.1	Symbolic meaning of nature		Abiotic regulation & maintenance services
3.2.1.2	Spiritual meaning of nature	5.1.1.3	Abiotic filtration, sequestration and storage of waste
3.2.1.3	Entertainment value of nature	5.2.1.2	Control of liquid flows
3.2.2.1	Existence value of nature		
3.2.2.2	Option or bequest value of nature		

Table 2: CICES V5.1 (Common International Classification of Ecosystem Services) abiotic ecosystem service classes. Class names were simplified by us to allow for a better overview. Classes considered relevant for the assessment of soil management and soil functions changes are marked in black.

No.	Abiotic		
	Provisioning	Regulation & Maintenance	Cultural
1	Surface water for drinking	Dilution by water bodies	Physical nat. features enabling active/passive interaction
2	Surface water for non-drinking purposes	Dilution by atmosphere	Physical nat. features enabling intellectual interactions
3	Freshwater for energy	Abiotic mediation by filtration/ sequestration/ storage or accumulation	Physical nat. features enabling spiritual/symbolic interactions
4	Seawater for energy	Mediation of nuisances by abiotic structures/processes	Physical nat. features with existence/option/bequest value
5	Groundwater for drinking	Physical barriers to mass flows	Other - Cultural (Abiotic)
6	Groundwater for non-drinking purposes	Physical barriers to liquid flows	
7	Groundwater for energy	Physical barriers to gaseous flows	
8	Other aqueous- Provisioning (Abiotic)	Maintenance and regulation by inorganic processes	
9	Food from minerals	Other - Regulation & Maintenance (Abiotic)	
10	Materials from minerals		
11	Energy from minerals		
12	Food (contribution) from non-minerals		
13	Materials from non-minerals		
14	Wind energy		
15	Solar energy		
16	Geothermal		
17	Other non-aqueous - Provisioning (Abiotic)		

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2. What do I want to assess? - Ecosystem Services - Case Studies

2.2.1. Ecosystem Services - Case Studies

During the development of the handbook, we published several studies that address how Ecosystem Services can be applied as indicators for soil-related impact assessments. Below, we present a selection of four of those publications and give short summaries of the content.

In Paul et al. (2021), a standardization of soil-related ecosystem services is explained. For doing so, it was assessed which of the classes of the International Classification of Ecosystem Services (CICES) are soil-related or affected by agricultural soil management. The authors reveal several challenges of the CICES classification system when applied to soils. For instance, the distinction between biotic and abiotic components is problematic, as soils are by definition systems of interrelated biotic and abiotic components. However, CICES can help to standardize ecosystem service assessments and therefore improve their relevance to policy.

Towards a Standardization of Soil-Related Ecosystem Service Assessments

Citation: Paul, C., Kuhn, K., Steinhoff-Knopp, B., Weißhuhn, P., & Helming, K. (2021). Towards a standardization of soil-related ecosystem service assessments. *European Journal of Soil Science*, 72(4), 1543-1558. <https://doi.org/10.1111/ejss.13022>

The study of Paul et al. (2022) gives an insight about how the indicator factsheets for the assessment perspective of the ecosystem services were developed, and describes the dataset in more detail. The dataset is based on a literature review that identified 180 research articles about indicators of ecosystem services in agriculture, of which 121 papers met the selection criteria. For each indicator, the recommended spatial scale was recorded, and the category of the input data (e.g. direct measurement, survey, expert assessment) is provided.

Dataset of Indicators for the Assessment of Ecosystem Services Affected by Agricultural Soil Management (Paul et al. 2022)

Citation: Paul, C., Donmez, C., Koeppe, P., Robinson, J. S., & Barnickel, S. (2022). Dataset of Indicators for the Assessment of Ecosystem Services Affected by Agricultural Soil Management. *Data*, 7(8), 102. <https://doi.org/10.3390/data7080102>

Dataset: The MS Word and PDF versions of the dataset are available through the BonaRes Repository (Leibniz Centre for Agricultural Landscape Research (ZALF), Germany, with the following data identification number: <https://doi.org/10.20387/bonares-mpzr-ja21>

MacPherson et al. (2020) evaluate how well farm-level sustainability assessment tools and models incorporate ecosystem services (ES) and contribute to the Sustainable Development Goals (SDGs). This investigation is important for comparing sustainability across farming systems as well as scaling up local practices to address global sustainability goals. The study found out that sustainability assessment tools cover ES and SDGs more comprehensively than models. Nonetheless, current tools and models do not sufficiently include the concept of ecosystem services.

Linking Ecosystem Services and the SDGs to Farm-Level Assessment Tools and Methods (MacPherson et al. 2020)

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Citation: MacPherson, J., Paul, C., Helming, K. (2020). Linking Ecosystem Services and the SDGs to Farm-Level Assessment Tools and Methods. *Sustainability*, 12(16), 6617. <https://doi.org/10.3390/su12166617>

The study conducted by Bartkowski et al. (2020) explores how economic valuation of soil-based ecosystem services can support sustainable soil management and inform policy decisions. Current studies are shown to focus on a narrow set of services and often use cost-based rather than preference-based valuation methods. This approach limits their relevance for political processes. Expanding the range of evaluated ecosystem services and using preference-based methods could improve the relevance of valuation for policy-making.

Potential of the Economic Valuation of Soil-Based Ecosystem Services to inform Sustainable Soil Management and Policy (Bartkowski et al. 2020)

Citation: Bartkowski, B., Bartke, S., Helming, K., Paul, C., Tehen, A. K., & Hansjürgens, B. (2020). Potential of the economic valuation of soil-based ecosystem services to inform sustainable soil management and policy. *PeerJ*, 8, e8749.

Link to the study: <https://doi.org/10.7717/peerj.87>

2. What do I want to assess? - Resource Use Efficiency



2.3 Resource Use Efficiency

Info-Box

In the context of agricultural soil management, we define resource use efficiency as the ratio between benefits generated by agricultural production processes and the amount of stressed resources used. Stressed resources are resources for which competing demands or resource use conflicts exist. This can be due to the fact that a resource is scarce (such as land, water or money) or because its use conflicts with other societal targets (such as pesticide application with biodiversity conservation). Increasing agricultural resource use efficiency is a target at the global, European and German national policy level. It is central to achieving a highly productive agricultural sector that minimises harmful externalities. Agriculture is characterised by the production of multiple benefits while utilising multiple resources. A comprehensive assessment therefore requires the appraisal of several efficiency indicators.

What is resource use efficiency?

In the context of soil management we define resource use efficiency as the ratio between benefits generated by agricultural production processes and the amount of resources used. We distinguish between stressed resources for which there is competing demand and abundant resources for which there is no competition. Competition is context-specific and can be due to demand exceeding resource limitations or due to conflicts between resource use and other societal targets (e.g. pesticide application conflicting with biodiversity preservation or emissions of greenhouse gasses conflicting with climate change mitigation). Only the amount of stressed resources is considered in efficiency assessments (di Maio et al., 2017).

$$\text{Resource Use Efficiency (RUE)} = \frac{\text{Benefits Generated}}{\text{Stressed Resource Used}} \quad \text{Eq.2: Definition of resource use efficiency}$$

As a benefit, any quantifiable, positive characteristic of a product can be chosen. This choice exerts a strong influence on calculated efficiencies and often determines efficiency rankings between production alternatives. For example, if weight of harvested biomass is considered, growing

2. What do I want to assess? - Resource Use Efficiency

strawberries is less efficient than growing ryegrass whereas the situation is reversed if the evaluation is based on gross profits.

As a resource, any of the resources used in the production process can be chosen. Here, the system boundaries must be clearly defined because substantial resource consumption can occur in pre- or post-processes related to the process under investigation. For example, if energy efficiency is assessed, it is relevant whether or not energy used in the production of inputs or machinery is considered. Finally, leakage effects, indirect land use changes and especially rebound effects should be accounted for (Lambin & Meyfroidt, 2011).

The following figure illustrates how different categories (impact areas) of soil related resource use efficiency are based on soil functions.

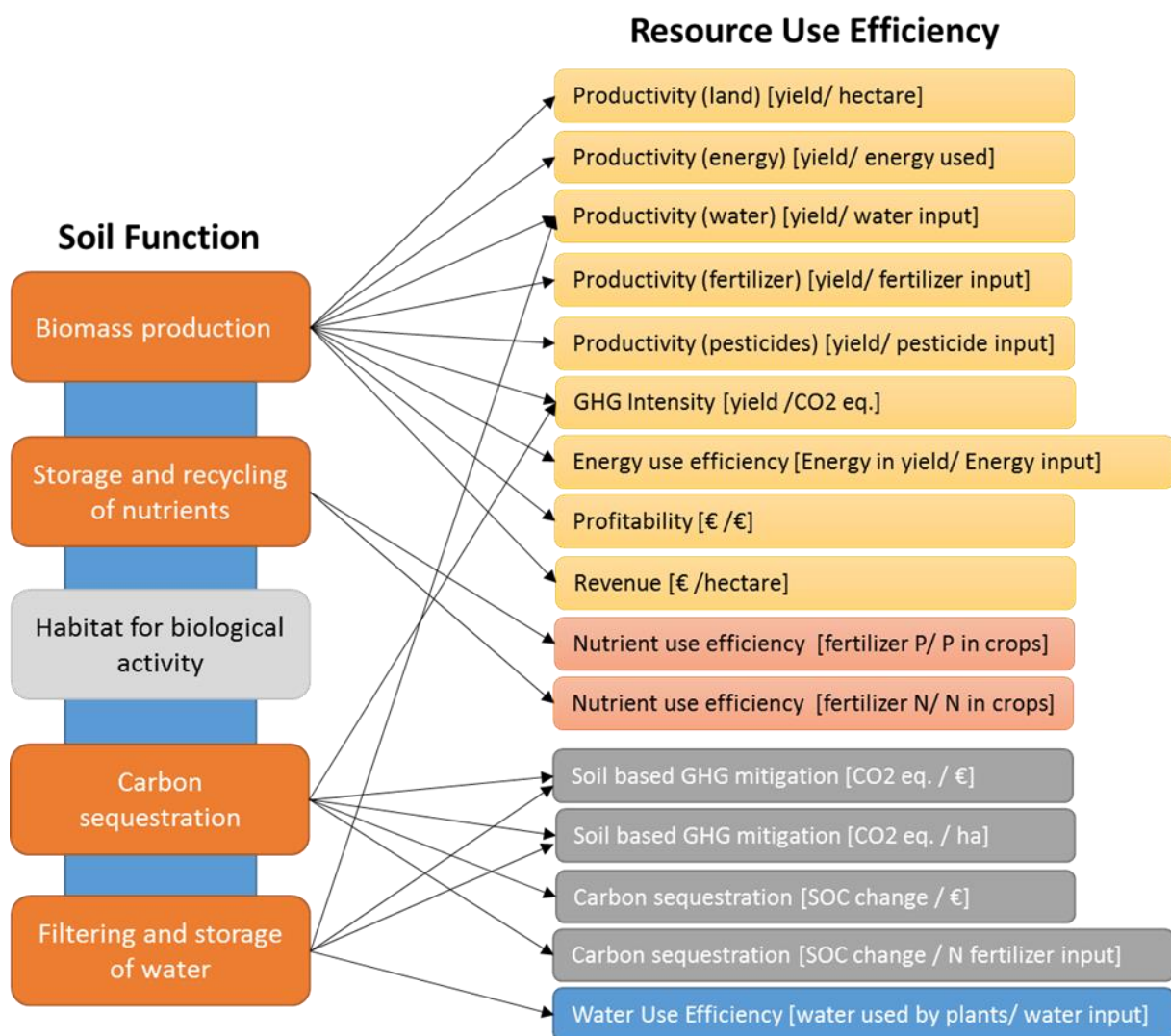


Figure 4: Connection between soil functions and selected resource use efficiency categories relevant for agricultural soil management. Please note that all soil functions are connected to and influencing each other.

Why is resource use efficiency relevant for soil management?

Increasing agricultural resource use efficiency is a target at many policy levels.

2. What do I want to assess? - Resource Use Efficiency

- Globally, the Sustainable Development Goal (SDG) 12 “sustainable consumption and production” target 12.2 seeks to achieve sustainable management and efficient use of natural resources by 2030 (General Assembly, 2015).
- At the European level, a 20% reduction of resource inputs within the food chain has been set as a milestone for 2020 (European Commission, 2011). This is to be reached through measures targeting production, distribution and consumption. Increasing efficiency of agricultural production is also a priority within the EU Rural Development Act (European Union, 2013; Spicka, 2015) in which energy efficiency, greenhouse gas emissions per unit produced and water use efficiency are explicitly named.
- At German national level, the 2014 Policy Strategy on Bioeconomy seeks to improve efficiency of agricultural production by increasing productivity while protecting natural resources and minimising greenhouse gas emissions (BMEL 2014).

Farmers have always sought to optimize their efficiency in the use of limited resources. The most obvious examples are efforts to optimize crop yields or revenues per hectare of land. The use of efficiency indicators in this regard is very common. However, increased awareness of the environmental consequences of resource use have extended the list of stressed resources. Today, there is a growing interest to achieve good yields with as little use of pesticides, fertilizer or greenhouse gas emissions as possible. Policy related assessments that do not focus on the individual farm or field but operate at higher spatial scales may also need to consider additional benefits, such as calories produced in a region or energy content of harvest. This results in the need for a whole suit of efficiency indicators.

So far, only few assessments of agricultural resource use efficiency documented in scientific literature explicitly address the role of soils. However, due to the paramount role of soils for crop growth, assessment results often implicitly reflect changes in soil functions. In the context of research to support the transition from a fossil fuel based economy towards a sustainable bioeconomy, it is necessary to determine to what degree agricultural management can increase resource use efficiencies by targeting soil functions and to what degree efficiencies can be increased irrespective of soils.

Resource use efficiency is central to achieving a highly productive agricultural sector while minimising harmful externalities. However, increasing efficiencies may also lead to trade-offs. For example, reducing the amount of labour required to produce a fixed 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 maximising the share of biomass harvested relative to net primary production (HANPP) conflicts with biodiversity targets (BIO Intelligence Service, 2012). The potential for such trade-offs should be considered in assessments of resource use efficiency.

How can resource use efficiency of soil management be measured?

The resource use efficiency of agricultural soil management can be assessed by means of efficiency indicators, calculated as the ratio between the amount of benefit generated and the amount of resources used (see Equation 2 in "What is resource use efficiency?"). What type of efficiency indicator is assessed, i.e. the selection of which benefits and which resource use are to be compared, should be based on the intended result of the agricultural management, its main inputs, and the characteristics

2. What do I want to assess? - Resource Use Efficiency

of management alternatives. More than one efficiency indicator may be required for a comprehensive assessment or to show trade-offs between different types of efficiency.

Temporal scale: Inter-annual yield variability is typical for agriculture. The use of multi-year averages for benefits and resources therefore results in indicators that are more representative of the management systems than single-year variants. Integrating production over several years is also necessary to account for perennial management effects, crop rotations and pre-crops effects (Preissel et al., 2015; Zhang et al., 2017). Where crop rotations of different length are to be compared, normalization can be achieved by dividing total benefits and resource use by the number of years in each rotation (Reckling et al., 2016).

Spatial scale: The spatial scale most suited to the analysis of resource use efficiency depends on the intended users of the assessment results. Farm or field level efficiency is of particular interest to practitioners, especially where they affect economic performance. Typical efficiency indicators at this scale are productivity (Alam et al., 2017; Moreau et al., 2012; Zhang et al., 2016), water use efficiency (WUE) (Pascual et al., 2016; Wei et al., 2016; Zhao et al., 2010), benefit cost ratio (BCR) (Alam et al., 2017; Rehman et al., 2011), nutrient use efficiency (NUE) (nitrogen: Buckley et al., 2016; Gu et al., 2017; phosphorous: Gerber et al., 2014; Zhang et al., 2016) and energy use efficiency (Hill et al., 2006; Arodudu et al., 2017).

Assessments with landscape or global implications are particularly relevant for policy makers. Indicators include greenhouse gas emissions per yield (Khakbazan et al., 2017; Steyn et al., 2016) or GDP contribution per domestic material consumption (European Commission, 2011; European Environment Agency, 2016). Efficiency indicators can also be tailored to assist the assessment of specific research or policy questions. 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 et al., 2016).

Tables 3 and 4 give an overview of recent studies on resource use efficiency in agriculture and on the efficiency indicators used.

Combining multiple benefits or resources

Agriculture is characterised by the production of multiple benefits such as food, feed, fibre or fuel while using multiple resources like land, water, energy and nutrients. It also generates profits, provides employment and creates habitats for plant and animal species while requiring capital and labour. For a comprehensive efficiency assessment, the appraisal of several benefits and resource uses is therefore essential. For this, assessments can either use multiple efficiency indicators or apply a single indicator in which multiple benefits or resources are combined.

The most common method to create combined indicators is to express all benefits or resources in monetary terms, based on their explicit or implicit market value. While practical, this approach is often criticised due to the difficulties of reflecting environmental and social consequences in monetary terms, and because values attributed to non-marketed goods vary strongly between assessments (Baveye, 2016).

2. What do I want to assess? - Resource Use Efficiency

Alternative methods are often based on benchmarking. For example, Lin & Hülsgarten (2017) determine land use efficiency for a crop rotation by first calculating multiple efficiency indicators for the rotation (such as dry matter per hectare, lipid production per hectare). In a second step, each of these indicators is divided by the respective efficiency of average production in the region. This creates a set of dimensionless values. Finally, the average of these values is calculated and used as the combined indicator. Another benchmarking approach derived from economics is data envelopment analysis (DEA). Linear combinations of all enterprises or processes within an assessment are used to calculate combinations with the highest (positive) output and smallest use of resources. These combinations constitute the so called efficiency frontier, for which an efficiency of 100% is assumed. Efficiency values of individual enterprises or processes are calculated relative to this frontier. All types of efficiencies can be combined in DEA. For example, Hoang & Alauddin (2010) used data envelopment analysis to create efficiency scores for 30 OECD countries based on agricultural production, costs, use of fertiliser and use of energy. Masuda (2016) calculated eco-efficiency of Japanese wheat production based on global warming potential, aquatic eutrophication potential and yield.

While combined efficiency indicators allow for a quick overview and may facilitate monitoring and communication with stakeholders and policy makers, the selection and weighing of the included efficiency categories and the interpretation of the resulting indicators is challenging. In detailed impact assessment, the use of multiple efficiency indicators may be preferable because they make trade-offs between different efficiency categories directly visible whereas such relationships may be obscured in the values of combined indicators.

Please note: Efficiency assessments are well suited to assess performance of agricultural production within a limited number of categories. However, they are unable to provide a holistic view of ecosystem interactions. In this regard, assessment of ecosystem services provides a well suited complementary perspective.

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Table 3: Non-integrated indicators for measuring efficiency in agriculture. Overview of studies published between 2008 and 2017 based on Web of Science Core Collection, applying search terms: “efficiency” (title) and “agriculture”, “indicator” (topic). Indicators used in three or more studies are highlighted in red.

		Seperate Indicators					
Resource	Benefit	Grain/fruit/ tuber weight	Aboveground biomass	Embodied nitrogen	Embodied energy	Revenue	Sequestered carbon
Agricultural land		Moreau et al., 2012 Phengphaengsy & Okudaira, 2008 Rehman et al., 2011 Steyn et al., 2016 Zhao et al., 2010			Lin et al., 2017	Baumaneet al., 2014 Li et al., 2013 Miklovicova & Miklovicova, 2012 Moreau et al., 2012 Rehman et al., 2011 Spicka, 2015	
		Alluvione et al., 2011 Khakbazan et al., 2017			Alluvione et al., 2011 Deike et al., 2008a Deike et al., 2008b Giambalvo et al., 2009 Khakbazan et al., 2017 Lin et al., 2017 Romanelli et al., 2012 Wasiaak & Ornyncz, 2015		
Energy		Khakbazan et al., 2017 Steyn et al., 2016			Khakbazan et al., 2017		
GHG emissions		Pasqual et al., 2016 Steyn et al., 2016 Wei et al., 2016 Zhao et al., 2010	Pasqual et al., 2016			Phengphaengsy & Okudaira, 2008	
Water						Li et al., 2013	
Human labour							
Fertiliser - N		Steyn et al., 2016 Rehman et al., 2011		Buckley et al., 2016 Godinot et al., 2014 Godinot et al., 2016 Gu et al., 2017 Moreau et al., 2012 Rehman et al., 2011	Clark & Tilman, 2017		
Fertiliser - P		Korkmaz et al., 2009 Steyn et al., 2016					
Pesticides						van Lierde et al., 2009	
Money (Costs)						Li et al., 2013 Miklovicova & Miklovicova, 2012 Rehman et al., 2011	Khakbazan et al., 2017

2. What do I want to assess? - Resource Use Efficiency

Table 4: Integrated indicators for measuring efficiency in agriculture. Overview of studies published between 2008 and 2017 based on Web of Science Core Collection, applying search terms: “efficiency” (title) and “agriculture”, “indicator” (topic).

Integrated Indicators		
Efficiency scores based on multiple inputs and outputs	Stochastic Frontier Analysis (SFA)	Data Envelopment Analysis (DEA)
	Boshraadi et al., 2008 Li et al., 2013	Aldanondo-Ochoa et al., 2014 Azad & Ancev 2014 Bojnec & Latruffe, 2011 Gomes et al., 2009 Hoang, 2011 Hoang & Alauddin, 2012 Lee & Park 2017 Masuda, 2016 Pagotto & Halog, 2015 Sabiha et al., 2017 Spicka, 2014 Spicka & Smutka, 2014 Wang et al., 2015

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2. What do I want to assess? - Resource Use Efficiency

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2. What do I want to assess? - Sustainable Development Goals



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2.4 Sustainable Development Goals (SDG)

Info-Box

The Sustainable Development Goals (SDG) are a set of goals and targets to be reached by 2030, agreed upon by, and requiring action from all United Nations (UN) member states. Soil functions play an important role for the realisation of multiple targets and underpin the achievement of the SDG agenda as a whole. Although the UN indicators for measuring progress on these targets are designed at the global level, successful achievement of the agenda requires national, regional and local efforts. It is therefore important to also connect the sustainable development goals to effects of policy and management options at these levels.

The Impact Assessment Platform supports the operationalisation of the SDG targets by defining linkages to soil related ecosystem services and agricultural resource use efficiency.

What are the Sustainable Development Goals?

The Sustainable Development Goals (SDG) were adopted in 2015 by the General Assembly of the United Nations (UN) as part of the 2030 Agenda for Sustainable Development. There are **17 SDGs** in total which include goals to end poverty and hunger, combat inequality and injustice, and tackle climate change by 2030. The SDGs are further broken down into 169 individual time-bound targets and there currently exist 230 indicators against which they can be measured. The goals are not binding under international law but UN member states have a legal obligation to issue progress reports up to the 2030 target date.

The SDGs are universal in nature meaning that they apply to and should be achieved in all countries. Furthermore, the 17 goals are “integrated and indivisible”, designed to balance the three dimensions

2. What do I want to assess? - Sustainable Development Goals

of sustainable development: the economic, social and environmental (UN, 2016). Efforts to achieve one goal should not hinder progress in other areas.

The SDGs build on the Millennium Development Goals (MDG) which were adopted by world leaders in 2000 to be reached by 2015. These were eight goals aimed primarily at reducing extreme poverty and the related consequences.

Why are the Sustainable Development Goals relevant in the context of soil management?

Despite only 4 explicit references to soils in the 169 SDG targets (targets 2.4, 3.9, 12.4, 15.3), soil functions play an important role for the realisation of a vast number of targets and underpin the achievement of the SDG agenda as a whole (Montanarella & Alva, 2015). Not only do they have a clear role in achieving SDGs related to the biophysical system (e.g. SDGs 2, 3, 6, 7, 12–15), they are also important to the achievement of socio-economic goals due to the multifunctional benefits they provide (Keesstra et al., 2016).

Unlike the MDGs which focused on the donor-recipient relationship between more developed and poorer countries, the SDGs are universal in nature, meaning that they apply to all countries and should be achieved in all countries. In Germany, Agenda 2030 forms the basis of the latest Sustainable Development Strategy (German Federal Government, 2021), which presents measures to implement the 17 SDGs across the economic, social and environmental spheres.

How can the SDGs be considered in assessments of soil management?

The UN indicators for measuring progress towards SDGs are designed for impact assessment at the global level and therefore do not directly relate to local, regional or even national decisions. However, successful achievement of the agenda requires efforts at every level in all UN member states. It is therefore important to draw connections between management options and the relevant SDG targets. The Impact Assessment Platform supports this by highlighting **25 SDG targets** that are directly connected to **agricultural management** and impact areas **under the assessment perspectives of soil related ecosystem services** and **agricultural resource use efficiency**. Table 5 lists the SDG targets for which connections are drawn and provides the codes for the respective impact areas, Table 6 lists the impact areas supported by the Impact Assessment Platform to which these codes refer to. The highest numbers of connections were found for target 2.04 (sustainable food production and resilient agriculture) and target 6.06 (protect and restore water related ecosystems).

On the platform, users may first select one of the SDG targets and then choose from a list of connected impact areas. A factsheet for the chosen impact area is then created which provides information on indicators, strengths & weaknesses pertaining to measurements, correlations with agricultural management and examples of published research.

Additional SDG targets and assessment perspectives, such as equity or human health impacts, may be added in future updates to the assessment platform.

2. What do I want to assess? - Sustainable Development Goals

Table 5: SDG targets related to agricultural management and impact areas under the perspectives of resource use efficiency and ecosystem services.

SDG	Target	Description
	01.02	By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions. Related Impact Areas: 6, 11, 16, 22, 27, 32, 36, 41, 47, 52, 63, 64, 65, 66, 67, 83
	01.05	By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters. Related Impact Areas: 73, 74, 75, 76, 80, 81, 87, 103
	02.04	By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality. Related Impact Areas: 1, 2, 8, 9, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 49, 50, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 73, 75, 77, 78, 79, 80, 81, 83, 84, 85, 86, 102, 103, 104
	02.05	By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed. Related Impact Areas: 66, 67
	03.09	By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination. Related Impact Areas: 37, 38, 39, 40, 41, 42, 61, 68, 69, 84, 85, 102, 86
	04.07	By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development. Related Impact Areas: 90, 91
	06.03	By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally. Related Impact Areas: 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 59, 60, 61, 68, 69, 75, 84, 85, 102, 103, 104
	06.04	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity. Related Impact Areas: 18, 19, 20, 21, 22, 23, 57, 63, 64, 65, 66, 67, 87, 99, 101

2. What do I want to assess? - Sustainable Development Goals

Table 5: SDG targets related to agricultural management and impact areas under the perspectives of resource use efficiency and ecosystem services (continued).

	07.02	By 2030, increase substantially the share of renewable energy in the global energy mix. Related Impact Areas: 2, 9, 13, 19, 25, 29, 35, 38, 44, 50, 5, 10, 15, 21, 26, 31, 40, 46, 65
	07.03	By 2030, double the global rate of improvement in energy efficiency. Related Impact Areas: 8, 9, 10, 11, 55
	08.02	Achieve higher levels of economic productivity through diversification, technological upgrading and innovation, including through a focus on high-value added and labour-intensive sectors. Related Impact Areas: 6, 11, 16, 22, 27, 32, 36, 41, 47, 52, 63, 64, 65
	08.04	Improve progressively, through 2030, global resource efficiency in consumption and production and endeavour to decouple economic growth from environmental degradation, in accordance with the 10-year framework of programmes on sustainable consumption and production, with developed countries taking the lead. Related Impact Areas: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 55, 18, 19, 20, 21, 22, 23, 57, 34, 35, 36, 60, 63, 64, 65, 73, 75, 77, 78, 79, 83, 84, 85, 86
	09.04	By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities. Related Impact Areas: 63, 64, 65, 66, 67, 68, 69, 73, 75, 77, 78, 79, 80, 81, 83, 84, 85, 86, 102, 103, 104
	10.01	By 2030, progressively achieve and sustain income growth of the bottom 40 per cent of the population at a rate higher than the national average. Related Impact Areas: 63, 64, 65
	11.04	Strengthen efforts to protect and safeguard the world's cultural and natural heritage. Related Impact Areas: 88, 92, 93, 95, 96, 97
	12.01	Implement the 10-year framework of programmes on sustainable consumption and production, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries. Related Impact Areas: 63, 64, 65, 66, 67, 68, 69, 73, 75, 77, 78, 79, 80, 81, 83, 84, 85, 86, 102, 103, 104
	12.02	By 2030, achieve the sustainable management and efficient use of natural resources. Related Impact Areas: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 55, 18, 19, 20, 21, 22, 23, 57, 34, 35, 36, 60, 73, 79, 83, 84, 85, 86
	12.04	By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment. Related Impact Areas: 68, 69, 70, 84, 85, 86, 102, 104
	13.01	Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries. Related Impact Areas: 55, 56, 57, 58, 59, 60, 61, 62, 54, 66, 67, 74, 75, 76, 80, 81, 87, 103

2. What do I want to assess? - Sustainable Development Goals

Table 5: SDG targets related to agricultural management and impact areas under the perspectives of resource use efficiency and ecosystem services (continued).

SDG	Target	Description
	13.02	Integrate climate change measures into national policies, strategies and planning. Related Impact Areas: 7, 12, 13, 14, 15, 16, 17, 23, 33, 42, 48, 53, 56, 83, 86, 87, 90, 91
	13.03	Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning. Related Impact Areas: 12, 13, 14, 15, 16, 17, 56, 90, 91
	14.01	By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution. Related Impact Areas: 28, 29, 30, 31, 32, 33, 59, 34, 35, 36, 60, 37, 38, 39, 40, 41, 42, 61, 68, 69, 73, 85, 102, 103, 104
	15.01	By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements. Related Impact Areas: 68, 69, 73, 79, 84, 87, 88, 89, 92, 93, 96, 97, 98, 99, 100, 101, 102, 103, 104
	15.03	By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world. Related Impact Areas: 73, 75, 79, 83, 103

2. What do I want to assess? - Sustainable Development Goals

Table 6: Impact areas supported by the BonaRes Assessment Platform. Areas from the perspective *Resource Use Efficiency* on the left (black numbers), areas from the perspective *Ecosystem Services* (blue numbers) on the right.

Nº	Impact Areas Resource Use Efficiency	Nº	Impact Areas Ecosystem Services
1	Grain/Fruit/ Tuber yield <i>per</i> Area of land	63	Food from plants
2	Aboveground Biomass <i>per</i> Area of land	64	Fibres from plants
3	Jobs <i>per</i> Area of land	65	Energy from plants
4	Embodied Nitrogen <i>per</i> Area of land	66	Seeds for breeding purposes
5	Embodied Energy <i>per</i> Area of land	67	Plants for breeding purposes
6	Financial benefits <i>per</i> Area of land	68	Bio-remediation
7	Sequestered Carbon <i>per</i> Area of land	69	Biotic filtration/sequestration/storage/accumulation
8	Grain/Fruit/ Tuber yield <i>per</i> Energy	70	Smell reduction
9	Aboveground Biomass <i>per</i> Energy	71	Noise reduction
10	Embodied Energy <i>per</i> Energy	72	Visual screening
11	Financial benefits <i>per</i> Energy	73	Erosion control
12	Grain/Fruit/ Tuber yield <i>per</i> GHG emissions	74	Mass movement buffering & reduction
13	Aboveground Biomass <i>per</i> GHG emissions	75	Hydrological cycle & water flow regulation
14	Embodied Nitrogen <i>per</i> GHG emissions	76	Wind protection
15	Embodied Energy <i>per</i> GHG emissions	77	Pollination
16	Financial benefits <i>per</i> GHG emissions	78	Seed dispersal
17	Sequestered Carbon <i>per</i> GHG emissions	79	Maintaining habitats
18	Grain/Fruit/ Tuber yield <i>per</i> Water	80	Pest control
19	Aboveground Biomass <i>per</i> Water	81	Disease control
20	Embodied Nitrogen <i>per</i> Water	82	Weathering & soil development
21	Embodied Energy <i>per</i> Water	83	Maintaining soil organic matter & nutrients
22	Financial benefits <i>per</i> Water	84	Chemical regulation of freshwaters
23	Sequestered Carbon <i>per</i> Water	85	Chemical regulation of salt waters
24	Grain/Fruit/ Tuber yield <i>per</i> Human labour	86	Chemical regulation of atmosphere
25	Aboveground Biomass <i>per</i> Human labour	87	Regulation of temperature/humidity/ventilation/transpiration
26	Embodied Energy <i>per</i> Human labour	88	Ecosystems enabling active enjoyment
27	Financial benefits <i>per</i> Human labour	89	Ecosystems enabling passive enjoyment
28	Grain/Fruit/ Tuber yield <i>per</i> Nitrogen fertilizer	90	Ecosystems enabling research
29	Aboveground Biomass <i>per</i> Nitrogen fertilizer	91	Ecosystems enabling education
30	Embodied Nitrogen <i>per</i> Nitrogen fertilizer	92	Culturally/historically important ecosystems
31	Embodied Energy <i>per</i> Nitrogen fertilizer	93	Aesthetically important ecosystems
32	Financial benefits <i>per</i> Nitrogen fertilizer	94	Symbolically important ecosystems
33	Sequestered Carbon <i>per</i> Nitrogen fertilizer	95	Ecosystems used for entertainment/representation
34	Grain/Fruit/ Tuber yield <i>per</i> Phosphorus fertilizer	96	Ecosystems with existence value
35	Aboveground Biomass <i>per</i> Phosphorus fertilizer	97	Ecosystems with option/bequest value
36	Financial benefits <i>per</i> Phosphorus fertilizer	98	Surface water for drinking
37	Grain/Fruit/ Tuber yield <i>per</i> Pesticides	99	Surface water for non-drinking purposes
38	Aboveground Biomass <i>per</i> Pesticides	100	Groundwater for drinking
39	Embodied Nitrogen <i>per</i> Pesticides	101	Groundwater for non-drinking purposes

2. What do I want to assess? - Sustainable Development Goals

Nº	Impact Areas Resource Use Efficiency
40	Embodied Energy <i>per</i> Pesticides
41	Financial benefits <i>per</i> Pesticides
42	Sequestered Carbon <i>per</i> Pesticides
43	Grain/Fruit/ Tuber yield <i>per</i> Money
44	Aboveground Biomass <i>per</i> Money
45	Embodied Nitrogen <i>per</i> Money
46	Embodied Energy <i>per</i> Money
47	Financial benefits <i>per</i> Money
48	Sequestered Carbon <i>per</i> Money
49	Grain/Fruit/ Tuber yield <i>per</i> Long-time investment
50	Aboveground Biomass <i>per</i> Long-time investment
51	Jobs <i>per</i> Long-time investment
52	Financial benefits <i>per</i> Long-time investment
53	Sequestered Carbon <i>per</i> Long-time investment
54	Yield stability <i>per</i> Long-time investment
55	Yield stability <i>per</i> Energy
56	Yield stability <i>per</i> GHG emissions
57	Yield stability <i>per</i> Water
58	Yield stability <i>per</i> Human labour
59	Yield stability <i>per</i> Nitrogen fertilizer
60	Yield stability <i>per</i> Phosphorus fertilizer
61	Yield stability <i>per</i> Pesticides
62	Yield stability <i>per</i> Money

Nº	Impact Areas Ecosystem Services
102	Abiotic mediation by filtration/sequestration/storage/accumulation
103	Physical barriers to liquid flows
104	Maintenance and regulation by inorganic processes

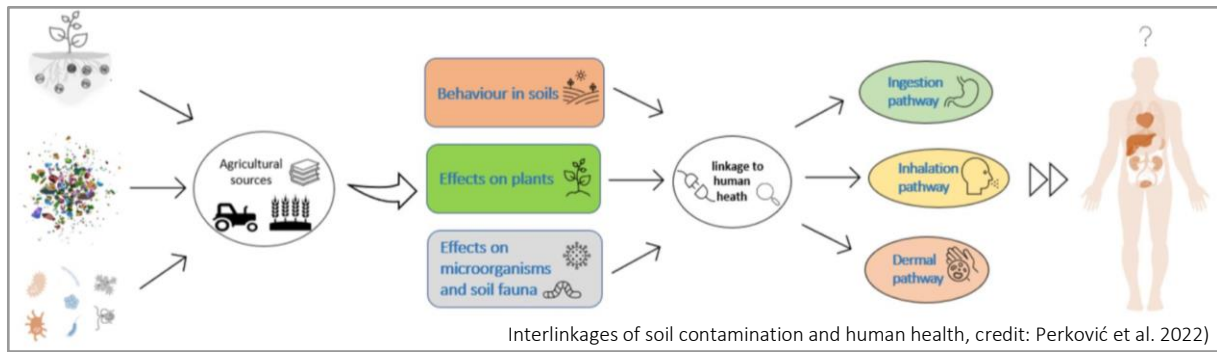
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2. What do I want to assess? - Soil Contamination and Human Health



2.5 Soil Contamination and Human Health

Info-Box

Soils play a fundamental role for human health and well-being (Zhu et al., 2019). According to the concept of "One Health", both soils and humans are part of a symbiotic environment and thus interconnected and interdependent (Amuasi et al., 2020). The One Health concept is an integrated approach that aims to sustainably balance and optimize the health of humans, animals, and ecosystems by recognizing the links between them (OHHLEP, 2022).

Intensification of agricultural production systems has led to soil contamination in many places and, as a consequence, increased the exposure of humans to soil contaminants (Karimyan et al., 2020). Humans are exposed to these contaminants through inhalation, dermal contact, or the consumption of food. At the same time, soil contamination may also impact flora and fauna of affected and surrounding areas. This can pose a wider threat to the environment and could lead to additional, indirect consequences for human health.

What types of contaminants can be found in soils?

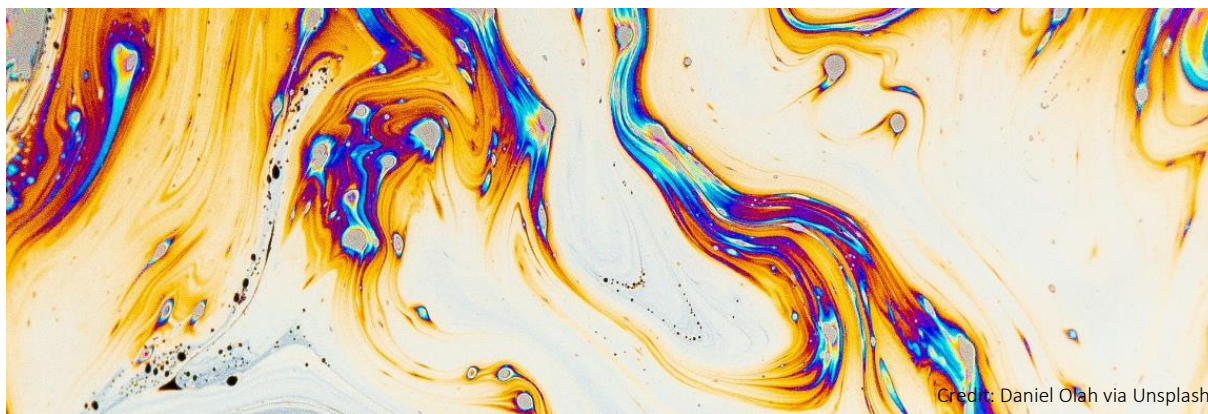
Some human-induced contaminants, such as heavy metals, are well-known and have been present in agricultural soils for a long time. Others, such as antibiotic-resistant bacteria or micro(nano)plastics represent emerging and novel threats. In the following sections, each of those contaminants and their interlinkages with soil health and human health are explored.

Challenges in assessing the impacts of soil contamination and human health

Impact assessments are an important tool for identifying and minimising human health risks arising from the accumulation of different soil contaminants. This is of particular importance with regard to measures reinforcing the concept of circular economy and nutrient cycling (e.g. sewage sludge as fertilizer) (Perković et al., 2022).

Since research on some of the contaminants has only emerged quite recently, there are still severe knowledge gaps which limit impact assessments. For example, little is known about the relative distribution of different contaminants in the soil, their combined effects, their pathways within the soil, and their long-term effect on soil health and human health. In order to close these knowledge gaps, long-term field studies, standardized protocols of measurement and comprehensive monitoring systems are needed (Perković et al., 2022).

2. What do I want to assess? - Soil Contamination - Heavy Metals



2.5.1 Heavy Metals

Info-Box

This group of contaminants includes metals (e.g., Cadmium, Cobalt, Mercury, Lead) and metalloids (e.g. Selenium, Antimony, Arsenic) with an atomic number greater than 20 (Sanaei et al., 2020) and a density greater than 5 g/cm^3 . Heavy metals are persistent and non-biodegradable, with some of them being toxic even at low concentrations.

Heavy metals naturally occur at site-specific (low) concentrations in soils, and some of them - such as Iron, Zinc, Nickel, Copper, or Magnesium - are essential micronutrients for plants, animals, and humans (Balseiro-Romero & Baveye, 2018). However, pollution or unsuitable agricultural management may also lead to higher concentrations and or increased bioavailability, thus causing toxic effects and threats to both soil health and human health (Demková et al., 2017).

Sources in agricultural soils

Reasons for elevated heavy metal concentrations in agricultural soils are mainly intentional applications of compounds containing high levels of heavy metals. These can be fertilizers (e.g., phosphate or nitrate fertilizers, livestock manure, composts, biosolids, or sewage sludge), lime, pesticides, or wastewater for irrigation (Alengebawy et al., 2021; Nicholson et al., 2003; Srivastava et al., 2017; Rai et al., 2019; Abreu-Junior et al., 2018; Giannakis et al., 2020).

For example, Phosphate (P)-based fertilizers can be a source of heavy metals such as Zinc or Cadmium (Rai et al., 2019) and may cause soil pollution, crop uptake, and bioaccumulation along the food chain, resulting in environmental and human health risks (Niño-Savala et al., 2019). P-fertilizers are estimated to contribute 45% to the total Cadmium-load in European croplands, while 55% of the total dietary intake of Cadmium by consumers is associated with Cadmium accumulation in soils (Marini et al., 2020).

The mobility and bioavailability of heavy metals is strongly influenced by soil conditions. Detailed risk assessments are essential if potentially contaminated material is to be applied to soil (Giannakis et al., 2020).

Mitigating the risk of soil pollution with heavy metals includes avoidance of excessive fertilizer use (Nag & Cummins, 2021), monitoring of fertilizer composition (Srivastava et al., 2017; Nag & Cummins, 2021), and periodic soil sampling and testing to assess the concentration and bioavailability of heavy

2. What do I want to assess? - Soil Contamination - Heavy Metals

metals (Nag & Cummins, 2021). Since heavy metals in animal manure originate from livestock feed, feed should be controlled and intentional feeding with heavy metals restricted to optimal doses rather than maximum permitted levels (Hejna et al., 2019).

Dispersion

Heavy metals incorporated within agricultural particulate matter (Li et al., 2015) can be extensively dispersed throughout the atmosphere (Hassanien et al., 2010). The lifetime of heavy metal-carrying particulate matter and their possible toxicity is a function of their size. Generally, the smaller and lighter a particle is, the longer it will stay in the atmosphere, while larger particles (>10 µm in diameter) tend to be deposited by gravity in a matter of hours (Hassanien et al., 2010)

Linkages between heavy metals and human health

As heavy metals can be absorbed by food plants or aerially deposited on their surface, the food chain has been reported to account for approximately 90% of total heavy metal intake (Demková et al., 2017; Sanaei et al., 2020). Additionally, they can be inhaled together with soil particles or (in specific cases or at high concentrations) absorbed through the skin.

It is important to note that the chemical species or compounds in which heavy metals occur determine their toxicological impact and may be more important than the total uptake. Studies report that heavy metals can impair neurological, cardiovascular, urogenital, endocrine, immune, digestive, respiratory, and detoxification functions of the body, causing a variety of health problems (Karimyan et al., 2020; Balali-Mood et al., 2021; Hassanien et al., 2010; Doabi et al., 2018). Additionally, some heavy metals (e.g., Arsenic, Cadmium, Chromium, Nickel) have carcinogenic effects (Karimyan et al., 2020; Balali-Mood et al., 2021).

Heavy metal concentration, exposure duration, and ingestion rate, as well as nutritional status and immune system and individual detoxification organ strength are factors affecting human health impacts (Sanaei et al., 2020; Hassanien et al., 2010).

Effects on flora and fauna

Heavy metal accumulation can reduce a soil's biological activity, causing reduced fertility and plant growth, loss of soil organic matter (Feszterová et al., 2021), loss of soil structure, and increased soil acidity (Alengebawy et al., 2021). Heavy metals can induce oxidative stress in plants, affect their photosynthetic processes, their respiration and transpiration, as well as the uptake and transport of essential micronutrients. Hence, they may inhibit plant development and growth, including germination and root elongation, resulting in a decrease in biomass and a potential reduction in productivity and yields (Srivastava et al., 2017; Niño-Savala et al., 2019; Khan et al., 2015; Feszterová et al., 2021; Abdel-Rahman et al., 2021). High concentrations of heavy metals can also cause plant death and motivate the selection of species with resistance mechanisms and high tolerances (Niño-Savala et al., 2019).

Heavy metal type, concentration, and bioavailability determine to what extent they will be absorbed by plants (Khan et al., 2015; Feszterová et al., 2021). Additionally, heavy metal uptake by plants also differs between plant species, as different plants have different uptake rates for specific metals (Khan et al., 2015; Gruszecka-Kosowska et al., 2019).

2. What do I want to assess? - Soil Contamination - Heavy Metals

Studies show that heavy metals in soils can have inhibitory effects on soil microbial and enzymes activities, microbial biomass, populations, growth, and metabolic processes (Alengebawy et al., 2021; Srivastava et al., 2017). Therefore, the abundance, diversity, and structure of the microbial communities can be affected (Hu et al., 2021), potentially causing functional changes in soil flora with implications for C or N cycling (Hodson et al., 2013). Overall though, despite the toxic effect of heavy metals, microorganisms such as bacteria, fungi, or algae can survive in their presence thanks to several evolutionary strategies enabling them to reduce or tolerate toxicity. Additionally, heavy metals in soil can act as evolutionary drivers, as studies show the ability of soil organisms to develop mechanisms by which they can tolerate or resist the effects of heavy metal-induced stress (e.g. acclimation and adaptation) (Hodson et al., 2013).

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2. What do I want to assess? - Soil Contamination - Micronanoplastics



2.5.2 Micronanoplastics

Info-Box

Microplastics are plastic particles with a diameter of less than 5 mm and more than 1 μm , that are brought to this size by microbial activities, photodegradation or mechanical forces. Nanoparticles are even smaller, with a diameter of less than 1 μm . The term Micronanoplastics considers both groups (Bartkova et al., 2017; Ullah et al., 2021).

Although Micronanoplastics have been extensively studied in aquatic systems, their presence and fate in agricultural systems are still insufficiently understood. They are persistent contaminants that are ubiquitous in the soil environment (Kumar et al., 2020). They are also of particular concern, as the use of plastic materials in agriculture is expected to further increase (Huang et al., 2020).

Sources in agricultural soils

1. the use of plastic materials in the production process, such as mulching films (Okeke et al., 2021; Bläsing & Amelung, 2018) greenhouse or tunnel materials, silage films, boxes, packaging materials, harvesting nests, plastic reservoirs, or irrigation tubes (Ng et al., 2018; Kim et al., 2020; Sarker et al., 2020; Isari et al., 2021);
2. the application of contaminated substances, such as sewage sludge, biosolids, or organic fertilizers, irrigation with treated wastewater or contaminated freshwater (Bläsing & Amelung, 2018; Wang et al., 2021); and
3. the application of substances intentionally containing plastics, such as polymer-based slow-release fertilizers or pesticides (Kumar et al., 2020).

Plastic mulching, mostly made by low-density polyethylene and polypropylene, has become a globally applied practice for plant protection from harsh climatological conditions. It is considered one of the major causes of micronanoplastic pollution in agricultural soils (Huang et al., 2020; Sarker et al., 2020). About 83,000 tons of mulch films were sold in Europe in 2019 (Campanale et al., 2021), with projections that the global market will grow until 2030 at a rate of 5.6% per year (Huang et al., 2020).

Behaviour in soils

Though soils, particularly agricultural soils, have been recognized as a major sink of micronanoplastics, the impacts of micronanoplastics on soil ecosystems remain uncertain (Boots et al., 2019). Because of their minute size, it is difficult to separate and isolate them from soil samples, hampering identification and observation procedures. Hence, future studies should focus on finding standardized analytical

2. What do I want to assess? - Soil Contamination - Micronanoplastics

methods to estimate micronanoplastics in soil samples as a basis for identifying and closing knowledge gaps about its effects in the soil environment (Allouzi et al., 2021).

Micronanoplastics and human health

Only limited evidence confirming the effects of micro- and nanoplastics on human health is available. However, the presence of micronanoplastics in agricultural soils leads to increased human uptake with food. This has been suggested to affect human health (oxidative stress, inflammation processes, genotoxicity, neurotoxicity, mitochondrial function) (Allouzi et al., 2021; Fournier et al., 2021).

Recent studies have found that micronanoplastics can be accumulated in the human intestines (Yu et al., 2022). This may cause gastrointestinal issues such as local inflammation and alter the community composition and diversity of intestinal microbes (Yu et al., 2022; Fackelmann & Sommer, 2019; Teles et al., 2020). Additionally, micronanoplastics further have the ability to pass through the intestinal barrier and enter the circulatory system, including the spleen and liver (Yu et al., 2022; Teles et al., 2020).

Most of the studies suggest that the main risk of micronanoplastics for human health arises from the release of additives which are known to be endocrine disruptors or carcinogenic (e.g., bisphenol A, phthalates) (Pathan et al., 2020), or from their ability to sequester co-pollutants from the environment (e.g., heavy metals, antibiotic-resistant bacteria), enhancing their transfer and uptake (Campanale et al., 2021; Campanale et al., 2020). Furthermore, owing to their tendency to adsorb other chemicals or soil constituents, plastic particles could cause bioaccumulation and bioamplification phenomena by adsorbing persistent organic pollutants, agrochemicals, heavy metals, antibiotics resistance genes, or pathogenic microorganisms. This significantly increases their potential environmental and health threat (Ullah et al., 2021; Wang et al., 2021; Da Costa et al., 2016).

Effects on flora and fauna

Very few studies have investigated the effects of micronanoplastics on the growth of plants. Micronanoplastics can accumulate in the roots of plants and then be transported to their leaves, flowers, and fruits (Tian et al., 2021). Different micronanoplastics may trigger different responses in soils and plants (De Souza Machado et al., 2019) and overall, neither a generally positive or negative effect on plants can be postulated at present (De Souza Machado et al., 2019; Rillig et al., 2019). Observations suggest that micronanoplastics may be able to delay germination, affect both vegetative and reproductive growth of plants, and exert eco- and genotoxicity to plants (Xu et al., 2019). On the other hand, they can promote roots and plant growth and result in higher total biomass. Furthermore, they may enhance the colonization of roots by soil microbes (De Souza Machado et al., 2019).

Likewise, the effect of micronanoplastics on soil fauna under real-life conditions is still poorly understood (Xu et al., 2019). Fungi and bacteria can promote the degradation of plastics (Wang et al., 2019), though the persistent and pervasive nature of micronanoplastics in the soil environment has been confirmed (Kumar et al., 2020). Micronanoplastics can alter soil microbial community diversity, as well as the activity of soil microbiota and enzymes. They may hence disturb microbial ecosystems and affect soil nutrient cycles (Xu et al., 2019). However, these effects display great variability (Sajjad et al., 2022) and may depend on micronanoplastic type, shape, size, concentration, and composition, as well as on soil characteristics such as texture (Xu et al., 2019; Sajjad et al., 2022). Negative effects

2. What do I want to assess? - Soil Contamination - Micronanoplastics

exerted by micronanoplastics may also be related to concomitant pollutants found on them (Xu et al., 2019).

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2. What do I want to assess? - Soil Contamination - Micronanoplastics

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2. What do I want to assess? - Soil Contamination - Antibiotic-resistant bacteria



2.5.3 Antibiotic-resistant bacteria

Info-Box

Resistance development against chemical agents is a natural phenomenon, yet the presence of antibiotic residues in agricultural soils can accelerate both the development and proliferation of resistant bacteria strains (Gudda et al., 2020).

It is well acknowledged that the expansion of resistances against antibiotics poses a growing risk to public health (He, Yan, Chen, 2020). However, the emergence and spread of antibiotic-resistant bacteria and antibiotic-resistant genes from agricultural systems and their contribution to the resistance of human pathogens are complex processes that are not yet well understood (Jechalke et al., 2014).

Studies have reported that low level concentrations of antibiotics (below minimum inhibitory concentrations), which can be found in food crops, might impact bacterial resistance selection, contributing to resistance enrichment (Gudda et al., 2020).

Sources in agricultural soils

Agricultural soils are natural reservoirs of antibiotics and therefore also of antibiotic-resistant bacteria and genes (ARBG) (Wang et al., 2020). Elevated levels of ARBG in agricultural soils are mainly caused by the continuous application of manure from animals that were given antibiotics for therapeutic or non-therapeutic purposes, the application of contaminated sewage sludge or biosolids, or irrigation with contaminated water or reclaimed wastewater (Wang et al., 2020; Pan et al. 2017). Additionally, some antibiotics are used as pesticides in crop production (Iwu et al., 2020).

Animal manure is considered a major source of ARBG in soils (Chen et al., 2016), as more than 50% of antibiotics in Europe are administered to livestock (Münch et al., 2020). 30–90% of these antibiotics are estimated to be excreted again largely non metabolized by the animals, resulting in commonly high residual antibiotic concentrations in animal manure (Marshall et al., 2011; Wang et al., 2015; Wang et al., 2021).

2. What do I want to assess? - Soil Contamination - Antibiotic-resistant bacteria

The risk of soil contamination from this source is increasing, as the global amount of manure application to agricultural soils is persistently growing due to a rising livestock production (Kabelitz et al., 2020). Additionally, the utilization of manure as an organic fertilizer is promoted by the EU, both in the context of expanding organic food production and as part of a circular economy (Tadić et al., 2021). This could further exert selection pressure for antibiotic resistances (Wang et al., 2015).

Behaviour in soils

Soils may represent a reservoir of both intrinsic and acquired antibiotic-resistant genes (Wang et al., 2021). When introduced into agricultural soils, antibiotics may be subjected to different processes, including transformation, sorption, plant uptake, removal with runoff, or transport into groundwater (Balseiro-Romero et al., 2018; Cycoń et al., 2019; Du & Liu, 2011). In addition, other contaminants discharged by human activities (e.g., heavy metals, persistent organic pollutants, microplastics, pesticides) may contribute to the selection and dissemination of resistances against antibiotics (Wang et al., 2020; Wang et al., 2021; Gorovtsov et al., 2018), making it very difficult to predict the evolution of antibiotic-resistant bacteria in polluted soils (Balseiro-Romero et al., 2018).

Fertilization with manure that contains antibiotic-resistant bacteria significantly contributes to airborne particular matter emergence (Kabelitz et al., 2020). Wind erosion, particularly when accelerated by agricultural operations such as tillage, further contributes to the emissions of antibiotic-resistant bacteria to the atmosphere (Münch et al., 2020; Kabelitz et al., 2020). These dynamic processes, which define the spatial-temporal distribution and thus human health risks of antibiotics, are closely interrelated (Du & Liu, 2011) and influenced by soil properties, climate factors, and physicochemical properties of antibiotics (Pan & Chu, 2017; Iwu et al., 2020; Cycoń et al., 2019; Zalewska et al., 2021).

Linkages between antibiotic-resistant bacteria and human health

As antibiotic-resistant bacteria and antibiotic-resistant genes (ARGB) can be absorbed by plants or can be found on their surface, the food chain has been suggested as a major pathway for human exposure (He et al., 2020; Wang et al., 2021). Ingestion of plants carrying ARGB may alter the human microbiome and promote the emergence of and selection for resistant bacteria inhabiting the human body (Marshall & Levy, 2011; Ben et al., 2018). This could reduce the efficiency of therapeutic antibiotics, increase the duration and seriousness of infections, and ultimately result in treatment failures or even mortality (Ben et al., 2018; Economou et al., 2015).

Another potential pathway for human exposure is the atmospheric dispersal of ARGB via dust or particulate matter that arise from agricultural soils treated with contaminated organic fertilizers such as manure or sewage sludge (Münch et al., 2020; Kabelitz et al., 2020). The risk of respiratory viral-bacterial coinfection should be considered in this regard, as with acquired antibiotic resistances they are expected to be more difficult to treat (Jin et al., 2021). However, understanding how transmitted antibiotic-resistant bacteria influence their counterparts in the respiratory system and exchange antibiotic resistant genes upon inhalation is insufficiently understood (Jin et al., 2021; Zhang et al., 2019).

Overall, the emergence and spread of antibiotic resistant bacteria and antibiotic resistant genes from agricultural systems and their contribution to the resistance of human pathogens are complex

2. What do I want to assess? - Soil Contamination - Antibiotic-resistant bacteria

processes that are not yet fully understood (Jechalke et al., 2014). More research is needed to quantify the risk of human exposure to antibiotics, antibiotic-resistant bacteria, and antibiotic-resistant genes (Iwu et al., 2020), particularly the risk of long-term consumption of low doses (Pan & Chu, 2017; Tadić et al., 2021). Additionally, little knowledge exists about antibiotic transformation products, their metabolites, mixtures, and associated resistance selection (Gudda et al., 2020).

Effects on flora and fauna

In soils contaminated with antibiotics, root uptake is considered an important route of exposure for plants. Studies indicate the accumulation and selection of antibiotic-resistant genes in different plant tissues such as leaves, stem, or fruits (Pan & Chu, 2017; Wang et al., 2021). This suggests that plants may contribute to the acquisition of antibiotic resistances in humans (Du & Liu, 2011). Moreover, residues of antibiotics may affect seed germination, photosynthesis, plant development, and productivity (Balseiro-Romero et al., 2018; Pan & Chu, 2017; Zhao et al., 2018; Matthews & Reinhold, 2013). However, depending mainly on the concentration of antibiotics, both inhibitory and stimulatory effects have been reported (Pan & Chu, 2017; Matthews & Reinhold, 2013).

Antibiotics may change the abundance of soil microorganisms, the microbial biomass, as well as overall microbial and enzyme activity (Cycoń et al., 2019), which in turn may disturb various soil processes mediated by microorganisms (Jechalke et al., 2014; Cycoń et al., 2019). They can significantly change the structure of soil microbial communities (Wang et al., 2021), particularly bacteria (Du & Liu, 2011), generating an environment for selection and outgrowth of antibiotic-resistant bacteria, which results in changes of entire microbial populations to antibiotic sensitivity (Cycoń et al., 2019). Studies suggest that low concentrations of antibiotics (below the minimum inhibitory concentration) are able to induce genetic changes in bacterial genomes, even between distantly related bacterial species (Cycoń et al., 2019).

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2. What do I want to assess? - Soil Contamination - Antibiotic-resistant bacteria

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3. Where and When? - Setting System Boundaries



3. Where and When? Setting System Boundaries

The definition of system boundaries is an obligatory first step in every impact assessment. System boundaries represent the thematic and spatio-temporal frame within which an assessment is conducted. Impacts that occur outside of this frame are not considered. The reason for setting system boundaries is threefold:

- **First**, potential users of the assessment results should be able to quickly find the information relevant to them. Having to search for this information amidst large amounts of other data would reduce the assessment's usefulness.
- **Second** and more important, the number of effects and impacts that could possibly be investigated is too high to be handled in a single assessment. Only by restricting an impact assessment to a predefined frame, the method becomes operable.
- **Third**, the choice of relevant impact categories varies with the system boundaries. Adequate impact categories and respective indicators can only be identified with clearly defined boundaries.

Setting system boundaries should be done with great deliberation and properly documented. Decisions taken at this step will strongly affect the assessment's results. In particular, decisions are required on:

- 1) The **purpose of the assessment** (decision-making level)
- 2) The **spatial and temporal frame**
- 3) The **impact areas** to be assessed

Purpose of the assessment (decision making level):

Generally speaking, assessments should be designed to be relevant for an intended target group, e.g., by focusing on the impacts of different options available to a group of decision makers. Farmers, for example, may require a different set of information from an impact assessment than policy makers or members of the local administration (for more information see chapter: *3.1 Purpose & Decision-Making Levels*).

Spatial and temporal frame:

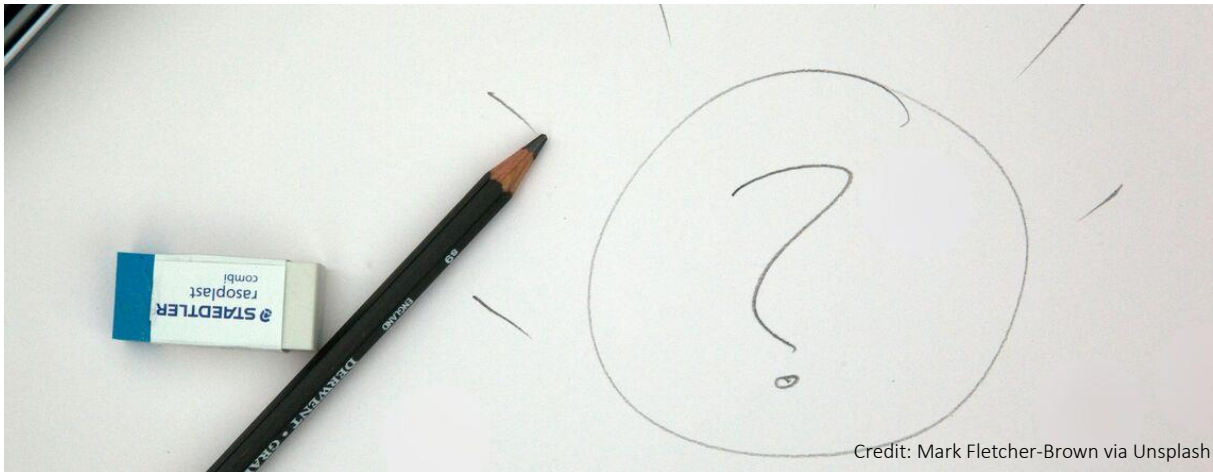
The Purpose of the assessment also influences the setting of the spatial and temporal frame. Another influencing factor are the impact areas that are analysed. Generally speaking, the frame must be set wide enough include all relevant impacts, but narrow enough to focus research efforts and avoid bloated data requirements (for more information see chapter: *3.2 Spatio-Temporal Scales*).

3. Where and When? - Setting System Boundaries

Impact area:

Finally, the impact areas for which effects are to be analysed and the methods and indicators by which they are assessed need to be chosen. The BonaRes Assessment Platform provides information on more than one hundred impact areas and on the methods and indicators to assess them. However, in any given assessment only a small selection of these impact areas **can and should** be used. The impact areas supported by the platform correspond to the assessment perspectives *Ecosystem Services*, *Resource Use Efficiency* and *Sustainable Development Goals* (for more information see chapter: 3.3 *Impact Area Selection*).

3. Where and When? - Setting System Boundaries - Purpose & Decision-Making Levels



3.1 Purpose & Decision-Making Levels

At the start of an assessment, the assessment's purpose must be defined in order to properly select the topic, set the system boundaries and choose impact areas and indicators. If the purpose is purely scientific with no practical application intended, these variables are all determined by the specific research question. However, if the assessment is intended to inform decision makers, it is useful to align its topic with the so-called decision-making **levels**, i.e. the scales at which the intended groups operate and at which different options are available to them.

Agricultural management for any given site is influenced by the decisions of multiple actors. These are farmers, but also retailers, consumers, administration and policy makers. For these groups, assessments are particularly useful if they compare impacts of different options available to them, thus facilitating informed choices. An assessment for farmers, for example, could compare the impacts of different systems for slurry application while an assessment for consumers could analyse the impacts of different dietary choices. Focusing on specific actor groups sets the spatial frame with regard to the assessment's topic, i.e. defines the scale at which options are analysed (see Table below). The assessment of impacts, however, should not be restricted to this scale and relevant effects that occur on another scale must not be ignored. For example, an impact assessment of farmers' options for increasing soil carbon sequestration will analyse effects of different management at the local scale, but also assess climatic impacts at the global scale.

Below we present a selection of decision makers that influence agricultural soil management and provide an overview of the spatial scales they operate on.

3. Where and When? - Setting System Boundaries - Purpose & Decision-Making Levels

Table 7: Decision makers that influence agricultural soil management and the spatial scales at which they mainly operate.

Decision Makers	Spatial Scale
Farmer	Farm - Region
Retailers	Regional - National
Consumers	Local - Regional - National
Local Administration	Local - Regional
Landscape Planning	Local - Regional
Regional Administration	Regional - National
National Government	National - Global
Multinational Institution	International - Global

3. Where and When? - Setting System Boundaries - Spatio-Temporal Scales



Credit: Red Zeppelin via Unsplash

3.2 Spatio-Temporal Scales

Info-Box

In impact assessments, the spatial and temporal scales are part of the system boundaries, that is the frame within which impacts are analysed. While boundaries that are drawn too wide will result in bloated data requirements, loss of focus and may obscure relevant findings amongst non-relevant data, boundaries that are drawn too narrow will cause misleading results because relevant impacts are not considered. *Adequate definition of both **spatial and temporal system boundaries** is therefore essential.* **Leakage effects** including **indirect land use changes** pose a particular challenge because they require a very wide boundary setting to be detected. A structured way to include effects at large spatial and temporal scales is **life-cycle assessment (LCA)**. This approach is data intensive though, thereby limiting the number of impact categories that can be analysed.

What are spatio-temporal scales?

Agricultural management has impacts that extend beyond the immediate effects manifesting at the field level. For example, application of pesticides and fertilizers may lead to high concentrations in surface runoff and contamination of adjacent surface waters, leaving soils bare over extended periods of time may lead to erosion. This typically does not affect soil fertility immediately, but leads to a decline in fertility over time. Through international trade linkages, large scale decisions on cultivation (such as decisions on the amount of national farmland dedicated to the production of energy crops) can even affect other world regions.

In impact assessments, it is therefore essential to define the system boundaries, i.e. the spatial and temporal frame within which effects are analysed. They define where and when impacts need to occur in order to be assessed. It is possible for assessments to conduct analyses at multiple spatial or temporal scales, for example analysing effects at field and at regional scale or effects within the current growing season and after ten years.

The selected spatio-temporal scales determine the set of available indicators and have a strong influence on the overall assessment results, because different processes occur at different spatial and temporal scales. The scales should therefore be defined at the start of an assessment and choices should be properly documented.

Why is the definition of spatio-temporal scales relevant for soil-related impact assessments?

3. Where and When? - Setting System Boundaries - Spatio-Temporal Scales

As with all research projects, the resources available for conducting an impact assessment are limited. This results in a trade-off between thematic, temporal and spatial width of the assessment. The wider the spatial and temporal scales are set, i.e. the more spatial scales from field to global and the more points in time are assessed, the lower is the number of impact areas that can be covered.

A definition of both spatial and temporal scales that fits the purpose of the assessment is essential. If spatio-temporal scales are set too wide, it will result in bloated data requirements, loss of focus and may even obscure relevant findings amongst non-relevant data. If on the other hand they are set too narrow, assessment results may be misleading because relevant impacts are not addressed. For example, effects of agricultural management on the biodiversity of farmland birds may not be visible at the field scale but manifest at the regional scale. Management for increasing soil organic carbon will hardly show an effect after a single year but may have measurable impacts after 20 years.

With regard to defining spatio-temporal scales, leakage effects and indirect land use changes pose a particular challenge because they require a very wide boundary setting to be detected (Lambin & Meyfroidt, 2011).

How can spatio-temporal scales be defined in soil-related impact assessments?

The spatial and temporal scales need to be chosen in a way that ensures that all relevant, potential impacts are addressed. This choice depends on the specific topic of the assessment, the purpose of the assessment and on the selected impact areas. For example, an impact assessment with the purpose to analyse policy options needs to cover impacts at the national or regional scale, while a farming system assessment would normally focus on the farm scale. However, if impact areas like habitats, aesthetic value or climate change mitigation are assessed, it may be necessary to expand the system boundaries to the landscape or even global scale.

Due to the complexity involved, expert-based pre-assessment and potentially additional research is required before the start of the actual impact assessment.

Inclusion of effects up to a global scale may be required to account for effects like leakage or indirect land use change, where local management decisions result in effects emerging in other world regions. At the temporal scale, the definitions must be sufficiently wide to capture relevant improvements or deteriorations of soil functions or ecosystem service provision, which often only emerge after considerable time lags (Fremier et al., 2013). In the context of agriculture, consideration of multiple years is highly recommended in order to account for long term management effects, crop rotations, pre-crop effects and inter-annual yield variability (Preissel et al., 2015; Zhang et al., 2017).

A structured way to include effects at large spatial and temporal scales is **life cycle assessment (LCA)**. LCA are usually conducted to analyse the use of resources (e.g. water, land, energy) and the occurrence of emissions (e.g. greenhouse gases, acidification, etc.) along a production process or product life cycle. However, the large spatio-temporal scales covered in LCAs lead to high data requirements and a high workload for assessments. This limits the number of impact areas that can be covered and results in a trade-off between spatio-temporal and thematic detail. Where a high number of impact areas needs to be assessed and the analysis of trade-offs between impact areas is in the focus of the study, LCA may therefore not be the method of choice and standard **multi criteria analysis (MCA)**, for which

3. Where and When? - Setting System Boundaries - Spatio-Temporal Scales

spatial and temporal scales are not formalised and can be freely adapted to the context of the research, may be preferable.

LCA focuses on environmental impacts of products and production processes (Roer et al., 2013). It seeks to integrate effects from all stages of the product cycle:

- Production and transport of required materials, machinery and fuels
- Production of the investigated product
- Distribution and use of the product
- Disposal or recycling of the product

This is a very complex and work intensive task and requires a substantial amount of information. It is usually facilitated by the use of LCA specific software and often draws on information from external, commercially available LCA databases (see www.nexus.openlca.org/databases for an overview). However, for a comparison between products or productions processes for which a part of the life cycle is considered to be identical, a full LCA may not be necessary. For different wheat varieties, for example, use and disposal will most likely be the same and an LCA comparing them may therefore focus on the remaining stages of the life cycle. Consequently, a number of studies use only partial LCAs, replacing the underlying “cradle to grave” or “cradle to cradle” concept with “cradle to farm-gate” or “farm-gate to farm-gate” (Brock et al., 2016; Hijazi et al., 2016).

LCAs can be used complementary to impact assessments when specific items (e.g. energy use) need to be assessed in detail along the value chain. Complex, systemic processes such as those related to ecosystem services are very difficult to be assessed with LCA.

Spatio-temporal boundary setting adequate for the respective assessment is necessary to ensure the validity of assessment results. Godinot et al. (2016) show the relevance of including production, transport and losses of inputs into the assessment of nitrogen use efficiencies. Likewise, Roer et al. (2013) demonstrate the considerable effect boundary setting has on assessment results by calculating LCAs of the same products using different system boundaries.

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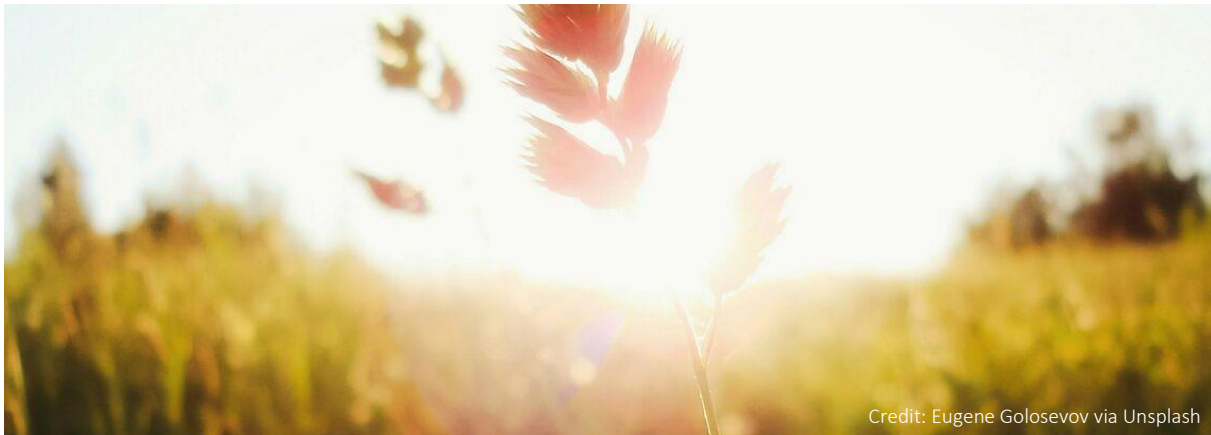
3. Where and When? - Setting System Boundaries - Spatio-Temporal Scales

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3. Where and When? - Setting System Boundaries - Impact Area Selection



3.3 Impact Area Selection

Info-Box

At the start of an assessment, researchers must decide what (potential) impacts they want to analyse. This is the stage in the assessment with the greatest risk of introducing bias: If a relevant area of impacts is not included, the study will inevitably underestimate the positive or negative effects of investigated options. This may also disrupt a ranking of options, resulting in good options to appear worse than they really are (because their particular advantages are not seen) and bad options to appear better than they are (because their negative implications do not become evident). Which impact areas are likely to be relevant for a given assessment should be determined by a scoping study before the start of the actual assessment. Such scopings can be based on analysing scientific literature and policy documents, or on consulting with experts. Ideally, stakeholders should be involved in the process.

Assessment studies **may not be able to address all of the impact areas that have been identified as relevant**, due to limitations in time, funding, personnel or data availability. This mostly applies to studies based on modelling or measurements. While those studies are still highly valuable for generating knowledge for a subset of impact areas, **they cannot provide a full assessment or justify a ranking of options**. For this, the results of those studies need to be complemented with data from other studies. A practical way to achieve a full assessment in spite of research limitations is to complement modelling or measurement approaches with expert assessments. In this case, the Impact Assessment Platform recommends to first determine which of the relevant impact areas can be addressed by modelling or measurement and to generate values based on expert assessment for the remaining ones.

What is impact area selection?

Impact area selection is the process of deciding which impacts are going to be investigated in a given assessment. Because this selection is highly relevant for the assessment results, the selection process should be systematic, transparent and well documented. The rationale on which the selection is based should be purely thematic, i.e. based on the question which impacts are likely to be affected.

Selecting impact areas based on data availability will not produce reliable assessment results that are suited to evaluate sustainability or compare options.

3. Where and When? - Setting System Boundaries - Spatio-Temporal Scales

Why is impact area selection relevant for the assessment of soil management?

Investigating impacts is complicated and usually requires thorough planning, as well as one or more of the following: calibrating and running models, conducting measurements, setting up and performing experiments or preparing literature reviews, stakeholder consultations or expert interviews. For this reason, impacts that are not specifically investigated, will most likely not be detected.

Where a management or policy option investigated in an assessment has significant positive or negative impacts, not addressing them will inevitably result in a biased assessment result. As an example, please consider two hypothetical management options A and B, both with their respective advantages and disadvantages. Figure 5 shows their performance for eleven impact areas from the assessment perspective ecosystem services. In the figure, impacts are given as percentages relative to a business-as-usual option, with values higher than 100 indicating a higher provision of the respective ecosystem service and values lower than 100 indicating a lower provision of the services.

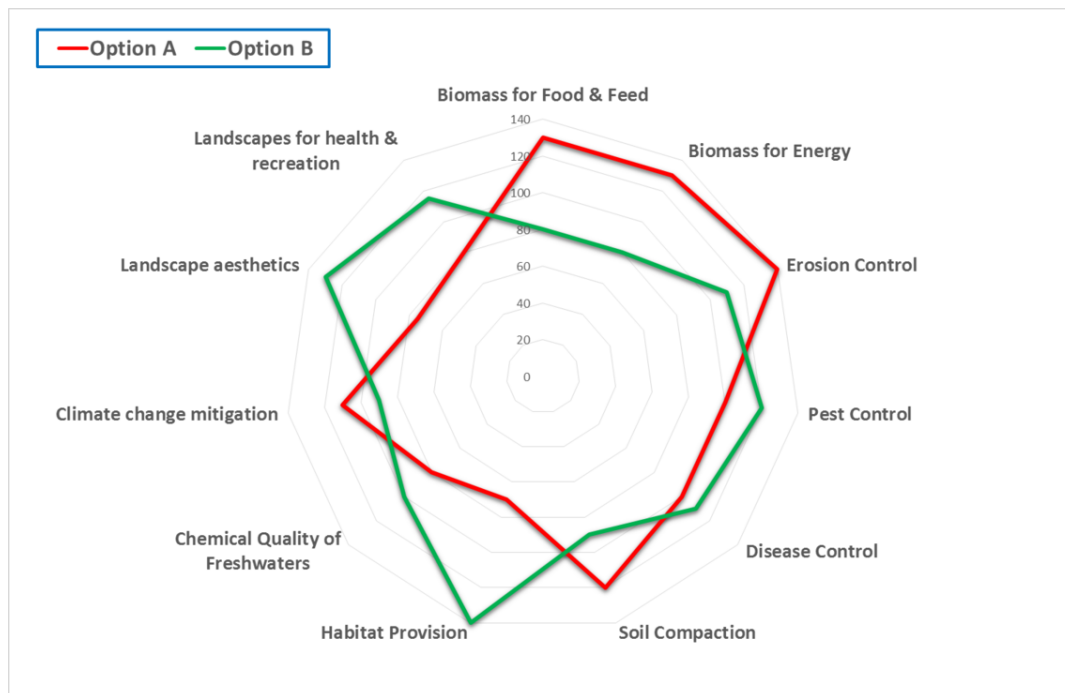


Figure 5: Two hypothetical management options (A and B) and their performance for eleven ecosystem services. Values represent percentages of service provision relative to business as usual.

In the example, both A and B have advantages and disadvantages, with neither being clearly better than the other. However, if only a subset of impact areas are addressed, this may change and depending on the selection, either option A (Figure 6) or option B (Figure 7) may appear to be more favourable.

3. Where and When? - Setting System Boundaries - Impact Area Selection

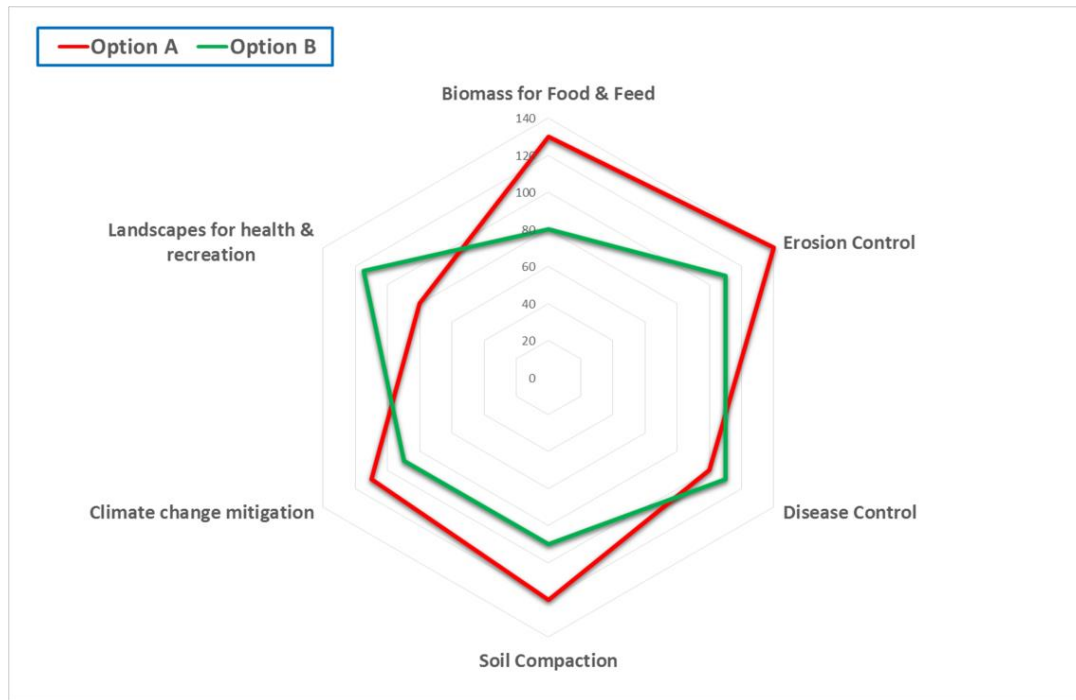


Figure 6: Two hypothetical management options (A and B) and their performance for 6 out of the 11 ecosystem services presented in Figure 5. Values represent percentages of service provision relative to business as usual. Option A appears to be more favourable than option B.

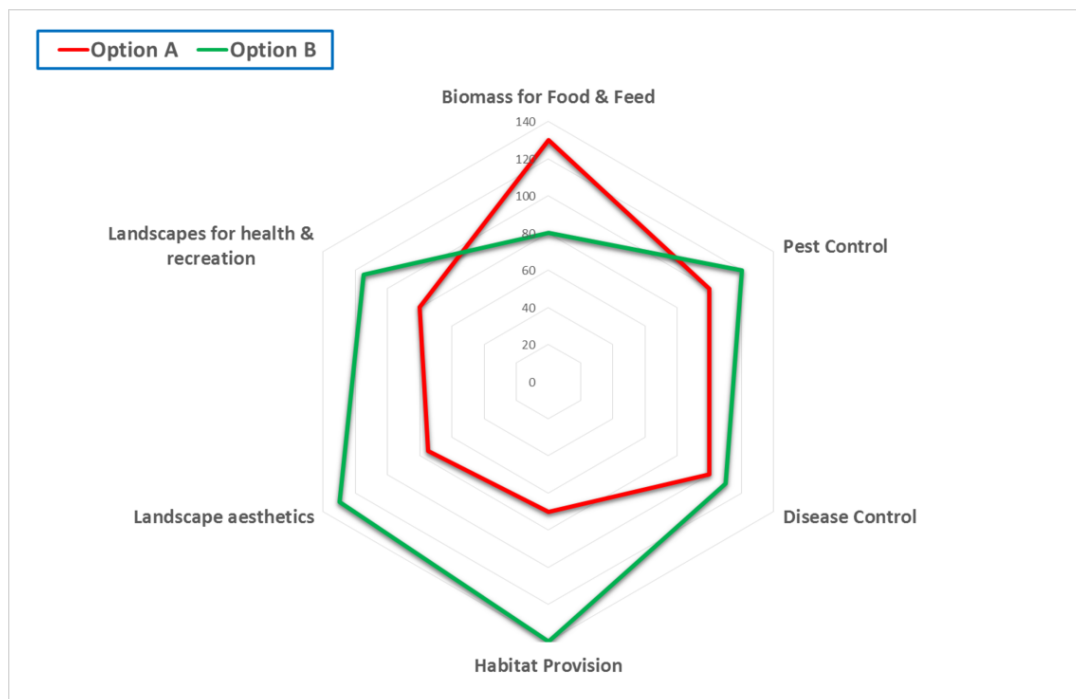


Figure 7: Two hypothetical management options (A and B) and their performance for 6 out of the 11 ecosystem services presented in Figure 5. Values represent percentages of service provision relative to business as usual. Option B appears to be more favourable than option A.

Not addressing all relevant impact areas will introduce a bias that makes the assessment results unreliable, even though all data generated may be state of the art. In a worst-case scenario, this may

3. Where and When? - Setting System Boundaries - Spatio-Temporal Scales

result in providing incomplete information to decision makers and lead to suboptimal management or policy choices which miss opportunities or have unforeseen, negative consequences.

How can impact areas be selected systematically?

Impact areas likely to be affected by an option may be identified through a (short) literature review, expert consultation, or a combination of both approaches. Ideally, stakeholders are also involved in the process to add their perspective as to what impacts should be considered.

For including stakeholders' views, assessments may adapt an approach applied in sustainability reporting, which is called "materiality analysis". It is used to identify topics for reporting that are material (i.e. relevant) and rank them according to their importance. These material topics are defined by the Global Reporting Initiative (GRI) as the most significant impacts of an organization on the economy, environment, and society (GRI 2024). The GRI developed a four-step process for identifying material topics (see fig. 8). This approach was developed after problems arose with the former application of the materiality matrix, which was presented in the first version of this handbook. As a consequence of incorrect interpretations of the materiality matrix, impacts were often assessed based on their significance to the organization rather than the overall economy, environment and society (GRI 2022). The new standard was developed to overcome these.

Figure 2. Process to determine material topics

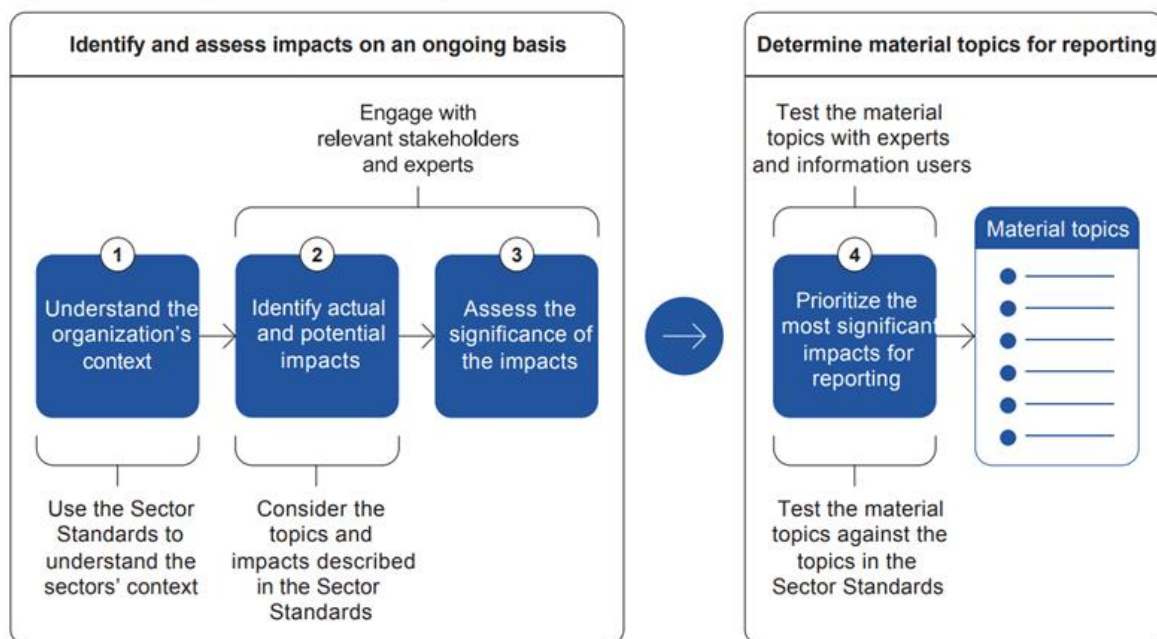


Figure 8: GRI process to determine material topics (GRI 2023).

The first three steps include the assessment of impacts, which has to be done regularly as a part of the day-to-day activities of an organisation (GRI 2023). During step number one and two, an agricultural organization must review the list of 26 likely material topics that were identified for the agriculture, aquaculture, and fisheries sector (see GRI 2024). For each topic, it must be determined if it is material in their case specifically. The different topics are linked to Sustainable Development Goals - for instance, the topic "13.2 Climate adaptation and resilience" is related to the SDGs "1 Zero poverty", "2

3. Where and When? - Setting System Boundaries - Impact Area Selection

Zero Hunger”, and “13 Climate Action” (see fig. 9). In the third step, the significance of the impacts is assessed. Finally, the last step involves prioritizing the identified impacts for reporting during the reporting period. In this step, the material topics are reviewed and compared to the previous reporting period (GRI 2023).

Table 2: Linkages between the likely material topics for the agriculture, aquaculture, and fishing sectors and the SDGs.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Topic 13.1 Emissions																	
Topic 13.2 Climate adaptation and resilience																	
Topic 13.3 Biodiversity																	
Topic 13.4 Natural ecosystem conversion																	
Topic 13.5 Soil health																	
Topic 13.6 Pesticides use																	
Topic 13.7 Water and effluents																	
Topic 13.8 Waste																	
Topic 13.9 Food security																	
Topic 13.10 Food safety																	
Topic 13.11 Animal health and welfare																	
Topic 13.12 Local communities																	
Topic 13.13 Land and resource rights																	
Topic 13.14 Rights of indigenous peoples																	
Topic 13.15 Non-discrimination and equal opportunity																	
Topic 13.16 Forced or compulsory labor																	
Topic 13.17 Child labor																	
Topic 13.18 Freedom of association and collective bargaining																	
Topic 13.19 Occupational health and safety																	
Topic 13.20 Employment practices																	
Topic 13.21 Living income and living wage																	
Topic 13.22 Economic inclusion																	
Topic 13.23 Supply chain traceability																	
Topic 13.24 Public policy																	
Topic 13.25 Anti-competitive behavior																	
Topic 13.26 Anti-corruption																	

Figure 9: Linkages between the likely material topics for the agriculture, aquaculture, and fisheries sectors and the SDGs (GRI 2024).

Stakeholder engagement is part of step two and three of the process. Stakeholders who are more severely affected should be prioritized, and potential barriers - such as language barriers or gender and power imbalances - must be identified and removed (GRI 2023). As part of the GRI standards, there is no fixed requirement on how the importance for stakeholders should be assessed. Consultations and workshops are possible, as are in-house assessments by the reporting organizations. In the context of impact assessments, this handbook recommends direct interaction with a well-documented and balanced selection of stakeholders. Where this is not possible, an analysis of policy strategy documents

3. Where and When? - Setting System Boundaries - Spatio-Temporal Scales

to identify relevant impact areas may be used as an alternative (Hermanns et al., 2017), though both approaches should ideally complement each other.

A materiality analysis always needs to be performed for a specific assessment, because the impact areas identified and the prioritization derived are based on the socio-economic and geophysical conditions at a certain point in time and space. Therefore, results of materiality analyses cannot be readily transferred to similar assessments at other locations. Even at the same location, the relevance of impact areas and their respective priorities may change over time due to the dynamics of norms and values, as well as due to advances in knowledge.

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4. How can I measure impacts? - Measurement, Modelling or Expert Assessment



4. How can I measure impacts? - Selecting Indicators

Several approaches exist to generate the data necessary to conduct impact assessments, each with their respective strengths and weaknesses. Most common are **Measurement, Modelling, or Expert Assessment**, while **Participatory Impact Assessments** can be used to utilize stakeholder knowledge and account for their value systems. For integrating and interpreting impacts across multiple impact areas, **Multi-Criteria-Analysis** and **Benchmarking** are valuable tools.

4.1 Indicator Factsheet

We generated factsheets about different impact areas that can be applied for soil-related impact assessments. The factsheets contain indicators used in literature, the spatial scale they are suitable at, and the type of data they require. They are useful as a guidance for measuring the impacts in an assessment - irrespective of the chosen approach (see 4.2 *Measurement, Modelling or Expert Assessment*). The Indicator Factsheets are provided for the Assessment Perspectives **Ecosystem Services** and **Resource Use Efficiency**. All factsheets can be found in the appendix of the handbook. An example factsheet with explanations (green boxes) is provided in **Appendix A: Indicator Factsheets: Example**.

Ecosystem Services

For structuring the impact areas related to the supply of ecosystem services, we use the **Common International Classification of Ecosystem Services (CICES)**. It uses a hierarchical classification and represents a standard that facilitates comparability and upscaling of ecosystem service research. More information on the CICES classification can be found under www.cices.eu. We provide factsheets for ecosystem services in **Appendix B: Indicator Factsheets: Ecosystem Services**.

Resource Use Efficiency

Resource use efficiency is the **ratio of benefits generated** and the amount of **resources used** for this. Resource use efficiencies are calculated for resources that are either limited (e.g., land, water, energy) or that may create conflicts with other societal targets (e.g., pesticides, greenhouse gas emissions). Based on a review of scientific literature, we identified resource use efficiencies relevant in the context of agricultural soil management. Factsheets for the resource use efficiency can be found in **Appendix C: Indicator Factsheets: Resource Use Efficiencies**.

Sustainable Development Goals

4. How can I measure impacts? - Measurement, Modelling or Expert Assessment

There are 17 SDGs in total, each with multiple underlying SDG targets. We connected relevant SDG targets to the impact areas of **Resource Use Efficiency** and **Ecosystem Services** in agricultural soil management. Please note, however, that this alignment is not as methodologically robust as the processes used to identify indicators for **Resource Use Efficiency** and **Ecosystem Services**. You can select indicator factsheets based on Sustainable Development Goals in the online version: <https://sustainability.zalf.de/research-tool/factsheet-selection-sustainable-development-goals>.

4.2 Measurement, Modelling or Expert Assessment

Once the impact areas have been selected, researchers are faced with the challenge to generate values that represent the impacts within them. Typically, researchers generate these values from either measurement, modelling or expert assessment. The three approaches are outlined below with a short description of their respective strengths and weaknesses.

Measurements

Experiments or empirical studies can be used to generate the required information, usually in the form of quantitative data. Researchers first need to decide which indicators to use for each impact area. After that, they may either conduct the measurements themselves or analyse results of published studies. This approach is supported by the Impact Assessment Platform through factsheets that list sample indicators for each impact area and reference examples of their application in current research.

In the context of **impact assessments**, core strengths of approaches based on measurements are the high level of detail that can be achieved, the low need for a-priori assumptions and the comparatively low risk of bias introduced by the researchers. Weaknesses are the high amount of time and effort required, which may limit the number of impact areas that can be covered, and the difficulty to measure effects of future scenarios that have no parallel in the present. Furthermore, the generalisation of measurement results is often challenging, which limits their transferability to other locations or situations.

Modelling

Where a high degree of prior knowledge on causal relationships already exists, researchers may use models for assessing impacts. Usually, models are designed to produce quantitative data, although qualitative models are also used. As above, researchers first need to select indicators to represent the respective impact areas. The information provided by the factsheets on the Impact Assessment Platform can be used to select indicators that are part of the output of existing models or to conceptualize requirements for new models.

In the context of impact assessments, core strengths of modelling approaches are the reproducibility of results, opportunities to investigate in detail the link between effects and underlying causes, including analyses of sensitivity, and options to analyse future scenarios that have no parallel in the present. Weaknesses are the high requirement of time, effort and information for generating new models, which also limits the options of tailoring a model to the needs of a specific assessment, and the high number of assumptions that need to be made by researchers in order to represent complex socio-ecological systems in a (simplified) model. Nevertheless, substantial progress has been made in

4. How can I measure impacts? - Measurement, Modelling or Expert Assessment

the last decade in integrated modelling and model coupling to address complex socio-ecological systems and assess land use impact scenarios (Helming et al., 2011; Ewert et al. 2015; Lotze-Campen et al., 2018).

Expert Assessment

Experts may be consulted to assess impacts, based on their expertise and experience with regard to the topic and the selected impact areas. Values for the impacts are usually provided as qualitative data, often expressed on an ordinal or categorical scale (e.g., a Likert-type scale with ratings ranging from “very negative” to “very positive”). In the context of expert assessments, the indicators provided by the factsheets on the Impact Assessment Platform can be used to specify what the expert assessment is based on and to facilitate communication between different experts. For example, if experts evaluate how the ecosystem service: provision of habitats would be affected by a specific agricultural management, they could draw on the indicators to explain whether their assessment is mainly based on the expected species diversity of farmland-birds, or on their abundance, or on the abundance of endangered plant species, or on a mix of criteria.

In the context of impact assessments, core strengths of expert-based approaches are fourfold: the adaptability to the specific context of the impact assessment, the low amount of time, work and data required, the opportunity for stakeholder involvement and shared learning. In addition, biases of impact area selection due to data availability can be avoided. Weaknesses are the danger of introducing bias through the selection of the consulted experts, the risk of low reproducibility with other experts or with the same group of experts at another point in time, and the lack of transparency of how the experts arrive at their assessment result. Thorough and comprehensible protocols for expert selection should be used to minimize the risk of introducing bias.

More information on expert-based assessments is also provided in the section titled: *4.4 Framework of Participatory Impact Assessment (FoPIA)*.

Please note: All three approaches have their limitations and advantages. For very complex assessments, it is therefore advisable to combine one or more of them. For example, an expert-based assessment could be done first as a scoping activity to address a high amount of impact areas and identify critical ones. These impact areas could then be investigated in more detail through measurements or modelling activities.

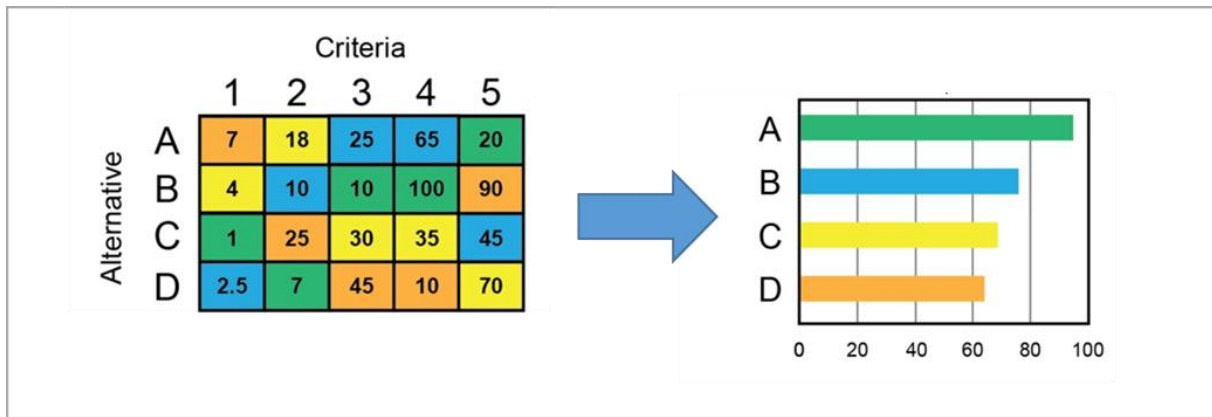
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4. How can I measure impacts? - Measurement, Modelling or Expert Assessment

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4. How can I measure impacts? - Multi-Criteria Analysis



4.3 Multi-criteria Analysis

Info-Box

Multi-criteria analysis (MCA) is a class of procedures designed to aid decision-making where options are evaluated based on more than one criterion, in particular where these criteria are measured in different units which cannot be readily converted into each other. Many different MCA procedures exist, but all are based on the principles of data normalization and of assigning weights to the different criteria in order to arrive at an integrated score for each option.

MCA procedures are very useful in multifunctional disciplines such as agriculture, where all management choices have multiple effects and involve **trade-offs** within and between the **social**, **economic** and **environmental** spheres.

What is multi-criteria analysis?

Multi-criteria analysis (MCA) is a structured procedure to compare and rank options while considering more than one criterion. This is achieved by normalizing all quantitative and/or qualitative information about an option, assigning weights to all criteria, and then combining the information into a single, integrated value. Multi-criteria analysis is a tool for dealing with the inevitable trade-offs within complex decision-making situations, which may also feature high uncertainty, different forms of information, and multiple stakeholder interests and perspectives. For this reason, MCA has gained momentum as a methodology for the evaluation of sustainability (Adams & Ghaly, 2007).

In the context of impact assessments, multi-criteria analysis can be used at the end of the research to combine the indicator values of multiple impact areas into integrated results and to rank the investigated management options.

Multi-criteria problems are common occurrences. For example, a farmer's decision over which crops to plant may depend on factors such as expected revenues, risk of crop failure, time requirements, or personal preferences. Weighing them against each other in order to find the optimal solution is difficult because factors are assessed in different units that can not objectively be converted into each other (e.g., how much additional revenue would exactly balance a higher risk of crop failure or a reduction in spare time?). These decisions always involve an element of normative valuation. Usually, they are made intuitively based on previous experience. In impact assessments, however, a structured approach is required to avoid subjectivity, guarantee transparency, and to address problems that are too complex to solve intuitively. Multi-criteria analysis facilitates this by providing a method to

4. How can I measure impacts? - Multi-Criteria Analysis

combine scientific assessments with normative value choices. Indicator values from different impact areas are first normalized to a common, dimensionless scale and then weights are assigned, based on the perceived importance of the impact area for the respective assessment. This second step is purely normative and should ideally be based on stakeholder involvement or on societal norms codified in laws or regulations. Because normative decisions are always subjective and the weights assigned may not be reproducible with a different set of stakeholders or with the same set of stakeholders at another time, it is very important to document how decision makers or stakeholder groups were selected, or by what method weights were derived from laws or regulations. Finally, for each option analysed in the assessment, the normalized indicator values representing an impact area are multiplied by the weights assigned to that area and all products are summed up to generate a total, integrated score. If the impact assessment investigated different options, they may then be ranked based on the integrated score.

Why is multi-criteria analysis relevant for the assessment of soil management?

Sustainability impact assessment is characterized by investigating multiple impact areas related to the **economic, ecological and social dimension**. The findings for each impact area will be represented by an indicator that comes in a specific unit, such as “number of ground-nesting bird species” or “tons of wheat”, which can not be easily converted into a common unit. However, to rank options and to decide which management is the most sustainable, exactly that is needed. Multi- criteria analysis provides a structured and transparent way to achieve integration of assessment results. MCA is particularly useful with regard to assessments of agricultural management, where management choices have multiple effects and usually involve trade-offs.

How can multi-criteria analysis be considered in assessments of soil management?

To explain the application of a multi-criteria analysis, we use a simplified example where a farmer needs to choose between **three alternative fertilisation options** and where only two impact areas from the perspective of resource use efficiency are assessed: productivity, measured as harvested ton of wheat per hectare, and nitrogen use efficiency (NUE), measured as kilogram nitrogen taken up by the crop per kilogram of nitrogen applied as fertilizer.

- Option A: Low fertiliser application rate
- Option B: High fertiliser application rate
- Option C: Intermediate fertiliser application rate

Table 8 shows hypothetical values for productivity and nitrogen use efficiency for each of the options.

Table 8: Hypothetical values for productivity and nitrogen use efficiency resulting from three fertilization intensities.

Option	Productivity [t/ha]	Nitrogen Use Efficiency [%]
A	3.9	65%
B	8.2	40%
C	6.3	55%

4. How can I measure impacts? - Multi-Criteria Analysis

Step 1 - Normalizing indicator values

The first step of the multi-criteria analysis is to convert all indicator values onto a numerical (dimensionless) scale to enable direct comparison. One approach often used is to **allot scores** between 0 and 100, with 100 representing the best possible result within the respective category and 0 representing the worst (Dodgson et al., 2009). Where a large number of options are compared, transformation into z-scores is also possible.

It is crucial to the validity of the MCA result that scores are determined as objectively as possible. For the current example, it is assumed that a productivity between a **maximum of 10 t/ha** and a **minimum of 2 t/ha** could normally be expected. A maximum score of 100 is therefore assigned to yields of 10 t/ha (or more) and a minimum score of 0 is assigned to yields of 2 t/ha (or less). Intermediate values are given proportionate scores along the scale. For nitrogen use efficiency, a maximum of 80% and a minimum 10% is assumed. The table below shows the resulting scores for each option.

Table 9: Hypothetical scores for productivity and nitrogen use efficiency resulting from three fertilization intensities.

Option	Productivity Score [0-100]	Nitrogen Use Efficiency Score [0-100]
A	24	79
B	78	43
C	54	64

Step 2 - Assigning weights to each impact area and multiplying with scores

Once values have been converted into a comparable numerical scale, the next step is to **assign weights to the impact areas that represent their relative importance**. For example, the farmer could decide to value both criteria equally (50/50) or put stronger emphasis on either productivity or nitrogen use efficiency (e.g., 60/40).

Step 3 - Calculating integrated scores and final assessment

Weighted scores are calculated by multiplying the score of an impact area with the weight it has been assigned. All weighted scores of an option are then summed up to create a total, integrated score. By comparing these integrated scores, a ranking can be achieved and the best option can be identified.

For example, if productivity and nitrogen use efficiency are considered by the farmer to have **equal** importance (50% each), Option B achieves the best outcome with a total score of 60, closely followed by option C with a total score of 59 (see Table 10).

Table 10: Calculation of integrated scores based on productivity and nitrogen use efficiency for an example of three fertilization intensities. A weighting of productivity: 50% and nitrogen use efficiency: 50% is assumed.

4. How can I measure impacts? - Multi-Criteria Analysis

Option	Productivity		Nitrogen Use Efficiency		Total Weighted Scores
	Score [0-100]	Weighted Score (Score * 50%)	Score [1-100]	Weighted Score (Score * 50%)	
A	24	12	79	39	51
B	78	39	43	21	60
C	54	27	64	32	59

If the farmer considers nutrient use efficiency to be more important and assigns a weight of **40% to productivity** and a weight of **60% to nitrogen use efficiency**, the best outcome is achieved by option C (see Table 11).

Table 11: Calculation of integrated scores based on productivity and nitrogen use efficiency for an example of three fertilization intensities. A weighting of productivity: 40% and nitrogen use efficiency: 60% is assumed.

Option	Productivity		Nitrogen Use Efficiency		Total Weighted Scores
	Score [0-100]	Weighted Score (Score * 40%)	Score [1-100]	Weighted Score (Score * 60%)	
A	24	10	79	47	57
B	78	31	43	26	57
C	54	22	64	39	60

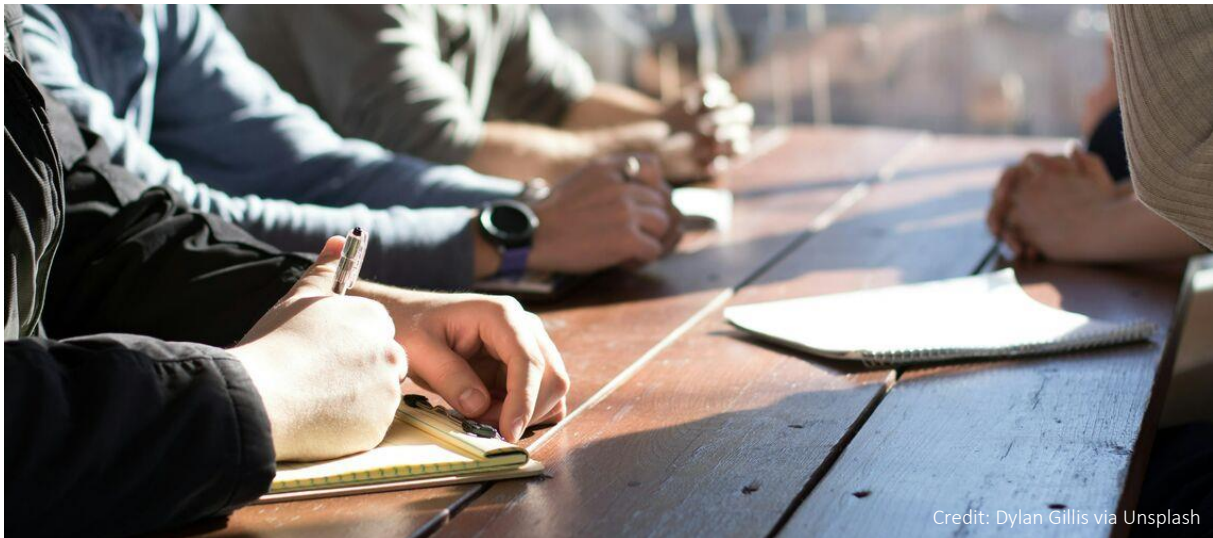
Obviously, which option is considered to achieve the best outcome is strongly dependent on the weights assigned to each impact area. The weighing process is inherently subjective and only has a limited precision. Where options achieve very similar integrated scores, it is therefore practical to consider their outcomes to be equal. In our example where productivity and nitrogen use efficiency were assigned equal weights, options B & C could therefore be considered to have the same merit (scores of 69 and 60).

In the interest of transparency, it is important to explain the reason for the assigned weights. This includes documenting if decision makers or larger groups of stakeholders were involved, what criteria were used for their selection and what methods were applied for arriving at the final weighting. **Please consider that the assigning of equal weights for all impact areas is also a normative decision that has a strong influence on the final assessment results.**

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4. How can I measure impacts? - Framework of Participatory Impact Assessment (FoPIA)



4.4 Framework of Participatory Impact Assessment (FoPIA)

Participatory Impact Assessment is a method that uses stakeholder input at all stages. This includes definition of scenarios, assessment of impacts and integration of results in a multi-criteria analysis (MCA).

The FoPIA framework was developed by Morris et al. (2011) for the assessment of land use scenarios in European regions. Three stages can be distinguished:

- 1) **Defining Scenarios:** After the general topic of the assessment has been set, stakeholder interviews are conducted to determine the form that policy interventions or management changes are likely to have within the different national circumstances. For example, farmers could be asked what types of climate change mitigation measures are likely to be introduced in their country. Land use scenarios are then designed based on the identified interventions or management changes.
- 2) **Assessing Scenario Impacts:** In a second step, a stakeholder workshop is conducted where participants (as experts) assess the likely impacts of the scenarios on nine impact categories. Of these categories, three represent the ecological dimension, three the economic dimension and three the social dimension of sustainability. The assessed impacts are then compared to sustainability limits set by the workshop participants.
- 3) **Integrated Evaluation:** Finally, a multi-criteria analysis is conducted. Participants assign weights to each impact category that reflect the importance they attribute to it. This allows the calculation of an overall score for each scenario and a ranking of the different scenarios according to this score. A more detailed description can be found in the section on multi-criteria analysis.

While FoPIA was originally developed for policy impact assessment in a European context, several case studies have since proven its adaptability and suitability for non-policy situations (Hermanns et al., 2017) and for use in non-European countries, and in particular for developing countries (König et al., 2013; König et al., 2014; Schindler et al., 2016; Graef et al., 2018).

4. How can I measure impacts? - Framework of Participatory Impact Assessment (FoPIA)

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4. How can I measure impacts? - Benchmarking



4.4 Benchmarking

Info-Box

Benchmarking uses information of similar organizations or processes to assess the gap between current and achievable performance. In the context of agriculture, benchmarking usually refers to a systematic comparison of the performance of farms producing under similar bio-geophysical conditions.

Benchmarking assesses performance in relative, rather than in absolute terms. This is particularly suited for assessing effects of agricultural management, because the strong influence of external factors such as climate, weather or soils on farm performance is difficult to isolate. Simple **benchmarking identifies best practices** from a set of samples and then **evaluates all samples relative to these best practice examples**. In more complex benchmarking where multiple evaluation criteria are applied, samples are not evaluated relative to a single best practice but relative to a so-called **efficiency frontier**, which represents the best performances considered achievable and which is calculated based on data from all samples. The most common parametric and non-parametric approaches to this are Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA) respectively.

What is benchmarking?

Benchmarking is a relative performance evaluation that compares the efficiency of similar organizations or processes. It is used in many sectors. In the context of agriculture, benchmarking usually refers to the systematic comparison of the performance of farms that produce under similar bio-geophysical conditions, using the same resources and producing the same type of products.

In the context of benchmarking, efficiency is defined more loosely than in the definition of resource use efficiency described in the previous sections. Here, efficiency implies a maximization of positive outputs and a minimization of inputs and of negative outputs. Evaluations of efficiency can be based on very different criteria, such as on provision of ecosystem services, effects on biodiversity or resource

4. How can I measure impacts? - Benchmarking

use. All impact areas presented on the Impact Assessment Platform can therefore be used in benchmarking.

Simple benchmarking first identifies best practices within a set of samples. It then evaluates all samples by assessing the difference between their performance and the performance of the best practices (Oh & Hildreth, 2016). More complex benchmarking methods that apply multiple evaluation criteria use data from all samples to calculate a so called efficiency frontier. This frontier represents the best performances considered achievable. The performance of all samples is then assessed relative to this frontier. The most common methods for this are Stochastic Frontier Analysis (SFA) and Data Envelopment Analysis (DEA).

Benchmarking is often conducted to improve organizational processes and to achieve higher standards of performance. This can be accomplished by learning from the experience of best practices or by copying their methods or processes (Malano et al., 2004). Benchmarking studies can also be used to assess the impact of policies (Bogetoft & Otto, 2010).

Why is benchmarking relevant for assessing soil management?

The performance of farms strongly depends on bio-geophysical site conditions. Where assessment seeks to evaluate different types of soil management, it is challenging to isolate and quantify the influence of external factors. For example, if a farmer in Finland achieves a harvest of 4.5 tons of wheat per hectare and a farmer in France achieves a yield of 7.0 tons, how much of this difference is then due to their respective managements and how much is an effect of the different agro-climatic zones?

To avoid such problems, performance is often measured in relative terms through benchmarking. In agriculture, benchmarking plays an important role in the context of assessing environmental impacts of farm performance, such as impacts related to water conservation or soil protection (Kuo et al., 2014). Results of benchmarking studies are useful at multiple decision making levels, enabling policymakers to assess the effect of agricultural policies (Quiroga et al., 2017) and allowing farmers to learn from best practice examples.

How can benchmarking be applied in assessments of soil management?

Benchmarking studies can be applied with different degrees of complexity. In the simplest form, only one criterion is used to evaluate performance and a best practice is identified which scores highest for this criterion. The best practice is then used to evaluate all other samples and to serve as an example. For instance, several wheat producing farms in a region could be compared in a benchmarking to identify the one that achieves highest yields. All other farms could then be evaluated relative to this and farmers could try to use the example to optimize their own management.

In a more complex form, several criteria are evaluated and the information of all samples are mathematically combined to form a so called “**efficiency frontier**”. The most common parametric method for this is **Stochastic Frontier Analysis (SFA)**, the most common non-parametric method is **Data Envelopment Analysis (DEA)**. Both methods have been developed as economic tools to evaluate the performance of companies, enterprises or non-profit organizations, which are referred to as “decision-making units (DMU)” in the literature (Malana & Malano, 2006). The abstract term DMU is used to

4. How can I measure impacts? - Benchmarking

highlight that the methods are applicable for all types of organizations where management (decision making) occurs. In the context of soil related impact assessments, the DMUs are usually farms.

Both SFA and DEA address the question of how the highest amount of positive outputs can be achieved with the lowest amount of inputs and the lowest amount of negative outputs . For this, they calculate an efficiency frontier line, which represents the (hypothetical) optimal combination of inputs (Oh & Hildreth, 2016). The efficiency of each DMU is calculated as the distance to this efficiency frontier and often reported as a percentage (with DMU positioned on the frontier line having an efficiency of 100%). SFA and DEA can be used to estimate overall efficiency of farms or management processes and rank them based on their performance. Additionally, the methods can be used to identify areas of inefficiency in order to support improvement.

Stochastic Frontier Analysis – SFA

Stochastic Frontier Analysis is a method developed from stochastic frontier production function models (Aigner et al., 1977). SFA is based on **parametric models**. Such models are defined a-priori except for a finite set of unknown parameters that need to be estimated from data. In SFA, these parameters often include effects of noise (random shocks unrelated to management, such as weather effects) and efficiencies (Bogetoft & Otto, 2010). An efficiency frontier is calculated based on actual input/output relationships, and the efficiencies of all DMU are measured relative to it. It is not necessary for any DMU in the sample to be positioned on the efficiency frontier, i.e. to achieve full efficiency.

With SFA approaches, hypotheses about production structure and degree of inefficiency can be assessed statistically. However, the method requires explicit parametric functions representing relationships between inputs and outputs, and distributional assumptions. For considering measurement errors and effects which cannot be controlled by the individual DMU, such as weather, an error term is incorporated in the calculations. The validity of SFA results depends on the accuracy of the assumptions made (Odeck, 2007).

Data Envelopment Analysis – DEA

DEA calculates the efficiency frontier line (highest positive outputs from lowest amount of inputs and negative outputs) from linear combinations of the samples. DMU that score highest in at least one criterion will always be positioned on the efficiency frontier. Two types of DEA models can be distinguished: The input-oriented model aims towards minimizing inputs while holding the amount of outputs constant. Output-oriented models on the other hand aim to increase outputs with the same amount of inputs (Malana & Malano, 2006).

As a difference to parametric models, **non-parametric** approaches such as DEA do not require any a-priori assumptions regarding the quality or distribution of the data, avoiding potential errors in this regard (Oh & Hildreth, 2016). However, this makes the methods sensitive to measurement errors or other noise affecting the dataset. In DEA, all parameters are calculated from the data in the sample. Environmental factors are not explicitly considered. It is therefore important to carefully select the sample to avoid comparing farms that work under different environmental conditions (Odeck, 2007).

4. How can I measure impacts? - Benchmarking

Please note: Both SFA and DEA allow to evaluate performance with regard to multiple inputs and outputs and facilitate an integrated evaluation (Bogetoft & Otto, 2010). Both SFA and DEA also have specific advantages and disadvantages to be considered when choosing methods. Alternatively, the methods can be combined to overcome the disadvantages, and such combinations have been applied in several studies dealing with benchmarking processes (Oh & Hildreth, 2016).

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5. What factors are difficult to assess? Additionality, Leakage Effects & Rebound Effects



5. What factors are difficult to assess that are difficult to assess? *Additionality, Leakage Effects & Rebound Effects*

Impact assessments build on knowledge about causalities. For some effects, though, this knowledge is still very limited, which makes it challenging to quantify impacts. Ignoring these effects may, however, lead to distorted results: Just because we cannot properly model an effect, does not mean that it doesn't exist!

In this handbook we address **additionality, leakage effects, and rebound effects** as assessment challenges. The importance of such effects can be illustrated by a simple (hypothetical) example: If an assessment were to analyse the impacts of afforestation of all agricultural areas in Europe, ignoring **leakage effects** and **indirect land use changes** (i.e. land use changes caused in other locations) would lead to assessment results showing overwhelmingly positive effects for climate change mitigation. However, it is more realistic to assume that such a scenario would also lead to strongly increased food imports, a surge in food prices and a conversion of natural areas in other countries to farmland. This conversion would then partially or fully offset any positive effects on the global climate. Assessments that ignore these effects may therefore produce misleading assessment results.

5. What factors are difficult to assess? Rebound Effects



5.1 Rebound Effects

Info-Box

Improvements in the technical efficiency of production processes are a means to reduce resource consumption. However, reductions achieved under real life conditions are usually smaller than what would theoretically be expected under *ceteris paribus* assumptions. Relevant actors (producers and consumers) will adapt their behaviour to account for the increased efficiencies, often causing additional resource use. This is called **rebound-** or **take back effect**. Rebound effects offset part or all of the resource savings that would otherwise be achieved by efficiency improvements. In extreme cases, they can even lead to an increase of total resource consumption (Jevons's paradox). Rebound effects are mainly explained by economic feedbacks. However, social-psychological factors are also relevant, especially for the consumer side.

Rebound effects can be divided into **direct effects**, **indirect effects** and **economy-wide effects**. They should be taken into account in all assessments dealing with efficiency improvements in order to obtain realistic estimates of resource savings and to adequately inform policy making.

What are Rebound Effects?

In many cases of efficiency increases, ex-post analysis reveals that reductions in total resource consumption are smaller than could be expected based on efficiency improvements. This effect is called **rebound-** or **take back effect** and results from changes in the behaviour of relevant actors after efficiency increases. The size of rebound effects (Equation. 1) is defined as the share of resource savings which would be expected from efficiency increases if all other factors remained unchanged (*ceteris paribus* situation), but which do not materialise due to adaptations in the behaviour of relevant actors.

5. What factors are difficult to assess? Rebound Effects

$$\text{Rebound Effect [\%]} = \left(1 - \frac{\text{Resource Saving}_{\text{actual}}}{\text{Resource Saving}_{\text{ceteris paribus}}} \right) * 100 \quad \text{Eq. 1: Definition of rebound effect size}$$

Rebound effect sizes vary and can be greater than 100% in extreme cases. This phenomenon is called backfire or Jevons's paradox, after British economist W.S. Jevons who observed in his book "The coal question" (1865) that more efficient use of coal through technical innovation led to higher instead of lower total consumption. Based on this, he postulated that higher fuel efficiencies always led to higher resource exploitation (Jevons, 1865; Alcott, 2005). The same theory was reiterated in the 1980s by economists Khazzoom and Brookes and termed by Saunders (1992) the Khazzoom–Brookes postulate. While Jevons's paradox was formulated for the energy sector, cases where both resource use efficiency and total resource use increased are also documented in the agricultural sector for increases in irrigation efficiency (Pfeiffer & Lin, 2014; Sun et al., 2016; Perry et al., 2017).

Rebound effects are best documented for the field of energy efficiencies but are also applicable to the efficient use of other resources relevant to agricultural management. The majority of studies on rebound effects focus on rebound effects occurring due to economic feedbacks, as more efficient resource use lowers production costs and the price of goods and services based on the respective resources. Under the assumption of rational economic agents, this price effect leads to increased production and/or consumption, thereby offsetting part or all of the initial resource savings (Kolstad et al., 2014). However, de Haan et al. (2015) point out that especially for consumers, the assumption of purely rational behaviour is not valid, and that social-psychological factors can also create rebound effects. Policies promoting efficiency increases can affect both economic variables and social-psychological factors thereby causing both forms of rebound effects.

Rebound effects can be divided into a) **direct**, b) **indirect** and c) **economy-wide effects** (Kolsadt et al., 2014). For rebound effects to occur, the resource use efficiency of a **process** must improve. In this section, we use the term process to refer to production processes which consume resources in order to provide services. These services can be immaterial (e.g. light, heat) or material (e.g. food, drinking water) and explicitly include the production of goods.

How can direct, indirect, and economy-wide rebound effects be defined?

A. Direct rebound effects

Direct rebound effects occur if efficiency increases in a process result in an increasing demand for it, thereby also creating additional demand for the resource it consumes.

From an economic point of view, higher efficiencies mean lower production costs. This can motivate producers to increase production. Furthermore, producers may opt to use the more efficient process to substitute other production factors. Where lower costs result in lower prices, consumers usually react to this with increased consumption which in turn creates demand for increased production.

From a social-psychological point of view, services produced by processes that consume fewer resources are perceived as more positive than those produced conventionally. This is especially the case if those services are labelled as socially or environmentally friendly (e.g. energy from renewable sources). Where consumers restrict their consumption due to awareness of resource use implications,

5. What factors are difficult to assess? Rebound Effects

they may be less hesitant to consume services from more efficient processes, thereby creating additional demand.

B. Indirect rebound effects

Indirect rebound effects occur if efficiency increases in a process result in an increasing demand for other processes that consume the same resource.

Where higher efficiency translates into financial gains for producers and/or consumers, all or part of this money is usually spent on additional consumption of goods and services. For example, if households switch to more energy efficient appliances, they will save on energy consumption and money. However, if this money is used to pay for a holiday flight, part or all of the savings are offset in an indirect rebound effect.

From a social-psychological point of view, de Haan et al. (2015) argue that many consumers implicitly evaluate their own behaviour and apply a budget to their resource consumption. Being more environmentally friendly in one respect therefore may lead to less self-restriction in other areas.

C. Economy-wide rebound effects

Economy wide effects are caused if not only individual actors are affected by the efficiency gains, but if there are resource use implications for the whole economy through increases in wealth, production or consumption; or through the introduction of technological innovations made possible by the more efficient process. For example, the introduction of chemical fertilizer dramatically increased the productivity (crop yield per hectare) of agricultural production but had implications that also affected economies as a whole.

Why are rebound effects relevant for assessing soil management?

Increasing resource use efficiency (RUE) is considered to create a win-win situation by improving farmers' economic performance while at the same time alleviating pressures on the environment (O'Brien et al., 2014). However, different actor groups may react to such efficiency increases and cause rebound effects that offset part or all of the potential resource savings. In extreme cases, resource consumption can even be higher after efficiency increases than before. Not accounting for rebound effects can therefore result in a severe overestimation of resource savings.

For the agricultural sector, there are a number of studies on rebound effects related to more efficient irrigation technologies (Berbel & Mateos, 2014; Dumont et al., 2013; Loch & Adamson, 2015; Mehmeti et al., 2016), some of them reporting rebound effects greater than 100% i.e. an increase in resource use rather than a reduction. Pfeiffer & Lin (2014) report an example from western Kansas/USA, where a shift to more efficient irrigation technologies correlated with increased total water use. They explain this effect by farmers changing from non-irrigated to irrigated crops, reducing fallow periods and increasing per hectare irrigation. Similarly, Sun et al. (2016) found that increased water use efficiencies in Bayannur/Inner Mongolia in the period between 2000 and 2010 coincided with increased total water consumption. These authors state that savings were utilised to increase production rather than to alleviate pressures on the environment. In a global FAO review on improved irrigation technology, Perry et al. (2017) concluded that the introduction of high-tech irrigation without accompanying controls on water allocation usually results in an increase rather than a reduction of water use.

5. What factors are difficult to assess? Rebound Effects

Several studies also address rebound effects related to higher agricultural yields in the context of the land sharing vs. land sparing debate (Mertz & Mertens, 2017; Phalan et al., 2011). Lambin & Meyfroidt (2011) discuss potential implications of rebound effects from raising agricultural productivity on the global demand for agricultural land. Ewers et al. (2009) show in a global study on yields and land use between 1979 and 1999 that land sparing occurred in some cases, but that for developed countries there was no evidence that increases in agricultural productivity resulted in lower per capita cropland demand. Addressing the link between agricultural productivity and greenhouse gas emissions, Valin et al. (2013) used the partial equilibrium model GLOBIOM to assess options for meeting the projected global food demand in 2050. In a scenario where all additional production was achieved through higher yields, they found strong demand-side rebound effects that reduced potential greenhouse gas savings by 50%. Studies on rebound effects related to efficiency increases in the agricultural use of other resources are mostly lacking. For a review on rebound effects in agriculture and an assessment of their relevance for emerging soil management practices, see Paul et al. (2019).

Impact assessments of efficiency measures need to consider potential rebound effects to ensure correct estimates of resource savings and to allow for an unbiased comparison between alternatives for reducing resource consumption. Assessment results that identify a risk of rebound effects can also be used to support the design of measures aimed at mitigating or preventing such effects.

How can rebound effects in soil management be assessed?

To assess rebound effects, it is useful to first determine whether economic or socio-psychological preconditions are fulfilled. Only if the efficiency increases result in lower production costs or affect consumers' perception of the final products are rebound effects likely to occur. While these conditions are usually met to some degree (and rebound effects therefore common), the actual cost reduction or change in consumers' perception may be very minor and the size of the resulting rebound effects too small to be of relevance. What effect sizes are considered relevant must be determined individually within the context of a particular assessment.

Paul et al. (2019) present a framework for assessing rebound effects in agricultural land and soil management (Figure 10). Similar to a flow chart, users can answer "yes" or "no" questions to find out whether the occurrence of different rebound types is likely. Factors determining the size of the rebound effects are given in blue boxes.

5. What factors are difficult to assess? Rebound Effects

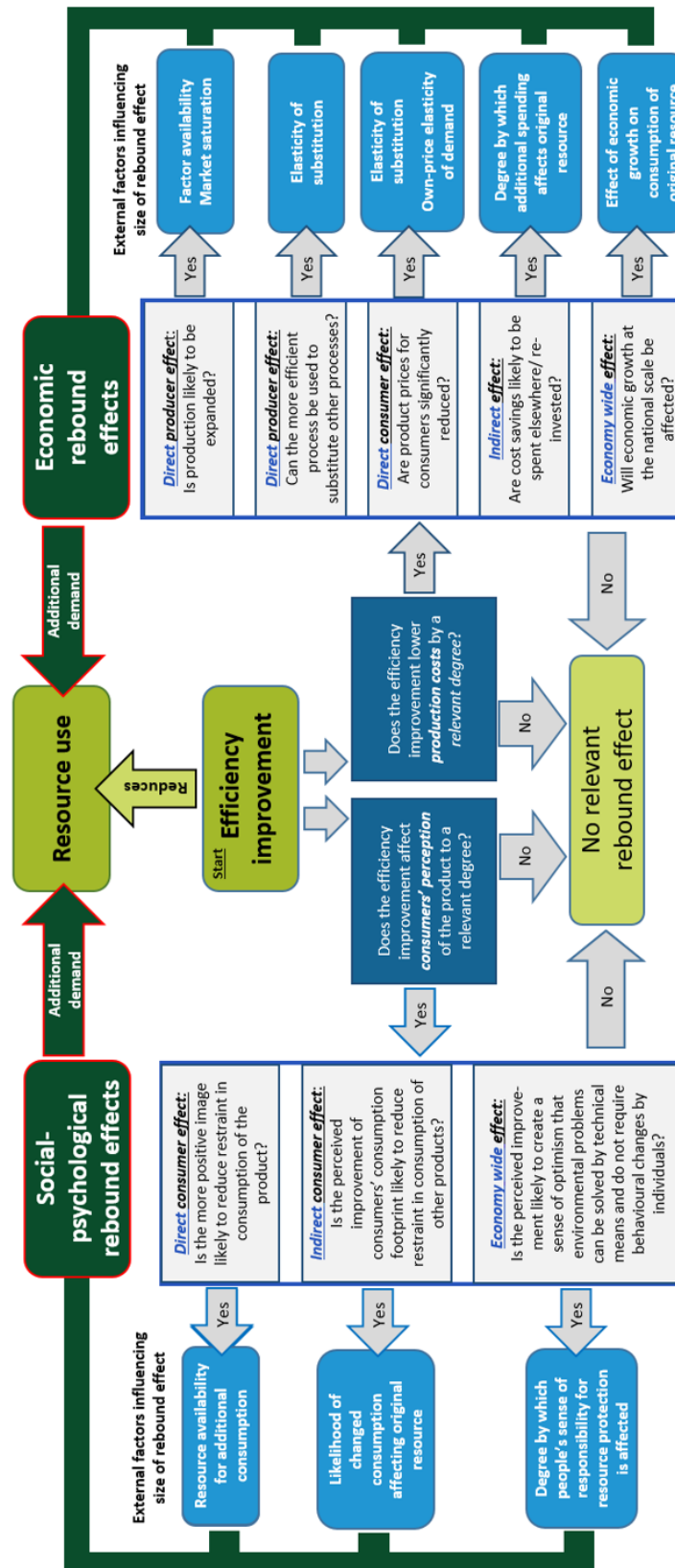


Figure 10: Framework for assessing economic or socio-psychological rebound effects from efficiency improvements. Factors determining the size of the rebound effects are presented in the blue boxes (Paul et al., 2019).

5. What factors are difficult to assess? Rebound Effects

There is scientific consensus regarding the existence of rebound effects, but little agreement on their size. Values provided in scientific literature for increases in energy efficiency vary considerably (for an overview of studies, see Huesemann & Huesemann, 2008 and Kolstad et al., 2014). However, while it is difficult to estimate effect sizes, the implicit assumption of zero rebound effects made by studies that choose to ignore them is not supported by scientific evidence (Maxwell et al., 2011).

De Haan et al. (2015) discuss complications involved in assessing the size of rebound effects and argue that studies based on top-down evaluations of time series tend to overestimate effect sizes due to problems of separating increased resource consumption caused by economic growth and increasing consumers' wealth from increased resource consumption caused by increased efficiencies. On the other hand, they consider process-based, bottom-up studies to generally underestimate rebound sizes because they cannot account for economy-wide effects.

Because rebound effects result from changes in the behaviour of different actors and are based on multiple variables, it is challenging to assess their effect size (particularly in ex-ante assessment). In many cases, only a very rough estimate will be possible. For rebound effects resulting from economic feedbacks, general equilibrium models can help to estimate reactions of market participants. For rebounds due to social-psychological factors, a major research gap exists. (Maxwell, 2011). The use of the rebound effect assessment framework (Paul et al., submitted) may facilitate an assessment of rebound effect sizes. In general, the following factors are considered to be positively related with the size of rebound effects (de Haan et al., 2015):

- Relative size of the efficiency improvement (%)
- Relative share of savings of total production costs (%)
- Degree to which production is limited by availability of the more efficiently used resource (e.g. limited allocation of irrigation water, limited amount of allowable fertiliser application)
- Degree to which the more efficient process can be used to substitute other production factors
- Relative price reductions for the final product (%)
- Degree by which the consumption of the product is perceived as more positive (e.g. social or environmentally friendly) than before
- Demand elasticity, degree to which demand is currently unsaturated
- Low degree of other costs associated with product consumption (e.g. in the field of mobility, travel-time is often more relevant than travel-cost)
- Degree to which the more efficiently used resource is also used in the production of alternative goods and services (the demand for which might increase with increasing wealth)
- Degree to which the more efficient resource use triggers technical innovation in other sectors

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5. What factors are difficult to assess? Rebound Effects - Case Studies

5.1.1 Rebound Effects - Case Studies

Here we present two research articles in which **rebound effects** were found in the context of agricultural land management. They highlight the importance of considering rebound effects in impact assessments.

The study of Paul et al. (2019) gives an overview of rebound effects related to resources used in agriculture, that were detected in current scientific literature. It furthermore presents a framework helping to assess potential rebound effects. The framework was applied to a test case of emerging technologies and practices in agricultural soil management in Germany. The authors found evidence for strong rebound effects in the context of agricultural land and soil management, especially for increases in productivity and a more efficient use of irrigation water.

Rebound Effects in Agricultural Land and Soil Management: Review and Analytical Framework (Paul et al. 2019)

Citation: Paul, C., Techen, A. K., Robinson, J. S., & Helming, K. (2019). Rebound effects in agricultural land and soil management: Review and analytical framework. *Journal of cleaner production*, 227, 1054-1067. <https://doi.org/10.1016/j.jclepro.2019.04.115>

The publication of Hamidov et al. (2022) follows on from these findings, as they studied the impact of the introduction of water-saving irrigation technologies in Uzbekistan based on an expert-based assessment of potential rebound effects. Uzbekistan can be seen as a test case for countries that face water scarcity as a severe challenge and at the same time have restricted data availability for model-based approaches. The results of the study suggest that rebound effects are likely to occur and might reduce the actual water savings, unless effective policy interventions are made.

Rebound Effects in Irrigated Agriculture in Uzbekistan: A Stakeholder-Based Assessment (Hamidov et al. 2022)

Citation: Hamidov, A., Kasymov, U., Djumaboev, K., & Paul, C. (2022). Rebound effects in irrigated agriculture in Uzbekistan: a stakeholder-based assessment. *Sustainability*, 14(14), 8375. <https://doi.org/10.3390/su14148375>

5. What factors are difficult to assess? Leakage Effects



5.2 Leakage Effects

Info-Box

In the context of impact assessments, we use the term **leakage effect** to describe situations where measures for improving the situation (e.g. environmental protection) in one location result in a shift of problematic activities to other locations. Leakage effects may partly or fully offset intended positive effects of environmental policies by displacing, rather than alleviating environmental pressures.

Leakage effects gained public attention mainly with regard to a displacement of greenhouse gas emission. The problem of potential “carbon leakage” has been addressed both in policy (European Commission, 2014) and science (Franzen & Mader, 2018; Naeyele & Zaklan, 2019).

Leakage effects can also cause Indirect Land Use Changes (ILUC). These are conversions from one land use type into another (such as from forest to cropland) that are caused by changes in the production level of an agricultural commodity in another, often far away location. Lambin & Meyfroidt (2011) present an example of how land zoning for environmental protection may lead to displacement of populations or a stronger reliance on agricultural imports, resulting in land use changes and an encroachment of natural ecosystems elsewhere. Additional forms of leakage effects may exist, such as stricter regulations for pesticide and fertilizer application leading to higher imports of agricultural commodities from countries where regulations are laxer. However, studies addressing this are currently lacking.

The possibility of leakage effects should be considered in the design and evaluation of policies. For impact assessments to be able to detect them, spatial scales must be set wide enough to also capture effects that appear outside the area of policy application.

What are leakage effects?

In the context of impact assessments, we use the term **leakage effect** to describe situations where measures for increased environmental protection in one location result in a shift of problematic activities to other locations. Leakage effects may partly or fully offset intended positive effects of

5. What factors are difficult to assess? Leakage Effects

environmental policies by displacing, rather than alleviating environmental pressures. They can occur at all geographical scales (Henders & Ostwald, 2014).

According to Watson et al. (2000), four leakage mechanisms can be distinguished:

- Activity displacement
- Demand displacement,
- Supply displacement
- Investment crowding

The term “investment crowding” describes a situation where (additional) investment in a project results in a reduction of investment from other sources. This mechanism is different from the other three in that it does not cause a shift of negative activities but rather a withdrawal of positive activities. It does *stricto sensu* not fall under our definition of leakage effects.

Leakage effects gained public attention mainly with regard to a potential displacement of greenhouse gas emission, the so-called “carbon leakage”. For example, if efforts are undertaken in a region to mitigate emissions, emission intensive production processes may simply be relocated, so that emission reductions at the global scale are smaller than those in the targeted region (Calvin et al., 2009). Because assessments only consider effects if they occur within the system boundaries, emissions due to leakage effects may easily be overlooked if the spatio-temporal scales are set too narrow, thereby resulting in an overestimation of mitigation efficiencies (Watson et al., 2000). The potential problem of carbon leakage is addressed both in policy (European Commission, 2014) and science (Franzen & Mader, 2018; Naegele & Zaklan, 2019).

With regards to land use, leakage effects can cause so called “indirect land use changes” (ILUC), often through a cascade of different displacement activities (Lambin & Meyfroidt, 2011; Watson et al., 2000). ILUC gained attention both in scientific research and in public discussions due to concerns that crop based biofuels might accelerate deforestation in the tropics.

ILUCs could diminish or offset the benefits of a reduced consumption of fossil fuels. Accordingly, several studies dealing with land-use changes or agricultural intensification, greenhouse gas emissions or deforestation connect these to leakage effects due to policy changes (Calvin et al., 2009; Henders & Ostwald, 2014; Lambin & Meyfroidt, 2011; Lee et al., 2006; Lim et al., 2016).

Additional forms of leakage effects are possible, such as stricter regulations for pesticide and fertilizer application leading to higher imports of agricultural commodities from countries where regulations are laxer. However, studies addressing this are currently lacking.

Why are leakage effects relevant for assessing soil management?

Policies and innovations aimed at improving soil management and reducing pressures on the environment may, depending on their specific design, come with the risk of leakage effects. This could compromise their environmental benefit. For example, reducing the area of intensive agricultural production may alleviate pressures on the environment locally, but due to a global demand for agricultural commodities may also lead to more agricultural production in other regions. Impact assessments that fail to consider leakage effects overestimate the overall positive impacts of measures or arrive at wrong conclusions.

5. What factors are difficult to assess? Leakage Effects

The risk of leakage effects should already be considered in the design of innovative soil management strategies. Impact assessments can be used to identify such risks and facilitate the design of additional measures to mitigate or prevent them.

How can leakage effects be considered in assessments of soil management?

Identifying the consequences that changes in one (production) system have on other systems at different geographical scales is challenging (Henders & Ostwald, 2014). Only where impact assessment also considers effects occurring outside of the locations targeted by policies or innovations will they be able to identify potential leakage effects. A wide setting of the spatio-temporal system boundaries, considering effects up to the global scale, may be necessary for this.

Focussing on land use change, Lim et al. (2016) describe in detail economic mechanisms relevant for the occurrence of leakage effects from conservation measures or agricultural intensification. They present a framework of market responses that can be used to identify where unintended policy outcomes are likely.

Henders & Ostwald (2014) reviewed applicability, strengths and weaknesses of assessment methods for quantifying leakage effects as unintended consequences of policies. This included methods such as equilibrium modelling, statistical correlations and causal-descriptive methods. For global overviews and for determining the drivers and the occurrence of leakage, these authors recommend top-down approaches such as Computable General Equilibriums (CGE) and Multi-Regional Input-Output Analysis (MRIO) models.

To find the connection between consumption and production across regions, they state that extended Material-flow Analysis (MFA) methods, representing bottom-up assessments, have a better resolution and can be used to cover the national level or to compare several countries.

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5. What factors are difficult to assess? Additionality



5.3 Additionality

Info-Box

Additionality is a well-established concept in the field of greenhouse gas reduction and carbon offsetting. It became prominent as a key concept of the Kyoto Protocol's Clean Development Mechanism (CDM) and Joint Implementation (UNFCCC, 2010). Additionality means that for assessing a specific intervention, only those outcomes should be considered that are additional to what would have happened without the intervention. For example, to evaluate the benefits of a campaign to save energy, only behavioural changes caused by the campaign should be considered, while reductions in energy consumption caused by technological progress should be ignored. The concept is fundamental for designing and evaluating result based payment schemes, such as carbon farming schemes or payments for ecosystem services.

The assessment of additionality can be a challenging task. In the following sections, an overview of the concept and some assessment tools are presented.

What is additionality?

A project to reduce greenhouse gas emissions is considered additional, if the greenhouse gas emission reductions or removals would not have occurred in the absence of the associated policy intervention or activity (IPCC, 2022).

An example for this could be a policy intervention which awards financial benefits to farmers applying no-till management methods. This effect of the intervention is the additional amount of farmers applying no-till methods compared to a scenario without the intervention. Possible reasons why farmers could also shift to no-till practices without an intervention include: attractive offers for no-till machinery, high energy prices, or unsuitable soil conditions for tilling.

Overall, additionality is a matter of causation (World Bank, 2016). Does a specific intervention cause the desired effects and if so, how much of the effect is due to the intervention and how much due to other factors. Therefore, additionality is **not** a comparison of before and after the intervention, but rather a comparison of scenarios 'with' and 'without' the intervention (Thamo & Pannell, 2016).

Additionality is a key criteria for results based payments, including the application of carbon credits, carbon farming (Paul et al., 2023), or payments for ecosystem services. Essentially, the concept of

5. What factors are difficult to assess? Additionality

additionality ensures that interventions are not accredited for effects that would have occurred anyway.

Why is additionality relevant for assessing soil management?

Analysing additionality is essential for realistic assessments of benefits and trade-offs of agricultural management options. Where payments are involved, assessments of additionality help to ensure the efficiency of these payments (II-AMT 2023).

How can additionality be applied in the context of soil management?

In practice, additionality is often poorly addressed. In the context of soil carbon certificates, it is sometimes claimed that interventions were additional if they exceeded legal requirements and would be economically unviable or unattractive without funding support (Paul et al. 2023). This is an oversimplification based on the assumption that farmers' management decisions are solely guided by economic short-term considerations, whereas long-term planning for and adaptation to future developments such as climate change (Mitter et al., 2020), as well as social consideration (Bartkowski and Bartke, 2018; Thamo and Pannell, 2016) have been established as significant factors influencing decision making.

Furthermore, it is important to consider the temporal dimension, as additionality is not static. Measures that are additional today, such as payments motivating the rewetting of a specific artificially drained organic soil, may lose the element of additionality if rewetting becomes common practice in the future due to changes in market, technologies or policies.

For the assessment of additionality in the context of agricultural soil management, the three steps of Thamo & Pannell (2016) can be applied. At first, it is important to identify whether a practice is additional or not (Thamo & Pannell 2016). The second step involves to pinpoint the benchmark practice that would be displaced by the activity under assessment (Thamo & Pannell 2016). For instance, the additionality of soil organic carbon increases of soil carbon certificates can be evaluated by a comparison with a counterfactual scenario without them (Bartkowski et al. 2021). Within the last step it is determined how much of the change compared to the baseline-scenario from the new practice is actually additional (Thamo & Pannell 2016). In comparison to the first two steps, this process is less frequently addressed and includes the measurement and monitoring of both the new practice as well as the benchmark practice (Thamo & Pannell 2016). Even if the first two steps remain unchanged, the result of the last one can vary in space and time (Thamo & Pannell 2016).

For doing the assessment, the tool of the demonstration and assessment of additionality can be used (II-AMT 2023). It provides a general framework for projects to determine whether activities can be considered additional as defined in Article 6 of the Paris Agreement. The pre-step ensures that the management practice is in line with the climate goals of the Paris Agreement and does not lead to the lock-in of emission levels (e.g. due to the prolongation of the lifetime of an emission intensive practice). Before the first financial commitments are made, a public notification has to be undertaken to show that carbon market revenues were considered in the investment decision. Step 2 involves a regulatory analysis to check if the practice is already mandated by law or other legal requirements in the present (step 2.1) or will be in the future (step 2.2). If this is not the case, the risks to financial additionality are assessed in step 3. This is done by evaluating whether the practice was already implemented without

5. What factors are difficult to assess? Additionality

incentives and if any non-monetary barriers exist to the implementation (e.g. unavailability of the technology). If barriers could prevent the realisation of the practice and/or the activity was realised without incentives already, an investment analysis has to be done in step 4. In this way it is tested if the practice would be unattractive without financial support.

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6. How can Future Developments be considered?



6 How can Future Developments be considered?

Info-Box

Foresight enables us to support decision-making by analyzing possible futures. Several definitions of foresight exist, which major and common features were summarized by Miles et al. (2008):

- Long-term orientation aimed to inform on the ongoing decisions set by assumptions that the future can be improved by enhanced understanding of opportunities and threats, driving forces and underlying processes of change.
- Use of a range of formal tools and techniques for developing the long-term analyses – including survey methods like Delphi, scenario workshops, explorative trend analysis, and often drawing on the results of modelling, SWOT studies etc.
- Involvement of a wide range of experts and often stakeholders in order to access relevant knowledge, to engage more participants in the policy process, and to establish networks for the ongoing coordination of actions and sharing information.
- Crossing disciplinary boundaries and professional compartments in order to address emerging world problems that know nothing of these impediments. This often requires extensive “translation” and fusion of knowledge from different sources.

Scenarios in the foresight context

Scenario development is among the most widely used methods in foresight (*Popper, 2008*). The IPCC (2013) states that “a scenario is a coherent, internally consistent and plausible description of a possible future state of the world. It is not a forecast; rather, each scenario is an alternative image of how the future can unfold”. Scenarios can be categorized as exploratory and normative scenarios. Exploratory scenarios identify drivers and represent possible futures, while normative scenarios illustrate how certain targets can be achieved.

Why foresight and scenarios in BonaRes?

BonaRes focuses on agricultural soil management foresight including the development of soil management scenarios at the German national (DE-SMPs) and regional (RSMPs) levels. The main aims of the BonaRes Foresight are to:

6. How can Future Developments be considered?

1. Identify relevant soil-related research questions by addressing which the risks and opportunities of emerging technologies and practices can be assessed with further contribution to the decision-making.
2. Develop common framework conditions for socioeconomic and integrated scenarios that allows for comparability and connectivity within the BonaRes studies. For example, exploratory scenarios on agricultural soil management can be a basis for soil modelling (e.g. BODIUM) in order to test the effectiveness of proposed agricultural soil management paths and associated policies.
3. To inform stakeholders on potential development paths and associated ongoing and upcoming actions. Scenario-based stakeholder involvement allows to enrich scenarios by bringing a wide range of expertise and knowledge on soil management together.

BonaRes Foresight Study

Taking appropriate actions to foster sustainable soil management requires the identification of drivers and trends of future soil management and the challenges and opportunities these offer. Thus, we conducted a foresight study for agricultural soil management in Germany, as an example for industrialized agricultural systems with low yield gaps.

Methods

We analyzed which factors drive soil management and how these drivers are potentially coining the development of soil management in Germany. The conceptual starting point of the analysis was the **DPSIR (Driver-Pressure-State-Impact-Response)** framework. From this we derived assumptions for potential developments of soil management in Germany.

In 2016 we reviewed a total of 267 different sources (Tehen and Helming 2017). The priority was given to peer-reviewed publications.

In spring of 2017 we conducted 19 semi-structured interviews (Tehen and Helming 2018) with experts from soil and agricultural sciences, agricultural business and authorities (see acknowledgements) to validate and complement our review results. The structured questions in the interviews were evaluated quantitatively and the open questions were evaluated with qualitative content analysis. Questions included the likelihood and possible timeline of the emergence of new management practices as identified in the literature review.

6. How can Future Developments be considered?

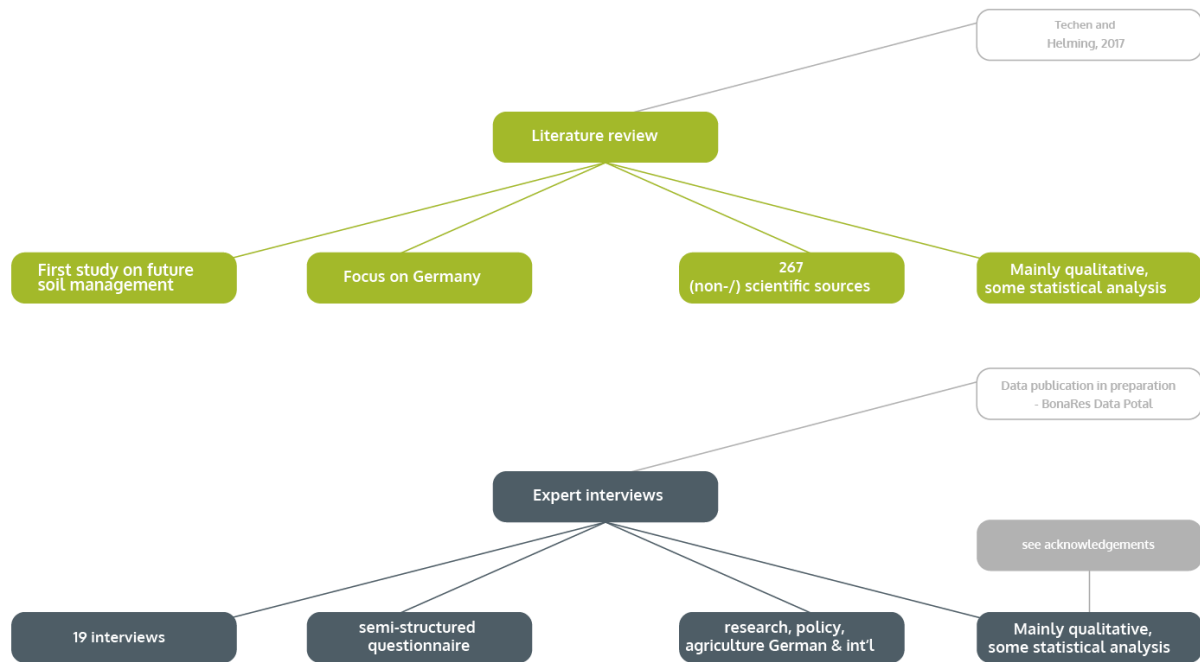


Figure 11: Literature review and expert interviews for the BonaRes foresight study.

Categories of Change

We identified two modes of future soil management changes:

1. **Quantitative** changes related to the applied quantities of given input factors.
2. **Qualitative** changes that can be subdivided into five categories: spatial patterns, crops and rotations, mechanical pressures, inputs into the soil and general soil conservation behavior.

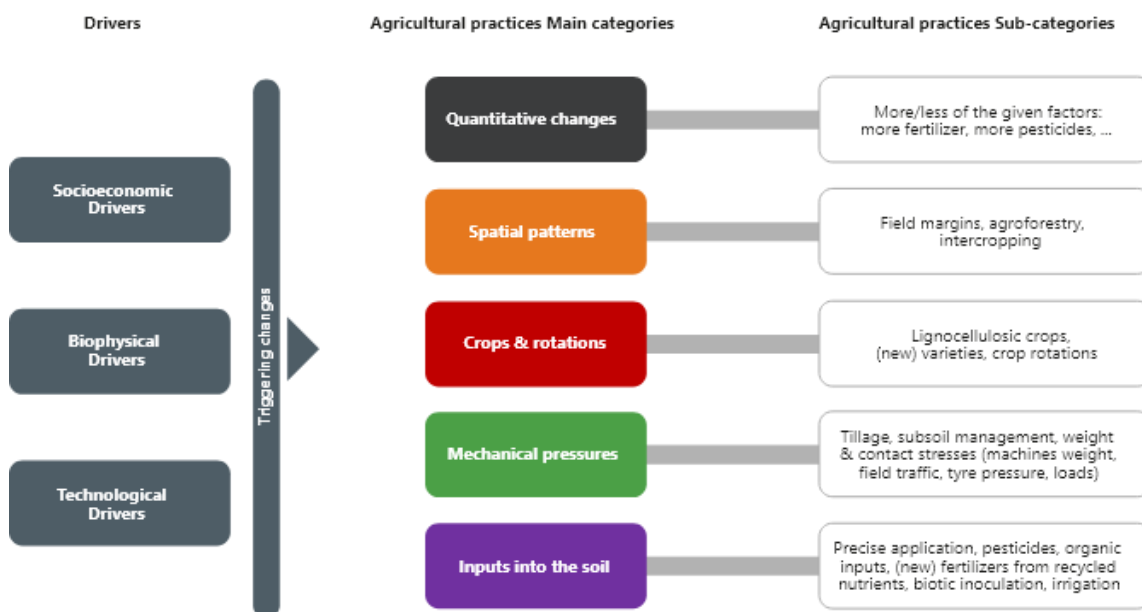


Figure 12: Drivers and Categories of changes in agricultural practices.

Dimensions of Change

6. How can Future Developments be considered?

The Figure below shows potential trends in soil management in Germany, organized along the dimensions of timing and signal strength. It is an interpretation of the quantitative results and the verbal comments of the expert interviews, on the basis of the literature review. Colors refer to the main categories of change.

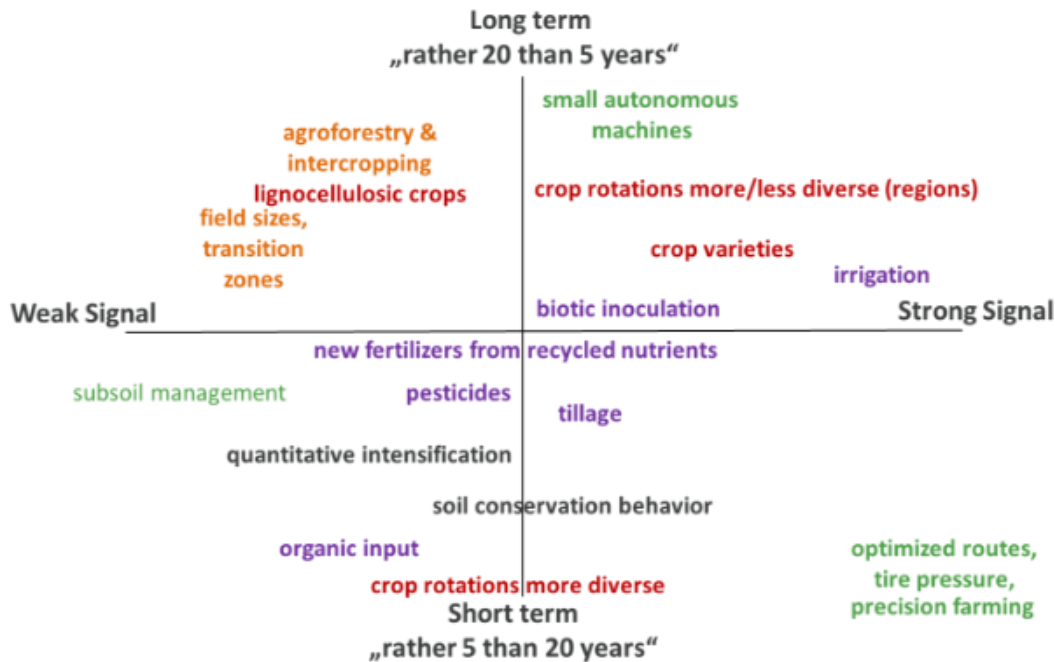


Figure 13: Potential trends in soil management in Germany. Colors refer to the main categories of change (see Fig. 12)

For instance, subsoil management is set on the far left because at this point in time indications for change of subsoil management practices are only coming from a fraction of the soil science community. On the far right is irrigation because most interviewees assumed that the acreage of irrigated agricultural land will increase in Germany, mainly due to climate change, even though it is assumed to increase already in the coming years.

On the bottom of the Figure “Dimensions of change” is precision farming and it is connected to making agricultural machines, such as tractors, autonomous. We have strong signals for machines becoming autonomous because this development is already ongoing. But this alone does not mean that the treatment of soils will change. This will only happen if the machines will change, too. In addition to the current but forcibly slowing trend towards larger machines, a countertrend to small, lightweight field robots is foreseeable.

Some of these small machines can already be found in the fields in the test phase. Small machines bring opportunities for smaller-scaled farming, intercropping and less weight stresses, which again can have a positive impact on all soil functions. Furthermore, their development is connected to very precise application of pesticides and fertilizers. But details and other impacts are unclear, e.g. the aspect of resource efficiency in terms of energy consumption.

Smaller-scaled systems that can be facilitated by smaller machines are for instance agroforestry systems, even though they are also possible with conventional machines. Research uncovering its economic and environmental benefits in temperate regions, together with technological

6. How can Future Developments be considered?

improvements in the use of, and demand for, lignocellulosic feedstocks for energy and industry could support a trend towards agroforestry.

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7. Learn more about sustainability impact assessments

Here, you find information about what a **Sustainability Impact Assessment** is, where it is applied, and how to conduct your own assessments.

Read more about the **BonaRes Assessment Framework**, which we use to assess the impacts of agricultural soil management. The BonaRes Assessment Framework builds on the more general **DPSIR Framework**, which is used to describe human-environmental systems.



Credit: Travis Leery via Unsplash

7.1 Impact Assessment

Info-Box

Impact assessment is a set of logical steps that prepares evidence for decision-makers about the potential positive and negative consequences of policy or management options. In the context of soil management, impact assessment is crucial to recognising possible consequences of management decisions on social and natural systems across spatial and temporal scales.

The assessment process involves the evaluation and comparison of the consequences of different soil management options according to six steps: identification of problems, definition of objectives, development of alternative options, analysis of impacts, comparison of options, and recommendation for evaluation, monitoring, and implementation.

What is an impact assessment?

Impact assessment is a method “to structure the analysis of human-environment interactions” (Helming and Pérez-Soba, 2011). It synthesises scientific knowledge to inform policy and management (Carpenter et al., 2006). The knowledge gained by impact assessment supports stakeholders in various areas of decision-making, such as soil management (de Olde et al., 2016), governance and policy formulation (Podhora et al., 2013), or research design for sustainable development (Bond et al., 2012).

Impact assessment prepares evidence on the advantages and disadvantages of possible management or policy options by assessing their potential impacts on intended and unintended, short-term and long-term issues relevant for society (SEC, 2009; Helming et al. 2013). Impact assessment in the context

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of natural resource use requires the definition of the activities and the environmental and societal system components that are evaluated.

Why apply impact assessment to soil management?

Impact assessment in the context of soil management is crucial in order to recognise the potential consequences of management decisions on social and natural systems across spatial and temporal scales. The assessment evaluates and compares the consequences of different soil management options. This includes management options suggested from a scientific perspective (e.g. fertilisation schemes, tillage technologies, bio-control and microorganism utilization, crop rotations and catch cropping, application of sensor technologies, irrigation), those stemming from bioeconomic innovations (e.g. new cultivars and harvesting technologies, on-site harvest processing) and those derived from policy implementation at local, national and international levels (e.g. greening measures, carbon certificates). The latter category is particularly important because agricultural policies defined at the European level (CAP) and international conventions, such as those for combating desertification (UNCCD), have implications for domestic production (e.g. reduction of protein imports). Likewise, domestic decisions on land management (e.g. renewable energy strategies) may have sustainability implications in other world regions due to global market adjustments (discussed in section IV.2).

Assessments include issues of social acceptance, risk perception, economic costs and benefits, as well as environmental impacts beyond the soil system such as the interaction with water, air, climate and biodiversity. In order to structure different assessment approaches and utilize them for evaluating options in the context of creating a sustainable bioeconomy, we developed the BonaRes Assessment Framework, the Impact Assessment Platform and the Handbook of Soil-Related Impact Assessment. These products provide a systematic approach to assessing impacts of soil management on societal targets.

Assessment results can be used to inform stakeholders and facilitate a better alignment of human-nature interactions with societal goals, such as efficient use of natural resources or sustainable development (Helming and Pérez-Soba, 2011). Stakeholders include:

- A. **Policy makers** that require assessments of current and future states of all soil functions and services, as well as tools to anticipate future driving forces and trends in soil management.
- B. **Biomass producers (farmers)** that require site-specific information to develop optimal management solutions for tillage, fertilisation, pest management, crop rotations, cultivar selection, and soil conservation. Information needs of this group are at the highest spatial (field) and temporal (up to days) resolution.
- C. **The biomass processing sector** that requires information on biomass quantities and qualities that can be made available at specific locations and points in time, including agricultural commodities and side products such as straw and residues.
- D. **The wider research community** that requires information on soil related impacts and interdisciplinary linkages for their research (e.g. agriculture, hydrology, biodiversity, ecosystem services, climate modelling).
- E. **Civil Society** and their institutions, which are concerned with effects of soil management on the environment and on human well-being.

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How to apply impact assessment to soil management?

For soil related impact assessment, we use a **set of six steps** based on the 7.2 *DPSIR Framework*. These steps can be seen as a dynamic process studying the societal reaction towards pressures on natural and human systems. It investigates a continuous loop of human-nature-human interactions. We put particular emphasis on the analytical step 4, the assessment step in the narrow sense, which evaluates the consequences of human activities on social and ecological systems from the perspective of societal targets, thereby taking an anthropocentric viewpoint.

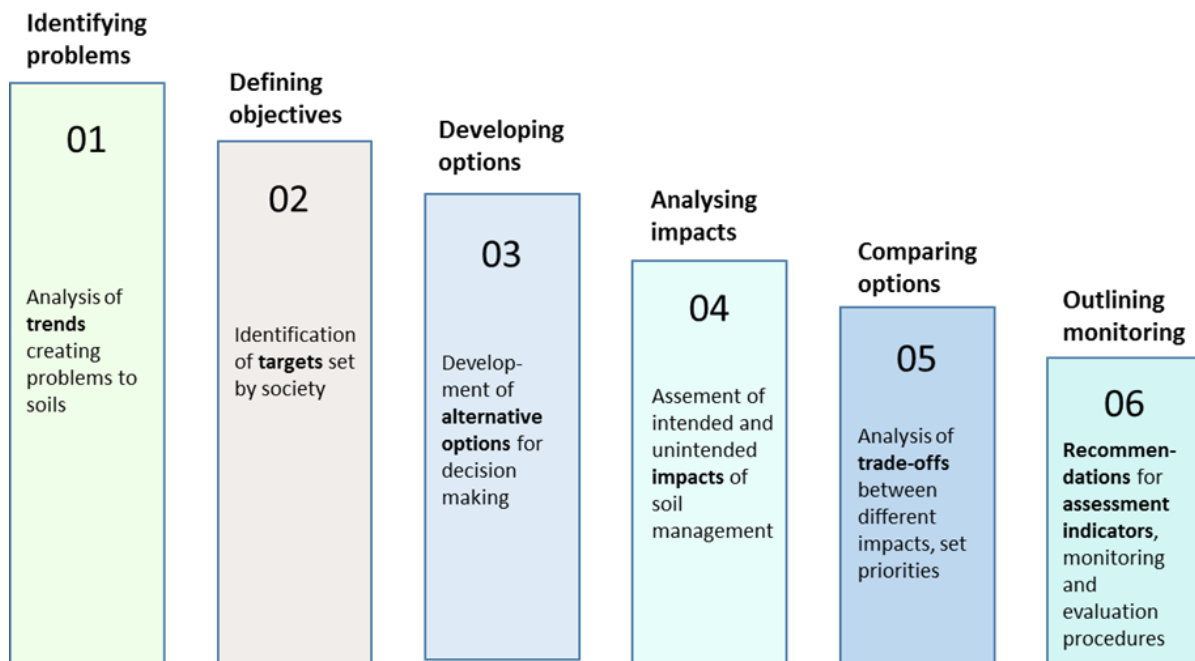


Figure 14: Steps of impact assessment (SEC, 2009; Helming et al., 2013) applied to soil management (Helming et al., 2018).

The six steps of impact assessment link the socio-economic system of societal target setting and decision-making with the natural system of biological, physical, and chemical process interactions (Figure 14). Adapted to soil research, the steps include:

1. Analysis of future trends and **driving forces** for soil management options and identification of problems.
2. Definition of human activities and options regarding soil management practices exerting **pressures** on soil systems.
3. Analysis of the effects of human activities on the **state** of soil processes and soil functions. This analytical step concerns the soil system and depicts how soil processes are affected by soil management, and how this in turn affects the ensemble of soil functions.
4. Assessment and valuation of direct and indirect **impacts** of soil management in the context of social, economic and environmental targets.
5. Comparing the impact of different options, analysing co-benefits and trade-offs. At this stage, case-specific priorities can be assigned to the different impact areas, enabling a ranking of the analysed options.
6. Recommendations for assessment indicators, monitoring procedures and the evaluation of policy implementation (Helming et al., 2013; Helming et al., 2018).

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Impact assessment of soil management practices under the perspectives of **resource use efficiency** and maintenance of **ecosystem services** is an emerging field of research that will be highlighted in this platform. The limited number of examples found in current literature have a predominantly economic focus (Speiser et al., 2013; Peters et al., 2011). Assessments considering societal decision-making, e.g., by farmers, represent a substantial research gap with the exception of a few studies e.g., in Europe (Giupponi & Rosato, 1999) and in developing countries (Tittonell et al., 2015; Wanyama et al., 2010).

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7.2 DPSIR Framework

Info-Box

The DPSIR framework helps to structure complex human-environmental systems into a sequence from **Driver, Pressure, State to Impact and Response (DPSIR)**. Due to its generic character, it can be used to investigate impacts of soil management on environmental and societal systems, to summarise existing knowledge of soil management research, and to detect research gaps. The DPSIR framework analytically links soil management (pressure) to soil functions (state) and its services (impact) that are assessed from the perspective of societal goals such as resource use efficiency or ecosystem services. Informed by the assessment results, society may react, governance may be adjusted (response) and steer soil management into a new direction (creating new drivers and restarting the sequence).

What is the DPSIR Framework?

The DPSIR framework describes a **five-step causal** relationship of human-nature interactions and was developed for the assessment of relations between human activities and the environment (Gabrielson and Bosch, 2003). It builds on the three-step PSI framework which was originally developed by the OECD (1993). The five analytical stages help to structure complex human-environmental systems in a sequence from **Driver, Pressure, State to Impact and Response (DPSIR)**. For example, driving forces, such as human needs for specific nutrition or improved technological facilities, lead to particular human activities in soil management and biomass production. These activities exert pressures on the environment, e.g., soil, which might change its properties and processes (“state”) and corresponding functions. The potential environmental system changes have impacts on the societal system which are then evaluated by impact assessments. Informed by the valuation results, a societal response might take place that alters drivers and resets the causal chain of pressures, states, and impacts.

In this way, the DPSIR framework captures change and dynamic processes in human-nature interactions. It helps to integrate knowledge from different disciplines via indicators in a cycle of impact assessment (Tscherning et al., 2012; Helming et al., 2013). One key strength of the concept lies in its adaptability to various impact areas, objectives and scales of analysis (Tscherning et al., 2012). Potential enhancements of the framework could be designed to also consider interconnections

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between stages beyond the connection from preceding to following stage (Niemeijer & De Groot, 2008).

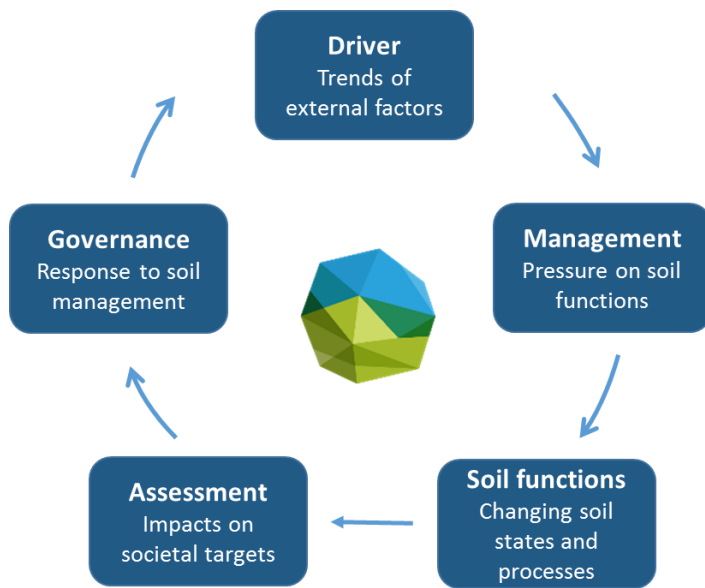


Figure 15: The DPSIR framework applied to soil functions in the socio-economic context, modified from Gabrielsen & Bosch (2003).

Why is the DPSIR relevant for soil-related impact assessments?

The DPSIR framework analytically links soil management to soil functions and impacts on societal goals and value systems such as resource use efficiency or ecosystem services. Its perspective on human-nature interactions makes it possible to integrate scientific evidence from different disciplines into one joint framework, helping to develop comprehensive strategies for soil management that both sustain and improve soil functions. Finally, the integrated knowledge helps to provide scientific evidence for a multitude of societal groups and stakeholders involved in soil management (politicians, farmers, planners etc.) in order to support decision-making.

How to apply the DPSIR framework to soil management?

Due to its generic character, the DPSIR framework can easily be applied to very different settings of soil research. A number of studies already use the framework to investigate impacts of soil management on environmental and societal systems. For example, DPSIR has been applied to analyse changes in agricultural management such as precision agriculture and manure input on different scales (Bouma et al., 2008), to illustrate how land degradation control could be more effective (Gislanddottir & Stocking, 2005), to analyse how salinity, acidity and erosion threaten the ecosystem services of food production and the regulation of water quality in Australia (Holland et al., 2015), and to detect co-evolution of soil and water conservation policy with human-environment linkages (Wang et al., 2015). Furthermore, studies that focus on particular stages of the framework or on the relationships between stages can be integrated into a full application of the DPSIR framework and a broader cause-effect relationship. For example, Smaling & Dixon (2006) investigate the state, impact and response of soil fertility and nutrient management in global farming systems.

Overall, DPSIR framework can be used to summarize existing knowledge of soil management research and to detect research gaps. A particular example that reviews and synthesises scientific evidence for

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all single analytical steps of the DPSIR framework is provided by Schjønnning et al. (2015). Their thematic focus is the potential compaction of sub soil due to mechanical stress by agricultural machinery. In detail, they identify studies describing external and internal drivers of particular field traffic practices, e.g., technical improvement and saving of labour costs cause the use of bigger and heavier machinery. They cite further studies that show how the pressure by field traffic on soils increases and has consequences for soil processes, such as higher bulk density, less pore volume size and reduced root system. This change of the soil state again has impacts on selected soil functions such as reduced biomass production, less storing and filtering capacities for water and nutrients. Furthermore, Schjønnning et al. (2015) present studies investigating the impact on the social system such as the calculation of the relation between yield loss and cost savings in machine operations (cost-effectiveness of alleviating or avoiding soil compaction). They present potential responses to desirable or undesirable impacts, ranging from provision of subsidies in the political system to farmers' changes in soil management (e.g., increased application of nutrients or planting of taproot plants) to technical improvements towards smaller machinery.

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7. Learn more about sustainability impact assessments - BonaRes Framework



7.3 BonaRes Assessment Framework

Info-Box

The BonaRes Assessment Framework has been developed to study impacts of soil management practices on societal targets. It is designed for agricultural systems in industrialised countries where both yield gap and contribution to gross domestic product (GDP) are low.

The BonaRes Assessment Framework is based on the DPSIR framework and the six steps of impact assessment. It links driving forces and management decisions to soil reactions, changes in soil functions and their impacts on societal targets. Impacts within the categories of resource use efficiency and ecosystem services are analysed. These two assessment perspectives are considered complementary and strongly correspond with requirements of the German bioeconomy strategies. Likewise, they are related to a number of targets under the United Nations' Sustainable Development Goals.

Application of the BonaRes Assessment Frameworks helps to structure research, define impact areas and indicators and to identify research gaps.

What is the BonaRes Assessment Framework?

The BonaRes assessment framework (Helming et al., 2018) is an analytical structure to guide research of impacts of soil management and soil function changes on societal targets. It links the DPSIR framework (Gabrielsen & Bosch, 2003) with the six steps of impact assessment. The framework has been developed to study impacts of soil management practices in industrialised agricultural systems characterised by low yield gaps and representing a low share of their countries GDP (gross domestic product), as is the case in most industrialized countries. Societal goals for soil management in these systems are often characterised by an ecosystem services perspective, i.e., increasing biomass production while maintaining the contribution of soil functions to the other ecosystem services, and by a perspective of resource use efficiency, i.e., an optimal return from invested resources. It is important to note that for other agricultural systems (e.g., smallholder farming in developing countries) additional and/or different assessment perspectives are appropriate, e.g., motivated by societal targets of nutrition, poverty alleviation or rural development.

7. Learn more about sustainability impact assessments - BonaRes Framework

The BonaRes Framework (Figure 16) allows two modes of interaction between soil management pressures and impacts: soil-born via changes in soil processes and soil functions (solid arrow) and management induced irrespective of changes in the soil system (thin arrows)

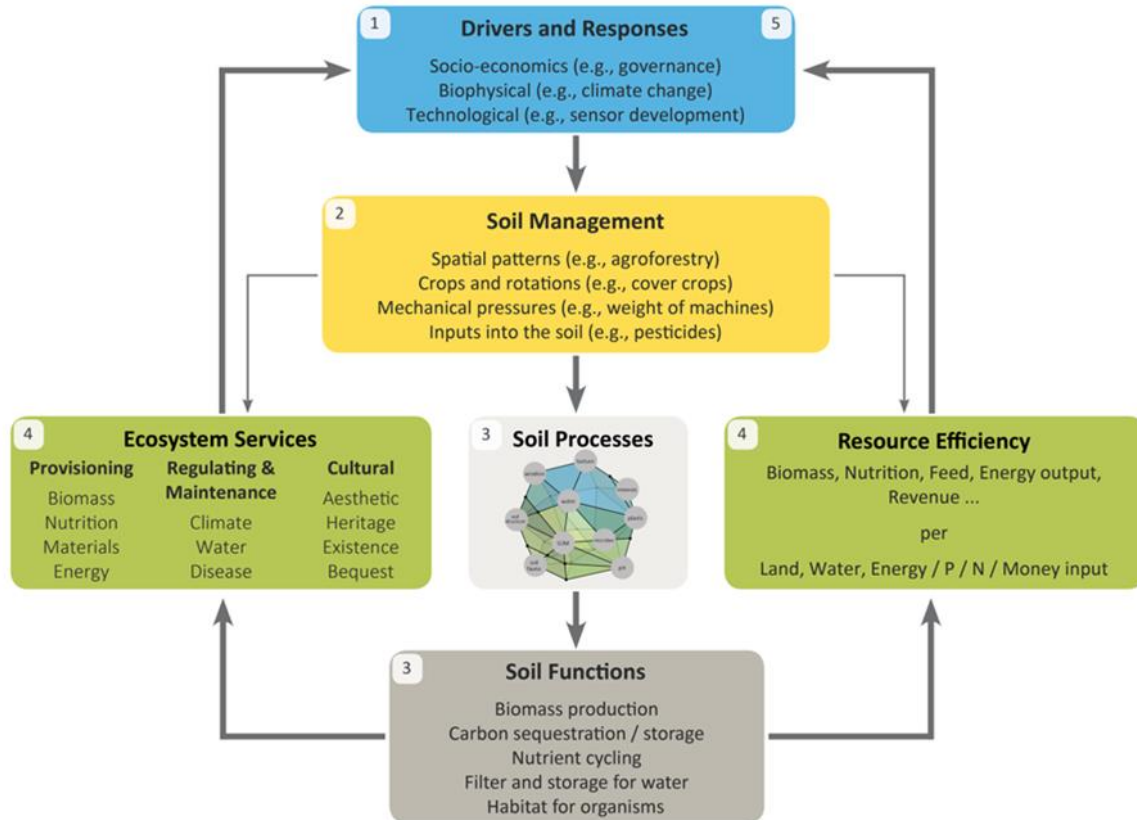


Figure 16: Analytical Framework for impact assessment of soil management and soil functions in BonaRes. Numbers refer to the five steps of the DPSIR framework: Drivers (1), Pressures (2), States (3), Impacts (4), and Responses (5) (Helming et al. 2018).

Why apply the BonaRes Assessment Framework to soil management?

The linkage between impacts of soil management and societal targets has only recently gained attention in scientific and policy debates. For achieving a sustainable bioeconomy, assessing impacts of different soil management options is a necessity. However, to the best of our knowledge, no systematic approach to an impact assessment of soil management and soil functions on societal targets has yet been developed.

The BonaRes Assessment Framework links driving forces and management decisions to soil reactions, soil functions changes and their impacts to societal targets. Because the multitude of such targets makes it impossible to assess all potential impacts, it is necessary to limit assessments to specific assessment perspectives. In the BonaRes Assessment Framework, we analyse impacts within the categories resource use efficiency and ecosystem services. These two perspectives are considered complementary, and they strongly correspond with requirements of the German bioeconomy

7. Learn more about sustainability impact assessments - BonaRes Framework

strategies. Furthermore, they are related to a number of targets under the United Nations' Sustainable Development Goals.

Ecosystem service perspective: The concept of ecosystem services aims to demonstrate the value of nature to human societies and specifically refers to the 'final' outputs of ecological systems, i.e., the goods and services directly consumed or used by people. The importance of managing soil functions to support ecosystem services is widely acknowledged. However, the operationalisation of linkages between soil management, soil functions, and ecosystem services remains a challenge, e.g., where studies use un-linked single indicators.

Resource use efficiency perspective: Resource use efficiency can generally be defined as the ratio of benefits (generated by a product or process) divided by the amount of (scarce) resources used for that purpose (di Maio et al., 2017). Within the context of research for sustainable bioeconomies, it is necessary to determine how soil functions affect resource use efficiencies and additionally, to what degree soil management can increase efficiencies independent from soil functions.

Currently, only few assessments documented in the literature explicitly address the role of soils, although assessment results often implicitly reflect changes in soil functions due to the fundamental role of soils for crop growth. In contrast, the focus of the BonaRes Assessment Framework is explicitly on soils. Its application will help to systemically assess and compare opportunities and threats of (current and novel) soil management practices at different spatial and temporal scales. Insights gained in this way will help to strengthen the science-policy interface. They 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.

How can the BonaRes Assessment Framework be applied to soil management?

The BonaRes Assessment Framework forms the basis of the **Impact Assessment Platform**. In particular, it is used to guide the development of a toolbox based on state-of-the-art research that provides indicators, methods and standards for impact assessment of soil management.

Systemising and test case application will reveal comprehensiveness and complementarity of the developed tools and identify further research needs of impact assessment.

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7. Learn more about sustainability impact assessments - Soil functions



7.4 Soil functions

Info-Box

Soil functions are dynamic soil properties that emerge from complex interacting biogeophysical processes within the soil and that are relevant for human well-being. They are the basis for soil related ecosystem services and resource use efficiency. The concept of soil functions highlights the relevance of soils for human societies and facilitates their structured scientific assessment.

Soil functions first gained prominence through the proposed European Soil Thematic Strategy (EU 2006). For agricultural soils, five functions are considered particularly relevant (Schulte et al., 2014; Helming et al., 2018; Vogel et al., 2018):

- production of plant biomass,
- storing and filtering of water,
- storing and recycling of nutrients,
- habitat provision,
- and carbon storage

What are soil functions?

According to the cascade model of ecosystem services (Haines-Young & Potschin, 2010), soil functions are bundles of soil-based, biophysical-chemical structures and processes with the capacity to provide services to human societies (de Groot et al., 2010). They can be seen as the basis for soil related ecosystem services, but also for soil related resource-use efficiency. Soil functions first gained prominence through the proposed European Soil Thematic Strategy (EU, 2006) where they represented soils' contribution to: food, fibre and biomass provision, filtering, storing and accumulating of water nutrients and carbon, providing habitats and preserving gene pools, providing a platform for human activities, and acting as a historical archive. In an agricultural context, the functions as a platform for activities or as a historical archive are usually not considered relevant, whereas the functions pertaining to water, nutrients and carbon are of the highest importance.

Consequently, Vogel et al. (2018) define the five (agricultural) soil functions listed below. Within this handbook and on the Impact Assessment Platform, we use their definitions, which describe the functions in the following way:

7. Learn more about sustainability impact assessments - Soil functions

Biomass production: *“Soils are indispensable for plant growth and herewith for the production of biomass, which can be used as food supply for humans and animals but also as raw material or energy source. The optimization of crop yields under strongly varying external conditions (temperature, precipitation frequency and intensity, etc.) is one of the biggest challenges with respect to biomass production. Soil fertility is linked to its non-rigid porous structure allowing for roots to penetrate, to store water while air and oxygen is also available and to retain nutrients to be used by plants and recycled by an enormous diversity of soil biota.*

Deficiencies in one or more of these conditions might be compensated by agricultural measures – e.g. compaction by tillage, missing nutrients by fertilization – on the long run, however, sustainable biomass production needs to rely on the natural capacity of soil to provide these essential features.”

Storage and recycling of nutrients: *“The cycling of macro- and micronutrients is an essential function of soils. Mineral weathering generates a slow but constant source of elements made available for biochemical cycles. Soils are biochemical reactors, where numerous organic and inorganic compounds are decomposed and transformed so that the nutrients become again available for soil biota and biomass production. The engine driving this reactor is the myriad of organisms living in soil and taking profit from the energy stored in plant residues. Some part of it, however, is protected from decomposition for quite a long time so that soils act as a substantial carbon pool. An important feature is the ability of soil to retain nutrient within the root zone and to avoid leaching towards groundwater or emission to the atmosphere where the same nutrients might be harmful (e.g. NO_3 in groundwater or N_2O in the atmosphere).”*

Carbon sequestration: *“Globally, there is more carbon in soils than in the atmosphere and the aboveground biomass together. Plants extract carbon dioxide from the atmosphere by photosynthesis and incorporate it in their cell structures. This carbon then enters the soil as root exudates from living plants, which are utilized by soil organisms, or by decomposition of plant litter. These processes release carbon dioxide back to the atmosphere. They are more or less rapid depending on climate, soil type, land use, and management practices. Since carbon dioxide is a greenhouse gas, increasing soil organic matter stocks in soil is considered as a possible solution to mitigate climate change. Soil organic matter has also beneficial effects on soil fertility, water retention, susceptibility to erosion, and diversity and activity of soil organisms.”*

Habitat for biological activity: *“There are more species living below ground than above. Soils provide the living space for an enormous diversity of organisms, but in turn, are also formed by soil biota. The activity and diversity of soil organisms are largely affected by biotic and abiotic factors (e.g., climate, soil properties), but also by land use and management practices. Soil organisms play important roles in a number of soil processes such as nutrient cycling, mixing of soil material and development of soil structure. Due to the high diversity of soil organisms, many species are thought to be redundant, which means that they can be replaced by other species fulfilling the same function. However, certain species may play an irreplaceable role in soil functions. Soil structure provides a multitude of niches where different species can coexist with reduced competition for food and reduced stress of being caught by predators. This is a fundamental difference to the living space above ground.”*

Filtering and storage of water: *“Depending on soil properties, precipitation water is partitioned into storage, groundwater recharge, evapotranspiration, and surface runoff. Due to its porous structure, water can infiltrate into soil and is retained there via capillary forces just like in a sponge, so that it is*

7. Learn more about sustainability impact assessments - Soil functions

available for plant growth and the development of other organisms. This reduces droughts and the generation of floods. Solutes and particles moving through soil have to pass the extensive inner surfaces of soil constituents where they might be sorbed or transformed. Hence, soils are also important to filter harmful substances, originating from industrial and agricultural production, municipal activities, or atmospheric deposits.”

Please note: Each of these functions is a collective term with numerous sub-functions. For example, the function “storing and recycling of nutrients” comprises individual functions for the storage of all macro- and micro-nutrients, as well as functions relevant for the transformation of the different molecules containing these nutrients.

Why are soil functions relevant for the assessment of agricultural soil management?

The importance of managing soil functions to support ecosystem services is widely acknowledged (Glaesner et al., 2014; Schulte et al., 2014; Breure et al., 2012). They represent the biogeophysical reality that is affected by agricultural management. Sustainable intensification, beyond a simple increase or reduction of management intensity, can only be achieved if management can be adjusted to soil internal processes in order to optimize the provision of soil functions. Higher provision of soil functions would then in turn lead to a higher provision of ecosystem services and a higher resource use efficiency.

How can soil functions be considered in the assessment of agricultural soil management?

Soil functions are part of the overall category of ecosystem functions and as such, closely related to ecosystem services. Ecosystem services, the “direct and indirect contributions of ecosystems to human well-being” (Kumar, 2010), are based on the use or appropriation of ecosystem functions (Boyd & Banzhaf, 2007). The underlying terminology builds on the cascade model by Potschin & Haines-Young (2011), where biophysical function or structure, ecosystem function, ecosystem service, benefit and (economic) value are connected elements along a cascade-chain (TEEB, 2010; Braat & de Groot, 2012; Haines-Young & Potschin, 2010; Potschin-Young et al., 2017). By definition, impacts analysed in an impact assessment occur at intersection between the biophysical and the human sphere. Because soil functions fully belong to the biophysical sphere, they are themselves not considered to be impacts. Rather, they are the biophysical basis for impacts such as ecosystem services and resource use efficiency.

However, the operationalisation of linkages between soil management, soil functions, and ecosystem services (Helming et al., 2018; Stavi et al., 2016; Schwilch et al., 2016) and resource use efficiency (Helming et al., 2018) remains a challenge. To address these linkages, a clearly defined terminology is imperative. Unfortunately, the hierarchical relationship between soil functions and ecosystem services is not as straight-forward as it should be, and there is an overlap in definitions as discussed by Baveye et al. (2016). Consequently soil function and soil related ecosystem service are often not clearly distinguished in current literature (an exception is e.g., Pulleman et al., 2012, investigating soil biodiversity). The overlap in definitions is particularly evident for the production of biomass (a soil function) and the provision of plant-based food, fibres and energy (an ecosystem services).

On the Impact Assessment Platform, we are focusing on soil-based ecosystem services and resource use in order to make the benefits of soils for human well-being visible and to inform sustainable soil

7. Learn more about sustainability impact assessments - Soil functions

management and policy. This also facilitates the integration of soil related impact assessments into a wider societal context. For the assessments we draw on biogeophysical information provided by the soil functions and their respective sub-functions. The individual linkages are highlighted in the sections on Ecosystem Services and Resource Use Efficiency.

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8. Conclusion & Outlook



8. Conclusion & Outlook

This handbook offers a guide to soil-related impact assessments. It provides, in a citable format, the information also presented on the Impact Assessment Platform². Both the handbook and the platform are designed to help identify the most sustainable soil management options. The focus on soils is due to soils' fundamental importance for meeting societal challenges such as food security, adaptation and mitigation of climate change, or biodiversity loss.

The updated version of the handbook now also contains lists of indicators for assessing impacts on ecosystem services and resource use efficiency on various spatial scales. While information on human health & soil health impacts has been added as well, we have not yet been able to compile comprehensive lists of indicators to support this. We hope to add these in the future editions. Likewise, novel developments such as the use of artificial intelligence and of large language models in soil-related impact assessments are topics we look forward to addressing.

This handbook details not only the process and challenges of conducting soil-related impact assessments, but also provides the Research Tool, which will guide the readers on how to conduct impact assessments by providing factsheets about different impact areas with brief descriptions of the respective topic. We attach these factsheets in the Appendix, so that readers can use and tailor it accordingly to their needs. In addition to that, factsheets are also available online on the Impact Assessment Platform.

The Handbook of Soil Related Impact Assessment is designed to be a living document. We envision the information presented therein to be continually updated and a substantial amount of new content to be added. On the online platform, this will be considered in the form of regular updates. For the handbook, new versions will be published at irregular intervals to account for these changes.

To conclude, we strongly encourage feedback from readers to improve both the handbook and the assessment platform, in order to make them a relevant practical tool to support soil related impact assessment.

² www.sustainability.zalf.de/impact-assessment-platform

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Appendix

A. Indicator Factsheets: Example



BONARES
Centre for Soil Research

Impact Area & Indicator Factsheet: **Resource Use Efficiency**

Definition:
$$\frac{\text{Aboveground Biomass}}{\text{Energy}}$$

Description

Benefit: This impact area refers to the total weight of all aboveground, harvestable parts of cultivated plants. It is suitable, where production is to be used for energy and other non-food purposes that can utilize the whole plant. Woody crops and forage crops will show high efficiencies in this impact area.

Resource: The use of energy usually refers to inputs of fuel or electricity. Solar irradiation is not considered because it is not a stressed resource, but also because the amount of this natural input would dwarf out all other energy inputs. Furthermore, energy from human or animal labour is usually not considered, although some studies explicitly include it (Arodudu et al., 2017).

Strength & weaknesses pertaining to measurement of this impact area

Biomass: Total amount aboveground biomass (production is generally easy to measure. However, the informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Energy: For this indicator, a number of standard values for agricultural management are readily available. LCA inventories even provide standard values for energy used in precursory processes. If the (fossil) energy input is used as a proxy for greenhouse gas emission, it is necessary to also consider the share of non-energy related GHG emission sources like drained soils or nitrous oxide from fertilizers.

Can be measured as

Biomass:

- yield, fresh weight [t]
- yield, dry matter weight [t]

The header provides an overview of the impact area to which the two indicators belong.

The definition shows the selected indicator for the impact assessment, in this example: aboveground biomass per energy

The description provides an overview of the benefits generated and the resources used by the indicator.

This section elaborates in detail on each selected indicator and their qualitative and quantitative measurements

Here, the metrics and units for the measurement of each indicator are given.

1



Impact Area & Indicator Factsheet: **Resource Use Efficiency**

Energy:

- total energy use [J]
- energy use from non-renewable sources [J]

The sample indicators show the categories of the input data that were used or recommended in research articles

Sample Indicators

Indicator values from	Survey	
Experiment or direct measurement	Statistical- or census data	
Expert assessment	Literature values	
Model	Maps or GIS	
Stakeholder participation	Not provided	

The tables provide an overview of different parameters (indicators) to measure the relationship between the two initially selected indicators. The measurement of the indicators is provided separately per spatial scale (field, regional, national, multinational and global)

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[275] Biomass/Energy	g * MJ ⁻¹	

Table 2: Regional Scale

Indicator	Unit	Indicator values from
^[190] Aboveground biomass/Absorbed photosynthetic active radiation	g * MJ ⁻¹	

Appendix – Ecosystem Services

B. Indicator Factsheets: Ecosystem Services

List of Factsheets (Ecosystem Services)

*CICES Class Name (Short version)	CICES Section	CICES Code
Cultivated terrestrial plants for nutrition	Provisioning (Biotic)	1.1.1.1
Cultivated terrestrial plants for materials	Provisioning (Biotic)	1.1.1.2
Cultivated terrestrial plants for energy	Provisioning (Biotic)	1.1.1.3
Genetic material from plants for breeding	Provisioning (Biotic)	1.2.1.2
Biotic remediation of waste	Regulation & Maintenance (Biotic)	2.1.1.1
Biotic filtration, sequestration and storage of waste	Regulation & Maintenance (Biotic)	2.1.1.2
Smell reduction	Regulation & Maintenance (Biotic)	2.1.2.1
Noise attenuation	Regulation & Maintenance (Biotic)	2.1.2.2
Visual screening	Regulation & Maintenance (Biotic)	2.1.2.3
Erosion control	Regulation & Maintenance (Biotic)	2.2.1.1
Mass movement control	Regulation & Maintenance (Biotic)	2.2.1.2
Hydrological cycle and flood control	Regulation & Maintenance (Biotic)	2.2.1.3
Wind protection	Regulation & Maintenance (Biotic)	2.2.1.4
Fire protection	Regulation & Maintenance (Biotic)	2.2.1.5
Pollination	Regulation & Maintenance (Biotic)	2.2.2.1
Nursery populations and habitats	Regulation & Maintenance (Biotic)	2.2.2.3
Pest control (including invasive species)	Regulation & Maintenance (Biotic)	2.2.3.1
Disease control	Regulation & Maintenance (Biotic)	2.2.3.2
Soil quality by weathering processes	Regulation & Maintenance (Biotic)	2.2.4.1
Soil quality by decomposition and fixing processes	Regulation & Maintenance (Biotic)	2.2.4.2
Chemical condition of freshwaters	Regulation & Maintenance (Biotic)	2.2.5.1
Chemical condition of salt waters	Regulation & Maintenance (Biotic)	2.2.5.2
Chemical composition of atmosphere and oceans	Regulation & Maintenance (Biotic)	2.2.6.1
Local regulation of air temperature and humidity	Regulation & Maintenance (Biotic)	2.2.6.2
Recreation through activities in nature	Cultural (Biotic)	3.1.1.1
Recreation through observation of nature	Cultural (Biotic)	3.1.1.2
Scientific interactions with nature	Cultural (Biotic)	3.1.2.1
Education and training interactions with nature	Cultural (Biotic)	3.1.2.2
Culture or heritage from interactions with nature	Cultural (Biotic)	3.1.2.3
Aesthetics from interactions with nature	Cultural (Biotic)	3.1.2.4
Symbolic meaning of nature	Cultural (Biotic)	3.2.1.1
Spiritual meaning of nature	Cultural (Biotic)	3.2.1.2
Existence value of nature	Cultural (Biotic)	3.2.2.1
Option or bequest value of nature	Cultural (Biotic)	3.2.2.2
Surface water for drinking	Provisioning (Abiotic)	4.2.1.1
Surface water for non-drinking purposes	Provisioning (Abiotic)	4.2.1.2
Groundwater for drinking	Provisioning (Abiotic)	4.2.2.1
Groundwater for non-drinking purposes	Provisioning (Abiotic)	4.2.2.2
Abiotic filtration, sequestration and storage of waste	Regulation & Maintenance (Abiotic)	5.1.1.3
Recreational interactions with abiotic nature	Cultural (Biotic)	6.1.1.1
Intellectual interactions with abiotic nature	Cultural (Biotic)	6.1.2.1
Symbolic and spiritual meaning of abiotic nature	Cultural (Biotic)	6.2.1.1
Non-use value of abiotic nature	Cultural (Biotic)	6.2.2.1

* CICES: Common International Classification of Ecosystem Services; shortened class names taken from Paul et al., 2019 (DOI: 10.1111/ejss.13022)

ECOSYSTEM SERVICES

Short name	Cultivated terrestrial plants for nutrition
CICES class name	Cultivated terrestrial plants (including fungi, algae) grown for nutritional purposes
CICES Section	Provisioning (Biotic)
CICES Class code	1.1.1.1

Brief Description

- Any crops and fruits grown for consumption by humans; food crops
- The ecological contribution to the growth of cultivated, land-based crops that can be harvested and used as raw material to produce food
- Does not include fodder and feed crops

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[35, 48] Yield	Not provided	 , 
[49] Yield	Mg * ha ⁻¹	
[13] Yield	kg * ha ⁻¹ * yr ⁻¹	
[26, 27] Yield	Mg * ha ⁻¹	
[1, 23] Grain yield	Mg * ha ⁻¹ * yr ⁻¹	
[38] Yield (maize, beans)	kg * ha ⁻¹ * harvest ⁻¹	

Appendix – Ecosystem Services

[59] Annual total crop yield (corn, soybean, wheat)	bushel * acre ⁻¹	
[37] Production of food	kg fresh weigh * m ⁻² * yr ⁻¹	
[1] Average grain yield over the last 50 years, applying a factor to account for changes in technology over time	t * ha ⁻¹	
[62] Total grass yield	t * ha ⁻¹	
[47] Forage: herbaceous biomass production	Not provided	
[47] Forage: herbaceous biomass cover	Not provided	
[59] Annual total forage crops and perennial grass yield (alfalfa, hay, pasture)	kg * ha ⁻¹	
[13] Production value of crop-pasture sequence	\$ * ha ⁻¹ * yr ⁻¹	
[45] Yield potential: Effect of organic and conventional farming are accounted for by using residuals of crop yields (after fitting farming system (conventional or organic) to yield quantities in t ha ⁻¹ , instead of reported yields.	t * ha ⁻¹	
[61] Biotic production	kg * m ⁻² * yr ⁻¹	
[24] Plant dry biomass per experimental pot	g	
[61] Net primary production (NPP)	kg dm * m ⁻² * yr ⁻¹	
[35] Land equivalent ratio	Not provided	
[33] Fruit yield	Mg * ha ⁻¹	
[38] Fruit yield	# * ha ⁻¹ * harvest ⁻¹	
[2] Coffee: number of fruiting nodes per hectare	# * ha ⁻¹	
[46] Grape yield: bunches per vine	#	
[46] Grape yield: bunch weight	g	
[46] Grape yield: yield per vine	kg	

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[46] Grape yield: 100 berries weight	g	
[35] Quality: Level of mycotoxins in crops	Not provided	 , 
[37] Concentration of trace metal elements relative to food quality standards	mg * kg of fresh matter ⁻¹	
[35] Percentage of polyunsaturated fatty acids in milk from cows (for fodder quality)	Not provided	 , 
[62] Total crude protein in yield	t * ha ⁻¹	 , 
[1] Grain protein content (winter wheat)	%	
[62] Crude protein concentration in grass yield (first cut, regrowth)	%	 , 
[33] Fruit quality: Fruit mass	g	 , 
[33] Fruit quality: Fruit size	mm	 , 
[33] Fruit quality: Fruit colour grade	Not provided	 , 
[33] Fruit quality: Titratable acidity	% of malic acid	 , 
[33] Fruit quality: Soluble solids concentration	%	 , 
[33] Fruit quality: Firmness	Newton or kg * cm ⁻²	 , 
[46] Grape quality: total soluble solids (sugar)	°Bx	
[46] Grape quality: titratable acidity	g * l ⁻¹	
[46] Grape quality	pH [-]	
[49] Mean individual fresh fruit mass (quality criterion for the market)	g * fruit ⁻¹	
[42] Combination of the following indicators to assess relative economic benefits of Forage Production: Site quality: <i>animal units supported per month and hectare, scaled to [0 -1]</i> Site opportunity: <i>distance to markets, scaled to [0 -1]</i> Complimentary inputs: <i>availability of water sources, scaled to [0 -1]</i>		 , 

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Reliability: <i>Risk of future service loss through urban development within a 3-mile radius, scaled to [0 -1]</i>		
[45] Use of bundles of indicator species that indicate agricultural landscapes with high value for crop yields identified for a certain region. Species may belong to different taxonomic groups	Not provided	
[67] Net primary productivity (NPP): average of total above and below ground dry mass at harvest over a 30-years simulation period	Mg / hectare * year)	
[68] Cropland yield	tons/hectare	
[68] 1000-grain weight	g	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[20] Index for average yield of common crops (e.g. corn, soybean and wheat). The index is calculated by dividing the observed value by a target value. Target values may be average or maximum values found in the region or empirical values from the literature. If the calculated index is higher than 1, it is set to one.	Index 0-1	 , 
[20] Index for alternate income opportunities provided by speciality (food) products. The index is calculated by dividing the observed value by a target value. Target values may be average or maximum values found in the region or empirical values from the literature. If the calculated index is higher than 1, it is set to one.	Index 0-1	 , 
[29] Accessibility: Share of land surface within 100 meters from road. Values were scaled [0-1]	%	
[29] Share of farmers with the expressed motivation of achieving a high economic value of the farm that indicates their production intensity. Values were scaled to [0-1]	%	
[29] Crop yield	t * ha ⁻¹ * yr ⁻¹	
[45] Yield potential: Effect of organic and conventional farming are accounted for by using residuals of crop yields (after fitting farming system (conventional or organic) to yield quantities in t * ha ⁻¹ , instead of reported yields.	t * ha ⁻¹	
[45] Use of bundles of indicator species that indicate agricultural landscapes with high value for crop yields identified for a certain region. Species may belong to different taxonomic groups.	Not provided	

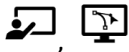
[56] Forage provision by pastures: calculated by a formula derived from expert assessment. Experts determined maximal DM yield, the selected up to 7 variables relevant for yield levels (soil pH, mean depth of a soil series, soil type, amount of phosphorous fertilizer applied, amount of lime applied, irrigation, altitude) and weighed them according to their importance.	$t\ dm\ *\ ha^{-1}\ *a^{-1}$	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[3] Production of edible crops	$kg\ *\ ha^{-1}\ *yr^{-1}$	
[6] Food and fodder from plants	$t\ *\ ha^{-1}\ *yr^{-1}$	
[10] Food crops output per unit sown area	$kg\ *\ ha^{-1}$	
[52] Average annual yield of all food crops in the region	$t\ *\ ha^{-1}$	
[51] Food production value: expert based index for ES provision by land cover class [1-5] multiplied by the area of land cover class [km ²] and literature-based monetary value of ES	$\$ \ * \ ha^{-1} \ * \ yr^{-1}$	
[51] Food production: expert based index for ES provision by land cover class [1-5] multiplied by the area of land cover class [km ²]	Index 1-5 * km ²	
[55] Grain production: total yield of rice, wheat, corn and soy	$t\ * \ ha^{-1}$	
[58] Grain output: total grain output from statistics, spatial allocation to grid cells of cultivated land based on the ratio of the cells' NDVI value relative to the NDVI of all cultivated land	$t\ * \ area^{-1} \ * \ yr^{-1}$	
[59] Annual total crop yield (corn, soybean, wheat)	bushel * acre ⁻¹	
[5] Average yield	$kg\ * \ ha^{-1}$	
[12] Yield	$kg\ * \ ha^{-1}\ * \ yr^{-1}$	
[12] Agricultural harvest/yield	100 kg grain equivalent unit (GEU) * ha ⁻¹ * yr ⁻¹	
[43] Agricultural yields	$t\ * \ ha^{-1}$	

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[41] Agricultural production; values were normalized [0-1] using benchmark values where available and observed values otherwise.	$t * ha^{-1}$	
[60] Total crop production per area (including agricultural and non-agricultural areas)	$t * ha^{-1} * yr^{-1}$	
[28] Crop production: values assigned are based on the land cover class. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) is adapted to the GlobCover dataset and used in this study.	Index 0-5	
[29] Crop yield (autumn wheat). Values were scaled [0-1]	$t * ha^{-1} * yr^{-1}$	
[44] Winter wheat yields	$t * ha^{-1}$	 , 
[55] Oil crop production: oil yield	$t * ha^{-1}$	
[25] Amount of forage	$Mg\ dm * ha^{-1}$	 , 
[59] Annual total forage crops and perennial grass yield (alfalfa, hay, pasture)	$kg * ha^{-1}$	
[15] Feed: Percentage of the area used for grazing	%	
[28] Fodder production: values assigned are based on land cover class. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) is adapted and used in this study.	Index 0-5	
[40] Fodder quantity: Above-ground biomass in mown grasslands	Not specified	
[40] Fodder quantity: Sward height	Not specified	
[40] Fodder quality: Lower Leaf tensile strength (Feed quality)	Not specified	
[40] Fodder quality: Abundance of legumes	Not specified	
[40] Fodder quality: Leaf crude protein content	Not specified	
[11] Total biomass production on agricultural land	$t\ DM$	
[53] Annual biomass yield	$t\ DM * ha^{-1} * yr^{-1}$	 , 
[53] Biomass stock in the landscape (crops and trees) at any one time	$t\ DM * ha^{-1}$	 , 
[14] Sum of arable land cells (GIS: 10m x 10m cells) within the two highest soil fertility classes	m^2	

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[21] Share of arable land use within a region	%	
[43] Acreage of farmland	ha	 , 
[50] Food production potential: total farmland area	ha * grid cell ⁻¹	
[31] Yield potential	1: very low - 5: very high	
[45] Yield potential: Effect of organic and conventional farming are accounted for by using residuals of crop yields (after fitting farming system (conventional or organic) to yield quantities in t ha ⁻¹), instead of reported yields.	t * ha ⁻¹	
[36] Soil fertility of arable fields: index based on water holding capacity, soil moisture and carbonate content.	Index 1-5	
[4] Area of agricultural ecosystems under sustainable management	Not provided	
[4] Organic farming	Not provided	
[7] Market value of products per hectare	\$ * ha ⁻¹ * yr ⁻¹	
[10] Gross farming output value per rural chemical fertilizer use	\$ * kg ⁻¹	
[10] Agricultural labor productivity [monetary agricultural output value/ agricultural labourer]	\$ * capita ⁻¹	
[19] Gross output of agricultural production (crops & livestock)	\$ * ha ⁻¹ * yr ⁻¹	 , 
[19] Net margin of agricultural production (including subsidies)	\$ * ha ⁻¹ * yr ⁻¹	 , 
[25] (Historical Analysis) Value of production: Sum of working hours needed to buy basic agric. commodities of 1 ha of land	h * ha ⁻¹	 , 
[29] Accessibility: Share of land surface within 100 meters from road that affects the level of agricultural production intensity. Values were scaled [0-1]	%	
[16] "Energy" of harvested crops	solar equivalent J	
[17] Biomass: Energy output from agricultural biomass	MJ * ha ⁻¹	

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^[18] Spatial mapping by stakeholders: stakeholders could place green stickers on a map to mark supply hotspots of this ecosystem service. Red stickers were used to mark locations where the supply of this service is declining. Two different sizes of stickers were used to represent a radius of 0.75 km or 1 km, respectively.	Index 0-5	
^[29] Share of farmers with the expressed motivation of achieving a high economic value of the farm. Values were scaled to [0-1]	%	
^[30] Direct goods provision (meat & grain): $NPP \times H \times Qf \times 1.5$; where NPP: Net primary production (0-1000), H: Harvest index by men (0-1), Qf: quality factor of primary outputs	Not provided	
^[45] Use of bundles of indicator species that indicate agricultural landscapes with high value for crop yields identified for a certain region. Species may belong to different taxonomic groups.	Not provided	
^[54] Percentage of the products of a land use class that is consumed by households as food	%	
^[54] Percentage of the products of a land use class that is used for animal feed	%	
^[54] Rating of current service provision per land use class by expert-stakeholders	Rating 0-10	
^[54] Rating of increases/decreases of service provision in scenarios, relative to the status quo	%	
^[64] Number of agricultural holdings	[#]	
^[64] Utilised agricultural area	[not provided]	
^[64] Area of arable land	[not provided]	
^[64] Production quality: agricultural area of PDO and/or PGI farms	[not provided]	
^[65] Mass of food crops/feed/livestock	tons/ (km ² * year)	
^[65] Calorific value of food crops/feed/livestock	MJ / (km ² * year)	

Table 4: National Scale

Indicator	Unit	Indicator values from
[11] Total biomass production on agricultural land	dm t	
[57] Yield	t * district ⁻¹ or t * nation ⁻¹	
[39] Yields of food and feed crops	t * ha ⁻¹ , t dm * ha ⁻¹ , MJ * ha ⁻¹	
[39] Grassland yields	t * ha ⁻¹ , t dm * ha ⁻¹ , MJ * ha ⁻¹	
[39] Food and feed crop area	ha	
[39] Grassland area	ha	
[21] Share of arable land use within a region	%	
[4] Area of agricultural ecosystems under sustainable management	Not provided	
[4] Organic farming	Not provided	
[8] Expert assessment for each land use, based on the indicators: yield/hectare; light, water, nutrient, warmth availability; disturbances, climate change (units not given)	very negative (-3) to very positive (+3)	
[9] Summed gross margin of production (area of crop multiplied by the gross margin per unit area)	\$	 , 
[34] Historical analysis: Production of "ecosystem service products" in a region: cereal crops, vegetables, hop, wine	Not provided	 , 
[34] Historical analysis: Occurrence of specific production areas in a region: orchards, orchard meadows, vineyards	Not provided	 , 
[34] Historical analysis: fodder or fodder used in a region: fodder-hay, fodder-oak	Not provided	 , 
[34] Historical analysis: Occurrence of specific livestock feeding system in a region: grazing, grazing/fodder-hay	Not provided	 , 
[22] Maximum stocking rate supported by pastures	Livestock units * ha ⁻¹	

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^[57] Quality: alpha-diversity of agricultural goods calculated as Pielou's (1969) J-index (evenness index): $J = (\text{sum of } (P_{it} * \ln(p_{it})) / \ln(S_t))$; where S_t is the number of crops recorded during year t , while p_{it} refers to the relative abundance of crop i [based on the crop's yield (weight)] during year t	[-]	
^[57] Quality: beta-diversity of agricultural goods calculated as Margalef's (1958) index of diversity (D): $D = S - 1 / \ln(N)$; where S is the number of species, and N represents the total yield (weight)	[-]	
^[57] Quality: gamma-diversity calculated from alpha- and beta diversity	[-]	
^[63] Downscaled crop production: Arable land cover classes are identified from satellite images. National crop production data is then downscaled to the respective land use classes, adjusting for crop cultivation intensity by assigning a weight of 1.25 to intensive of 0.66 to extensive croplands.	t/km ²	
^[63] Fodder production potential: Area of rainfed agricultural land [not provided]	Not provided	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
^[17] Biomass: Energy output from agricultural biomass	MJ * ha ⁻¹	
^[32] Crops: values assigned are based on Corine land cover classes. The matrix defined by Burkhard et al. (2009; DOI: 10.3097/LO.200915) was used and modified for the context of riparian zones.	Index 0-5	
^[32] Fodder: Values assigned are based on Corine land cover classes. The matrix defined by Burkhard et al. (2009; DOI: 10.3097/LO.200915) was used and modified for the context of riparian zones.	Index 0-5	
^[21] Share of arable land use within a region	%	
^[4] Area of agricultural ecosystems under sustainable management	Not provided	
^[4] Organic farming	Not provided	

Table 6: Global Scale

Indicator	Unit	Indicator values from

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^[4] Area of agricultural ecosystems under sustainable management	Not provided	
^[4] Organic farming	Not provided	
^[66] Yield	ton/km ²	

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Ecosystem Service	Cultivated terrestrial plants for materials
CICES class name	Fibres and other materials from cultivated plants, fungi, algae and bacteria for direct use or processing (excluding genetic materials)
CICES Section	Provisioning (Biotic)
CICES Class code	1.1.1.2

Brief Description

- Material from plants, fungi, algae or bacterial that can be used by humans, including use as animal feed
- The ecological contribution to the production of plants, fungi, algae or bacteria that can be harvested and used as animal feed or raw material for non-nutritional purposes

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[14] Yield	Not provided	
^[19] Biotic production	kg * m ⁻² * yr ⁻¹	
^[19] Net primary production (NPP)	kg dm * m ⁻² * yr ⁻¹	
^[20] Net primary productivity (NPP): average of total above and below ground dry mass at harvest over a 30-years simulation period	Mg / (hectare * year)	

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Table 2: Regional Scale

Indicator	Unit	Indicator values from
[6] Yield	$\text{kg} * \text{ha}^{-1} * \text{yr}^{-1}$	
[17] Annual biomass yield	$\text{t dm} * \text{ha}^{-1} * \text{yr}^{-1}$	 ,  , 
[3] Biomass for industrial use/processing	$\text{t} * \text{ha}^{-1} * \text{yr}^{-1}$	
[12] Provisioning of material: Modelled biomass yield	$\text{t dm} * \text{ha}^{-1} * \text{yr}^{-1}$ $\text{t dm} * \text{ha}^{-1}$	 ,  , 
[16] Timber production in the region	m^3	
[8] Crop production: assigned value depends on the land cover class. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
[8] Production of biochemicals and medicine: assigned value depends on the land cover class. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
[15] Cultivated medicinal plants: expert-based index for ES provision by land cover class [1-5] multiplied by area of land cover class [km2]	Index 1-5 * km^{-2}	 ,  , 
[15] Cultivated medicinal plants' value: expert-based index for ES provision by land cover class [1-5] multiplied by area of land cover class [km2] and literature-based monetary value of ES	$\$ * \text{ha}^{-1} * \text{yr}^{-1}$	 ,  , 
[17] Biomass stock in the landscape (crops and trees) at any one time	$\text{t dm} * \text{ha}^{-1}$	 ,  , 
[2] Annual growth rates of woody species representative for the land use type	$\text{t db} * \text{ha}^{-1}$	
[9] Yield potential	very low 1 to very high 5	
[7] Share of arable land use within each NUTS2 region	%	
[18] Percentage of the products of a land use class that is used for construction purposes (e.g., roofs, pillars)	%	
[1] Area of agricultural ecosystems under sustainable management	Not provided	

[1] Organic farming	Not provided	
[15] Agricultural inputs (e.g. materials, compost): expert based index for ES provision by land cover class [1-5] multiplied by area of land cover class [km ²]	Index 1-5 * km ⁻²	 ,  , 
[15] Agricultural inputs ¹ (Support for local production base e.g. materials for floating agricultural bed, compost and irrigation) value: expert based index for ES provision by land cover class [1-5] multiplied by area of land cover class [km ²] and literature-based monetary value of ES	\$ * ha ⁻¹ * yr ⁻¹	 ,  , 
[18] Rating of current service provision per land use class by expert-stakeholders	0-10	
[18] Rating of increases/decreases of service provision in scenarios, relative to the status quo	%	

Table 3: National Scale

Indicator	Unit	Indicator values from
[5] Total biomass production on agricultural land	t dm	
[13] Yields of fibre crops	t * ha ⁻¹ t dm * ha ⁻¹ MJ * ha ⁻¹	
[13] Yields of crops used for medicinal and cosmetic purposes	t * ha ⁻¹ t dm * ha ⁻¹ MJ * ha ⁻¹	
[13] Fibre crop area	ha	
[13] Area of crops used for medicinal and cosmetic purposes	ha	
[1] Area of agricultural ecosystems under sustainable management	Not provided	
[1] Organic farming	Not provided	
[4] Summed gross margin of production (area of crop multiplied by the gross margin per unit area)	\$	 , 
[11] Historical analysis: materials used in (farmhouse) buildings in a region: carrier material (e.g., straw, bendable wood), insulation (e.g., moss), stable wood, timber, weatherproof wood, weather protection roofing (e.g., straw,	Not provided	 , 

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reed), flowers, ropes (e.g., hemp), special wood used for handcrafts/ornamentation		
^[11] Historical analysis: materials used for agricultural purposes in a region: mulching, peat, plaggen, river sediments, hedges	Not provided	 , 

Table 4: Multinational Scale

Indicator	Unit	Indicator values from
^[1] Area of agricultural ecosystems under sustainable management	Not provided	
^[1] Organic farming	Not provided	
^[7] Biomass: Energy output from agricultural biomass	MJ * ha ⁻¹	
^[10] Crops: values for Corine land cover classes based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0-5	
^[10] Biochemicals & medicines: values for Corine land cover classes based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0-5	

Table 5: Global Scale

Indicator	Unit	Indicator values from
^[1] Area of agricultural ecosystems under sustainable management	Not provided	
^[1] Organic farming	Not provided	

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No.	Citation
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8*	Zhang ZM, Gao JF, Fan XY, Lan Y, Zhao MS (2017) Response of ecosystem services to socioeconomic development in the Yangtze River Basin, China. <i>Ecological Indicators</i> 72: 481-493. DOI: 10.1016/j.ecolind.2016.08.035
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^{5*} The impact area discussed on this factsheet is not a focus of the cited paper

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19*	Tang LL, Hayashi K, Kohyama K, Leon A (2018) Reconciling Life Cycle Environmental Impacts with Ecosystem Services: A Management Perspective on Agricultural Land Use. Sustainability 10(3): 630. DOI: 10.3390/su10030630
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Ecosystem Service	Cultivated terrestrial plants for energy
CICES class name	Cultivated plants (including fungi, algae) grown as a source of energy'
CICES Section	Provisioning (Biotic)
CICES Class code	1.1.1.3

Brief Description:

- Plant materials used as a source of energy
- The ecological contribution to the growth of cultivated crops that can be harvested and used as a source of biomass-based energy

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[3] Yield	kg * ha ⁻¹ * yr ⁻¹	
^[1] Biotic production	kg * m ⁻² * yr ⁻¹	
^[1] Net primary production (NPP)	kg dry matter * m ⁻² * yr ⁻¹	
^[2] Fuelwood production	volume * ha ⁻¹	
^[23] Net primary productivity (NPP): average of total above and below ground dry mass at harvest over a 30-years simulation period [Mg / hectare * year]	Mg / (hectare * year)	

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Table 2: Regional Scale

Indicator	Unit	Indicator values from
[6] Yield	kg * ha ⁻¹ * yr ⁻¹	
[10] Biomass yield	t dry matter * ha ⁻¹ * yr ⁻¹	 ,  , 
[18] Total biomass production on agricultural land	t dry matter	
[8] Yield potential	1: very low - 5: very high	
[4] Annual growth rates of woody species representative for a given land use type	t dry matter * ha ⁻¹	
[12] Share of arable land use within each NUTS2 region	%	
[9] Number of areas and total area covered by firewood species	#, ha	 ,  , 
[10] Biomass stock in the landscape (crops and trees) at any one time	t dry matter * ha ⁻¹	 ,  , 
[13] Energy output from agricultural biomass	MJ * ha ⁻¹	
[7] Energy (biomass): values are assigned to land cover classes. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0 - 5	
[11] Percentage of the products of a land use class that is used for fuel	%	
[11] Rating of current service provision per land use class by expert-stakeholders	0 - 10	
[11] Rating of increases/decreases of service provision in scenarios, relative to the status quo	%	
[9] Number of households using biogas plants	#	 ,  , 
[21] Biomass: Energy output from agricultural biomass	MJ * ha ⁻¹	
[22] Fraction of the plant component (e.g. sugar content) used for biofuel production	kg / (km ² * year)	

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Table 3: National Scale

Indicator	Unit	Indicator values from
[19] Yields of energy crops	t * ha ⁻¹ , t dry matter * ha ⁻¹ , MJ * ha ⁻¹	
[18] Total biomass production on agricultural land	t dry matter	
[19] Yields of grassland for energy production	t * ha ⁻¹ , t dry matter * ha ⁻¹ , MJ * ha ⁻¹	
[19] Production of biofuel, biodiesel, bioethanol	ktoe	
[12] Share of arable land use within each NUTS2 region	%	
[19] Energy crop area	ha	
[19] Grassland for energy area	ha	
[17] Summed gross margin of production (area of crop multiplied by the gross margin per unit area)	\$	 
[16] Expert assessment for each land use class based on the indicators: yield/hectare; light, water, nutrient, warmth availability; disturbances, climate change [units not given]	very negative (-3) to very positive (+3)	
[15] Historical analysis: Production of "ecosystem service products" in a region: firewood-hedges, firewood-trees, fuel-peat	Not provided	 

Table 4: Multinational Scale

Indicator	Unit	Indicator values from
[13] Biomass: Energy output from agricultural biomass	MJ * ha ⁻¹	
[20] Crops: Values were assigned to Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	

[20] Wood fuel: Values were assigned to Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	
[12] Share of arable land use within each NUTS2 region	%	

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^{6*} The impact area discussed on this factsheet is not a focus of the cited paper

No.	Citation
13	Mouchet MA, Paracchini ML, Schulp CJE, Sturck J, Verkerk PJ, Verburg PH, Lavorel S (2017) Bundles of ecosystem (dis)services and multifunctionality across European landscapes. <i>Ecological Indicators</i> 73: 23-28. DOI: 10.1016/j.ecolind.2016.00.026
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17	Holland RA, Eigenbrod F, Armsworth PR, Anderson BJ, Thomas CD, Heinemeyer A, Gillings S, Roy DB, Gaston KJ (2011) Spatial covariation between freshwater and terrestrial ecosystem services. <i>Ecological Applications</i> 21(6): 2034-2048. DOI: 10.1890/09-2195.1
18	Kirchner M, Schmidt J, Kindermann G, Kulmer V, Mitter H, Prettenthaler F, Rudisser J, Schuppenlehner T, Schonhart M, Strauss F, Tappeiner U, Tasser E, Schmid E (2015) Ecosystem services and economic development in Austrian agricultural landscapes - The impact of policy and climate change scenarios on trade-offs and synergies. <i>Ecological Economics</i> 109: 161-174. DOI: 10.1016/j.ecolecon.2014.11.005
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20	Clerici N, Paracchini ML, Maes J (2014) Land-cover change dynamics and insights into ecosystem services in European stream riparian zones. <i>Ecohydrology and Hydrobiology</i> 14(2): 107-120. DOI: 10.1016/j.ecohyd.2014.01.002
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Ecosystem Service	Genetic material from plants for breeding
CICES class name	Higher and lower plants (whole organisms) used to breed new strains or varieties
CICES Section	Provisioning (Biotic)
CICES Class code	1.2.1.2

Brief Description

Higher and lower plants that can be used to maintain populations or develop new varieties

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Regional Scale

Indicator	Unit	Indicator values from
^[1] Trends in genetic diversity of cultivated plants of major socioeconomic impact	Not provided	

Table 2: National Scale

Indicator	Unit	Indicator values from
^[1] Trends in genetic diversity of cultivated plants of major socioeconomic impact	Not provided	

Table 3: Multinational Scale

Indicator	Unit	Indicator values from
^[1] Trends in genetic diversity of cultivated plants of major socioeconomic impact	Not provided	

Table 4: Global Scale

Indicator	Unit	Indicator values from
^[1] Trends in genetic diversity of cultivated plants of major socioeconomic impact	Not provided	⊘

References

No.	Citation
1 ^{7*}	Feld CK, Sousa JP, da Silva PM, Dawson TP (2010) Indicators for biodiversity and ecosystem services: towards an improved framework for ecosystems assessment. Biodiversity and Conservation 19(10): 2895-2919. DOI: 10.1007/s10531-010-9875-0

^{7*} The impact area discussed on this factsheet is not a focus of the cited paper

Ecosystem Service	Biotic remediation of waste
CICES class name	Bio-remediation by micro-organisms, algae, plants, and animals
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.1.1.1

Brief Description:

Transformation of organic and inorganic materials, including fertilizers and pesticides, by plants, animals, bacteria, fungi or algae. Biotic remediation of wastes mitigates their harmful effects and reduces the costs of disposal by other means.

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[2] Organic waste used	kg * m ⁻² * yr ⁻¹	
[1] Natural attenuation/ clean groundwater: Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: I – Indicator value, i – variable i measured, i_{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log (\frac{i}{i_{max}})$ is subtracted from the sum instead of added. For this ES, variables were: -Soil organic matter [% dw] -Bacterial biomass [mg C *(g dw)⁻¹] -pH in KCl -Physiological diversity bacteria [bBiolog. CLPP: Hill's slope]	-	 , 

Appendix – Ecosystem Services

-Water soluble P (Pw) [mg * l ⁻¹] and extractable P (PAL) [mg * kg ⁻¹]		

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[3] Share of nitrogen retained during water passage between agricultural sub-catchment and sea. Values were scaled [0-1]	%	
[3] Share of farmers that express clearly a value and care for the health of the land. Values were scaled [0-1]	%	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[6] Nitrate leaching	kg * ha ⁻¹ * yr ⁻¹	
[5] Risk of nitrate leaching: exchange frequency of the soil water in the root layer. Infiltration rate divided by field capacity	%	
[3] Share of nitrogen retained during water passage between agricultural sub-catchment and sea. Values were scaled [0-1]	%	
[3] Share of farmers that express clearly a value and care for the health of the land. Values were scaled to [0-1]	%	
[4] Nutrient regulation: assigned values depend on the land cover class. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0 - 5	
[7] Share of riparian forest cover in 25 m buffer along rivers. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	%	
[7] Share of natural forest cover in municipality's surface. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	%	

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[8] Water purification and provision, calculated as: $W = NPP * (1 - VCNPP) * IC_s * S_{cf}$ With: W – water purification and provision, NPP – Net Primary Production calculated from NDVI-values and expressed on a relative scale set to [0 – 1000], VCNPP – coefficient of variation of NPP [0 – 1], IC_s – soil infiltration capacity [0 – 1], S_{cf} – slope average correction factor of the study area [0 – 1]	n/a	
[8] Waste purification, calculated as: $W = NPP * (1 - VCNPP) * I_w * O_w * 1.75$ With: NPP – Net Primary Production calculated from NDVI-values and expressed on a relative scale set to [0 – 1000], VCNPP – coefficient of variation of NPP [0 – 1], I_w – water input to the system (calculated as rainfall * (1-runoff coefficient) and scaled to a range of [0 – 1]), O_w – water bodies occupancy percentage and flat floodplain area [0 – 1]	n/a	
[11] Volume of purified water	m ³ / (km ² * year)	
[11] Mass of a specific nutrient retained	ton/ (km ² * year)	
[12] Area of undisturbed creek banks that serve as buffers to pesticide and fertilizer runoff	n/a	

Table 4: National Scale

Indicator	Unit	Indicator values from
[9] "Recycling capacity" of external nutrients: Amount of phosphorus in pig manure that can be spread on tillage soils and P deficient grassland soils.	t P * yr ⁻¹	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[10] Nutrient regulation: Values were assigned to Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 1	

References

No.	Citation
1	Rutgers M, van Wijnen HJ, Schouten AJ, Mulder C, Kuiten AMP, Brussaard L, Breure AM (2012) A method to assess ecosystem services developed from soil attributes with stakeholders and data of four arable farms. Science of the Total Environment 415: 39-48. DOI: 10.1016/j.scitotenv.2011.04.041

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2	Grard BJP, Chenu C, Manouchehri N, Houot S, Frascaria-Lacoste N, Aubry C (2018) Rooftop farming on urban waste provides many ecosystem services. <i>Agronomy for Sustainable Development</i> 38(1): 2. DOI: 10.1007/s13593-017-0474-2
3	Andersson E, Nykvist B, Malinga R, Jaramillo F, Lindborg R (2015) A social–ecological analysis of ecosystem services in two different farming systems. <i>Ambio</i> 44(1): 102-112. DOI: 10.1007/s13280-014-0603-y
4 ^{8*}	Zhang ZM, Gao JF, Fan XY, Lan Y, Zhao MS (2017) Response of ecosystem services to socioeconomic development in the Yangtze River Basin, China. <i>Ecological Indicators</i> 72: 481-493. DOI: 10.1016/j.ecolind.2016.08.035
5	Bastian O, Lupp G, Syrbe RU, Steinhäuser R (2013) Ecosystem services and energy crops - Spatial differentiation of risks. <i>Ekologia Bratislava</i> 32(1): 13-29. DOI: 10.2478/eko-2013-0002
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11	Gasparatos A, Romeu-Dalmau C, von Maltitz GP, Johnson FX, Shackleton C, Jarzebski MP, Jumbe C, Ochieng C, Mudombi S, Nyambane A, Willis K (2018) Mechanisms and indicators for assessing the impact of biofuel feedstock production on ecosystem services. <i>Biomass & Bioenergy</i> 114: 157-173. DOI: 10.1016/j.biombioe.2018.01.024
12	Groot JCJ, Yalaw SG, Rossing WAH (2018) Exploring ecosystem services trade-offs in agricultural landscapes with a multi-objective programming approach. <i>Landscape and Urban Planning</i> 172: 29-36. DOI: 10.1016/j.landurbplan.2017.12.008

^{8*} The impact area discussed on this factsheet is not a focus of the cited paper

Ecosystem Service	Biotic filtration, sequestration and storage of waste
CICES class name	Filtration/sequestration/storage/accumulation by micro-organisms, algae, plants, and animals
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.1.1.2

Brief Description:

- Filtering organic or inorganic substances from water or air, including filtering fertilizers and pesticides from water through the soil matrix
- The fixing storage of an organic or inorganic substance by plants, animals, bacteria, fungi or algae that mitigates its harmful effects and reduces the costs of disposal by other means

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Filtering and buffering: -Soil organic carbon [%] -Acetate esterase enzyme activity [not provided] -Bulk density [g * cm ⁻³] -Basal soil respiration [mg CO ₂ * g ⁻¹]	Not provided	
^[3] Soil carbon (0-100cm)	kg C * m ⁻²	
^[2] Natural attenuation/ clean groundwater: Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: I – Indicator value, i – variable i measured, i _{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables	-	 , 

Appendix – Ecosystem Services

Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log(\frac{i}{i_{max}})$ subtracted from the sum instead of added. For this ES, variables were: -Soil organic matter [% dw] -Bacterial biomass [mg C * g dw⁻¹] -pH in KCl -Physiological diversity bacteria [bBiolog. CLPP: Hill's slope] -Water soluble P (Pw) [mg * l⁻¹] and extractable P (PAL) [mg * kg⁻¹]		

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[4] Share of nitrogen retained during water passage between agricultural sub-catchment and sea. Values were scaled [0-1]	%	
[4] Share of farmers that express clearly a value and care for the health of the land. Values were scaled to [0-1]	%	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[10] Nitrate leaching	kg * ha ⁻¹ * yr ⁻¹	
[5] Nitrogen loss	kt N	
[8] Risk of nitrate leaching: exchange frequency of the soil water in the root layer. Infiltration rate divided by field capacity	%	
[4] Share of nitrogen retained during water passage between agricultural sub-catchment and sea. Values were scaled [0-1]	%	
[6] Mechanical filtration capacity: infiltration capacity, calculated as: $C = soil_{perm} * (1 - s)$ With: C – mechanical filtration capacity, soil_{perm} – soil permeability [cm * d⁻¹], s – share of anthropogenic surface sealing	cm * d ⁻¹	
[6] Physicochemical filtration capacity, calculated as: $C = CEC * (1 - s)$	cmol(+) * kg dm ⁻¹	

Appendix – Ecosystem Services

With: C – physicochemical filtration capacity, CEC – effective cation exchange capacity [cmol(+) * kg dm ⁻¹], s – share of anthropogenic surface sealing)		
^[9] Share of natural forest cover in municipality's surface. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	%	
^[4] Share of farmers that express clearly a value and care for the health of the land. Values were scaled to [0-1]	%	
^[7] Nutrient regulation: Assigned values depend on the land cover class. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0 - 5	
^[11] Water purification and provision, calculated as: $W = NPP * (1 - VCNPP) * IC_s * S_{cf}$ With: W – water purification and provision, NPP – Net Primary Production calculated from NDVI-values and expressed on a relative scale set to [0 – 1000], VCNPP – coefficient of variation of NPP [0 – 1], IC _s – soil infiltration capacity [0 – 1], S _{cf} – slope average correction factor of the study area [0 – 1]	-	
^[11] Waste purification, calculated as: $W = NPP * (1 - VCNPP) * I_w * O_w * 1.75$ With: NPP – Net Primary Production [0-1000], VCNPP – coefficient of variation of NPP [0-1], I _w – water input to the system [0-1], O _w – water bodies occupancy percentage and flat floodplain area [0-1]	-	
^[13] Volume of purified water	m ³ / (km ² * year)	
^[13] Mass of a specific nutrient retained	ton/ (km ² * year)	
^[14] Area of undisturbed creek banks that serve as buffers to pesticide and fertilizer runoff	n/a	

Table 4: Multinational Scale

Indicator	Unit	Indicator values from
^[12] Nutrient regulation: Values were assigned for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	

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14	Groot JCJ, Yalew SG, Rossing WAH (2018) Exploring ecosystem services trade-offs in agricultural landscapes with a multi-objective programming approach. <i>Landscape and Urban Planning</i> 172: 29-36. DOI: 10.1016/j.landurbplan.2017.12.008

^{9*} The impact area discussed on this factsheet is not a focus of the cited paper

Ecosystem Service	Smell reduction
CICES class name	Smell reduction
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.1.2.1

Brief Description

- Reduction of smell
- The reduction in the impact of odors on people that mitigates its harmful or stressful effect

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: National Scale

Indicator	Unit	Indicator values from
^[1] Hedgerow length	Not specified	

References

No.	Citation
1	Maes J, Liqueste C, Teller A, Erhard M, Paracchini ML, Barredo JI, Grizzetti B, Cardoso A, Somma F, Petersen JE, Meiner A, Gelabert ER, Zal N, Kristensen P, Bastrup-Birk A, Biala K, Piroddi C, Egoh B, Degeorges P, Fiorina C, Santos-Martín F, Naruševičius V, Verboven J, Pereira HM, Bengtsson J, Gocheva K, Marta-Pedroso C, Snäll T, Estreguil C, San-Miguel-Ayán J, Pérez-Soba M, Grêt-Regamey A, Lillebø AI, Malak DA, Condé S, Moen J, Czucz B, Drakou EG, Zulian G, Lavalle C (2016) An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. Ecosystem Services 17: 14-23. DOI: 10.1016/j.ecoser.2015.10.023

Ecosystem Service	Noise attenuation
CICES class name	Noise attenuation
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.1.2.2

Brief Description

- Reducing noise, e.g. by planting hedges
- The reduction in the impact of noise on people that mitigates its harmful or stressful effect

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: National Scale

Indicator	Unit	Indicator values from
^[1] Hedgerow length	Not specified	

References

No.	Citation
1	Maes J, Liqueste C, Teller A, Erhard M, Paracchini ML, Barredo JI, Grizzetti B, Cardoso A, Somma F, Petersen JE, Meiner A, Gelabert ER, Zal N, Kristensen P, Bastrup-Birk A, Biala K, Piroddi C, Egoh B, Degeorges P, Fiorina C, Santos-Martín F, Naruševičius V, Verboven J, Pereira HM, Bengtsson J, Gocheva K, Marta-Pedroso C, Snäll T, Estreguil C, San-Miguel-Ayanz J, Pérez-Soba M, Grêt-Regamey A, Lillebø AI, Malak DA, Condé S, Moen J, Czúcz B, Drakou EG, Zulian G, Laval C (2016) An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. Ecosystem Services 17: 14-23. DOI: 10.1016/j.ecoser.2015.10.023

Ecosystem Service	Visual screening
CICES class name	Visual screening'
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.1.2.3

Brief Description

- Screening unsightly things, e.g. by planting hedges
- Reduction in the visual impact of human structures on people that mitigates its harmful or stressful effect

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: National Scale

Indicator	Unit	Indicator values from
^[1] Hedgerow length	Not specified	

References

No.	Citation
1	Maes J, Liqueste C, Teller A, Erhard M, Paracchini ML, Barredo JI, Grizzetti B, Cardoso A, Somma F, Petersen JE, Meiner A, Gelabert ER, Zal N, Kristensen P, Bastrup-Birk A, Biala K, Piroddi C, Egoh B, Degeorges P, Fiorina C, Santos-Martín F, Naruševičius V, Verboven J, Pereira HM, Bengtsson J, Gocheva K, Marta-Pedroso C, Snäll T, Estreguil C, San-Miguel-Ayanz J, Pérez-Soba M, Grêt-Regamey A, Lillebø AI, Malak DA, Condé S, Moen J, Czúcz B, Drakou EG, Zulian G, Lavalle C (2016) An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. Ecosystem Services 17: 14-23. DOI: 10.1016/j.ecoser.2015.10.023

Ecosystem Service	Erosion control
CICES class name	Control of erosion rates
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.1.1

Brief Description

- Reducing soil erosion
- Reducing the loss of material through the stabilizing effects of plants and animals, e.g. earthworms increasing aggregate stability. Erosion control reduces the loss of valuable topsoil and the associated effects of carbon loss, pollution and human health risks (dust)

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Sediment lost by erosion	t * yr ⁻¹	
^[8] Soil loss	Not provided	
^[9] Annual total sediment yield in runoff	t * ha ⁻¹	
^[2] Erosion regulation potential	t * ha ⁻¹ * yr ⁻¹	
^[5] Erosion by water	t * ha ⁻¹ * yr ⁻¹	
^[6] Erosion by water	t * ha ⁻¹ * yr ⁻¹	
^[5] Erosion by wind (measured with DIN 19706 method)	-	
^[6] Erosion by wind (measured with DIN 19706 method)	-	

Appendix – Ecosystem Services

[3] Change in soil height, measured by means of pins hammered into the soil at the beginning of measurements	mm	
[7] Bare soils	Not provided	
[3] Soil mulch cover (non-living vegetative biomass)	kg * ha ⁻¹	
[7] Litter cover	Not provided	
[7] Biological soil cover	Not provided	
[4] Drainage	mm * yr ⁻¹	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[11] Prevention of water erosion: rate of water infiltration into the soil	mm * ha ⁻¹	
[12] Bank stability: Share of irrigation channel bank considered stable (not vertical, un-vegetated or eroded), expressed as a four-level index	%, Index: poor-fair-good-excellent	
[12] Vegetation cover, expressed as a four-level index	%, Index: poor-fair-good-excellent	
[10] Index for share of fields with continuous living cover. The index is calculated by dividing the observed value by a target value. Target values may be average or maximum values found in region or empirical values from literature. If the calculated index is higher than 1, it is set to one.	Index 0 - 1	 , 
[10] Index for share of farm fields protected by conservation structures such as field buffers. The index is calculated by dividing the observed value by a target value. Target values may be average or maximum values found in region, or empirical values from literature. If the calculated index is higher than 1, it is set to one.	Index 0 - 1	 , 

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[35] Annual average erosion	kg * ha ⁻¹ * yr ⁻¹	
[25] Erosion rate calculated by modified Universal-Soil-Loss-Equation (USLE)	t * ha ⁻¹ * yr ⁻¹	
[31] Annual soil erosion, assessed using the Revised Universal Soil Loss Equation (RUSLE)	t soil * ha ⁻¹ * yr ⁻¹	

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[20] Modelled erosion, calculated with LANCA model (simplified Universal Soil Loss Equation (USLE)) and with Revised Universal Soil Loss Equation (RUSLE)	$t \text{ soil} * ha^{-1} * yr^{-1}$	
[32] Potential soil erosion level calculated with Revised Universal Soil Loss Equation (RUSLE)	$t * ha^{-1} * yr^{-1}$	 , 
[36] Soil erosion by water, calculated with Revised Universal Soil Loss Equation (RUSLE)	$t \text{ soil} * ha^{-1} * yr^{-1}$	
[9] Annual total sediment yield in runoff	$t * ha^{-1}$	
[35] Annual average sediment in rivers	$t * yr^{-1}$	
[35] Annual average sediment retention	$kg * ha^{-1} * yr^{-1}$	
[19] Sediment retention, calculated with InVEST model based on universal soil loss equation and the land use/land cover specific sediment removal efficiencies	$Mg * ha^{-1}$	
[35] Annual sediment retention to reservoirs	$kg * yr^{-1}$	
[27] Modelled rates of water caused erosion and accumulation for a 10-year rainfall event	$t * ha^{-1}$	
[23] Erosion control: Difference between the calculated erosion (using the Universal Soil Loss Equation) for a situation of bares soils and the current situation (considering the factors C: land cover management and P: supporting practices)	$kg * m^{-2}$	
[28] Erosion control: Difference between the calculated erosion (using the InVEST Model based on the Universal Soil Loss Equation) in a model run that accounts for land cover and land management and in one that does not	$t * ha^{-1}$	
[33] Erosion control: Difference between the calculated erosion (using the InVEST Model based on the Revised Universal Soil Loss Equation) in a model run that accounts for land cover and land management and in one that does not	$t * ha^{-1}$	
[15] Erosion control: Difference between the calculated erosion rates (using the Universal Soil Loss Equation) with- and without considering land cover	$t \text{ soil} * \text{pixel area}^{-1} \text{ (e.g., } 30 \text{ m} * 30 \text{ m)}$	
[34] Soil conservation calculated by RUSLE equation: $A = R * K * LS * (1 - C * P)$ With: A – soil conservation, R – rainfall erosivity factor, K – soil erodibility factor, LS – slope length and steepness factor, C – cover and management factor, P – conservation practice factor	$t * ha^{-1} * yr^{-1}$	
[14] Soil erosion protection: C-factor in the Universal Soil Loss Equation (USLE)	-	
[17] Soil erosion protection: C-factor in the Universal Soil Loss Equation (USLE)	-	

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[29] Soil formation and erosion prevention: expert-based index for ES provision by land cover class [1-5] multiplied by the area of land cover class	km ²	 ,  , 
[29] Soil formation and erosion prevention value: expert-based index for ES provision by land cover class [1-5] multiplied by the area of land cover class and a literature-based monetary value of ES	km ² , \$ * ha ⁻¹ * yr ⁻¹	 ,  , 
[30] Wind erosion: Expert-/stakeholder rating of how much of erosion control can be provided by a landscape (represented by a land use map), using a 6-point Lickert-scale	none - highest capacity	
[30] Wind erosion: Expert/stakeholder rating based on pairwise comparisons of landscapes (represented by land use maps) in an Analytical Hierarchical Process (AHP). Experts select the landscape with higher capacity for providing erosion control and rate the difference between the two landscapes	1: equal capacity - 9: absolute preference of one landscape	
[18] "Emergy" of topsoil loss, calculated as: $E = L_{OM} * T_{OM} + L_N * T_N + L_P * T_P + L_K * T_K$ With: E – Emergy, L _{OM} – loss of topsoil organic matter, T _{OM} – transformity of organic matter, L _N – loss of topsoil nitrogen, T _N – transformity of nitrogen, L _P – loss of topsoil phosphorus, T _P – transformity of phosphorus, L _K – loss of topsoil potassium, T _K – transformity of potassium	seJ	
[35] Number of prevented hazards	# * yr ⁻¹	
[26] Area affected by erosion	ha	 ,  , 
[24] Share of areas without erosion problems relative to municipality's surface. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	%	
[13] Erosion control capacity: values are assigned for different land cover classes. Index values were taken from Burkhard et al. (2012, DOI:10.1016/j.ecolind.2011.06.019)).	Index 0 - 5	
[21] Erosion regulation: values are assigned for different land cover classes. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0 - 5	
[16] Relative erosion sensitivity (based on modified Universal Soil Loss Equation (USLE)), considering soil type, slope, land use and distance to water	-	
[22] Resistance to soil erosion from water, calculated using the Universal Soil Loss Equation (USLE): $Resistance = USLE\ K\_factor\ (soil) * USLE\ S\_factor\ (slope)$		
[22] Resistance to soil erosion from wind	1: very low - 5: very high	

[32] Rating of current service provision per land use class by expert-stakeholders	Rating 0 - 10	 , 
[32] Rating of increases/decreases of service provision in scenarios, relative to the status quo	%	 , 
[37] Soil protection $SP = NPP * (1 - VC_{NPP}) * (1 - S_{cf}) * 1.5$ With: NPP – Net Primary Production calculated from NDVI-values and expressed on a relative scale set to [0 – 1000], VC_{NPP} – coefficient of variation of NPP [0 – 1], S_{cf} – slope average correction factor of the study area [0 – 1].	Not specified	
[38] Soil protection factor. Region-specific and land use specific protection factor. Only areas with erosion risk > 2 t * ha ⁻¹ (calculated using the Universal Soil Loss Equation) are considered.	Not specified	 , 
[35] Natural barriers against floods (dunes, mangroves, wetlands, coral reefs)	ha	
[35] Vegetation cover	%	
[35] Conservation of river banks	km	
[43] Amount of retained soil per unit area	tons / (km ² * year)	

Table 4: National Scale

Indicator	Unit	Indicator values from
[41] Calculated current water Erosion (using modified Universal Soil Loss Equation (USLE))	t * ha ⁻¹ * yr ⁻¹	 , 
[40] Soil erosion risk	Not specified	
[41] Avoided water Erosion: Difference in calculated erosion (modified Universal Soil Loss Equation (USLE)) between the real situation and a hypothetical situation without vegetative cover	t * ha ⁻¹ * yr ⁻¹	 , 
[41] Water Erosion avoided due to small scale structures in arable land: Difference in calculated erosion (modified Universal Soil Loss Equation (USLE)) between a situation without small scale structures and a situation where erosive slope length is reduced by small scale structures	t * ha ⁻¹ * yr ⁻¹	 , 
[40] Percentage of soil cover in cropland (conservation tillage (low tillage), zero tillage, winter crops, cover crop or intermediate crop, plant residues)	%	
[40] Density of hedgerows	Not specified	
[40] Percentage of grassland cover	%	

Appendix – Ecosystem Services

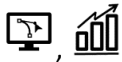
[41] Share of organic cultivation in a federal state's arable land	%	
[39] Expert assessment of erosion control for each land use class	very negative (-3) to very positive (+3)	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[42] Erosion regulation: values assigned for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	

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Ecosystem Service	Mass movement control
CICES class name	Buffering and attenuation of mass movement
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.1.2

Brief Description

- Reducing the frequency and/or severity of landslides and avalanches that would otherwise harm people and/or their property
- The reduction in the speed of movement of solid material by virtue of the stabilizing effects of plants and animals (e.g. earthworms increase aggregate stability) that mitigates or prevents damage to human or human health

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Regional Scale

Indicator	Unit	Indicator values from
^[1] Spring litter in un-mown plots (alpine grasslands; high amounts of litter increase risk of snow gliding)	Not specified	
^[2] Number of landslide per year	#	 ,  , 
^[2] Area affected by landslide	ha	
^[3] Supply of landside regulation, based on: 1.) deriving a formula for calculating landslide risk by using an Analytic Hierarchy Process (AHP) 2.) creating an ES potential map (high risk= low potential, low risk = high potential) (Expert assessment was used to assign discrete values for each class of variables in AHP process and mapping of ES potential).	Index 0 - 5	

Table 2: National Scale

Indicator	Unit	Indicator values from
^[4] Expert assessment for each land use class based on the indicators: soil cover; trees; landslides; flooding; debris flow (units not given)	very negative (–3) to very positive (+3)	
^[5] Density of hedgerows	Not specified	

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Ecosystem Service	Hydrological cycle and flood control
CICES class name	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.1.3

Brief Description

- Regulating the flow of water in our environment
- Living organisms regulate the speed of water flows through ecosystems, improving the storage of water in soils, reducing the frequency or severity of floods and thereby reducing the risk of damage to human property or health

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Water (in)filtration capacity	$\text{m}^3 * \text{m}^{-2} * \text{yr}^{-1}$, $\text{mol} * \text{m}^{-2}$	
^[7] Infiltration: unsaturated hydraulic conductivity	$\text{mm} * \text{h}^{-1}$	 , 
^[5] Water infiltration into the soil (using Beerkan test)	$\text{mm} * \text{h}^{-1}$	
^[7] Deep percolation	mm	 , 
^[4] Drainage below the bottom of the root zone (in the dryland context; low drainage is desirable to avoid salinization)	$\text{mm} * \text{yr}^{-1}$	
^[6] Water drainage	$\text{mm} * \text{yr}^{-1}$	 , 

[10] Modelled drainage	mm * yr ⁻¹	 , 
[15] Water drainage	mm * yr ⁻¹	
[14] Water loss through drainage and runoff	mm * yr ⁻¹	
[7] Hortonian runoff	mm during growing season	 , 
[18] Flood regulation: annual number of days with runoff>10mm	#	
[17] Quantity: Share of rain water that evapotranspires on site (without creating runoff) (urban agriculture)	%	
[2] Water movement and availability: -Soil porosity [%] -Water-filled pore space [%] -Electrical conductivity [$\mu\text{S cm}^{-1}$] -pH [-]		
[2] Accommodate water entry: -Stable aggregate index [not provided] -Bulk density [g * cm^{-3}] -Earthworms [not provided]		
[5] Soil macroporosity (0 - 10 cm)	Cm	
[3] Soil water holding capacity (0-20 cm), calculated by sample drying & rewetting	g H ₂ O * g soil ⁻¹	
[11,12] WHC water holding capacity in topsoil (0-20cm)	%	
[16] Water holding capacity	%	
[13] Available Water Capacity (AWC); the amount of water held between conventional field capacity and wilting point, estimated according to texture and organic matter up to the rooting depth, excluding stones	%	
[6] Mean water content in different soil depths	g H ₂ O * 100 g dry soil ⁻¹	 , 
[14] Soil moisture in topsoil (0-5 cm) and at rooting depth (5-60 cm)	cm * cm ⁻³ , %	
[10] Soil water content on a specific date (July, the most water-limited part of the growing season)	g H ₂ O * g soil ⁻¹	 , 
[15] Mean soil humidity in topsoil (0-30cm) during observation period	% dm	
[5] Plant-available soil water (0 - 10 cm)	cm	

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[7] Water stress	prop. of days	 , 
[13] Soil Aridity Index (SAI); average number of days with dry soil in the upper soil layer where roots accumulate	d * yr ⁻¹	
[17] Water Quality: Weighted average concentration of TOC, TIC, NO ⁻³ , and NH ⁺⁴ in leachate (Retention of elements and molecules, leaching, biodegradation)	mg * l ⁻¹	
[8] Soil hydrological functions indicator based on a principal component analysis (PCA) of 12 variables assessed at 0-10 cm and 10-20 cm. Variables included: -Volumetric and gravimetric moisture content -Micro (<0.03 µm), meso (0.03–3 µm) and macro (>3 µm) porosity -Plant available water retained between water holding capacity and wilting point -Aggregate stability, bulk density, resistance to vertical penetration, shear strength resistance, Variables with significant contribution (>50 % of the maximum value) to either of the first two principal component axes were selected. Their contribution to PCA axes 1 and 2 multiplied by the overall variability explained by each PCA axis. These weighted factors were summed up and scaled to a range of 0.1 - 1.0.	-	
[9] Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: I – indicator value, i – variable i measured, i_{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log (\frac{i}{i_{max}})$ is subtracted from the sum instead of added. For this ES, variables were: -Soil organic matter [% dw] -Earthworm abundance [# * m⁻²] -Bacterial biomass [mg C * g dw⁻¹] -Number of earthworm taxa [-]	-	 , 

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[20] Rate of water infiltration into the soil	mm * ha ⁻¹	
[19] Four-level index based on the number of days streamflow is extended through seepage losses in channel irrigation systems (which recharge groundwater aquifers).	Index poor-fair-good-excellent	

[19] Flood protection: Four-level index based on share of water lost through seepage in open channel irrigation [%]. The higher the value, the better.	Index poor-fair-good-excellent	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[21] Water holding capacity	$m^3 * ha^{-1}$	 , 
[22] Water retention capacity	$m^3 * ha^{-1}$	
[30] Soil water storage capacity. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	mm	
[22] Runoff coefficient	-	
[23] Mitigated runoff: difference between total input precipitation by storm event and runoff	mm, $m^3 * km^{-2}$	
[23] Mitigated runoff: percentage of mitigated flood water (intercepted, absorbed, or detained flood water, divided by total precipitation) multiplied by the number of beneficiaries at risk of flooding	-	
[23] Mitigated runoff: runoff Curve Number (CN). The CN determines the approximate amount of direct runoff from a rainfall event in a particular area.	Range 30 - 100	
[18] Inverse indicator. Flood regulation: annual number of days with runoff > 10mm	#	
[24] Flood regulation: (runoff) curve number	-	
[36] Number of extreme (runoff) events	$\# * yr^{-1}$	
[22] Groundwater recharge	$m^3 * ha^{-1}$	
[35] Baseflow regulation, calculated using InVEST model	Not provided	
[22] Evapotranspiration	mm	
[22] Share of sealed soils	%	
[30] Soil water infiltration capacity. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	$cm * h^{-1}$	
[37] Water infiltration: annual subsurface water flow	$mm * y^{-1}$	

Appendix – Ecosystem Services

[31] Water yield: rainfall - actual annual evapotranspiration (using InVEST's Hydropower Water Yield model)	$\text{m}^3 * \text{yr}^{-1} * \text{grid cell}^{-1}$	
[25] Moderation of extreme events: Percentage of the total area of the region that contains native vegetation	%	
[27] Water regulation index. The index is based on soil physical characteristics, including volumetric and gravimetric moisture content, porosity, plant available water (based on water retention curves), aggregate stability, bulk density, penetration resistance and shear strength resistance.	Index 0.1 - 1	
[32] Water flow management: expert-based index for ES provision by land cover class [1-5], multiplied by the area of the land cover class	km^2	 ,  , 
[32] Water flow management value: expert-based index for ES provision by land cover class [1-5], multiplied by the area of the land cover class and a literature-based monetary value of the ecosystem service	$\text{km}^2, \$ * \text{ha}^{-1} * \text{yr}^{-1}$	 ,  , 
[27] Bio-indicator: Presence of specific ant species is used as an indicator for high, medium or low provision of this ecosystem service. Suitable indicator species must first be identified by correlation between presence of species and ecosystem service provision.	-	
[26] Flood regulation score: preventative and mitigation functions of vegetation and soils. Score calculated after Nedkov and Burkhard (2012), using the parameters: interception, infiltration, surface runoff and peak flow.	Score 0 - 100	 , 
[28] Flood protection: Values are assigned based on land cover classes. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0 - 5	
[29] Reduction of flash flood risk: total area of flooded buildings (relative to total catchment area) in a 100-year rainfall event.	%	 , 
[32] Flood control: expert-based index for ES provision by land cover class [1-5] multiplied by the area of the land cover class	km^2	 ,  , 
[32] Flood control value: expert-based index for ES provision by land cover class [1-5], multiplied by the area of the land cover class and a literature-based monetary value of the ecosystem service	$\text{km}^2, \$ * \text{ha}^{-1} * \text{yr}^{-1}$	 ,  , 
[33] Flood regulation: Expert-/stakeholder rating of how much of this ES can be provided by a landscape (represented by a land use map), using a 6-point Lickert-scale	Scale none - highest capacity	
[33] Flood regulation: Expert-/stakeholder rating based on pairwise comparisons of landscapes (represented by land use maps) in an Analytical Hierarchical Process (AHP). Experts select the landscape with higher capacity for providing this ES and rate the difference between the two landscapes	Rating 1: equal capacity - 9: absolute preference of one landscape	
[34] Flood regulation, calculated as: maximum number of annual flood events in time series - average number of annual	#	

Appendix – Ecosystem Services

flood events during time series. Only events where damages exceed a certain cost are counted.		
[38] Flood regulation supply Indicator: normalized total river discharge within five days after a modelled precipitation event. Calculated with the hydrological model STREAM	Index 0 - 1	
[40] Flood risk: expected cost of temporary disruption of transport infrastructure	\$ * ha ⁻¹ * yr ⁻¹	 , 
[40] Flood risk: expected cost damages to residential properties	\$ * ha ⁻¹ * yr ⁻¹	 , 
[39] Disturbance control, calculated as: $DC = I_W * O_W * 1.25$ With: DC – Disturbance control, I _w – water input to the system, calculated as rainfall * (1–runoff coefficient) and scaled to a range of [0 – 1000], O _w – water bodies occupancy percentage and flat floodplain area [0 – 1]	-	
[41] Flood regulation supply: continuous index, based on the variability of the peak discharge at the outlet of a catchment in dependence of land use and soil distribution	-	
[40] Floodplain capacity to store water: time to fill storage capacity (T) [days], calculated as: $T = \frac{S}{86400 * Q_{med}}$ With: T – Index of flood storage [d], S – Storage volume [m ³], Q _{med} – Median annual flood [m ³ * s ⁻¹]	d	 , 
[40] Space for water (in floodplains): theoretical proportion of floodplain area flooded annually, calculated by dividing the area of the indicative floodplain by the total area of the floodplain, and multiplying by the annual flood probability.	-	 , 
[42] Flood regulation supply index. The index represents the capacity of catchments to retain precipitation as a function of a catchments' topography and hydrology, water holding capacity of the soil, and land use.	0 - 1	
[45] Volume of irrigation water	n/a	
[45] Volume of surface water used for irrigation	n/a	
[45] Volume of groundwater used for irrigation and in restoration consortiums	n/a	

Table 4: National Scale

Indicator	Unit	Indicator values from

Appendix – Ecosystem Services

[43] Water quantity: Expert assessment for each land use class, based on the indicator: above-ground runoff [not provided]	very negative (-3) to very positive (+3)	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[43] Flood regulation supply: continuous index, based on the variability of the peak discharge at the outlet of a catchment in dependence of land use and soil distribution	0 - 1	
[44] Flood protection: Values are assigned to Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	

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Ecosystem Service	Wind protection
CICES class name	Wind protection
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.1.4

Brief Description

- Protecting people and/or their property from strong winds
- Reduction in the speed of air movement by plants that mitigates or prevents potential damage to human or human health

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Regional Scale

Indicator	Unit	Indicator values from
^[3] Storm protection: expert-based index for ES provision by land cover class [1-5] multiplied by the area of the land cover class [km ²]	Index 1-5 * km ⁻²	 ,  , 
^[3] Storm protection value: expert-based index for ecosystem service provision by land cover class [1-5], multiplied by the area of the land cover class [km ²] and a literature-based, monetary value of the ecosystem service	\$ * ha ⁻¹ * yr ⁻¹	 ,  , 

Table 2: National Scale

Indicator	Unit	Indicator values from
^[1] Historical analysis: storm protection in a region: occurrence of trees and hedges planted around houses as storm protection	Not provided	 , 
^[2] Storm protection: Density of hedgerows	Not specified	

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Short name	Fire protection
CICES class name	Fire protection
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.1.5

Brief Description

- Protecting people and/or their property from fire
- The reduction in the frequency, intensity, or speed of spreading of fires by virtue of the presence of plants and animals that mitigates or prevents potential damage to human property or human health

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Property loss due to fires, calculated as a combination of: • Site quality: population within 3 mile radius [0 - 1] • Site opportunity: value of property at risk [0 - 1] • Complementary inputs: is the site within or adjacent to a major urban area [0 - 1] • Reliability: Risk of future service loss through urban development within 3 mile radius [0 - 1]	Index [0 - 1]	 , 

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[2] Fire risk index. The index is based on the vegetations vulnerability to wildfires, climatic conditions, and topography.	Index [-]	

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Table 4: National Scale

Indicator	Unit	Indicator values from
[3] (Historical analysis) Protection against fires from lightning strikes: occurrence of big trees near houses that were able to attract lightning and thereby protect the houses	[not provided]	 , 

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[2] Fire risk index. The index is based on the vegetations vulnerability to wildfires, climatic conditions, and topography.	Index [-]	

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3	Dittrich A, von Wehrden H, Abson DJ, Bartkowski B, Cord AF, Fust P, Hoyer C, Kambach S, Meyer MA, Radzevičiūtė R, Nieto-Romero M, Seppelt R, Beckmann M (2017) Mapping and analysing historical indicators of ecosystem services in Germany. Ecological Indicators 75: 101-110. DOI: 10.1016/j.ecolind.2016.12.010

Ecosystem Service	Pollination
CICES class name	Pollination (or 'gamete' dispersal in a marine context)
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.2.1

Brief Description

- Pollinating fruit trees and other plants
- The fertilization of crops by animals that maintains or increases the abundance and/or diversity of plant species that people use or enjoy, or benefit from

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Pollen transported by pollinators	kg * yr ⁻¹	
^[11] Abundance and diversity of pollinators	Not provided	 , 
^[15] Abundance of bumblebees	Not provided	
^[15] Plant Simpson diversity as an indicator for bumblebee abundance.	Not provided	
^[11] Number of seeds per fruit	#	 , 
^[11] Share of fruit set pollinated	%	 , 

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[8] Share of cropland area less than 100m from a non-cropland edge other than water or impervious surfaces. Values were scaled to [0-1]	%	
[8] Share of farmers that consider open landscapes a valued landscape feature. Values were scaled to [0-1]	%	
[12] Vegetation diversity: four-level index based on the number of plant species	Index [poor-fair-good-excellent]	
[19] Richness of pollinators: Total number of Sphingidae collected	#	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[2] Area of potential nesting sites for wild bees	m ²	
[2] Distance between potential nesting sites for wild bees and nearest arable land cell (GIS 10x10 m cells)	m	
[2] Number of visitations from wild bees to arable fields, calculated as the sum of visitation probabilities based on proximity between potential nesting sites and arable fields	-	
[3] Relative pollination potential: continuous index, based on the availability of floral resources, bee flight ranges and the availability of nesting sites	-	
[5] Share of land cover suitable as pollinator habitat in the direct vicinity of cropland	%	
[8] Share of cropland area less than 100m from a non-cropland edge other than water or impervious surfaces. Values were scaled to [0-1]	%	
[13] Share of area reachable by cavity and ground-nesting pollinator species, assuming 100 and 350 m flight and foraging distances, calculated using the equations by (Lonsdorf et al., 2009)	%	
[8] Share of farmers that consider open landscapes a valued landscape feature. Values were scaled to [0-1]	%	
[6] Pollination contribution by ecosystems (index): For each cropland, a) the crop pollination dependency ratio was calculated based on the specific crop type, b) the pollinator visitation probability was calculated as a regression between distance to natural habitat and visitation rate. The sum of a) and b) was then assigned to the closest natural ecosystem.	-	

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^[7] Pollination: Values are assigned based on land cover class. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
^[10] Habitat scores: number of bee species and medicinal plant species found in a specific land use class divided by benchmark value (number of species in land use class with the highest absolute number of species)	%	 , 
^[16] Number of bird & bee pollinators per hectare	# * ha ⁻¹	 ,  , 
^[16] Yield of pollinated crops	t * ha ⁻¹	 ,  , 
^[17] Abundance of pollinators	Not provided	
^[17] Richness of pollinators	Not provided	
^[17] Diversity of pollinators	Not provided	
^[17] Effects of pollinators	Not provided	
^[18] Area pollination indicators (Lonsdorf et al., 2009), calculated for different assumptions regarding the distances that pollinators can cover (100 m, 350 m, 500 m): - Area providing flowering [ha] - Area suitable for nesting of wild bees and bumblebees - Share of flowering sites reachable from nesting sites	[ha] [ha] [%]	
^[21] Seed weight of pollinated plants	tons / (km ² * year)	

Table 4: National Scale

Indicator	Unit	Indicator values from
^[4] Resilience of pollination service: number of pollinators morphospecies in the (primarily) pollinator taxa: Lepidoptera, Cerambycidae, Buprestidae and Aculeata. Two or more specimens are considered the same morphospecies if an entomologically trained person (but non-specialist for the respective species groups) can not see external morphological differences. To save costs, only seven weeks where maximum catches are expected were sampled, only the four weeks with the highest catches were identified.	#	
^[5] Share of land cover suitable as pollinator habitat in the direct vicinity of cropland	%	
^[14] Pollination potential	Not specified	
^[14] Pollinators distribution	Not specified	

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[14] Pollinators species richness	Not specified	
[14] Number of beehives	Not specified	
[14] Areal coverage of vegetation features supporting pollination (hedgerows, flower strips, High Nature Value Farmland etc.)	Not specified	
[20] Pollinator visitation probability: Land use classes providing wild bee habitats are identified, with grassland/steppe; garrigue and woodland considered full habitats (100%) and arable land and orchards considered partial habitats (50%). Visitation Probability is then calculated as: Visitation Probability = $e^{(-0.00104 \times \text{Distance\_to\_habitat})}$.	[-]	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[3] Relative pollination potential: continuous index, based on the availability of floral resources, bee flight ranges and the availability of nesting sites	[-]	
[9] Pollination: Corine land cover classes based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0-5	

References

No.	Citation
1 ^{11*}	Fagerholm N, Torralba M, Burgess PJ, Plieninger T (2016) A systematic map of ecosystem services assessments around European agroforestry. Ecological Indicators 62: 47-65. DOI: 10.1016/j.ecolind.2015.11.016
2	Lautenbach S, Kugel C, Lausch A, Seppelt R (2011) Analysis of historic changes in regional ecosystem service provisioning using land use data. Ecological Indicators 11(2): 676-687. DOI: 10.1016/j.ecolind.2010.09.007
3	Mouchet MA, Paracchini ML, Schulp CJE, Sturck J, Verkerk PJ, Verburg PH, Lavorel S (2017) Bundles of ecosystem (dis)services and multifunctionality across European landscapes. Ecological Indicators 73: 23-28. DOI: 10.1016/j.ecolind.2016.00.026
4	Obrist MK, Duelli P (2010) Rapid biodiversity assessment of arthropods for monitoring average local species richness and related ecosystem services. Biodiversity and Conservation 19(8): 2201-2220. DOI: 10.1007/s10531-010-9832-y
5	Schulp CJE, Van Teeffelen AJA, Tucker G, Verburg PH (2016) A quantitative assessment of policy options for no net loss of biodiversity and ecosystem services in the European Union. Land Use Policy 57: 151-163. DOI: 10.1016/j.landusepol.2016.05.018
6	Vigl LE, Tasser E, Schirpke U, Tappeiner U (2017) Using land use/land cover trajectories to uncover ecosystem service patterns across the Alps. Regional Environmental Change 17(8): 2237-2250. DOI: 10.1007/s10113-017-1132-6

^{11*} The impact area discussed on this factsheet is not a focus of the cited paper

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No.	Citation
7*	Zhang ZM, Gao JF, Fan XY, Lan Y, Zhao MS (2017) Response of ecosystem services to socioeconomic development in the Yangtze River Basin, China. <i>Ecological Indicators</i> 72: 481-493. DOI: 10.1016/j.ecolind.2016.08.035
8	Andersson E, Nykvist B, Malinga R, Jaramillo F, Lindborg R (2015) A social–ecological analysis of ecosystem services in two different farming systems. <i>Ambio</i> 44(1): 102-112. DOI: 10.1007/s13280-014-0603-y
9	Clerici N, Paracchini ML, Maes J (2014) Land-cover change dynamics and insights into ecosystem services in European stream riparian zones. <i>Ecohydrology and Hydrobiology</i> 14(2): 107-120. DOI: 10.1016/j.ecohyd.2014.01.002
10	Cotter M, Häuser I, Harich FK, He P, Sauerborn J, Treydte AC, Martin K, Cadisch G (2017) Biodiversity and ecosystem services—A case study for the assessment of multiple species and functional diversity levels in a cultural landscape. <i>Ecological Indicators</i> 75: 111-117. DOI: 10.1016/j.ecolind.2016.11.038
11	Demestihias C, Plénet D, Génard M, Raynal C, Lescourret F (2017) Ecosystem services in orchards. A review. <i>Agronomy for Sustainable Development</i> 37(2): 12. DOI: 10.1007/s13593-017-0422-1
12	Fleming WM, Rivera JA, Miller A, Piccarello M (2014) Ecosystem services of traditional irrigation systems in northern New Mexico, USA. <i>International Journal of Biodiversity Science, Ecosystem Services and Management</i> 10(4): 343-350. DOI: 10.1080/21513732.2014.977953
13	Kay S, Crous-Duran J, Ferreiro-Domínguez N, García de Jalón S, Graves A, Moreno G, Mosquera-Losada MR, Palma JHN, Rocés-Díaz JV, Santiago-Freijanes JJ, Szerencsits E, Weibel R, Herzog F (2018) Spatial similarities between European agroforestry systems and ecosystem services at the landscape scale. <i>Agroforestry Systems</i> 92(4): 1075-1089. DOI: 10.1007/s10457-017-0132-3
14	Maes J, Lique C, Teller A, Erhard M, Paracchini ML, Barredo JI, Grizzetti B, Cardoso A, Somma F, Petersen JE, Meiner A, Gelabert ER, Zal N, Kristensen P, Bastrup-Birk A, Biala K, Piroddi C, Egoh B, Degeorges P, Fiorina C, Santos-Martín F, Naruševičius V, Verboven J, Pereira HM, Bengtsson J, Gocheva K, Marta-Pedroso C, Snäll T, Estreguil C, San-Miguel-Ayán J, Pérez-Soba M, Grêt-Regamey A, Lillebø AI, Malak DA, Condé S, Moen J, Czúcz B, Drakou EG, Zulian G, Lavalle C (2016) An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. <i>Ecosystem Services</i> 17: 14-23. DOI: 10.1016/j.ecoser.2015.10.023
15*	Peters VE, Campbell KU, Dienno G, García M, Leak E, Loyke C, Ogle M, Steinly B, Crist TO (2016) Ants and plants as indicators of biodiversity, ecosystem services, and conservation value in constructed grasslands. <i>Biodiversity and Conservation</i> 25(8): 1481-1501. DOI: 10.1007/s10531-016-1120-z
16	Adhikari S, Baral H, Nitschke CR (2018) Identification, Prioritization and Mapping of Ecosystem Services in the Panchase Mountain Ecological Region of Western Nepal. <i>Forests</i> 9(9): 554. DOI: 10.3390/f9090554
17	Duarte GT, Santos PM, Cornelissen TG, Ribeiro MC, Paglia AP (2018) The effects of landscape patterns on ecosystem services: meta-analyses of landscape services. <i>Landscape Ecology</i> 33(8): 1247-1257. DOI: 10.1007/s10980-018-0673-5
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No.	Citation
20	Balzan MV, Caruana J, Zammit A (2018) Assessing the capacity and flow of ecosystem services in multifunctional landscapes: Evidence of a rural-urban gradient in a Mediterranean small island state. Land Use Policy 75: 711-725. DOI: 10.1016/j.landusepol.2017.08.025
21	Gasparatos A, Romeu-Dalmau C, von Maltitz GP, Johnson FX, Shackleton C, Jarzebski MP, Jumbe C, Ochieng C, Mudombi S, Nyambane A, Willis K (2018) Mechanisms and indicators for assessing the impact of biofuel feedstock production on ecosystem services. Biomass & Bioenergy 114: 157-173. DOI: 10.1016/j.biombioe.2018.01.024

Ecosystem Service	Nursery populations and habitats
CICES class name	Maintaining nursery populations and habitats (Including gene pool protection)
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.2.3

Brief Description

- Providing habitats for wild plants and animals
- The presence of ecological conditions necessary for sustaining populations of species

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Biodiversity & habitats: Earthworms	Not provided	
^[2] Species richness of birds	#	
^[2] Species richness of farmland birds	#	
^[2] Species richness of birds listed as vulnerable or threatened in Annex I of the EU Birds Directive	#	
^[6] Overall species richness of flowers relevant to pollinators	#	
^[6] Overall species richness of flowers	#	
^[15] Herbaceous species richness	#	
^[9] Ant species richness as a predictor of overall bird species richness and abundance.	#	

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[7] Aboveground biodiversity: number of trees species with DBH $\geq$ 1 cm	# per plot	
[16] Number of carabid- and plant species (alpha diversity)	#	 , 
[16] Number of red listed species	#	 , 
[7] Aboveground biodiversity: Shannon index of trees species with DBH $\geq$ 1 cm in the plot	-	
[12] Diversity of plant community (calculated from species richness and structural diversity)	Dimensionless	
[13] Diversity of plant community (calculated from species richness and structural diversity)	Dimensionless	
[14] Abundances of soil microarthropods (Acari: Oribatida, Acari: Mesostigmata and Collembola)	Not provided	
[7] Belowground biodiversity: Number of arthropods per soil pit (25 cm x 25 cm x 30 cm)	#	
[7] Belowground biodiversity: Number of earthworms per soil pit (25 cm x 25 cm x 30 cm)	#	
[7] Belowground biodiversity: macrofauna richness per soil pit (25 cm x 25 cm x 30 cm)	# of species	
[7] Belowground biodiversity: macrofauna diversity per soil pit (25 cm x 25 cm x 30 cm) calculated as Shannon index	-	
[1] Biodiversity & habitats: Microarthropod-based soil quality index	Not provided	
[1] Biodiversity & habitats: dsDNA content (Fornasier et al., 2014, DOI:10.1016/j.ecolind.2014.03.028)	$\mu\text{g dsDNA} \cdot \text{g}^{-1}$ soil	
[2] Connectivity. Weighted Euclidean distance between smaller patches of natural habitat and the nearest large habitat patch (i.e. $>25 \text{ km}^2$). Distances were weighted by the resistance values of land use types in between areas of natural habitat. Resistance values were expert-based, and no distinction was made for species-specific dispersal capacities. In summary, built-up areas were assigned a high resistance value (10), cropland and open water were assigned intermediate resistance values (4), and other land use types, including pasture and recently abandoned farmland, were assigned low resistance values (1 or 2).	Not provided	
[3] Distance-to-Nature-Potential (DNP)	Index 0 - 1	
[9] Plant species richness as a predictor of butterfly abundance and species richness	#	
[6] Colour richness of flowers relevant for pollinators	# of colour groups visible to pollinators: green, white, yellow, purple, violet, UV	

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[11] Habitat for arthropods: total number of plant species	#	
[9] Plant Simpson diversity as a predictor of bee and beetle abundance.	Index 0 - 1	
[9] Floristic Quality Assessment (FQA) as a predictor of butterfly species richness and abundance. FQA is the sum of the products of a species' "coefficient of conservatism" and its percentage of cover (or presence/absence data), calculated over all species.	-	
[17] Share of semi-natural habitats	%	
[11] Habitat for soil microbes and invertebrates: Soil carbon (0-100cm)	kg C * m ⁻²	
[12] Share of years within management period in which protection plant products were used	%	
[13] Share of years within management period in which protection plant products were used	%	
[5] Groundcover: annual mean daily value expressed as a fraction	%	
[3] Relative reduction in species richness	%	
[3] Relative reduction in species functional diversity	%	
[3] Number of species lost regionally and globally	# * m ⁻²	
[6] Functional stability: Average species richness of flowers within colour groups during the flowering season (of flowers relevant for pollinators)	# of species	
[6] Functional intensity: Average size of flowers or discernible sub-sets of inflorescences that are relevant for pollinators	cm	
[17] Carabidae diversity and traits	Not provided	
[16] Difference among carabid- and plant species compositions under different management types (beta diversity)	-	 , 
[14] Biodiversity indices for microbial communities (Shannon, Pielou, Evenness); based on genetic fingerprinting of microbial communities in DNA extracted from bulk soil, rhizosphere soil, and roots.	Not provided	

[9] AntQA index as a predictor of abundance of grassland bird and butterfly species. AntQa is the sum of the products of an ant species' "coefficient of conservatism" and its percentage of presence/absence in an area, calculated over all species.		
[10] EPX (ecosystem-service performance index) Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: I – Indicator value, i – variable i measured, i_{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log (\frac{i}{i_{max}})$ is subtracted from the sum instead of added. For this ecosystem service, variables were: -pH in KCl -Number of earthworm taxa [-] -Number of nematode taxa [-] -Number of micro-arthropode taxa [-] -Physiological diversity bacteria [biolog. CLPP: Hill's slope]	-	 , 
[8] Soil biodiversity indicator) based on a principal component analysis (PCA) of soil macro invertebrate data. Variables included: -Abundance of soil macro invertebrate communities (endogeic earthworms, epigeic earthworms, termites, ants, coleoptera, myriapoda, other litter invertebrate) [individuals * m²] -Taxonomic richness of soil macro invertebrates [not provided] -Sum of soil macro invertebrate collected at each plot [individuals * m²] Variables with significant contribution (>50% of the maximum value) to either of the first two principal components, axes were selected and their contribution to PCA axes 1 and 2 multiplied by the overall variability explained by each PCA axis. These weighted factors were summed up and scaled to a range of 0.1 - 1.0.	-	
[4] Coffee plantations: 5 level shade index	Index 5 (unshaded monoculture) - 1 (leguminous trees and other plants)	
[57] Cumulative avian species richness: number of species and number of breeding pairs observed during 4 site visits, walking at a slow pace and thoroughly surveying the entire site.	n/a	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[18] Vegetation richness: Number of planted crop species The index is calculated by dividing the observed value with a target value. Target values may be average or maximum values found in region or empirical values from the literature. If the calculated index is higher than 1, it is set to one.	Index 0 - 1	
[18] Number of different land cover types The index is calculated by dividing the observed value with a target value. Target values may be average or maximum values found in region or empirical values from the literature. If the calculated index is higher than 1, it is set to one.	Index 0 - 1	
[18] Share of the farmland in non-crop vegetation (percent of non-crop) The index is calculated by dividing the observed value with a target value. Target values may be average or maximum values found in region or empirical values from the literature. If the calculated index is higher than 1, it is set to one.	Index 0 - 1	
[18] Share of the farmland covered by rare landscape elements (e.g. wetlands, riparian areas, primary forest and prairie) The index is calculated by dividing the observed value with a target value. Target values may be average or maximum values found in region or empirical values from the literature. If the calculated index is higher than 1, it is set to one.	Index 0 - 1	
[18] Birds: observed of indicator species The index is calculated by dividing the observed value with a target value. Target values may be average or maximum values found in region or empirical values from the literature. If the calculated index is higher than 1, it is set to one.	Index 0 - 1	
[18] Native to total bird species ratio: Index based on observation of indicator species The index is calculated by dividing the observed value with a target value. Target values may be average or maximum values found in region or empirical values from the literature. If the calculated index is higher than 1, it is set to one.	Index 0 - 1	
[19] Structural vegetation diversity: four-level index based on the number of different vegetation height classes that occur together (grass, shrubs, trees)	Index poor-fair-good-excellent	
[21] Number of plant species observed during surveys within 1000 m from a farmhouse. Values were scaled [0-1].	#	

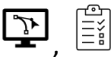
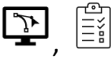
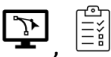
[17] Carabidae diversity and traits	Not provided	
[20] Biodiversity index based on number of moths, birds, bees, fruit flies, spiders, ants, soil macrofauna, termites, earthworms, and small, medium, and tall plants	Index 0.1 - 1	
[21] Number of bird species observed during surveys within 300 m from farmhouse. Values were scaled [0-1].	#	
[22] Red-list biodiversity potential: weighted sum of red-listed species; number of red-listed species across all sampled taxonomic groups in each landscape, weighted by the respective IUCN category in the Swedish national red list. Multipliers were: near threatened (1), vulnerable (2), endangered (3), regionally extinct (4).	#	
[22] Use of bundles of indicator species identified for a certain region. Species may belong to different taxonomic groups	Not provided	
[19] Wildlife diversity: four-level index based on the number of species occurring	Index poor-fair-good-excellent	
[17] Share of semi-natural habitats	%	
[21] Landscape variation: length of land cover "edges" per hectare land surface. Values were scaled [0-1].	km * ha ⁻¹	
[21] Share of farmers surveyed that consider open landscapes valuable landscape elements. Values were scaled [0-1].	%	

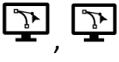
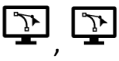
Table 3: Regional Scale

Indicator	Unit	Indicator values from
[21] Number of plant species observed during surveys within 1000 m from farmhouse. Values were scaled [0-1].	#	
[23] Biodiversity of plant species: number of species	#	
[23] Biodiversity of plant species: total abundance (i.e. species cover)	Not provided	
[23] Biodiversity of plant species: true species diversity (i.e. exponential of Shannon entropy)	-	
[25] Richness of wild higher plants	#	
[37] Plant diversity: Plants Simpson's biodiversity index	Index 0 - 1	
[41] Number of weed species on arable land per relevé (method of Braun-Blanquet, 1964)	#	

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[17] Carabidae diversity and traits	Not provided	
[21] Number of bird species observed during surveys within 300 m from farmhouse. Values were scaled [0-1].	#	
[25] Richness of wild higher animals	#	
[29] Terrestrial vertebrate species richness, calculated with the GAP Analysis program from the U.S. Geological Survey	# of species * ha ⁻¹	
[31] Biodiversity & biological activity index: The index is based on the collection and sorting of soil macrofauna (including ants) into 16 taxonomic groups (e.g., Oligochaeta, Isoptera, Coleoptera) largely separated by order.	Index 0.1 - 1	
[31] Bio-indicator: Presence of specific ant species is used as an indicator for high, medium or low provision of this ecosystem service. Suitable indicator species must first be identified by a correlation between the presence of species and ecosystem service provision.		
[46] Number of endangered species of vertebrates, invertebrates and plants	# * km ⁻²	
[22] Red-list biodiversity potential: weighted sum of red-listed species; number of red-listed species across all sampled taxonomic groups in each landscape, weighted by the respective IUCN category in national red list. Multipliers were: near threatened (1), vulnerable (2), endangered (3), regionally extinct (4).	#	
[22] Use of bundles of indicator species identified for a certain region. Species may belong to different taxonomic groups	Not provided	
[24] Biological diversity: composition of flora and fauna communities in relation to the potential natural communities	Not provided	
[25] Number of endemic species	#	
[28] Wetland habitats: Number of unique species in wetlands and floodplains	#	
[34] Bioscore index based on national biodiversity map. Scores are calculated as sum of scores for the distribution of endangered species (1-9), and from scores based on selected species and habitat indicators (1-11). All intensively cultivated fields are assigned a score of 0 by default.	Index 0 - 20	
[35] Alpha, beta and gamma diversity of bird species and woody species. Bird species values based on point measurements, recording all birds seen or heard up to a 30 m radius within a 10 min period (except flyover birds). Woody species values based on determining all woody plants with diameter at breast height > 5 cm.	-	

Appendix – Ecosystem Services

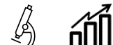
[36] Habitat scores: number of species found in a specific land use class divided by benchmark value (number of species in land use class with the highest absolute number of species).	%	
[36] Habitat scores for endangered species: number of endangered species found in a specific land use class divided by benchmark value (number of endangered species in land use class with the highest absolute number of endangered species).	%	
[45] Number and identity of selected species in rivers or lakes	#	
[45] Biodiversity value (e.g., species richness, species composition)	Not provided	
[49] Mean species value per hectare: score based on the habitat suitability for all vertebrate and vascular plant species listed in the UK Biodiversity Action Plan, each rated [0 – 1] multiplied by their respective colonization potential, each [0 – 1]. The scores are weighted so that each species contributes equally, regardless of how many habitat types it occurs in.	-	
[40] Genetic Resources: Number and varieties of species	#	
[17] Share of semi-natural habitats	%	
[44] Share of semi-natural habitat	%	
[44] Number of the semi-natural habitat types	#	
[21] Landscape variation: length of land cover "edges" per hectare land surface. Values were scaled [0-1].	km * ha ⁻¹	
[25] Diversity of ecosystem types	#	
[25] Proportion of woodland, garden and grassland area in total	%	
[26] Area of "ecological compensation areas"	ha	
[38] Share of special protection area relative to municipality's surface area. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	%	
[38] Share of habitats of community interest relative to municipality's surface area. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	%	
[39] Designated Natura 2000 areas	ha	

Appendix – Ecosystem Services

[27] Indicator for ecological integrity, based on: -Naturalness: Hemeroby index [not provided] -Land use diversity: Number of plant species [not provided] -Landscape fragmentation (landscape metrics): Effective mesh size [not provided], -Core area index [not provided] -Landscape diversity: Shannon diversity index [-] -Patch density [not provided] -Shape index [not provided] -Habitat connectivity: Cost distance analysis [not provided]	Index 1 - 100	
[32] Habitat index from InVEST model	Index 0 - 1	
[33] Size and distribution of strictly protected areas (nature reserves, biosphere reserve, Natura 2000)	Not provided	
[42] Landscape heterogeneity: Satoyama index, calculated as Simpson's diversity index for land uses multiplied by the proportion "non-urban, non-agricultural" land use classes.	Index 0 - 1	
[43] Providing nurseries, habitat for species and conserving genetic diversities: expert-based index for ecosystem service provision by each land cover class [1-5], multiplied by the area of the land cover class	km ²	 ,  , 
[43] Providing nurseries, habitat for species and conserving genetic diversities value: expert-based index for ecosystem service provision by each land cover class [1-5], multiplied by the area of the land cover class and literature-based monetary value of the ecosystem service	km ² , \$ * ha ⁻¹ * yr ⁻¹	 ,  , 
[44] Structural diversity measured by the Simpson diversity index	-	
[45] Ecological-morphological status	preferences, e.g., good, neutral, bad	
[45] Floodplain area	ha	
[23] Floodplains: Riparian Quality Index (RQI). The index considers (i) average width of riparian corridor; (ii) longitudinal continuity, coverage and distribution pattern of riparian corridor (woody vegetation); (iii) composition and structure of riparian vegetation; (iv) age diversity and natural regeneration of woody species; (v) bank conditions; (vi) floods and lateral connectivity; and (vii) substratum and vertical connectivity	Index 0 - 100	 , 
[46] Number of ecosystem types per area (based on classification in national ecosystem assessment)	# * area ⁻¹	
[47] Habitat richness based on landscape metrics: Simpson diversity index	-	
[47] Habitat richness based on landscape metrics: Share of seminatural habitat	%	

[47] Habitat richness based on landscape metrics: Number of seminatural habitat types	#	
[48] Biodiversity conservation, calculated as: $BC = NPP * (1 - VC_{NPP}) * I_W * N_f$ With: BC – Biodiversity conservation, NPP – Net Primary Production calculated from NDVI-values and expressed on a relative scale set to (0 -1000), VC_{NPP} – coefficient of variation of NPP [0 – 1], I_W – water input to the system, calculated as <i>rainfall</i> * (1-runoff coefficient) and scaled to a range of [0 -1], N_f – naturalness factor considering naturalness and structural complexity of the ecosystem [0 – 1]	-	
[49] Habitat conservation score, based on conservation priorities and significance of habitats. Conservation priorities were derived from the policy document, while significance was determined by calculating the proportion of the national and regional resource that occurred for each habitat type at each site, and particular site-specific features.	-	
[21] Share of farmers surveyed that consider open landscapes valuable landscape elements. Values were scaled [0-1].	%	
[30] Spatial mapping by stakeholders: stakeholders could place green stickers on a map to mark the supply hotspots of this ecosystem service. Red stickers were used to mark locations where the supply of this service is declining. Two different sizes of stickers were used to represent a radius of 0.75 km or 1 km, respectively.	-	

Table 4: National Scale

Indicator	Unit	Indicator values from
[53] Area weighted mean species richness of vascular plants	# of species	
[50] Diversity of breeding bird species (Simpson-index)	-	
[50] Number of farmland bird species	#	
[51] Species diversity: Expert assessment for each land use class, based on the indicators: species number; endangered species; invasive species (units not given)	very negative (-3) to very positive (+3)	
[52] Species of conservation concern: based on species listed in U.K. Biodiversity Action Plan and recorded in a grid cell (further specification lacking)	not provided	

Appendix – Ecosystem Services

[51] Genetic diversity: Expert assessment for each land use class, based on the indicator: crop variety (units not given)	very negative (–3) to very positive (+3)	
[51] Habitat diversity: Expert assessment for each land use class, based on the indicators: intensive agriculture; homogeneity; fragmentation; extensive/organic agriculture (units not given)	very negative (–3) to very positive (+3)	
[53] Degree of naturalness: 7-point scale indicator	1 (natural) - 7 (artificial)	
[54] Area of high nature value farmland	ha	
[55] Share of high nature value farmland	%	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[56] Biodiversity: Values assigned for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	

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Ecosystem Service	Pest control (including invasive species)
CICES class name	Pest control (including invasive species)
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.3.1

Brief Description

- Controlling pests and invasive species
- The reduction in the abundance of pests by biological interactions such as predation, competition or parasitism

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Injuries by root-lesion nematodes: Number of root-lesion nematode in 100 g of roots	# * 100g ⁻¹	
^[1] Injuries by root-knot nematodes: Number of root-knot nematode in 100 g of roots	# * 100g ⁻¹	
^[7] Level of injury severity, fruit loss, leaf loss, LAI loss	%	 , 
^[9] Damage from pests six weeks after planting. Based on visual inspection of 40 randomly selected plants.	Index 1-3	
^[5] Biological control: total number of plant species	#	
^[15] Nematode abundance	Not provided	
^[9] Weed cover	kg * ha ⁻¹	
^[15] Weed biomass	Not provided	
^[15] Weed density	Not provided	

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[7] Rates of predation by natural enemies, rates of parasitism by parasitoids	Not provided	 , 
[7] Indicators or models to assess the impact of pesticides	Not provided	 , 
[11] Abundance of ladybird beetles (natural enemies of aphids and other sap-sucking pest species)	Not provided	
[11] Plant Simpson diversity as predictor of beetle abundance	Not specified	
[11] Abundance of birds from species that are known insectivores in agricultural fields	Not provided	
[11] Ant species richness as predictor of the abundance of birds, including those from species that are known insectivores.	Not provided	
[12] Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: i – variable i measured, i_{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log (\frac{i}{i_{max}})$ is subtracted from the sum instead of added. For this ecosystem service, variables were: -Soil organic matter [% dw] -pH in KCl -Number of nematode taxa [-] -Number of micro-arthropod taxa [-] -Density of nematode plant-parasites [number per 100 g soil]	-	 , 
[14] Aphid biocontrol index; based on pairwise pot experiment introducing and exposing twenty-four aphids over a five-day period. The number of pests in an open treatment was divided by the number of pests in a caged treatment that excluded ground-dwelling and flying natural enemies. Values were standardized to a maximum value of 1.	Index 0-1	
[14] Use of bundles of indicator species identified for a certain region. Species may belong to different taxonomic groups	Not provided	
[21] Carabid activity density	-	
[21] Number of carabid species caught in pitfall traps	#	
[21] Spider activity density	-	
[21] Rove beetle activity density	-	

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Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[6] Share of cropland area less than 100m from a non-cropland edge other than water or impervious surfaces. Values were scaled to [0-1]	%	
^[6] Share of farmers surveyed that clearly expresses a value and care for the health of the land. Values were scaled to [0-1]	%	
^[8] Vegetation diversity: four-level index based on the number of plant species	Index [poor-fair-good-excellent]	
^[14] Aphid biocontrol index; based on pairwise pot experiment introducing and exposing twenty-four aphids over a five-day period. The number of pests in an open treatment was divided by the number of pests in a caged treatment that excluded ground-dwelling and flying natural enemies. Values were standardized to a maximum value of 1.	Index 0-1	
^[14] Use of bundles of indicator species identified for a certain region. Species may belong to different taxonomic groups	Not provided	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[16] Pest abundance	Not provided	
^[16] Pest richness	Not provided	
^[16] Pest damage	Not provided	
^[16] Natural enemy abundance	Not provided	
^[16] Natural enemy richness	Not provided	
^[16] Natural enemy diversity	Not provided	
^[16] Direct natural enemy effects on pest reduction	Not provided	
^[2] Capacity for biological regulation: number of habitats for pest control species	Not provided	
^[3] Number of species providing natural control of invertebrate and rodent pest species	#	
^[14] Aphid biocontrol index; based on pairwise pot experiment introducing and exposing twenty-four aphids over a five-day period. The number of pests in an open treatment was divided by the number of pests in a caged treatment that excluded ground-dwelling and flying natural enemies. Values were standardized to a maximum value of 1.	Index 0-1	

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[13] Number of cases of reduced pest infestation in the locality	#	
[6] Share of cropland area less than 100m from a non-cropland edge other than water or impervious surfaces. Values were scaled to [0-1]	%	
[6] Share of farmers surveyed that clearly expresses a value and care for the health of the land. Values were scaled to [0-1]	%	
[14] Use of bundles of indicator species identified for a certain region. Species may belong to different taxonomic groups	Not provided	
[17] Expert-/stakeholder rating of how much of this ES can be provided by a landscape (represented by a land use map)	6-point Lickert-scale (none – highest capacity)	
[17] Expert-/stakeholder rating based on pairwise comparisons of landscapes (represented by land use maps) in an Analytical Hierarchical Process (AHP). Experts select the landscape with higher capacity for providing this ES and rate the difference between the two landscapes	1 (equal capacity) – 9 (absolute preference of one landscape)	
[18] Area used for organic agriculture	n/a	
[19] Pests' natural enemy biomass	n/a	
[19] Pests' egg predation	n/a	
[19] For plants with insecticidal properties: amount of active ingredient	kg/ km ⁻²	
[19] Amount of insecticide used per unit	tons / km ⁻²	
[20] Area of flower strips suitable for natural enemies of agricultural pests	n/a	

Table 4: National Scale

Indicator	Unit	Indicator values from
[4] Resilience of pest control service: number of arthropod morphospecies from (primarily) carnivorous taxa divided by number of morphospecies from (primarily) herbivorous taxa. Two or more specimens are considered the same morphospecies if an entomologically trained person (but non-specialist for the respective species groups) cannot see external morphological differences	[-]	
[10] Density of hedgerows	m * ha ⁻¹	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[3] Number of species providing natural control of invertebrate and rodent pest species	#	

References

No.	Citation
1	Allinne C, Savary S, Avelino J (2016) Delicate balance between pest and disease injuries, yield performance, and other ecosystem services in the complex coffee-based systems of Costa Rica. <i>Agriculture Ecosystems & Environment</i> 222: 1-12. DOI: 10.1016/j.agee.2016.02.001
2 ^{13*}	Fürst C, Frank S, Witt A, Koschke L, Makeschin F (2013) Assessment of the effects of forest land use strategies on the provision of ecosystem services at regional scale. <i>Journal of Environmental Management</i> 127: S96-S116. DOI: 10.1016/j.jenvman.2012.09.020
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5	Syswerda SP, Robertson GP (2014) Ecosystem services along a management gradient in Michigan (USA) cropping systems. <i>Agriculture Ecosystems & Environment</i> 189: 28-35. DOI: 10.1016/j.agee.2014.03.006
6	Andersson E, Nykvist B, Malinga R, Jaramillo F, Lindborg R (2015) A social–ecological analysis of ecosystem services in two different farming systems. <i>Ambio</i> 44(1): 102-112. DOI: 10.1007/s13280-014-0603-y
7	Demestihis C, Plénet D, Génard M, Raynal C, Lescourret F (2017) Ecosystem services in orchards. A review. <i>Agronomy for Sustainable Development</i> 37(2): 12. DOI: 10.1007/s13593-017-0422-1
8	Fleming WM, Rivera JA, Miller A, Piccarello M (2014) Ecosystem services of traditional irrigation systems in northern New Mexico, USA. <i>International Journal of Biodiversity Science, Ecosystem Services and Management</i> 10(4): 343-350. DOI: 10.1080/21513732.2014.977953
9	Kearney SP, Fonte SJ, García E, Siles P, Chan KMA, Smukler SM (2019) Evaluating ecosystem service trade-offs and synergies from slash-and-mulch agroforestry systems in El Salvador. <i>Ecological Indicators</i> 105: 264-278. DOI: 10.1016/j.ecolind.2017.08.032
10	Maes J, Liqueste C, Teller A, Erhard M, Paracchini ML, Barredo JI, Grizzetti B, Cardoso A, Somma F, Petersen JE, Meiner A, Gelabert ER, Zal N, Kristensen P, Bastrup-Birk A, Biala K, Piroddi C, Egoh B, Degeorges P, Fiorina C, Santos-Martín F, Naruševičius V, Verboven J, Pereira HM, Bengtsson J, Gocheva K, Marta-Pedroso C, Snäll T, Estreguil C, San-Miguel-Ayanz J, Pérez-Soba M, Grêt-Regamey A, Lillebø AI, Malak DA, Condé S, Moen J, Czúcz B, Drakou EG, Zulian G, Lavalle C (2016) An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. <i>Ecosystem Services</i> 17: 14-23. DOI: 10.1016/j.ecoser.2015.10.023
11*	Peters VE, Campbell KU, Dienno G, García M, Leak E, Loyke C, Ogle M, Steinly B, Crist TO (2016) Ants and plants as indicators of biodiversity, ecosystem services, and conservation value in constructed grasslands. <i>Biodiversity and Conservation</i> 25(8): 1481-1501. DOI: 10.1007/s10531-016-1120-z
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13	Adhikari S, Baral H, Nitschke CR (2018) Identification, Prioritization and Mapping of Ecosystem Services in the Panchase Mountain Ecological Region of Western Nepal. <i>Forests</i> 9(9): 554. DOI: 10.3390/f9090554

^{13*} The impact area discussed on this factsheet is not a focus of the cited paper

Appendix – Ecosystem Services

No.	Citation
14	Birkhofer K, Rusch A, Andersson GKS, Bommarco R, Dänhardt J, Ekbom B, Jönsson A, Lindborg R, Olsson O, Rader R, Stjernman M, Williams A, Hedlund K, Smith HG (2018) A framework to identify indicator species for ecosystem services in agricultural landscapes. <i>Ecological Indicators</i> 91: 278-286. DOI: 10.1016/j.ecolind.2018.04.018
15	Daryanto S, Fu BJ, Wang LX, Jacinthe PA, Zhao WW (2018) Quantitative synthesis on the ecosystem services of cover crops. <i>Earth-Science Reviews</i> 185: 357-373. DOI: 10.1016/j.earscirev.2018.06.013
16	Duarte GT, Santos PM, Cornelissen TG, Ribeiro MC, Paglia AP (2018) The effects of landscape patterns on ecosystem services: meta-analyses of landscape services. <i>Landscape Ecology</i> 33(8): 1247-1257. DOI: 10.1007/s10980-018-0673-5
17	Inkoom JN, Frank S, Greve K, Furst C (2018) A framework to assess landscape structural capacity to provide regulating ecosystem services in West Africa. <i>Journal of Environmental Management</i> 209: 393-408. DOI: 10.1016/j.jenvman.2017.12.027
18	Chatzinikolaou P, Viaggi D, Raggi M (2018) Using the Ecosystem Services Framework for Policy Impact Analysis: An Application to the Assessment of the Common Agricultural Policy 2014-2020 in the Province of Ferrara (Italy). <i>Sustainability</i> 10: 890. DOI: 10.3390/su10030890.
19	Gasparatos A, Romeu-Dalmau C, von Maltitz GP, Johnson FX, Shackleton C, Jarzebski MP, Jumbe C, Ochieng C, Mudombi S, Nyambane A, Willis K (2018) Mechanisms and indicators for assessing the impact of biofuel feedstock production on ecosystem services. <i>Biomass & Bioenergy</i> 114: 157-173. DOI: 10.1016/j.biombioe.2018.01.024
20	Groot JCJ, Yalew SG, Rossing WAH (2018) Exploring ecosystem services trade-offs in agricultural landscapes with a multi-objective programming approach. <i>Landscape and Urban Planning</i> 172: 29-36. DOI: 10.1016/j.landurbplan.2017.12.008
21	Van Vooren L, Reubens B, Ampoorter E, Broekx S, Pardon, P, Van Waes C, Verheyen K (2018) Monitoring the Impact of Hedgerows and Grass Strips on the Performance of Multiple Ecosystem Service Indicators. <i>Environmental Management</i> 62: 241-259. DOI:10.1007/s00267-018-1043-4

Ecosystem Service	Disease control
CICES class name	Disease control
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.3.2

Brief Description

- Controlling disease
- Reduction in the severity or spread rate of infections by bacteria, viruses or fungi through biological interactions

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Leaf damages: Maximal percentage of young leaves infected in the year	%	
^[1] Plant damages: Dieback. Percentage of (coffee) plants infected in the plot	%	
^[3] Damage from diseases six weeks after planting. Based on visual inspection of 40 randomly selected plants.	Index 1 - 3	
^[1] Fruit Damages: Incidence of Ceratocystis canker. Maximal percentage of fruits infected in the year	%	
^[2] Level of injury severity, fruit loss, leaf loss, LAI loss	%	 , 
^[2] Indicators or models to assess the impact of pesticides	Not provided	 , 
^[4] Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$	-	 , 

Appendix – Ecosystem Services

With: i – variable i measured, i_{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log(\frac{i}{i_{max}})$ is subtracted from the sum instead of added. For this ecosystem service, variables were: -Soil organic matter [% dw] -pH in KCl -Number of nematode taxa [-] -Number of micro-arthropod taxa [-] -Density of nematode plant-parasites [number per 100 g soil]		

Table 2: Regional Scale

Indicator	Unit	Indicator values from
^[6] Disease prevalence	Not provided	
^[6] Host and vector abundances	Not provided	
^[6] Infection levels	Not provided	
^[7] Expert-/stakeholder rating of how much of this ecosystem service can be provided by a landscape (represented by a land use map)	6-point Likert-scale (none - highest capacity)	
^[7] Expert-/stakeholder rating based on pairwise comparisons of landscapes (represented by land use maps) in an Analytical Hierarchical Process (AHP). Experts select the landscape with higher capacity for providing this ecosystem service and rate the difference between the two landscapes	1 (equal capacity) - 9 (absolute preference of one landscape)	
^[5] Human diseases: number of diseases and effects among local inhabitants	#	
^[9] Area used for organic agriculture	n/a	

Table 3: National Scale

Indicator	Unit	Indicator values from
^[8] Density of hedgerows	m * ha ⁻¹	

References

No.	Citation
1	Allinne C, Savary S, Avelino J (2016) Delicate balance between pest and disease injuries, yield performance, and other ecosystem services in the complex coffee-based systems of Costa Rica. <i>Agriculture Ecosystems & Environment</i> 222: 1-12. DOI: 10.1016/j.agee.2016.02.001
2	Demestihis C, Plénet D, Génard M, Raynal C, Lescourret F (2017) Ecosystem services in orchards. A review. <i>Agronomy for Sustainable Development</i> 37(2): 12. DOI: 10.1007/s13593-017-0422-1
3	Kearney SP, Fonte SJ, García E, Siles P, Chan KMA, Smukler SM (2019) Evaluating ecosystem service trade-offs and synergies from slash-and-mulch agroforestry systems in El Salvador. <i>Ecological Indicators</i> 105: 264-278. DOI: 10.1016/j.ecolind.2017.08.032
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5	Adhikari S, Baral H, Nitschke CR (2018) Identification, Prioritization and Mapping of Ecosystem Services in the Panchase Mountain Ecological Region of Western Nepal. <i>Forests</i> 9(9): 554. DOI: 10.3390/f9090554
6	Duarte GT, Santos PM, Cornelissen TG, Ribeiro MC, Paglia AP (2018) The effects of landscape patterns on ecosystem services: meta-analyses of landscape services. <i>Landscape Ecology</i> 33(8): 1247-1257. DOI: 10.1007/s10980-018-0673-5
7	Inkoom JN, Frank S, Greve K, Furst C (2018) A framework to assess landscape structural capacity to provide regulating ecosystem services in West Africa. <i>Journal of Environmental Management</i> 209: 393-408. DOI: 10.1016/j.jenvman.2017.12.027
8	Maes J, Liqueste C, Teller A, Erhard M, Paracchini ML, Barredo JJ, Grizzetti B, Cardoso A, Somma F, Petersen JE, Meiner A, Gelabert ER, Zal N, Kristensen P, Bastrup-Birk A, Biala K, Piroddi C, Egoh B, Degeorges P, Fiorina C, Santos-Martín F, Naruševičius V, Verboven J, Pereira HM, Bengtsson J, Gocheva K, Marta-Pedroso C, Snäll T, Estreguil C, San-Miguel-Ayanz J, Pérez-Soba M, Grêt-Regamey A, Lillebø AI, Malak DA, Condé S, Moen J, Czucz B, Drakou EG, Zulian G, Lavalle C (2016) An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. <i>Ecosystem Services</i> 17: 14-23. DOI: 10.1016/j.ecoser.2015.10.023
9	Chatzinikolaou P, Viaggi D, Raggi M (2018) Using the Ecosystem Services Framework for Policy Impact Analysis: An Application to the Assessment of the Common Agricultural Policy 2014-2020 in the Province of Ferrara (Italy). <i>Sustainability</i> 10: 890. DOI: 10.3390/su10030890.

Ecosystem Service	Soil quality by weathering processes
CICES class name	Weathering processes and their effect on soil quality
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.4.1

Brief Description

- Ensuring soils form and develop
- Decomposition of minerals that helps maintain soil fertility

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Regional Scale

Indicator	Unit	Indicator values from
^[1] Net annual prevention of soil erosion through soil formation	$t * ha^{-1} * yr^{-1}$	 ,  , 
^[2] Soil formation and erosion prevention: expert-based index for ecosystem service provision by land cover class [1-5], multiplied by the area of the land cover class	km^2	 ,  , 
^[2] Soil formation and erosion prevention value: expert-based index for ecosystem service provision by land cover class [1-5], multiplied by the area of the land cover class and a literature-based monetary value of the ecosystem service	$\$ * yr^{-1}$	 ,  , 

Table 2: National Scale

Indicator	Unit	Indicator values from
^[3] Share of organic farming	%	
^[3] Soil organic matter content	%	
^[3] pH of topsoil	-	

[3] Cation exchange capacity	cmol(+) * kg ⁻¹	

References

No.	Citation
1	Adhikari S, Baral H, Nitschke CR (2018) Identification, Prioritization and Mapping of Ecosystem Services in the Panchase Mountain Ecological Region of Western Nepal. Forests 9(9): 554. DOI: 10.3390/f9090554
2	Huq N, Bruns A, Ribbe L (2019) Interactions between freshwater ecosystem services and land cover changes in southern Bangladesh: A perspective from short-term (seasonal) and long-term (1973-2014) scale. Science of the Total Environment 650: 132-143. DOI: 10.1016/j.scitotenv.2018.08.430

Ecosystem Service	Soil quality by decomposition and fixing processes
CICES class name	Decomposition and fixing processes and their effect on soil quality
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.4.2

Brief Description

- Ensuring that organic matter in our soils is maintained
- Decomposition of biological materials and the incorporation of the contained carbon and nutrients into the soils

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Nutrient cycling: -pH -Cation exchange capacity -Water-filled pore space	Not provided	
^[1] C cycling: -Soil organic carbon -KMnO ₄ oxidizable C -Beta-glucosidase activity -Metabolic CO ₂ quotient	Not provided	
^[2] Soil organic carbon depletion	kg C * ha ⁻¹ * yr ⁻¹	
^[1] N cycle: -Total nitrogen -Potentially mineralizable nitrogen -Leucine aminopeptidase activity -N-acetyl glucosamine activity	Not provided	
^[3] Biological nitrogen fixation	kg N * ha ⁻¹ * yr ⁻¹	-

[1] P cycle: -Available inorganic P -Alkaline phosphomonoesterase activity -Phosphodiesterase activity	Not provided	
[4, 20] Soil organic carbon in topsoil (0-20cm)	g * kg ⁻¹	
[6] Soil organic carbon (0-20 cm), calculated from loss on ignition	%	
[5] Carbon stocks in soil biomass (0-30 cm)	Mg * ha ⁻¹	
[7] Soil organic carbon stock over a 2.5 m deep soil profile	kg * ha ⁻¹	
[12] Total soil organic carbon (0-20 cm, 20-60 cm)	g * kg ⁻¹	
[12] Soil carbon stock in 0 -20 and 20 – 60 cm depth	Mg * ha ⁻¹	
[14] Soil organic carbon concentration in top soil (0-5 cm) and rooting layer (5-60 cm)	%, g * g ⁻¹	
[14] Soil organic carbon stock in top soil (0-5 cm) and rooting layer (5-60 cm)	kg * ha ⁻¹	
[17] Soil carbon (0-100cm)	kg C * m ⁻²	
[18] Carbon stock in soil: organic C contained in topsoil (0–30 cm) after 20 years of management	t * ha ⁻¹	
[19] Carbon stock in soil: organic C contained in topsoil (0–30 cm) after 20 years of management	t * ha ⁻¹	
[21] C _{tot} : Total carbon content in soil sample (0-7.5 cm), measured as weight loss on ignition	%	
[21] C _{org} : Organic carbon content in soil sample (0-7.5 cm,) measured by wet combustion (Cr ₂ O ₇ oxidation) and colorimetric analysis	%	
[21] C _{labile} : Labile carbon content in soil sample (0-7.5 cm), measured by oxidation with 333 mM KMnO ₄ and spectral analysis at 565 nm	%	
[21] CMI: Carbon management index, calculated as: $CMI = \frac{C_{totagr}}{C_{totnat}} * \frac{C_{labileagr}}{C_{non-labileagr}} * \frac{100}{\frac{C_{labilenat}}{C_{non-labilenat}}}$ With: C _{totagr} – C _{tot} in agricultural site, C _{totnat} – C _{tot} under native vegetation, C _{labileagr} – C _{labile} in agricultural site, C _{non-labileagr} – C _{non-labile} in agricultural site, C _{labilenat} – C _{labile} under native vegetation, C _{non-labilenat} – C _{non-labile} under native vegetation	Index 0 - 100	

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[21] LCMI: Landscape carbon management index, calculated as: $LCMI = CMI_{nat} * S_{nat} + CMI_{grass} * S_{grass} + CMI_{crop} * S_{crop}$ With: CMI_{nat} – CMI (native vegetation), S_{nat} – share of native vegetation in landscape, CMI_{grass} – CMI (grassland), S_{grass} – share of grassland in the landscape, CMI_{crop} – CMI (cropland), S_{crop} – share of cropland in the landscape	-	
[13] Litter cover	cm	
[13] Biological soil cover	cm	
[12] Soil carbon/nitrogen ratio (0-20cm)	-	
[17] C/N ratio in soil (0-100 cm)	-	
[4] TN - total nitrogen in topsoil (0-20cm)	g * kg ⁻¹	
[4] Net N mineralisation	mg * kg ⁻¹	
[6] Total N content in soil samples (0-20 cm), calculated from dry combustion data	%	
[7] Nitrogen mineralization	kg TN * ha ⁻¹ * yr ⁻¹	
[20] Net N mineralisation	mg * kg ⁻¹	
[8] Soil nitrogen availability: Soil organic nitrogen variation	kg N * ha ⁻¹ * yr ⁻¹	
[8] Soil nitrogen availability: Mean, maximal and minimal soil nitrate concentration over a time period	mg NO ₃ -N * kg dry soil ⁻¹	
[12] Total nitrogen in soil (0-20 cm, 20-60 cm)	g * kg ⁻¹	
[14] Soil total nitrogen concentration in top soil (0-5 cm) and rooting layer (5-60 cm)	%, g * g ⁻¹	
[14] Soil total nitrogen stock in top soil (0-5 cm) and rooting layer (5-60 cm)	kg * ha ⁻¹	

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[15] Amount of organic nitrogen stocked or destocked within the soil	kg N * ha ⁻¹ * yr ⁻¹	
[15] Mean nitrate concentration in topsoil (0–30 cm)	mg NO ₃ ⁻ N * kg dm ⁻¹	
[17] Nitrate leaching	kg NO ₃ ⁻ N * ha ⁻¹ * yr ⁻¹	
[19] Nitrate concentration in seepage water	mg * l ⁻¹ * yr ⁻¹	
[18] Nutrient use efficiency (N): Total harvested biomass in dry matter (DM) produced per unit of nutrient assimilated	kg * kg biomass ⁻¹	
[20] TN - total nitrogen in topsoil (0-20cm)	g * kg ⁻¹	
[4] Plant available phosphorus in topsoil (0-20cm): Bray P	mg * kg ⁻¹	
[6] Soil phosphorous content (0-20 cm), calculated from acetate extraction & ICP data	mg P * kg soil ⁻¹	
[14] Soil total phosphorus concentration in top soil (0-5 cm) and rooting layer (5-60 cm)	%, g * g ⁻¹	
[14] Soil total phosphorus stock in top soil (0-5 cm) and rooting layer (5-60 cm)	kg * ha ⁻¹	
[18] Nutrient use efficiency (P): Total harvested biomass in dry matter (DM) produced per unit of nutrient assimilated	kg * kg biomass ⁻¹	
[19] Nutrient use efficiency (N & P): Total harvested biomass in dry matter (DM) produced per unit of nutrient assimilated	kg * kg biomass ⁻¹	
[19] Phosphorus loss - particulate	kg * ha ⁻¹ * yr ⁻¹	
[20] Plant available phosphorus in topsoil (0-20cm): Bray P	mg * kg ⁻¹	
[6] Soil potassium content (0-20 cm), calculated from acetate extraction & ICP data	mg P * kg soil ⁻¹	
[12] Soil cation exchange capacity (CEC)	cmol * kg ⁻¹	
[12] Exchangeable Ca, Mg, K and Na	cmol * kg ⁻¹	
[4,20] pH in topsoil (0-20cm)	-	

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[6] Soil pH (water)	-	
[12] pH (soil:water = 1:5)	-	
[12] Total equivalent CaCO_3	%	
[12] Electrical conductivity (soil:water = 1:5)	$\text{mS} \cdot \text{cm}^{-1}$	
[5] Indicator of chemical soil quality in topsoil (0-10 cm), based on pH H_2O ; CEC; exchangeable K^+ , Ca^{2+} , Mg^{2+} , Al^{3+} & NH_4^+ and extractable phosphorus concentrations	0.1 - 1	
[13] Soil nutrients (0–10 cm)	$\text{kg} \cdot \text{ha}^{-1}$	
[9] Soil composition: -pH (in H_2O) -total soil organic matter (SOM) [%] -available phosphorus (P) [$\text{mg} \cdot \text{kg}^{-1}$] -potassium (K) [$\text{mg} \cdot \text{kg}^{-1}$] -calcium (Ca) [$\text{cmolc} \cdot \text{kg}^{-1}$] -magnesium (Mg) [$\text{cmolc} \cdot \text{kg}^{-1}$] using the Mehlich-3 method -bulk density [$\text{g} \cdot \text{cm}^{-3}$]	-	
[10] Chemical soil fertility indicator based on a principal component analysis (PCA) of 20 variables evaluated at 0–10 cm and 10–20 cm. Variables included: -C and N contents -Cation exchange capacity (CEC) -Al saturation -Concentrations of Ca, K, Mg, P Bray II, Al, B, Fe, Mn, Cu, Zn -Soil pH measured in 2:1 water solution Variables with significant contribution (>50 % of the maximum value) to either of the first two principal component axes were selected and their contribution to PCA axes 1 and 2 multiplied by the overall variability explained by each PCA axis. These weighted factors were summed up and scaled to a range of 0.1 - 1.0.	Index 0.1 - 1.0	
[12] Decomposition rate of commercially available tea bags (weight loss)	$\text{g} \cdot \text{d}^{-1}$	
[12] Decomposition rate of commercially available tea bags (stabilization factor); factor associated with labile compounds that become recalcitrant and do not decompose.	Range 0 - 1	
[4] Microbial biomass of bacteria and fungi in topsoil (0-20cm), based on characterization by extracted phospholipid fatty acids (PLFAs)	$\text{mg C} \cdot \text{g}^{-1}$	

[6] Biomass of bacteria, saprophytic fungi and arbuscular mycorrhizal fungi (0-20 cm), calculated from phospho- and neutral lipid fatty acid analysis data (PLFA, NLFA) data	nmol * g soil ⁻¹	
[20] Microbial biomass of bacteria and fungi in topsoil (0-20cm), based on characterization by extracted phospholipid fatty acids (PLFAs)	mg C * g ⁻¹	
[12] Enzyme activity: soil analysis for -N-acetyl-β-glucosaminidase (NAG) -β-glucosidase (β-G) -butyrate esterase (BUT) -acid phosphatase (AP) -arylsulphatase (ARYL) -β-xylosidase (XYL) -cellulose (CELL) -acetate esterase (AC) activity	kat	
[12] Sum of soil enzyme activity: sum of the percentage of the maximum value found for a specific enzymatic response across all enzymes investigated	-	
[11] Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: i – variable I measured, i_{max} – maximum ecological potential of variable I in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log (\frac{i}{i_{max}})$ is subtracted from the sum instead of added. a) with a focus on "nutrient retention and release", variables for this ecosystem service were: -Soil organic matter [% dw] -Earthworm abundance [number * m⁻²] -pH in KCl -Potential C mineralization [mg C * kg soil⁻¹ * week⁻¹] -Potential N mineralization [mg N * kg soil⁻¹ * week⁻¹] -Water-soluble P (Pw) and extractable P (PAL) b) with a focus on "fragmentation and mineralization of soil organic matter", variables for this ecosystem service were: -Soil organic matter [% dw] -Earthworm abundance [# * m⁻¹] -Bacterial biomass [mg C * g dw⁻¹] -Physiological diversity bacteria [biolog. CLPP: Hill's slope] -Potential C mineralization [mg C * kg soil⁻¹ * week⁻¹] -Potential N mineralization [mg N * kg soil⁻¹ * week⁻¹]		 , 

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[16] Soil fertility, indicated by high organic matter, low bulk density, high soil nutrient contents: -Soil organic matter [%] -Bulk density [$\text{g} \cdot \text{cm}^{-3}$] -Percent weight of C [%] -Percent weight of N [%] -C:N Ratio [-]		
[42] SOC in top soil (0–20 cm) at the end of a 30-year simulation period	Mg of carbon / hectare	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[22] Topsoil carbon stock: calculated from bulk density and total C content at 0–10, 10–20, and 20–30 cm depths	Mg C * ha^{-1}	
[22] Soil chemical quality index based on exchangeable Ca^{2+} , Mg^{2+} , K^{+} , Al^{3+} and NH_4^{+} , and extractable P contents at a 0–10 cm depth	0.1 - 1	
[24] Index of soil quality BISQ (richness; structure; function)	Not provided	
[23] Vegetation diversity: four-level index based on the number of plant species	poor-fair-good-excellent	
[24] Earthworm biomass and diversity	$\text{g} \cdot \text{m}^{-2}$, species # * m^{-2}	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[26] Soil organic carbon stock (30 cm)	t C * ha^{-1}	
[28] Soil organic carbon content (0-30 cm)	%	 , 
[30] Soil organic carbon stock	t C * ha^{-1}	
[35] Soil organic carbon content	$\text{g} \cdot \text{kg}^{-1}$	
[27] Organic matter layer thickness in topsoil (0-10cm)	cm	
[27] Organic matter content in topsoil (0-10 cm)	% Weight	

[33] Topsoil organic carbon content	%	
[36] Carbon storage in aboveground, belowground, soil, and dead organic carbon, calculated with InVEST model based on land use/land cover information	Mg * ha ⁻¹	
[37] Soil carbon stock	kg C * ha ⁻¹	
[23] C _{tot} : Total carbon content in soil sample (0-7.5 cm), measured as weight loss on ignition	%	
[23] C _{org} : Organic carbon content in soil sample (0-7.5 cm,) measured by wet combustion (Cr ₂ O ₇ oxidation) and colorimetric analysis	%	
[23] C _{labile} : Labile carbon content in soil sample (0-7.5 cm), measured by oxidation with 333 mM KMnO ₄ and spectral analysis at 565 nm	%	
[23] CMI: Carbon management index, calculated as: $CMI = \frac{C_{totagr}}{C_{totnat}} * \frac{C_{labileagr}}{C_{non-labileagr}} * \frac{100}{\frac{C_{labilenat}}{C_{non-labilenat}}}$ With: C _{totagr} – C _{tot} in agricultural site, C _{totnat} – C _{tot} under native vegetation, C _{labileagr} – C _{labile} in agricultural site, C _{non-labileagr} – C _{non-labile} in agricultural site, C _{labilenat} – C _{labile} under native vegetation, C _{non-labilenat} – C _{non-labile} under native vegetation		
[23] LCMI: Landscape carbon management index, calculated as: $LCMI = CMI_{nat} * S_{nat} + CMI_{grass} * S_{grass} + CMI_{crop} * S_{crop}$ With: CMI _{nat} – CMI (native vegetation), S _{nat} – share of native vegetation in landscape, CMI _{grass} – CMI (grassland), S _{grass} – share of grassland in the landscape, CMI _{crop} – CMI (cropland), S _{crop} – share of cropland in the landscape		
[34] Nitrogen loss	kt N	
[35] Total nitrogen content	g * kg ⁻¹	
[35] Total phosphorus content	mg * g ⁻¹	
[25] Total "Energy" of the amounts of nitrogen, potassium and phosphorus in the soil	seJ	
[35] pH	-	

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[29] Soil chemical fertility index. The index is based on the parameters: pH, SOM, total N, available P, Al saturation, cation exchange capacity, and macronutrient concentrations at the 0–10 cm and 10–20 cm depths.	0.1 - 1	
[32] Maintenance of soil fertility: expert based index for ecosystem service provision by land cover class [1-5], multiplied by the area of the land cover class	km ²	 ,  , 
[32] Maintenance of soil fertility value: expert based index for ecosystem service provision by land cover class [1-5]. multiplied by the area of the land cover class and a literature-based monetary value of the ecosystem service	\$ * ha ⁻¹ * yr ⁻¹	 ,  , 
[24] Index of soil quality BISQ (richness; structure; function)	Not provided	
[31] Natural soil production capacity: (for historic analyses in Germany) Prussian Taxation soil production capacity index	1 - 8	 , 
[31] Natural soil production capacity: (for Germany) German soil inventory production potential index (for historical analyses); index value represents the percentage of potential yield relative to most productive soils in Germany.	1 - 100	 , 
[29] Bio-indicator: Presence of specific ant species is used as an indicator for high, medium or low provision of this ES. Suitable indicator species must first be identified by a correlation between presence of species and ecosystem service provision.	low-medium-high	
[24] Earthworm biomass and diversity	g * m ⁻² , species # * m ⁻²	

Table 4: National Scale

Indicator	Unit	Indicator values from
[39] Soil organic carbon in topsoil layer	t	
[38] Soil fertility: Expert assessment for each land use class based on chemical (e.g., N, P, K, Ca), physical (e.g., aggregate stability; bulk density; percolation stability), and biological (e.g., mycorrhizae; microbial biomass; earthworm biomass) indicators	very negative (-3) to very positive (+3)	
[40] Area of N fixing crops	ha, m ²	
[24] Index of soil quality BISQ (richness; structure; function)	Not provided	
[24] Earthworm biomass and diversity	g * m ⁻² , species # * m ⁻²	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
^[41] Nutrient regulation: Index values for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	
^[24] Index of soil quality BISQ (richness; structure; function)	Not provided	
^[24] Earthworm biomass and diversity	g * m ⁻² , species # * m ⁻²	

Table 6: Global Scale

Indicator	Unit	Indicator values from
^[24] Index of soil quality BISQ (richness; structure; function)	Not provided	
^[24] Earthworm biomass and diversity	g * m ⁻² , species # * m ⁻²	

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Ecosystem Service	Chemical condition of freshwaters
CICES class name	Regulation of the chemical condition of freshwaters by living processes
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.5.1

Brief Description

- Controlling the chemical quality of freshwater
- Maintenance of good chemical condition of freshwater by plant or animal species that enable human use
- This class should be used “where anthropogenic waste and pollution input is minimal, and a more natural regime maintains the quality of water bodies concerned and where this contributes to human well-being” (Haines-Young, 2023). For mitigating effects of strong anthropogenic contaminations, classes 2.1.1.1 (Biotic remediation of waste) and 2.1.1.2 (Biotic filtration, sequestration and storage of waste) should be used.

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[5] Seepage rate - amount of water that leaves the rooting zone toward the groundwater table	mm * yr ⁻¹	
^[6] Seepage rate - amount of water that leaves the rooting zone toward the groundwater table	mm * yr ⁻¹	
^[2] Concentration of nitrates in drained water	mg NO ₃ ⁻ * l ⁻¹	
^[5] Nitrate concentration in seepage water	mg * l ⁻¹	

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[6] Nitrate concentration in seepage water	$\text{mg} \cdot \text{l}^{-1} \cdot \text{yr}^{-1}$	
[10] Soil mineral nitrogen content at the end of summer (0-90 cm, measured between October 1st and November 15th)	$\text{kg} \cdot \text{ha}^{-1}$	
[4] Nitrate leaching	$\text{kg NO}_3^- \cdot \text{N} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$	
[9] Nitrate leaching prevention: nitrate concentration in drained water	$\text{mg NO}_3^- \cdot \text{l}^{-1}$	
[8] NO_3^- loss through leaching and runoff, following cover crop or fallow period	$\text{kg} \cdot \text{ha}^{-1}$	
[11] Groundwater: annual total nitrate (NO_3^- -N) leached at the bottom of the soil profile	$\text{kg} \cdot \text{ha}^{-1}$	
[1] Nitrogen mineralization	$\text{kg N}_{\text{tot}} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$	
[11] Surface water: annual total phosphorus yield in runoff	$\text{kg} \cdot \text{ha}^{-1}$	
[8] Dissolved P loss through leaching and runoff, following cover crop or fallow period	$\text{kg} \cdot \text{ha}^{-1}$	
[7] Total P leached from experimental pot 1 day after applying phosphorus solution	μg	
[5] Phosphorus loss (particulate phosphorus removed by water erosion)	$\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$	
[6] Phosphorus loss (particulate phosphorus removed by water erosion)	$\text{kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$	
[6] Erosion by water	$\text{t} \cdot \text{ha}^{-1}$	
[2] Concentration of pesticides in drained water	$\mu\text{g} \cdot \text{l}^{-1}$	
[6] Share of years within management period in which protection plant products were used	%	
[42] Mineral nitrogen content in soils (0–90 cm), calculated as the sum of NO_3^+ -N and NH_4^+ -N	kg/ha	
[42] Soil phosphorus extractable in calcium-chloride (0–10 cm)	p.p.m.	
[42] Soil phosphorus (0–10 cm) measured as Olsen-P	p.p.m.	

[3] Natural attenuation/ clean groundwater: Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: I – indicator value, i – variable i measured, i_{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log (\frac{i}{i_{max}})$ is subtracted from the sum instead of added. For this ecosystem service, variables were: -Soil organic matter [% dw] -Bacterial biomass [mg C * g dw⁻¹] -pH in KCl -Physiological diversity bacteria [bBiolog. CLPP: Hill's slope] -Water-soluble P (Pw) and extractable P (PAL)		 , 

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[14] Share of nitrogen retained during water passage between agricultural sub-catchment and sea	%	
[12] Share of waterways protected by buffers. The index is calculated by dividing the observed value with a target value. Target values may be average or maximum values found in region, or empirical values from literature. If the calculated index is higher than 1, it is set to one.	Index 0 - 1	
[13] Macroinvertebrates: index based on number of aquatic macroinvertebrates species	poor - fair - good - excellent	
[13] Turbidity: index based on the turbidity of water in the stream channel	poor - fair - good - excellent	
[14] Share of farmers that express clearly a value and care for the health of the land	%	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[20] Freshwater supply: Annual groundwater recharge	cm * yr ⁻¹	 , 
[15] N export with seepage water	kg N * ha ⁻¹	
[28] Nitrogen leaching	kg N * ha ⁻¹ * yr ⁻¹	

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[31] Nitrate leaching	$\text{kg} * \text{ha}^{-1} * \text{yr}^{-1}$	
[11] Groundwater: annual total nitrate ($\text{NO}_3\text{-N}$) leached at the bottom of the soil profile	$\text{kg} * \text{ha}^{-1}$	
[33] Potential nitrate leaching, estimated from agricultural productivity and associated inputs	$\text{kg NO}_3^- * \text{ha}^{-1} * \text{yr}^{-1}$	
[23] Risk of nitrate leaching: exchange frequency of the soil water in the root layer. Infiltration rate divided by field capacity	%	
[14] Share of nitrogen retained during water passage between agricultural sub-catchment and sea	%	
[35] Water purification: Nitrogen retention	$\text{g N} * \text{yr}^{-1} * \text{m}^{-2}$	
[21] Groundwater quality: Probability of groundwater nitrate concentration <3.0 mg per litre	0 - 1	 ,  , 
[26] Nitrogen retention at watershed level calculated with InVEST's Nutrient Retention Model. Calculation based on nitrogen loading and vegetation filtering value for different land-use classes.	$\text{t N} * \text{yr}^{-1} * \text{grid cell}^{-1}$	
[29] Total nitrogen export that reaches the nearest stream, calculated with InVEST model	$\text{t} * \text{ha}^{-1}$	
[11] Surface water: annual total phosphorus yield in runoff	$\text{kg} * \text{ha}^{-1}$	
[20, 21] Surface-water quality: Annual phosphorus loading, calculated using the InVEST model	$\text{kg} * \text{ha}^{-1}$	 ,  , 
[29] Total phosphorus export that reaches the nearest stream, calculated with InVEST model	$\text{t} * \text{ha}^{-1}$	
[15] P export with seepage water	$\text{kg N} * \text{ha}^{-1}$	
[28] Phosphorus loss	$\text{kg P} * \text{ha}^{-1} * \text{yr}^{-1}$	
[18] Phosphorus retention, calculated with InVEST model	$\text{kg} * \text{ha}^{-1}$	
[16] Total N and P loading in lakes	$\text{t} * \text{yr}^{-1}$	
[16] Outflow N and P loading in lakes	$\text{t} * \text{yr}^{-1}$	
[16] N and P retention in lakes	$\text{t} * \text{yr}^{-1}$	
[16] N and P concentration in lakes	$\text{mg} * \text{l}^{-1}$	

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[25] Water quality: concentrations of nitrogen, phosphorus, and sediments (including suspended solids and turbidity)	mg * l ⁻¹	
[30] Leakage of nutrients	kg * ha ⁻¹ * yr ⁻¹	
[30] Turnover rates of nutrients, e.g., N, P	kg * yr ⁻¹	
[30] Total dissolved solids	mg * l ⁻¹	
[30] Decomposition rate of organic matter	kg * ha ⁻¹	
[34] Water quality of freshwater ecosystems	Not provided	
[30] Area occupied by riparian forests	ha	
[24] Share of natural forest cover in municipality's surface. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	%	
[17] Area of buffer strips alongside rivers. Buffer strips are defined as areas connected to the river system and belonging to the land use classes: pasture, open space/heathland, woodland/single tree, tree hedgerow/hedgerow, arable field boundaries, grassland boundaries, deciduous tree dominated forest, coniferous tree dominated forest, or peatland	m ²	
[17] Arable land uphill from buffer strips alongside rivers	m ²	
[17] Arable land on slopes steeper than 3% uphill from buffer strips alongside rivers	m ²	
[17] Potential erosion from buffer strips and the area uphill from them (using RUSLE equation)	t * yr ⁻¹	
[19] Mechanical filtration capacity: infiltration capacity, calculated as: $IC = s_p * (1 - s)$ With: IC – infiltration capacity, s _p – soil permeability [cm/day], s – share of anthropogenic surface sealing)	cm * d ⁻¹	 , 
[19] Physicochemical filtration capacity, calculated as: $C = CEC_{eff} * (1 - s)$ With: C – physicochemical filtration capacity, CEC _{eff} – effective cation exchange capacity, s – share of anthropogenic surface sealing	cmol(+) * kg dm ⁻¹	 , 
[22] Water purification: values for land cover classes. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0 - 5	

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[27] Mediation of water pollution such as excess nitrogen removal: expert based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class	km ²	
[27] Mediation of water pollution such as excess nitrogen removal value: expert based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class and a literature-based monetary value of the ecosystem service	\$ * ha ⁻¹ * yr ⁻¹	
[32] Water purification and provision, calculated as: $W = NPP * (1 - VCNPP) * IC_s * S_{cf} * 1.75$ With: W – water purification and provision, NPP – Net Primary Production calculated from NDVI-values and expressed on a relative scale set to [0 – 1000], VCNPP – coefficient of variation of NPP [0 – 1], IC_s – soil infiltration capacity [0 – 1], S_{cf} – slope average correction factor of the study area [0 – 1]	-	
[32] Waste purification, calculated as: $W = NPP * (1 - VCNPP) * I_w * O_w * 1.75$ With: W – waste purification, NPP – Net Primary Production [0 - 1000], VCNPP – coefficient of variation of NPP [0 – 1], I_w – water input to the system [0 – 1], O_w – water bodies occupancy percentage and flat floodplain area [0 – 1]	-	
[14] Share of farmers that express clearly a value and care for the health of the land. Values were scaled to [0-1]	%	
[40] Volume of purified water	m ³ /(km ² * year)	
[40] Mass of a specific nutrient retained	ton/ (km ² * year)	
[41] Area of undisturbed creek banks that serve as buffers to pesticide and fertilizer runoff	n/a	

Table 4: National Scale

Indicator	Unit	Indicator values from
[37] Denitrification capacity	kg N * ha ⁻¹ * yr ⁻¹	
[37] Phosphorus sorption capacity	kg P * ha ⁻¹ * yr ⁻¹	
[38] Chemical status	Not provided	
[38] Ecological status	Not provided	
[34] Water quality of freshwater ecosystems	-	

Appendix – Ecosystem Services

[36] Water quality: Expert assessment for each land use class, based on the indicators: nutrient efficiency; pesticides (units not given)	very negative (-3) to very positive (+3)	
[38] Groundwater: Indicators of groundwater quality	Not specified	
[38] Wetlands: Potential of water purification of wetlands	Not specified	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[34] Water quality of freshwater ecosystems	-	
[35] Water purification: Nitrogen retention	g N * yr ⁻¹ * m ⁻²	
[39] Water purification: values for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	

Table 6: Global Scale

Indicator	Unit	Indicator values from
[34] Water quality of freshwater ecosystems	-	

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^{15*} The impact area discussed on this factsheet is not a focus of the cited paper

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No.	Citation
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Ecosystem Service	Chemical condition of salt waters
CICES class name	Regulation of the chemical condition of salt waters by living processes
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.5.2

Brief Description

- Controlling the chemical quality of salt water
- Maintenance of the chemical condition of salt waters by plant or animal species that enable human use or health
- This class should be used “where anthropogenic waste and pollution input is minimal, and a more natural regime maintains the quality of water bodies concerned and where this contributes to human well-being.” (Haines-Young, 2023) . For mitigating effects of strong anthropogenic contaminations, classes 2.1.1.1 (Biotic remediation of waste) and 2.1.1.2 (Biotic filtration, sequestration and storage of waste) should be used.

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[7] NO ₃ – loss through leaching and runoff, following cover crop or fallow period	Not provided	
^[7] Dissolved P loss through leaching and runoff, following cover crop or fallow period	Not provided	
^[8] Nitrate leaching prevention: nitrate concentration in drained water	mg NO ₃ * liter of drained water ⁻¹	

Table 2: Farm Scale

Indicator	Unit	Indicator values from

Appendix – Ecosystem Services

[3] Share of nitrogen retained during water passage between agricultural sub-catchment and sea.	%	
[3] Share of farmers that express clearly a value and care for the health of the land.	%	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[1] Phosphorus retention, calculated with InVEST model	kg * ha ⁻¹	
[6] Costal nitrogen load per agricultural area in the watershed: amount of nitrogen leached from soils (and not retained) that reaches the coast, divided by the agricultural area	t * ha ⁻² * yr ⁻¹	 , 
[9] Nitrogen retention at watershed level calculated with InVEST's Nutrient Retention Model. Calculation based on nitrogen loading and vegetation filtering value for different land-use classes	t N * yr ⁻¹ * grid cell ⁻¹	
[11] Leakage of nutrients	kg * ha ⁻¹ * yr ⁻¹	
[11] Turnover rates of nutrients, e.g., N, P	kg * yr ⁻¹	
[11] Total dissolved solids	mg * l ⁻¹	
[11] Decomposition rate of organic matter	kg * ha ⁻¹	
[2] Water purification: ecosystem service supply depends on the land cover class. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was and used in this study.	Index 0-5	
[3] Share of nitrogen retained during water passage between agricultural sub-catchment and sea.	%	
[3] Share of farmers that express clearly a value and care for the health of the land.	%	
[10] Mediation of water pollution such as excess nitrogen removal: expert based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class [km ²]	Index 1-5 * km ⁻²	 ,  , 
[10] Mediation of water pollution such as excess nitrogen removal value: expert based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class [km ²] and a literature-based monetary value of the ecosystem service	\$ * ha ⁻¹ * yr ⁻¹	 ,  , 
[11] Area occupied by riparian forests	ha	
[12] Mass of a specific nutrient retained	ton/ (km ² * year)	
[12] Volume of purified water	m ³ /(km ² * year)	

Table 4: National Scale

Indicator	Unit	Indicator values from
[5] Indicators of groundwater quality	Not specified	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[4] Water purification: Values for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0-5	

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No.	Citation
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¹⁶* The impact area discussed on this factsheet is not a focus of the cited paper

Ecosystem Service	Chemical composition of atmosphere and oceans
CICES class name	Regulation of chemical composition of atmosphere and oceans
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.6.1

Brief Description

- Regulating our global climate
- Regulation of the concentrations of gasses in the atmosphere that positively impact in global climate
- Regulation of the concentration of chemical substances in the oceans, which has a positive impact on humans

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[29] Long term carbon stabilization: Carbon content in microaggregate-within-macroaggregate fraction (c.f. Six & Paustian, 2014. DOI: 10.1016/j.soilbio.2013.06.014)	Not provided	
[42] Soil organic carbon content (0–10 cm)	Not provided	
[55] Soil organic carbon (SOC) stock (0-20cm)	Mg * ha ⁻¹	 , 
[14] Carbon stock in soil (0-30 cm)	Mg * ha ⁻¹	
[24] Soil organic carbon (0–30 cm) after 20 years of management	Mg * ha ⁻¹	
[25] Soil organic carbon (0–30 cm) after 20 years of management	Mg * ha ⁻¹	
[14] Carbon in trees (dbh≥10 cm) and bushes (dbh <10 cm, height >2 m)	Mg * ha ⁻¹	
[37] Carbon stored in aboveground woody biomass; carbon stored in topsoil (0–20 cm)	Mg * ha ⁻¹	

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[38] Carbon storage in aboveground biomass (sum of herbaceous and tree components) and soils (upper 20 cm)	Mg * ha ⁻¹	
[44] Amounts of carbon fixed in the soil and in the annual organs of orchard trees	kg * ha ⁻¹ * yr ⁻¹	
[33] Carbon sequestered in soil and orchard-trees	kg * ha ⁻¹ * unit time ⁻¹	
[51] Climate regulation: annual net ecosystem exchange (NEE) of carbon	Mg C * ha ⁻¹	
[44] Prevention of N denitrification: yearly amount of denitrified nitrogen	kg N ₂ O-N * ha ⁻¹ * yr ⁻¹	
[33] Greenhouse gas mitigation: Cumulative denitrified nitrogen	kg N ₂ O-N * ha ⁻¹ * unit time ⁻¹	
[54] Greenhouse gas emissions	CO ₂ equ. * ha ⁻¹	
[23] Net global warming impact of soil carbon sequestration, agronomic N fertilizer application, lime application, fuel usage, nitrous oxide (N ₂ O) emissions, and methane (CH ₄) oxidation	g CO ₂ e * m ⁻² * yr ⁻¹	 , 
[33] Greenhouse gas mitigation: Cumulative amounts of CO ₂ emitted by agricultural operations	kg C * ha ⁻¹ * unit time ⁻¹	 , 
[38] Emissions of GHG (CO ₂ , CH ₄ , N ₂ O) measured by static chamber techniques in the field	CO ₂ equ.	
[43] Emissions of CO ₂ and N ₂ O	Not provided	
[41] Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: i – variable i measured, i_{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, log ($\frac{i}{i_{max}}$) is subtracted from the sum instead of added. For this ecosystem service, variables were: -Soil organic matter [% dw] -Bacterial biomass [mg C /g dw] -pH in KCl -Physiological diversity bacteria [biolog. CLPP: Hill's slope]	-	 , 
[58] SOC in top soil (0–20 cm) at the end of a 30-year simulation period	Mg of carbon / hectare	
[59] SOC in top soil (0–20 cm)	tons / hectare	

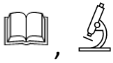
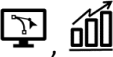
Table 2: Farm Scale

Indicator	Unit	Indicator values from
[34] Climate regulation: Vegetation cover [%], expressed as a four-level index	poor-fair-good-excellent]	
[53] Vegetation carbon stock: Above ground dry biomass of trees, bushes, and herbaceous plants	Mg C * ha ⁻¹	

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[53] Topsoil carbon stock: calculated from bulk density and total C content at 0–10, 10–20, and 20–30 cm depths	Mg C * ha ⁻¹	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[1] Carbon sequestration	kg * ha ⁻¹ * yr ⁻¹	
[15] Carbon sequestration rate (above and belowground)	Mg * ha ⁻¹ * yr ⁻¹	
[36, 47] Carbon sequestration rate: sum of above and below ground crop and tree biomass and soil organic carbon (SOC)	t * ha ⁻¹ * yr ⁻¹	
[5] Carbon sequestration: annual change in above- & below ground biomass. Values are monetarized based on an estimated social cost of carbon of \$43/ton.	\$ * ha ⁻¹ * yr ⁻¹	
[4] Carbon sequestration in soil & biomass	kg C * ha ⁻¹	
[9] Organic carbon stored in soils and above- and belowground biomass, divided by area	kg * m ⁻²	
[3] Carbon sequestered in above- and belowground biomass of woody species	t CO ₂ eq. * ha ⁻¹ * yr ⁻¹	
[16] Carbon sequestration: Amount of carbon that is sequestered from land use, land use change and forestry	C * km ⁻² * yr ⁻¹	
[52] Above- and belowground carbon stored in living plant material.	t C * ha ⁻¹ * yr ⁻¹	
[31] Carbon sequestration: identification of areas with peat soils or carbon-rich semi-terrestrial areas	Not provided	
[21] Carbon sequestration: Values based on land use by assigning a country-specific, land use type specific emission factor to each land use type. The emission factor also considers forest age and soil carbon stock.	Not provided	
[49] Soil organic carbon stock, values for CORINE land cover classes	t C * ha ⁻¹	
[26] Carbon stock of above- and below ground phytomass within different land cover classes	Mg C * ha ⁻¹	
[35] Carbon storage: Carbon stored in aboveground biomass, belowground biomass, and soils; calculated by combining the InVEST model with wood production figures.	Mg * ha ⁻¹	
[36] Carbon stock: sum of above and below ground crop and tree biomass and soil organic carbon (SOC)	t C * ha ⁻¹	
[21] Carbon stocks in soil and vegetation. Based on land use by assigning a region-specific, age-specific biomass carbon stock to the land use types "forest" and "(semi-)natural vegetation"	Not provided	
[40] Carbon stored in soil and biomass. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	t C * ha ⁻¹	
[46] Carbon stock in living biomass, deadwood, litter, and soils	t C * ha ⁻¹	

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[47] Annual carbon stock: above and below ground biomass, soil organic carbon	$t\ C * ha^{-1}$	
[45] Carbon stored in aboveground biomass, belowground biomass, soil and dead organic matter (calculated with InVEST's Carbon Storage and Sequestration model). Values for all pools per land-use class were taken from Japan's National Greenhouse Gas Inventory Report.	$t * ha^{-1} * grid\ cell^{-1}$	
[49] Total carbon stock for CORINE land cover classes, calculated as the sum of aboveground biomass, belowground biomass, litter and soil organic carbon	$t\ C * ha^{-1}$	 ,  , 
[27] Total carbon stored in landscape, calculated with InVEST model	Mg	
[12] Carbon storage capacity	$t\ C * ha^{-1}$	
[17] Carbon flow change: Carbon stock in vegetation (above- and belowground) + soil organic carbon stock (1 m). Values are compared to values for a reference situation.	$t\ C * ha^{-1}$	 , 
[10] Greenhouse gas emissions	1000 t CO ₂ eq.	
[19] Greenhouse gas balance of entire agricultural production system, including emissions from soils and fabrication of fertilizers and machinery	CO ₂ eq. * $ha^{-1} * yr^{-1}$	 , 
[8] Climate change mitigation: Annual carbon sequestration and GHG emissions, using the methodology for the LULUCF sector in Finland's National Inventory of greenhouse gases	CO ₂ equ. * km^{-2}	 , 
[49] Annual Gross Primary Production, based on "Moderate Resolution Imaging Spectroradiometer (MODIS) 17" satellite datasets	$t\ C * ha^{-1} * yr^{-1}$	 ,  , 
[49] Annual total Net Primary Production, based on "Moderate Resolution Imaging Spectroradiometer (MODIS) 17" satellite datasets	$t\ C * ha^{-1} * yr^{-1}$	 ,  , 
[18] Carbon capture: $NPP \times (1 - VC_{NPP}) \times (1 - Ow)$; where NPP: Net Primary Production calculated from NDVI-values and expressed on a relative scale set to (0 - 1000), VC_{NPP} : coefficient of variation of NPP (0 - 1), Ow: water bodies occupancy percentage and flat floodplain area (0 - 1). Ow is used to reflect that water cover is negatively correlated with plant cover and therefore by proxy with carbon capture	-	
[50] Carbon sequestration and oxygen production: net primary productivity	$t\ C * area^{-1} * yr^{-1}$	
[51] Climate regulation: annual net ecosystem exchange (NEE) of carbon	Mg C * ha^{-1}	
[52] Net ecosystem productivity	$t\ C * ha^{-1} * yr^{-1}$	
[48] Carbon sequestration: net primary productivity (NPP) using CASA (Carnegie-Ames-Stanford Approach) ecosystem model	gC * ha^{-1}	
[8] Airborne nutrient input: Exceedance of empirical critical loads of nitrogen in Natura 2000 sites	mg N * m^{-2}	 , 
[13] "Emergy" of O ₂ release by crops (derived from yield and a dollar price for O ₂) and "emergy" of CO ₂ absorption soils (based on organic matter accumulation)	solar equivalent Joules	

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[20] Index based on: a) Carbon storage: aboveground carbon in living biomass and soil carbon in the surface layer (0–20 cm) [tons C/ha] b) Greenhouse gas emissions: Emissions of CO ₂ , CH ₄ , and N ₂ O measured at monthly intervals [CO ₂ equ. flux] Both a and b were scaled to a range of 0.1-1 (whereby 0.1 denotes the highest GHG emissions) and averaged.	-	
[20] Bio-indicator: Presence of specific ant species is used as an indicator for high, medium or low provision of this ES. Suitable indicator species must first be identified by a correlation between the presence of species and ES provision.	low-medium-high	
[28] Global climate regulation: values for ecosystem service supply based on land cover classes. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
[49] Global climate regulation service, expert-based index values for CORINE land cover classes published by Burkhard et al. (2014, DOI: 10.3097/LO.201434).	Index 0-5	 ,  , 
[1] NO ₂ dry deposition velocity	mm * s ⁻¹ * ha ⁻¹	 , 
[57] Amount of carbon stored in the above/below ground biomass and soil over a specified amount of time (e.g. 20-years)	ton / km ²	

Table 4: National Scale

Indicator	Unit	Indicator values from
[2] GHG emissions: methane (CH ₄) from livestock (both through the production of manure and enteric fermentation); nitrous oxide (N ₂ O) from the application of inorganic fertilizers; and carbon dioxide (CO ₂) associated with changes in carbon stocks in above and below ground biomass (making allowance for soil type) and from the burning of fossil fuels to power agricultural machinery and production of fertilizers and pesticides	CO ₂ equ. * area ⁻¹ * yr ⁻¹	
[2] GHG emissions: as above, valuation based on UK official non traded carbon value	Money * area ⁻¹ * yr ⁻¹	
[11] GHG emissions from agriculture	t CO ₂ eq.	
[21] Carbon sequestration. Based on land use by assigning a country-specific, land use type specific emission factor to each land use type. The emission factor also considers forest age and soil carbon stock.	Not provided	
[22] Carbon sequestration by farm afforestation	t CO ₂ eq. * ha ⁻¹ * yr ⁻¹	
[39] Carbon sequestered by permanent crops and grassland	Not specified	

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[7] Carbon stored in vegetation and soils	kg C * m ⁻²	
[21] Carbon stocks in soil and vegetation. Based on land use by assigning a region-specific, age-specific biomass carbon stock to the land use types "forest" and "(semi-)natural vegetation"	Not provided	
[6] Global climate: Expert assessment for each land use class based on the indicators: CO ₂ , CH ₄ , N ₂ O, NO, and soot emissions	very negative (-3) to very positive (+3)	
[6] Air quality: Expert assessment for each land use class based on the indicators: nitrous oxide, ammonia, and soot emissions; trees	very negative (-3) to very positive (+3)	
[56] NO ₂ deposition velocity: calculated as a linear function of wind speed at 10m height and land cover type.	mm/s	
[56] NO ₂ removal flux calculated as the product of modelled NO ₂ concentration and deposition velocity. Deposition velocity is calculated as a linear function of wind speed at 10m height and land cover type.	t/(ha*year)	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[16] Carbon sequestration: Amount of carbon that is sequestered from land use, land use change and forestry	C * km ⁻² * yr ⁻¹	
[32] Global climate regulation: values for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0-5	

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Ecosystem Service	Local regulation of air temperature and humidity
CICES class name	Regulation of temperature and humidity, including ventilation and transpiration
CICES Section	Regulation & Maintenance (Biotic)
CICES Class code	2.2.6.2

Brief Description

- Mediation of ambient atmospheric conditions (including micro- and mesoscale climates) by virtue of presence of plants
- Regulating the physical quality of air to create a local climate that is beneficial for people or their property

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[7] Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: i – variable i measured, i_{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log (\frac{i}{i_{max}})$ is subtracted from the sum instead of added. For this ecosystem service, variables were: -Soil organic matter [% dw] -Bacterial biomass [mg C /g dw] -pH in KCl -Physiological diversity of bacteria [biolog. CLPP: Hill's slope]	-	 , 

Appendix – Ecosystem Services

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[4] Canopy shading: four-level index based on the degree of canopy shading	poor-fair-good-excellent	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[1] Cool air production	$\text{m}^3 * \text{ha}^{-1} * \text{h}^{-1}$	
[1] Leaf area index	-	
[1] Albedo	%	
[6] Evapotranspiration (local climate regulation). Values were normalized [0-1] using benchmark values where available and observed values otherwise.	mm	
[2] Local climate regulation: values for ecosystem service supply based on the land cover class. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
[8] Local climate regulation: expert-based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class [km^2]	Index 1-5 * km^2	 ,  , 
[8] Local climate regulation value: expert-based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class [km^2] and a literature-based monetary value of the ecosystem service	$\$ * \text{ha}^{-1} * \text{yr}^{-1}$	 ,  , 
[9] Expert-/stakeholder rating of how much of this ecosystem service can be supplied by a landscape (represented by a land use map)	6-point Lickert-scale (none - highest capacity)	
[9] Expert-/stakeholder rating based on pairwise comparisons of landscapes (represented by land use maps) in an Analytical Hierarchical Process (AHP). Experts select the landscape with higher capacity for supplied this ecosystem service and rate the difference between the two landscapes	1 (equal capacity) - 9 (absolute preference of one land-scape)	

Table 4: National Scale

Indicator	Unit	Indicator values from
[5] Amount of biomass	Not specified	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[3] Local climate regulation: values for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones	Index 0-5	
[3] Air quality regulation: values for Corine land cover classes, based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones	Index 0-5	

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¹⁸* The impact area discussed on this factsheet is not a focus of the cited paper

Ecosystem Service	Recreation through activities in nature
CICES class name	Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through active or immersive interactions
CICES Section	Cultural (Biotic)
CICES Class code	3.1.1.1

Brief Description

- Using the environment for sport and recreation; using nature to help stay fit
- The biophysical characteristics or qualities of ecosystems or species that humans engage with, in ways that require physical and cognitive effort

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[13] Capacity for nature-based recreation: The indicator is based on the vicinity of water, land relief, accessibility from urban areas, presence of HNV farmland and variation in land cover.	-	
^[23] Abundance of birds with hunting value	Not provided	
^[23] Ant species richness as the predictor of the abundance of birds, including those with hunting value.	Not provided	

Appendix – Ecosystem Services

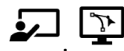
[25] Recreational hunting. Values are based on the following indicators: - Site quality: habitat suitability for prey [low, medium, high] - Site opportunity: population within 1.5 ha travel distance, scaled to [0 -1] - Complementary inputs: availability of campsites in the area [0 -1] - Scarcity: Existence of alternative sites with same quality within the same travel distance [0 -1] - Reliability: Risk of future service loss through urban development within a 3-mile radius [0 -1]	Not provided	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[30] Recreation opportunities: Indicator calculated by a formula derived from survey and expert assessment. Up to five attributes were considered: singular natural resources, scenic beauty, accessibility, tourism attraction capacity, and tourism use aptitude. Results were corrected by carrying capacity of land use types, considering factors such as flora and fauna factor, perimeter area ratio and slope factor.	persons * ha ⁻¹	

Table 2: Regional Scale

Indicator	Unit	Indicator values from
[4] Tourism: Ratio of tourism income to GDP	%	
[7] Potential number of visitors calculated from population statistics and assuming travel distance of 80 km for daily trips and 8 km for short trips	#	
[7] Actual number of visits from surveys or statistics	#	
[24] Density of rural tourism establishments. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	# * km ⁻² Y	
[26] Number of visitors	# * yr ⁻¹	
[14] Zone of visual influence: share of the site that is visible by different user groups (pedestrians, cyclists, small vehicle users, train users) due to the layout of footpaths, roads and rail-networks	%	
[14] Visual quality index (VQI), based on 19 parameters (terrain ruggedness, presence of: waterfalls, wells and springs, area of standing water, length of flowing water, presence of the coast, habitat richness, area of woodland, presence of single	Index 0-1	

Appendix – Ecosystem Services

large trees, number of plant species, hedgerow length, number of vegetation colours, area of human-influenced land, number of spot utilities/quarries, building area, road length, dry-stone walls length, presence of scheduled ancient monuments, presence of designated historic parks or gardens, presence of listed buildings)		
^[29] Forest recreation: share of land that is forested	%	
^[5] Area of natural or semi-natural habitats not affected by roadside noise louder than 55dB(A)	m ²	
^[5] Area of natural or semi-natural habitats not affected by roadside noise louder than 55dB(A) and accessible from the nearest city within a given time constraint	m ²	
^[15] (Designated) recreational trails	km	
^[26] Area covered by recreational landscape	ha	 ,  , 
^[6] Total number of recreational areas	#	
^[9] Recreation & ecotourism potential, calculated based on: *Distance to singular natural resources (e.g., diverse forests, presence of water bodies) [0 -100] *Scenic beauty (viewsheds) [0-100] *Accessibility (gaussian distance to roads) [km] *Tourism attraction capacity (distance to natural attractions concentration [1-100], variety of natural attractions [1-100], distance to tourism services [km]) *Tourism use aptitude [1-100] (based on land cover) Selection and weighing of factors based on expert assessment	Index 0 - 100	
^[9] Recreation & ecotourism opportunities, calculated as: (Recreation & ecotourism potential /100) * ((physical carrying capacity of an area) * (erodibility of the area) * (correction factor for account for fauna) * (perimeter/area ratio))	persons * ha ⁻¹	
^[1] Recreational potential: calculated by a composite model that considers the degree of naturalness, nature protection, and presence of water.	Index 0–1	
^[8] Recreation potential: continuous index, based on presence of certain ecosystems (i.e., forest, coastline), certain ecosystem characteristics (i.e., naturalness) and their accessibility	-	
^[12] Recreational potential, calculated as the sum of scores for density of public rights of way (footpaths, bridleways), the cultural heritage value of land use and proximity of similar alternative sites, each (1-5), multiplied by the score for the population living within 3 km travel distance of any part of the site (1-5)	-	 , 
^[17] Recreation & aesthetic values: values are assigned to different land cover classes. The matrix by Burkhard et al., 2012 (DOI: 10.1016/j.ecolind.2011.06.019) was adapted the and used in this study.	Index 0-5	
^[16] Recreational surface per capita, calculated as recreational areas (forests, abandoned land, water courses and grassland	ha * capita ⁻¹	

Appendix – Ecosystem Services

areas) within a distance of 5 km to settlements divided by the number of residents		
^[19] Recreational potential: the following indicators were normalized, and the average was calculated: - Degree of naturalness: hemeroby index based on the land cover type [1 (natural/ without actual human impact) - 7 (artificial)] - Protected areas: occurrence of protected areas [not provided] - Attractiveness of water bodies: Distance to the nearest stagnant surface water body or water courses of the first or second order	Not provided	
^[22] Recreation potential: (modelled utility value of recreational nature areas (considering both quality of the area and distance to a person) divided by population density)	[0-1]	 , 
^[27] Recreation: expert-based index for ecosystem service supply by land cover class [1-5] multiplied by the area of the land cover class [km ²]	Index 1-5 * km ⁻²	 ,  , 
^[27] Recreation value: expert-based index for ecosystem service supply by land cover class [1-5] multiplied by the area of the land cover class [km ²] and a literature-based monetary value of the ecosystem service	\$ * ha ⁻¹ * yr ⁻¹	 ,  , 
^[11] Spatial mapping by stakeholders: stakeholders could place green stickers on a map to mark the supply hotspots of this ecosystem service. Red stickers were used to mark locations where the supply of this service is declining. Two different sizes of stickers were used to represent a radius of 0.75 km or 1 km, respectively.	Index 0-5	
^[32] Index based on: -naturalness (based on Corine Landcover Class), -level of conservation (based on presence of protected areas) - accessibility to human population (based on distance from areas with high population density)	-	 ,  , 
^[18] Roadside variation: number of "land use patches" intersected by or adjacent to all roads and paths, except motorways and railways, divided by total road length. Values were scaled [0-1]	km ⁻¹	 , 
^[18] Accessibility: Share of the land surface within 100 meters from a road. Values were scaled [0-1]	%	 , 
^[31] (Water activities): Turnover from tourism	\$ * ha ⁻¹	
^[31] (Water activities): Status of fish population	ka * ha ⁻¹	
^[31] (Water activities): Status of fish population	[species and age structure]	
^[31] (Water activities): Median water clarity as a measure of swimming suitability	m	
^[31] (Water activities): Number of sites with excellent bathing quality	#	
^[31] (Water activities): Number of visitors or facilities (e.g., hotels or restaurants)	#	

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[33] Number of visitors arrivals	#	
[33] Number of domestic visitors arrivals	#	
[33] Number of foreign visitors arrivals	#	
[33] Number of active enterprises in the area	#	
[33] Number of active enterprises in agriculture (crop production, support activities to agriculture)	#	
[33] Number of active enterprises in accommodation and food services activities	#	
[33] Number of farms with other gainful activities (agritourism, recreational and social activities)	#	
[33] Number accommodation establishments	#	
[33] Number of hotels and similar establishments	#	
[33] Number of holiday- and other short-stay accommodations, camping grounds, recreational vehicle parks and trailer parks	#	
[34] For services that can be monetized: value of cultural services	USD / km ² * year)	
[34] For services that can not be monetized: qualitative value assessment using Likert-scales	-	
[35] Visibility of creeks from cycle paths	n/a	

Table 4: National Scale

Indicator	Unit	Indicator values from
[2] Number of visits per year	# * area ⁻¹ * yr ⁻¹	
[2] Valuation: Number of visits per year multiplied by value indicator. The value indicator depends on the habitat mix for that location	\$ * area ⁻¹ * yr ⁻¹	
[3] Number of "day leisure visits" (any round trip of less than one day in duration made from home or a holiday destination for leisure purposes)	# * grid cell ⁻¹	
[7] Potential number of visitors calculated from population statistics and assuming travel distance of 80 km for daily trips and 8 km for short trips	#	 ,  , 
[7] Actual number of visits from surveys or statistics	#	 ,  , 
[10] Number of visitors per year	#	
[21] Number of visitors in agricultural areas	Not specified	
[21] Number of rural enterprises offering tourism-related services	Not specified	

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[21] Number of hunting licences	Not specified	
[20] Modelled probability of visitation by recreationists/tourists (0-1), based on land cover class, mean elevation, distance from nearest major road, path density, county and population.	-	 , 
[21] Farm tourism	Not specified	
[21] Walking and biking trails	Not specified	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[8] Recreation potential: continuous index, based on presence of certain ecosystems (i.e., forest, coastline), certain ecosystem characteristics (i.e., naturalness) and their accessibility	-	

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^{19*} The impact area discussed on this factsheet is not a focus of the cited paper

No.	Citation
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Ecosystem Service	Recreation through observation of nature
CICES class name	Characteristics of living systems that enable activities promoting health, recuperation or enjoyment through passive or observational interactions
CICES Section	Cultural (Biotic)
CICES Class code	3.1.1.2

Brief Description

- Watching plants and animals where they live; using nature to destress
- The biophysical characteristics or qualities of ecosystems or species that are viewed/observed by people or enjoyed in other passive ways by virtue of sounds and smells, etc.

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[17] Capacity for nature-based recreation indicator. The indicator is based on the vicinity of water, land relief, accessibility from urban areas, presence of HNV farmland and variation in land cover.	[-]	
^[3] Hedges between agriculture and other use	Not provided	
^[3] Number of elements and land cover types in a viewshed	#	
^[3] Diversity of land cover/ land use types (calculated by adapting Shannon Index 'H', Gini index, or Simpson's Diversity Index' D')	[-]	
^[28] Abundance of large butterflies (species with median wingspan>5.4 cm)	Not provided	

Appendix – Ecosystem Services

[28] Abundance of birds that are either: colourful species, species that people attract to their homes with feeders or species with hunting value	Not provided	
[28] Ant species richness as a predictor of the abundance of birds, including those described above	Not provided	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[3] Hedges between agriculture and other use	Not provided	
[3] Number of elements and land cover types in the viewshed	#	
[3] Diversity of land cover/ land use types (calculated by adapting Shannon Index 'H', Gini index, or Simpson's Diversity Index' D')	-	
[23] Four-level index based on the provision of walking trails/ecotourism/environmental education	poor-fair-good-excellent	
[33] Recreation opportunities: Indicator calculated by a formula derived from survey and expert assessment. Up to five attributes were considered: singular natural resources, scenic beauty, accessibility, tourism attraction capacity, and tourism use aptitude. Results were corrected by carrying capacity of land use types, considering factors such as flora and fauna factor, perimeter area ratio and slope factor.	persons * ha ⁻¹	 ,  , 

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[7] Tourism: Ratio of tourism income to GDP	%	
[18] Average travel cost of tourists	\$ * yr ⁻¹	
[11] Potential number of visitors calculated from population statistics and assuming travel distance of 80 km for daily trips and 8 km for short trips	#	 ,  , 
[11] Actual number of visits from surveys or statistics	#	 ,  , 
[29] Density of rural tourism establishments. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	# * km ⁻²	
[30] Number of visitors	# * yr ⁻¹	 ,  , 

Appendix – Ecosystem Services

[32] Forest recreation: share of land that is forested	%	
[9] Area of natural or semi-natural habitats not affected by roadside noise louder than 55dB(A)	m ²	
[9] Area of natural or semi-natural habitats not affected by roadside noise louder than 55dB(A) and accessible from the nearest city within a given time constraint	m ²	
[19] (Designated) recreational trails	km	
[30] Area covered by recreational landscape	ha	 ,  , 
[10] Total number of recreational areas	#	
[4] Number of areas used for social amenity (e.g., picnic areas) in the area	#	
[13] Recreation & ecotourism potential, calculated based on: *Distance to singular natural resources (e.g., diverse forests, presence of water bodies) [0 -100] *Scenic beauty (viewsheds) [0-100] *Accessibility (gaussian distance to roads) [km] *Tourism attraction capacity (distance to natural attractions concentration [1-100], variety of natural attractions [1-100], distance to tourism services [km]) *Tourism use aptitude [1-100] (based on land cover) Selection and weighing of factors based on expert assessment	Index 0 - 100	
[13] Recreation & ecotourism opportunities, calculated as: (Recreation & ecotourism potential /100) * ((physical carrying capacity of an area) * (erodibility of the area) * (correction factor for account for fauna) * (perimeter/area ratio))	persons * ha ⁻¹	
[1] Recreational potential calculated by a composite model that considers the degree of naturalness, nature protection, and presence of water. Dimensionless index	Index 0-1	
[12] Recreation potential: continuous index, based on presence of certain ecosystems (i.e., forest, coastline), certain ecosystem characteristics (i.e., naturalness) and their accessibility	-	
[16] Recreational potential, calculated as the sum of scores for density of public rights of way (footpaths, bridleways), the cultural heritage value of land use and proximity of similar alternative sites, each (1-5), multiplied by the score for the population living within 3 km travel distance of any part of the site (1-5)	-	 , 
[21] Recreation & aesthetic values: values are assigned to different land cover classes. The matrix by Burkhard et al., 2012 (DOI: 10.1016/j.ecolind.2011.06.019) was adapted the and used in this study.	Index 0-5	
[20] Recreational surface per capita, calculated as recreational areas (forests, abandoned land, water courses and grassland areas) within a distance of 5 km to settlements divided by the number of residents	ha * capita ⁻¹	

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[24] Recreational potential: the following indicators were normalized, and the average was calculated: - Degree of naturalness: hemeroby index based on the land cover type [1 (natural/ without actual human impact) - 7 (artificial)] - Protected areas: occurrence of protected areas [not provided] - Attractiveness of water bodies: Distance to the nearest stagnant surface water body or water courses of the first or second order	Not provided	
[27] Recreation potential: (1- (modelled utility value of recreational nature areas (considering both qualities of the area and distance to a person) divided by population density))	0-1	 , 
[31] Recreation: expert-based index for ES provision by land cover class [1-5] multiplied by the area of land cover class [km ²]	Index 1-5 * km ⁻²	 ,  , 
[31] Recreation value: expert-based index for ecosystem service supply by land cover class [1-5] multiplied by the area of the land cover class [km ²] and a literature-based monetary value of the ecosystem service	\$ * ha ⁻¹ * yr ⁻¹	 ,  , 
[15] Spatial mapping by stakeholders: stakeholders could place green stickers on a map to mark the supply hotspots of this ecosystem service. Red stickers were used to mark locations where the supply of this service is declining. Two different sizes of stickers were used to represent a radius of 0.75 km or 1 km, respectively.	Index 0-5	
[35] Index based on naturalness (based on Corine Landcover Class), level of conservation (based on presence of protected areas) and accessibility to the human population (based on distance from areas with high population density)	-	 , 
[22] Roadside variation: number of “land use patches” intersected by or adjacent to all roads and paths, except motorways and railways, divided by total road length. Values were scaled [0-1]	km ⁻¹	
[22] Accessibility: Share of the land surface within 100 meters from the road. Values were scaled [0-1]	%	
[34] (Water activities): Numer of river watching sites	#	
[34] (Water activities): Number of visitors or facilities (e.g. hotels or restaurants)	#	
[34] (Water activities): Length of walkway or cycleway	km	
[34] (Water activities): Turnover from tourism	\$ * ha ⁻¹	
[8] Open landscapes: Share of land under agricultural cultivation (keeping landscapes open through agriculture is seen as increasing aesthetic value)	%	
[3] Hedges between agriculture and other use	Not provided	

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[3] Diversity of land cover/ land use types (calculated by adapting Shannon Index 'H', Gini index, or Simpson's Diversity Index' D')	[-]	
[8] Diversity of landscapes: Shannon index of land use	[-]	
[3] Number of elements and land cover types in a viewshed	#	
[34] Proximity to urban areas of scenic rivers or lakes	km	
[18] WTP - willingness to pay for landscape preservation considering likely landscape changes	\$	
[37] Number of visitors arrivals	#	
[37] Number of domestic visitors arrivals	#	
[37] Number of foreign visitors arrivals	#	
[37] Number of active enterprises in the area	#	
[37] Number of active enterprises in agriculture (crop production, support activities to agriculture)	#	
[37] Number of active enterprises in accommodation and food services activities	#	
[37] Number of farms with other gainful activities (agritourism, recreational and social activities)	#	
[37] Number accommodation establishments	#	
[37] Number of hotels and similar establishments	#	
[37] Number of holiday- and other short-stay accommodations, camping grounds, recreational vehicle parks and trailer parks	#	
[38] For services that can be monetized: value of cultural services	USD / km ² * year)	
[38] For services that can not be monetized: qualitative value assessment using Likert-scales	-	

Table 4: National Scale

Indicator	Unit	Indicator values from
[2] Number of visits per year	# * area ⁻¹ * yr ⁻¹	
[2] Valuation: Number of visits per year multiplied by value indicator. The value indicator depends on the habitat mix for that location	\$ * area ⁻¹ * yr ⁻¹	
[6] Number of "day leisure visits" (any round trip of less than one day in duration made from home or a holiday destination for leisure purposes)	# * grid cell ⁻¹	

Appendix – Ecosystem Services

[11] Potential number of visitors calculated from population statistics and assuming travel distance of 80 km for daily trips and 8 km for short trips	#	
[11] Actual number of visits from surveys or statistics	#	
[14] Number of visitors per year	#	
[26] Number of visitors in agricultural areas	Not specified	
[26] Number of rural enterprises offering tourism-related services	Not specified	
[26] Number of birdwatchers	Not specified	
[26] Farm tourism	Not specified	
[25] Modelled probability of visitation by recreationists/tourists, based on land cover class, mean elevation, distance from a nearest major road, path density, county and population.	0-1	
[26] Walking and biking trails	Not specified	
[3] Number of elements and land cover types in a viewshed	#	
[3] Hedges between agriculture and other use	Not provided	
[3] Diversity of land cover/ land use types (calculated by adapting Shannon Index 'H', Gini index, or Simpson's Diversity Index' D')	-	
[36] Opportunities for experiential uses of landscapes number of habitats protected in Annex 1 of the EC Habitats Directive (Council Directive 92/43/EEC). Point values are interpolated using inverse distance weighting.	-	
[36] Frequency data of preferences: respondents of a questionnaire are asked to identify 3 places and landscapes that they have visited and are of high aesthetic value, the predominant land use/cover of each site, and the recreational activities they normally carry out at these locations. Frequency data from this preference assessment is then mapped for the identified sites.	n/a	
[36] Frequency of responses associating land use/cover with aesthetic values are asked to identify 3 places and landscapes that they have visited and are of high aesthetic value, the predominant land use/cover of each site, and the recreational activities they normally carry out at these locations. Frequency data from this preference assessment was then mapped for the identified sites.	n/a	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[3] Hedges between agriculture and other use	Not provided	
[3] Number of elements and land cover types in a viewshed	#	

Appendix – Ecosystem Services

[3] Diversity of land cover/ land use types (calculated by adapting Shannon Index 'H', Gini index, or Simpson's Diversity Index' D')	-	
[12] Recreation potential: continuous index, based on presence of certain ecosystems (i.e., forest, coastline), certain ecosystem characteristics (i.e., naturalness) and their accessibility	-	

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Ecosystem Service	Scientific interactions with nature
CICES class name	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge
CICES Section	Cultural (Biotic)
CICES Class code	3.1.2.1

Brief Description

- Researching nature
- The biophysical characteristics or qualities of species or ecosystems that are the subject for in situ research

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Regional Scale

Indicator	Unit	Indicator values from
^[1] Spatial mapping by stakeholders: stakeholders could place green stickers on a map to mark the supply hotspots of this ecosystem service. Red stickers were used to mark locations where the supply of this service is declining. Two different sizes of stickers were used to represent a radius of 0.75 km or 1 km, respectively.	Index 0-5	
^[2] Number of studies conducted in the area	#	 , 
^[3] Number of monitoring sites (by scientists)	#	

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²¹* The impact area discussed on this factsheet is not a focus of the cited paper

Ecosystem Service	Education and training interactions with nature
CICES class name	Characteristics of living systems that enable education and training
CICES Section	Cultural (Biotic)
CICES Class code	3.1.2.2

Brief Description

- Teaching nature
- The biophysical characteristics or qualities of species or ecosystems (settings/cultural spaces) that are the subject matter for in situ teaching or skill development

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Farm Scale

Indicator	Unit	Indicator values from
^[1] Four-level index based on the provision of walking trails/ecotourism/environmental education	Index poor-fair-good-excellent	

Table 2: Regional Scale

Indicator	Unit	Indicator values from
^[2] Number of educative panels in the area	#	
^[4] Number of environmental-education related facilities	# * ha ⁻¹	
^[3] Spatial mapping by stakeholders: stakeholders could place green stickers on a map to mark the supply hotspots of this ecosystem service. Red stickers were used to mark locations where the supply of this service is declining. Two different sizes of stickers were used to represent a radius of 0.75 km or 1 km, respectively.	Index 0-5	
^[6] For services that can be monetized: value of cultural services	USD / km ² * year	

Appendix – Ecosystem Services

^[6] For services that can not be monetized: qualitative value assessment using Likert-scales	-	⊘

Table 3: National Scale

Indicator	Unit	Indicator values from
^[5] Number of didactic farms	#	⊘

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²²* The impact area discussed on this factsheet is not a focus of the cited paper

Ecosystem Service	Culture or heritage from interactions with nature
CICES class name	Characteristics of living systems that are resonant in terms of culture or heritage
CICES Section	Cultural (Biotic)
CICES Class code	3.1.2.3

Brief Description

- The things in nature that help people identify with the history or culture of where they live or come from
- The biophysical characteristics or qualities of species or ecosystems that contribute to cultural heritage or historical knowledge

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Quality and number of man-made structures (hedges, stone walls)	Not provided, #	
^[11] Index [not provided]: Panoramic photographs are created on site that show the 'best representation' of the landscape. In a questionnaire, respondents from the same region are asked if they perceive the landscape as "traditional".	n/a	 , 

Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[1] Quality and number of man-made structures (hedges, stone walls)	Not provided, #	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[1] Quality and number of man-made structures (hedges, stone walls)	Not provided, #	
[2] Total area with outstanding historical or cultural significance	ha	
[9] Heritage: Participatory mapping. Respondents in an online survey mark on a map area in their region where different cultural ecosystem services are supplied. Then, the proportion of markings in each of the investigated land cover classes is calculated. After that, values are calculated for sub-regions. The proportions are multiplied with the area extent of the respective land cover classes in the sub-region and result for all land cover classes are summed up.	ha	
[5] Share of open land classified as semi-natural grassland (within a 5 km radius around farmhouse)	%	
[3] Agricultural heritage index: heritage value of the cultivation of native potato varieties, calculated based on the heritage value of the potato species, the systems of knowledge and social networks: The heritage value of the species is represented by: -Number of native potato varieties cultivated by the farmer -Type of native potato varieties cultivated by the farmer -Exchange of native potato seed -Quantity of native potato for self-consumption/quantity harvested -Quantity of native potato cultivated/quantity of commercial potato cultivated -Storage and use of own native potato seed Systems of knowledge are represented by: -Cultivation practices used to come from inheritance -Cultivation practices were learned by working at the farm -Main reason to grow native potato is a tradition across generations -Soil fertilization is made with farm-made products (organic fertilizers, algae) Social networks are represented by: -Exchange of native potato seed -Number of know farmers that integrate your network of seed exchange -The farmer participates in "minga", a traditional labour sharing custom between farms -The farmer uses a mix of family and hired labour The selection and weighing of sub-indicators are based on expert assessment. Indicators are spatially mapped based on distance from the service provider (traditional farmer).	Index 1 - 100	 ,  , 

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[3] Agricultural heritage benefit, based on willingness to pay (WTP) value for the preservation of the traditional potato cultivation and mapped by distributing the total amount in dollar (WTP population share of traditional potato cultivators that live in the region) between all agricultural fields in the region, using "Agricultural heritage index" as weighing factor.	\$ * ha ⁻¹	
[7] WTP - willingness to pay for landscape preservation considering likely landscape changes	€	
[4] Landscape value, based on conformity of land use and land use changes with nationally defined landscape character for the respective region	-	
[5] Share of farmers surveyed that state that their farm should look well-tended for	%	
[5] Share of farmers surveyed that attach value to cultural heritage elements, such as stone walls, hedgerows, etc.	%	
[5] Share of farmers surveyed that enjoy keeping animals	%	
[6] Negative indicator: Spring litter in un-mown plots (alpine grasslands: this is considered lack of "stewardship" which may diminish cultural heritage value)	Not specified	
[7] Average travel cost of tourists	€ * yr ⁻¹	
[8] Sense of place: Number of people acknowledging the ecosystem as relevant for their identity, value and the place of their origin	#	

Table 4: National Scale

Indicator	Unit	Indicator values from
[1] Quality and number of man-made structures (hedges, stone walls)	Not provided, #	
[10] Number of monuments in agricultural areas	#	
[10] Number of certified products that require traditional landscape management	#	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[1] Quality and number of man-made structures (hedges, stone walls)	Not provided, #	

References

No.	Citation
1	Carvalho-Ribeiro S, Correia TP, Paracchini ML, Schupbach B, Sang AO, Vanderheyden V, Southern A, Jones P, Contreras B, O'Riordan T (2016) Assessing the ability of rural agrarian areas to provide cultural ecosystem services (CES): A multi scale social indicator framework (MSIF). <i>Land Use Policy</i> 53: 8-19. DOI: 10.1016/j.landusepol.2015.04.024
2	Liu S, Crossman ND, Nolan M, Ghirmay H (2013) Bringing ecosystem services into integrated water resources management. <i>Journal of Environmental Management</i> 129: 92-102. DOI: 10.1016/j.jenvman.2013.06.047
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4	Posthumus H, Rouquette JR, Morris J, Cowing DJG, Hess TM (2010) A framework for the assessment of ecosystem goods and services; a case study on lowland floodplains in England. <i>Ecological Economics</i> 69(7): 1510-1523. DOI: 10.1016/j.ecolecon.2010.02.011
5	Andersson E, Nykvist B, Malinga R, Jaramillo F, Lindborg R (2015) A social–ecological analysis of ecosystem services in two different farming systems. <i>Ambio</i> 44(1): 102-112. DOI: 10.1007/s13280-014-0603-y
6	Quétier F, Lavorel S, Daigney S, de Chazal J (2009) Assessing ecological and social uncertainty in the evaluation of land-use impacts on ecosystem services. <i>Journal of Land Use Science</i> 4(3): 173-199. DOI: 10.1080/17474230903036667
7	van Berkel DB, Verburg PH (2014) Spatial quantification and valuation of cultural ecosystem services in an agricultural landscape. <i>Ecological Indicators</i> 37: 163-174. DOI: 10.1016/j.ecolind.2012.06.025
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9	Jaligot R, Chenal J, Bosch M, Hasler S (2019) Historical dynamics of ecosystem services and land management policies in Switzerland. <i>Ecological Indicators</i> 101: 81-90. DOI: 10.1016/j.ecolind.2019.01.007
10	Maes J, Liqueste C, Teller A, Erhard M, Paracchini ML, Barredo JI, Grizzetti B, Cardoso A, Somma F, Petersen JE, Meiner A, Gelabert ER, Zal N, Kristensen P, Bastrup-Birk A, Biala K, Piroddi C, Egoh B, Degeorges P, Fiorina C, Santos-Martín F, Naruševičius V, Verboven J, Pereira HM, Bengtsson J, Gocheva K, Marta-Pedroso C, Snäll T, Estreguil C, San-Miguel-Ayán J, Pérez-Soba M, Grêt-Regamey A, Lillebø AI, Malak DA, Condé S, Moen J, Czucz B, Drakou EG, Zulian G, Lavalle C (2016) An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. <i>Ecosystem Services</i> 17: 14-23. DOI: 10.1016/j.ecoser.2015.10.023
11	Assandri G, Bogliani G, Pedrini P, Brambilla M (2018) Beautiful agricultural landscapes promote cultural ecosystem services and biodiversity conservation. <i>Agriculture Ecosystems & Environment</i> 256: 200-210. DOI: 10.1016/j.agee.2018.01.012

Ecosystem Service	Aesthetics from interactions with nature
CICES class name	Characteristics of living systems that enable aesthetic experiences
CICES Section	Cultural (Biotic)
CICES Class code	3.1.2.4

Brief Description

- The beauty of nature
- The biophysical characteristics or qualities of species or ecosystems that are appreciated for their inherent beauty

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[2] Presence of water bodies	Not provided	
^[2] Presence of sublime features, e.g., mountains	Not provided	
^[3] Functional diversity: Colour richness of flowers	# of colour groups visible to humans: white, yellow, purple, violet	
^[3] Functional intensity: Average size of flowers or discernible sub-sets of inflorescences (of colour groups visible to humans)	cm	
^[3] Functional stability: Average species richness of flowers within groups visible to humans during the flowering season	# of species	
^[3] Overall species richness of flowers in colour groups visible to humans	# of species	

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[3] Overall species richness of flowers	# of species	
[4] Abundance of large butterflies (species with median wingspan >5.4 cm)	Not provided	
[4] Abundance of birds that are either: colourful species or species that people attract to their homes with feeders	Not provided	
[4] Ant species richness as predictor of the abundance of birds, including those described above.	Not provided	
[26] Rating score [1 - 10]: Panoramic photographs are created on site that show the 'best representation' of the landscape. In a questionnaire, respondents are asked to rate them based purely on aesthetic criteria. The median score across all questionnaires is used.	n/a	 , 

Table 2: Farm Scale

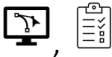
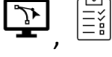
Indicator	Unit	Indicator values from
[2] Presence of water bodies	Not provided	
[2] Presence of sublime features, e.g., mountains	Not provided	
[5] Aesthetic landscape enhancement by a specific feature	poor-fair-good-excellent	
[6] Roadside variation: number of "land use patches" intersected by or adjacent to all roads and paths, except motorways and railways, divided by total road length	km ⁻¹	 , 
[6] Landscape variation: length of land cover "edges" per hectare land surface	km * ha ⁻¹	 , 
[6] Share of farmers surveyed that state that their farm should look well-tended	%	 , 
[6] Share of farmers surveyed that consider open landscapes valuable landscape elements	%	 , 

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[1] Complexity: -Number of independently perceived visual elements in the scene -Visual richness, the degree of scene intricateness and "how much is going on." -The amount of information or the number of elements in	not provided	

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the immediate environment -The promise of more information if one has more time to observe from the specific point -The degree of simplicity versus complexity in the spatial structure -Presence of multiple elements with diverse forms elements at a given resolution -Diversity, richness and interspersed of landscape -The amount of diversity or variety in a scene, the engaging amount of information -The perceived degree of landscape variety (from not varied to varied) -Composition, distribution, organization and variation of landscape elements contributing to visual richness and diversity		
^[1] Diversity: -The degree of perceived visual variation among landscape elements -Visual diversity; the number and degree of image elements or different features -The diversity of landscape components "as the expression of vertical relationships between land use and abiotic features." -"Simply describes differences in nature, quality or aspect", also "the nature and relative size of the fields within the farm." -Composition, diversity, and relative abundance (evenness) of landscape cover types and land uses	not provided	⊘
^[1] Heterogeneity: grain size, visual compartmentalization and versatility within the landscape	not provided	⊘
^[1] Biodiversity: diversity of plants, insects or specific ecological groups relevant to scenic properties	not provided	⊘
^[1] Texture: The attribute of visual quality evaluated as smooth, medium or rough, or proportion of the landscape area covered by it	not provided	⊘
^[1] Pattern: presence of regularly repeated elements or clear patterns	not provided	⊘
^[1] Variety: -Scene as being varied or diverse in overall content; "diversity of colors, textures, shapes and masses, forms and spaces or other visible attributes that add a diversity or mixture of visual experiences."	not provided	⊘
^[1] Color diversity and contrast: -Variety of colors, chromatic diversity, visual contrast among available colors	not provided	⊘

[1] 3D complexity: -Heterogeneity in tree height and vertical vegetation layers -Visual grouping, density and structuring of vegetation, thinning intensity (managed ecosystems) -Presence of specific structural vegetation forms such as a tree, bush -Presence/absence & diversity of man-made elements, either overall or as a modification to the landscape, sometimes as an undesirable factor	not provided	⊘
[1] Edge: -Presence, amount or density of distinct borders between areas -Presence of linear edge features such as hedgerows, walls, tree lines; visual properties of field margins -Edge condition	not provided	⊘
[1] Relief: -Topographic heterogeneity, variability in relief, non-uniform geomorphology, the contrast between flat and sloping	not provided	⊘
[1] Ephemera and seasonality: -Presence of elements and types of land use that change with seasons or overtime -Perception of seasonal change	not provided	⊘
[1] Time depth: -Visual evidence of historical continuity and diversity, sometimes as architectural variety and presence of landmarks -Level of succession (in woodlands)	not provided	⊘
[2] Presence of water bodies	Not provided	⊘
[2] Presence of sublime features, e.g., mountains	Not provided	⊘
[6] Roadside variation: number of land use patches intersected by or adjacent to all roads and paths, except motorways and railways, divided by total road length	km ⁻¹	
[6] Landscape variation: length of land cover "edges" per hectare land surface	km * ha ⁻¹	
[6] Share of farmers surveyed that state that their farm should look well-tended	%	
[6] Share of farmers surveyed that consider open landscapes valuable landscape elements	%	

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[7] Natural-aesthetical value: expert opinion/regional preferences	Not provided	
[7] Recreation potential: number of visitors	#	
[18] Average travel cost of tourists	€ * yr ⁻¹	
[8] Visibility of particularly beautiful spots (e.g., mountains, open water, forests, heterogeneous landscapes)	Index 0 - 100	
[14] Occurrence of protected areas, large forests, water bodies	Not provided	
[9] Open landscapes: Share of land under agricultural cultivation (keeping landscapes open through agriculture is seen as increasing aesthetic value)	%	
[9] Diversity of landscapes: Shannon index of land use	-	
[10] Number of residential properties in the direct vicinity of major rivers (number of properties is seen here as an indicator for aesthetic appreciation and inspiration)	#	
[11] Spatial mapping by stakeholders: stakeholders could place green stickers on a map to mark the supply hotspots of this ecosystem service. Red stickers were used to mark locations where the supply of this service is declining. Two different sizes of stickers were used to represent a radius of 0.75 km or 1 km, respectively	Index 0 - 5	
[12] Modelled landscape aesthetic value for a viewpoint: 360° panoramic photos of representative landscapes are created and assigned aesthetic scores [1-10] by stakeholders. The response is used to calibrate a regression model that relates landscape elements within the photos with the assigned aesthetic score. The following features are considered in the model: - Landscape metrics (area-weighted mean patch area distribution [m²]) - median radius of gyration distribution [m²] - modified Simpson's evenness index [-] - number of patches [#] - patch richness [-] - range perimeter–area ratio distribution [-] - coefficient of variation of shape index distribution [-] - median of shape index distribution [-]. - Land use classes (Settlement [0/1], Road [0/1], Forest [0/1], Water [0/1])	-	 , 

- Viewshed in three distance zones (near zone 0–1.5 km, middle zone 1.5–10 km, far zone 10–50 km) [m ²]		
[13] Recreation & aesthetic values: values for land cover classes. The matrix by Burkhard et al., 2012 (DOI: 10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
[15] Flower diversity: Plants Simpson's biodiversity index	Not specified	
[16] Visual quality index (VQI), based on 19 parameters (terrain ruggedness, presence of: waterfalls, wells and springs, area of standing water, length of flowing water, presence of the coast, habitat richness, area of woodland, presence of single large trees, number of plant species, hedgerow length, number of vegetation colours, area of human-influenced land, number of spot utilities/quarries, building area, road length, dry-stone walls length, presence of scheduled ancient monuments, presence of designated historic parks or gardens, presence of listed buildings)	Index 0 - 1	
[17] Utility sum based on the following indicators: -Level of the presence of linear landscape elements within a grid cell [1 - 3]: hedgerows, tree rows, tree alleys and windbreaks -Level of the presence of point landscape elements within a grid cell [1 - 3]: hedgerows, tree rows, tree alleys and windbreaks -Level of presence of livestock within a grid cell [0 - 1]: occurrence of grasslands used as a proxy -Level of the diversity of crop production within a grid cell [1 - 3]: average plot size within field blocks used as a proxy	-	
[19] Landscape beauty index; Values per land use class based on: - a questionnaire-based photo survey on alpine landscapes - topographical visibility analysis (from DEM) - Shannon index of landscape diversity (Shannon index) Each of the three components was weighted equally.	Not provided	
[20] Area providing an aesthetic and inspiring environment	ha	
[21] Aesthetic value of landscapes: values from landscape preference studies	Not provided	
[22] Cumulative viewshed: visibility of green areas (such as farmland and forest) from residential land (using the visibility function in ArcGIS's Spatial Analyst)	#	
[23] Landscape aesthetics and landmark: Participatory mapping. Respondents in an online survey mark on map areas in their region where different cultural ecosystem services are supplied. Then, the proportion of markings in	ha	

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each of the investigated land cover classes is calculated. After that, values are calculated for subregions. The proportions are multiplied with the area extent of the respective land cover classes in the sub-region, and result for all land cover classes are summed up.		
[18] Willingness to pay (WTP) for landscape preservation considering likely landscape changes	€	

Table 4: National Scale

Indicator	Unit	Indicator values from
[2] Presence of water bodies	Not provided	
[2] Presence of sublime features, e.g., mountains	Not provided	
[24] Shannon Diversity Index of landscapes	-	
[25] Number of visitors in agricultural areas	#	
[27] Frequency of responses associating land use/cover with aesthetic values are asked to identify 3 places and landscapes that they have visited and are of high aesthetic value and the predominant land use/cover of each site. Frequency data from this preference assessment was then mapped for the identified sites.	Not provided	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[2] Presence of water bodies	Not provided	
[2] Presence of sublime features, e.g., mountains	Not provided	

References

No.	Citation
1	Dronova I (2017) Environmental heterogeneity as a bridge between ecosystem service and visual quality objectives in management, planning and design. Landscape and Urban Planning 163: 90-106. DOI: 10.1016/j.landurbplan.2017.03.005
2	Carvalho-Ribeiro S, Correia TP, Paracchini ML, Schupbach B, Sang AO, Vanderheyden V, Southern A, Jones P, Contreras B, O'Riordan T (2016) Assessing the ability of rural agrarian areas to provide cultural ecosystem services (CES): A multi scale social indicator framework (MSIF). Land Use Policy 53: 8-19. DOI: 10.1016/j.landusepol.2015.04.024

No.	Citation
3	Kutt L, Lohmus K, Rammi IJ, Paal T, Paal J, Liira J (2016) The quality of flower-based ecosystem services in field margins and road verges from human and insect pollinator perspectives. <i>Ecological Indicators</i> 70: 409-419. DOI: 10.1016/j.ecolind.2016.06.009
4 ^{23*}	Peters VE, Campbell KU, Dienno G, García M, Leak E, Loyke C, Ogle M, Steinly B, Crist TO (2016) Ants and plants as indicators of biodiversity, ecosystem services, and conservation value in constructed grasslands. <i>Biodiversity and Conservation</i> 25(8): 1481-1501. DOI: 10.1007/s10531-016-1120-z
5	Fleming WM, Rivera JA, Miller A, Piccarello M (2014) Ecosystem services of traditional irrigation systems in northern New Mexico, USA. <i>International Journal of Biodiversity Science, Ecosystem Services and Management</i> 10(4): 343-350. DOI: 10.1080/21513732.2014.977953
6	Andersson E, Nykvist B, Malinga R, Jaramillo F, Lindborg R (2015) A social–ecological analysis of ecosystem services in two different farming systems. <i>Ambio</i> 44(1): 102-112. DOI: 10.1007/s13280-014-0603-y
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8	Gret-Regamey A, Weibel B, Bagstad KJ, Ferrari M, Geneletti D, Klug H, Schirpke U, Tappeiner U (2014) On the Effects of Scale for Ecosystem Services Mapping. <i>Plos One</i> 9(12): e112601. DOI: 10.1371/journal.pone.0112601
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11	Palomo I, Martin-Lopez B, Zorrilla-Miras P, Del Amo DG, Montes C (2014) Deliberative mapping of ecosystem services within and around Donana National Park (SW Spain) in relation to land use change. <i>Regional Environmental Change</i> 14(1): 237-251. DOI: 10.1007/s10113-013-0488-5
12	Schirpke U, Timmermann F, Tappeiner U, Tasser E (2016) Cultural ecosystem services of mountain regions: Modelling the aesthetic value. <i>Ecological Indicators</i> 69: 78-90. DOI: 10.1016/j.ecolind.2016.04.001
13*	Zhang ZM, Gao JF, Fan XY, Lan Y, Zhao MS (2017) Response of ecosystem services to socioeconomic development in the Yangtze River Basin, China. <i>Ecological Indicators</i> 72: 481-493. DOI: 10.1016/j.ecolind.2016.08.035
14	Bastian O, Lupp G, Syrbe RU, Steinhäufner R (2013) Ecosystem services and energy crops - Spatial differentiation of risks. <i>Ekologia Bratislava</i> 32(1): 13-29. DOI: 10.2478/eko-2013-0002
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^{23*} The impact area discussed on this factsheet is not a focus of the cited paper

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No.	Citation
16	Swetnam RD, Harrison-Curran SK, Smith GR (2017) Quantifying visual landscape quality in rural Wales: A GIS-enabled method for extensive monitoring of a valued cultural ecosystem service. <i>Ecosystem Services</i> 26: 451-464. DOI: 10.1016/j.ecoser.2016.11.004
17	Ungaro F, Hafner K, Zasada I, Piorr A (2016) Mapping cultural ecosystem services: Connecting visual landscape quality to cost estimations for enhanced services provision. <i>Land Use Policy</i> 54: 399-412. DOI: 10.1016/j.landusepol.2016.02.007
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19	Vigl LE, Tasser E, Schirpke U, Tappeiner U (2017) Using land use/land cover trajectories to uncover ecosystem service patterns across the Alps. <i>Regional Environmental Change</i> 17(8): 2237-2250. DOI: 10.1007/s10113-017-1132-6
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21	Duarte GT, Santos PM, Cornelissen TG, Ribeiro MC, Paglia AP (2018) The effects of landscape patterns on ecosystem services: meta-analyses of landscape services. <i>Landscape Ecology</i> 33(8): 1247-1257. DOI: 10.1007/s10980-018-0673-5
22	Hashimoto S, DasGupta R, Kabaya K, Matsui T, Haga C, Saito O, Takeuchi K (2018) Scenario analysis of land-use and ecosystem services of social-ecological landscapes: implications of alternative development pathways under declining population in the Noto Peninsula, Japan. <i>Sustainability Science</i> 14: 53-75. DOI: 10.1007/s11625-018-0626-6
23	Jaligot R, Chenal J, Bosch M, Hasler S (2019) Historical dynamics of ecosystem services and land management policies in Switzerland. <i>Ecological Indicators</i> 101: 81-90. DOI: 10.1016/j.ecolind.2019.01.007
24	Kirchner M, Schmidt J, Kindermann G, Kulmer V, Mitter H, Prettenhaler F, Rudisser J, Schuppenlehner T, Schonhart M, Strauss F, Tappeiner U, Tasser E, Schmid E (2015) Ecosystem services and economic development in Austrian agricultural landscapes - The impact of policy and climate change scenarios on trade-offs and synergies. <i>Ecological Economics</i> 109: 161-174. DOI: 10.1016/j.ecolecon.2014.11.005
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26	Assandri G, Bogliani G, Pedrini P, Brambilla M (2018) Beautiful agricultural landscapes promote cultural ecosystem services and biodiversity conservation. <i>Agriculture Ecosystems & Environment</i> 256: 200-210. DOI: 10.1016/j.agee.2018.01.012
27	Balzan MV, Caruana J, Zammit A (2018) Assessing the capacity and flow of ecosystem services in multifunctional landscapes: Evidence of a rural-urban gradient in a Mediterranean small island state. <i>Land Use Policy</i> 75: 711-725. DOI: 10.1016/j.landusepol.2017.08.025

Ecosystem Service	Symbolic meaning of nature
CICES class name	Elements of living systems that have symbolic meaning
CICES Section	Cultural (Biotic)
CICES Class code	3.2.1.1

Brief Description

- Using nature as a national or local emblem
- The biophysical characteristics or qualities of species or ecosystems that are recognized by people for their cultural, historical or iconic character and which are used as emblems or signifiers or some kind (e.g. national animals or flowers, Sherwood Forest)

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Regional Scale

Indicator	Unit	Indicator values from
^[1] Spatial mapping by stakeholders: stakeholders could place green stickers on a map to mark the supply hotspots of this ecosystem service. Red stickers were used to mark locations where the supply of this service is declining. Two different sizes of stickers were used to represent a radius of 0.75 km or 1 km, respectively.	Index 0-5	
^[2] Willingness to pay (WTP) for landscape preservation, considering likely landscape changes	€	
^[2] Average travel cost of tourists	€ * yr ⁻¹	

Appendix – Ecosystem Services

^[4] Inspiration, spiritual and religious values: Participatory mapping. Respondents in an online survey mark on a map the areas in their region where different cultural ecosystem services are supplied. Then, the proportion of markings in each of the investigated land cover classes is calculated. After that, values are calculated for subregions. The proportions are multiplied with the area extent of the respective land cover classes in the sub-region, and results for all land cover classes are summed up.	ha	
^[5] Number of spiritual facilities per landscape	# * ha ⁻¹	
^[6] Qualitative value assessment using Likert-scales	-	

Table 2: National Scale

Indicator	Unit	Indicator values from
^[3] Symbolic species	Not specified	

References

No.	Citation
1	Palomo I, Martin-Lopez B, Zorrilla-Miras P, Del Amo DG, Montes C (2014) Deliberative mapping of ecosystem services within and around Donana National Park (SW Spain) in relation to land use change. Regional Environmental Change 14(1): 237-251. DOI: 10.1007/s10113-013-0488-5
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4	Jaligot R, Chenal J, Bosch M, Hasler S (2019) Historical dynamics of ecosystem services and land management policies in Switzerland. Ecological Indicators 101: 81-90. DOI: 10.1016/j.ecolind.2019.01.007
5 ²⁴ *	Phama HV, Torresan S, Critto A, Marcomini A (2019) Alteration of freshwater ecosystem services under global change - A review focusing on the Po River basin (Italy) and the Red River basin (Vietnam). Science of the Total Environment 652: 1347-1365. DOI: 10.1016/j.scitotenv.2018.10.303
6	Gasparatos A, Romeu-Dalmau C, von Maltitz GP, Johnson FX, Shackleton C, Jarzebski MP, Jumbe C, Ochieng C, Mudombi S, Nyambane A, Willis K (2018) Mechanisms and indicators for assessing the impact of biofuel feedstock production on ecosystem services. Biomass & Bioenergy 114: 157-173. DOI: 10.1016/j.biombioe.2018.01.024

²⁴* The impact area discussed on this factsheet is not a focus of the cited paper

Short name	Spiritual meaning of nature
CICES class name	Spiritual meaning of nature
CICES Section	Cultural (biotic)
CICES Class code	3.2.1.2

Brief Description

- The things in nature that have spiritual importance for people
- The biophysical characteristics or qualities of species or ecosystems (settings/landscapes/cultural spaces) that are deemed to have sacred or religious significance for people

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[1] Participatory mapping of inspiration, spiritual and religious values: Respondents in an online survey mark on a map areas in their region where different cultural ES are provided. Then, the proportion of markings in each of the investigated land cover classes is calculated and multiplied with the area extent of the respective land cover classes in the sub region. Finally, the result for all land cover classes are summed up.	[ha]	
^[2] For services that can be monetized: value of cultural services	[\$ * km ⁻² * yr ⁻¹]	
^[2] For services that can not be monetized: qualitative value assessment using Likert-scales	[-]	

Table 4: National Scale

Indicator	Unit	Indicator values from
^[3] Religious monuments	[not specified]	

^[3] Pilgrim paths in agro-ecosystems	[not specified]	

References

No.	Citation
1	Jaligot R, Chenal J, Bosch M, Hasler S (2019) Historical dynamics of ecosystem services and land management policies in Switzerland. <i>Ecological Indicators</i> 101: 81-90. DOI: 10.1016/j.ecolind.2019.01.007
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Ecosystem Service	Existence value of nature
CICES class name	Characteristics or features of living systems that have an existence value
CICES Section	Cultural (Biotic)
CICES Class code	3.2.2.1

Brief Description

- The things in nature that should be conserved
- The biophysical characteristics or qualities of species or ecosystems (settings/landscapes/cultural spaces) which people seek to preserve because of their non-utilitarian qualities

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Combination of the following indicators: Existence value of a target species. Site quality: habitat suitability for prey (low, medium, high) Existence value of a target species. Site opportunity: local level of habitat fragmentation, scaled to [0 -1] Existence value of a target species. Scarcity: Risk of species population falling below viable population size, scaled to [0 - 1] Existence value of a target species. Reliability: Risk of future service loss through urban development within a 3-mile radius, scaled to [0 -1]	-	 , 

Table 2: Regional Scale

Indicator	Unit	Indicator values from

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[2] Intrinsic value of biodiversity: values for land cover classes. The matrix by Burkhard et al., 2012 (DOI: 10.1016/j.ecolind.2011.06.019) was used in this study.	Index 0 - 5	
[3] Existence value: Participatory mapping. Respondents in an online survey mark on a map the areas in their region where different cultural ecosystem services are supplied. Then, the proportion of markings in each of the investigated land cover classes is calculated. After that, values are calculated for subregions. The proportions are multiplied with the area extent of the respective land cover classes in the sub-region, and results for all land cover classes are summed up	ha	
[4] Number of spiritual facilities per landscape	# * ha ⁻¹	
[4] Number of national parks	#	

Table 3: National Scale

Indicator	Unit	Indicator values from
[5] Diversity of breeding bird species (Simpson-Index)	-	
[5] Number of farmland bird species	#	
[6] Species of conservation concern: based on species listed in the U.K. Biodiversity Action Plan and recorded in a grid cell	Not provided	
[7] Cropland or grassland in protected agricultural areas (e.g., Natura2000, Biosphere reserves, IUCN category V areas, World Heritage UNESCO sites related to agricultural landscape, landscape conservation areas)	ha	

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3	Jaligot R, Chenal J, Bosch M, Hasler S (2019) Historical dynamics of ecosystem services and land management policies in Switzerland. Ecological Indicators 101: 81-90. DOI: 10.1016/j.ecolind.2019.01.007
4*	Pham HV, Torresan S, Critto A, Marcomini A (2019) Alteration of freshwater ecosystem services under global change - A review focusing on the Po River basin (Italy) and the Red River

²⁵* The impact area discussed on this factsheet is not a focus of the cited paper

No.	Citation
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Ecosystem Service	Option or bequest value of nature
CICES class name	Characteristics or features of living systems that have an option or bequest value
CICES Section	Cultural (Biotic)
CICES Class code	3.2.2.2

Brief Description

- The things in nature that we want future generations to enjoy or use
- The biophysical characteristics or qualities of species or ecosystems (settings/landscapes/cultural spaces) which people seek to preserve for future generations

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Adaptability/ flexibility of soils as an option for land use change. Indicator value calculated as: $I = \frac{\sum \log (\frac{i}{i_{max}}) }{n}$ With: I – Indicator value, i – variable i measured, i_{max} – maximum ecologic potential of variable i in benchmark reference, n – number of variables. Where performance is considered better than in the benchmark and deviation, therefore, has a positive effect, $\log (\frac{i}{i_{max}})$ is subtracted from the sum instead of added. For this ecosystem service, variables were: -Soil organic matter [% dw] -Earthworm abundance [number*m⁻²] -Number of earthworm taxa [-] -Number of nematode taxa [-]	-	 , 

Appendix – Ecosystem Services

-Number of micro-arthropods taxa [-] -Physiological diversity bacteria [biolog. CLPP: Hill's slope]		

Table 2: Regional Scale

Indicator	Unit	Indicator values from
[2] Intrinsic value of biodiversity: values for land cover classes. The matrix by Burkhard et al., 2012 (DOI: 10.1016/j.ecolind.2011.06.019) was dataset and used in this study.	Index 0 - 5	

Table 3: National Scale

Indicator	Unit	Indicator values from
[3] Cropland or grassland in protected agricultural areas (e.g., Natura2000, Biosphere reserves, IUCN category V areas, World Heritage UNESCO sites related to agricultural landscape, landscape conservation areas)	#	

References

No.	Citation
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²⁶* The impact area discussed on this factsheet is not a focus of the cited paper

Ecosystem Service	Surface water for drinking
CICES class name	Surface water for drinking
CICES Section	Provisioning (Abiotic)
CICES Class code	4.2.1.1

Brief Description

- Drinking water from aboveground sources
- Natural, surface water bodies that provide a source of drinking water

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Annual total drainage	mm	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[2] Mean annual water flow	$\text{m}^3 * \text{s}^{-1} * \text{ha}^{-1}$	
^[3] Streamflow calculated by SWAT model	$\text{m}^3 * \text{time}^{-1}$	
^[3] Surface runoff calculated by application of ECOSER protocol (www.eco-ser.com.ar)	$\text{m}^3 * \text{ha}^{-1}$	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[1] Annual total drainage	mm	

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[5, 12] Precipitation – evapotranspiration, calculated with InVEST model)	$m^3 * ha^{-1} * yr^{-1}$	
[7] Surface water yield: mean annual precipitation - mean annual evapotranspiration; calculated with InVEST model.	mm	
[13] Water yield: calculated as annual precipitation - evapotranspiration	$m^3 * area^{-1} * yr^{-1}$	
[11] Potential water yield, calculated as precipitation - evapotranspiration	mm	 , 
[16] Provisioning of water: Groundwater recharge rate calculated from water balance	mm	
[14] Annual average water yield	$mm * yr^{-1}$	
[14] Annual sectoral water yield (e.g., domestic, agriculture and industry)	$mm * yr^{-1}$	
[8] Runoff: renewable water supply. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	mm	
[14] Annual river runoff	$m^3 * yr^{-1}$	
[15] Annual water flow that is available from surface waters	$mm * yr^{-1}, m^3 * yr^{-1}$	
[14] Water level	m	
[14] Number of extreme (runoff) events	$\# * yr^{-1}$	
[14] Annual average sediment in rivers	$t * yr^{-1}$	
[14] Total dissolved solids	$mg * l^{-1}$	
[14] Leakage of nutrients	$kg * ha^{-1} * yr^{-1}$	
[9] Surface area of water bodies	ha	 ,  , 
[9] Number of traditional water sources	#	 ,  , 
[6] Freshwater supply: values for land cover classes. The matrix by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0 - 5	
[10] Water for drinking and non-drinking uses: expert-based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class	km^2	 ,  , 
[10] Water for drinking and non-drinking uses' value: expert-based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class and a literature-based monetary value of ES	$km^2, \$ * ha^{-1} * yr^{-1}$	 ,  , 
[11] Rating of current service supply per land use class by expert-stakeholders	Rating 0 - 10	 , 
[11] Rating of increases/decreases of service provision in scenarios, relative to the status quo	%	 , 
[17] Water purification and provision: $W = NPP * (1 - VCNPP) * IC_s * S_{cf} * 1.75$ With: W – water purification and provision, NPP – Net Primary Production [0-1000], VCNPP – coefficient of variation of NPP [0–1], IC_s – soil infiltration capacity [0–1], S_{cf} – “slope average” correction factor of the study area [0–1]		

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[21] Freshwater recharge from the entire landscape	m ³ / (km ² * year)	

Table 4: National Scale

Indicator	Unit	Indicator values from
[18] Supply and demand of drinking water, calculated by multiplying modelled average surface water runoff by the number of people living downstream and the average estimated domestic water use	m ³ * yr ⁻¹	
[19] High Nature Value farmland	Not specified	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[20] Freshwater: values for Corine land cover classes based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	

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No.	Citation
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Ecosystem Service	Surface water for non-drinking purposes
CICES class name	Surface water used as a material (non-drinking purposes)
CICES Section	Provisioning (Abiotic)
CICES Class code	4.2.1.2

Brief Description

- Surface water that humans use for things other than drinking
- Natural, surface water bodies that provide water for uses such as irrigation, production or cooling

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[1] Annual total drainage	mm	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[2] Mean annual water flow	$\text{m}^3 * \text{s}^{-1} * \text{ha}^{-1}$	
^[3] Streamflow calculated by SWAT model	$\text{m}^3 * \text{time}^{-1}$	
^[3] Surface runoff calculated using the ECOSER protocol (www.eco-ser.com.ar)	$\text{m}^3 * \text{ha}^{-1}$	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[1] Annual total drainage	mm	
^[6, 13] Precipitation – Evapotranspiration, calculated with InVEST model	$\text{m}^3 * \text{ha}^{-1} * \text{yr}^{-1}$	

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[8] Surface water yield: mean annual precipitation - mean annual evapotranspiration, calculated with InVEST model	mm	
[14] Water yield: calculated as annual precipitation - evapotranspiration	$m^3 * area^{-1} * yr^{-1}$	
[12] Potential water yield, calculated as precipitation - evapotranspiration	mm	 , 
[17] Provisioning of water: Groundwater recharge rate based calculated from water balance	mm	
[15] Annual average water yield	$mm * yr^{-1}$	
[15] Annual sectoral water yield (e.g., domestic, agriculture and industry)	$mm * yr^{-1}$	
[9] Runoff: renewable water supply. Values were normalized [0-1] using benchmark values where available and observed values otherwise.	mm	
[15] Annual river runoff	$m^3 * yr^{-1}$	
[16] Annual water flow that is available from surface waters	$mm * yr^{-1}, m^3 * yr^{-1}$	
[15] Water level	m	
[15] Number of extreme (runoff) events	$\# * yr^{-1}$	
[15] Annual average sediment in rivers	$t * yr^{-1}$	
[15] Total dissolved solids	$mg * l^{-1}$	
[15] Leakage of nutrients	$kg * ha^{-1} * yr^{-1}$	
[10] Surface area of water bodies	ha	 ,  , 
[10] Number of traditional water sources	#	 ,  , 
[7] Freshwater supply: values for land cover classes. The matrix by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0 - 5	
[11] Water for drinking and non-drinking uses: expert-based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class	km^2	 ,  , 
[11] Water for drinking and non-drinking uses' value: expert-based index for ecosystem service supply by land cover class [1-5] multiplied by the area of the land cover class and a literature-based monetary value of the ecosystem service	$km^2, \$ * ha^{-1} * yr^{-1}$	 ,  , 
[12] Rating of current service provision per land use class by expert-stakeholders	0 - 10	 , 
[12] Rating of increases/decreases of service supply in scenarios, relative to the status quo	%	 , 
[18] Water purification and provision, calculated as: $W = NPP * (1 - VCNPP) * IC_s * S_{cf} * 1.75$ With: NPP – Net Primary Production [0-1000], VCNPP – coefficient of variation of NPP [0–1], IC_s – soil infiltration capacity [0–1], S_{cf} – “slope average” correction factor of the study area [0–1]	-	
[4] Agricultural water use for irrigation: Average irrigation water use over three years	$GL * a^{-1}$	

[5] Spatial mapping by stakeholders: stakeholders could place green stickers on a map to mark the supply hotspots of this ecosystem service. Red stickers were used to mark locations where the supply of this service is declining. Two different sizes of stickers were used to represent a radius of 0.75 km or 1 km, respectively.	Index 0 - 5	
[22] Irrigated area	Not provided	
[22] Area irrigated using surface water	Not provided	
[23] Freshwater recharge from the entire landscape	m ³ / (km ² * year)	

Table 4: National Scale

Indicator	Unit	Indicator values from
[20] Surface water availability	m ³ * person ⁻¹ * yr ⁻¹	
[20] Water abstracted	km ³ * yr ⁻¹	
[19] Supply and demand of irrigation water, calculated by multiplying average modelled surface water runoff [not provided] by the downstream areas of irrigable agriculture [not provided] and estimated annual water demand per hectare per year [not provided]. Water demand per hectare was adjusted for the amount of annual rainfall.	l * d ⁻¹	
[19] Supply and demand of water for hydropower dams, calculated by multiplying average modelled surface water runoff [not provided] by the water demand for hydropower dams using electrical production as proxy [MWh]	l * d ⁻¹	
[20] Water use per sector	%	
[20] Wetlands: the surface of flood-prone areas	ha	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[21] Freshwater supply: values for Corine land cover classes based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones.	Index 0 - 5	

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No.	Citation
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No.	Citation
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^{28*} The impact area discussed on this factsheet is not a focus of the cited paper

No.	Citation
	R, Herzog F (2018) Spatial similarities between European agroforestry systems and ecosystem services at the landscape scale. <i>Agroforestry Systems</i> 92(4): 1075-1089. DOI: 10.1007/s10457-017-0132-3
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Ecosystem Service	Groundwater for drinking
CICES class name	Ground (and subsurface) water for drinking
CICES Section	Provisioning (Abiotic)
CICES Class code	4.2.2.1

Brief Description

- Drinking water from below ground sources
- Ground water bodies or aquifers that provide a source of drinking water

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[23] Groundwater replenishment	$\text{m}^3 * \text{m}^{-2} * \text{yr}^{-1}$	
^[5, 22] Annual total drainage	$\text{mm} * \text{yr}^{-1}$	
^[6] Seepage rate: the amount of water that leaves the rooting zone toward the groundwater table	$\text{mm} * \text{yr}^{-1}$	
^[7] Seepage rate: the amount of water that leaves the rooting zone toward the groundwater table	$\text{mm} * \text{yr}^{-1}$	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[14] Aquifer recharge from irrigation channels: Four-level index based on the share of water lost through seepage in open channel irrigation [%]. The higher the value, the higher the recharge	poor-fair-good-excellent	
^[14] Aquifer recharge from irrigation channels: Four-level index based on the share of irrigation channels that are unlined [%]. The higher the value, the higher the recharge	poor-fair-good-excellent	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[1] Groundwater recharge, calculated with the soil-water balance model (SWBM) by the U.S. Geological Survey	mm	
[15] Provisioning of water: Groundwater recharge rate calculated from water balance	mm	
[2] Groundwater recharge, calculated as: (Precipitation - Evapotranspiration) * (1 - Share of anthropogenic surface sealing) / (Discharge factor). Discharge factor [-] is determined based on distance from the surface to groundwater and slope.	mm * yr ⁻¹	
[12] Groundwater recharge: mean annual infiltration rate	l * m ⁻²	
[19] Groundwater recharge: Share of precipitation not used by evapotranspiration or surface-runoff	%	
[4, 16] Freshwater supply: Annual groundwater recharge	cm * yr ⁻¹	
[21] Groundwater recharge rate	mm * ha ⁻¹ * yr ⁻¹	
[10] Groundwater recharge: values for land cover classes. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
[20] Water yield: calculated as annual precipitation - evapotranspiration	m ³ * area ⁻¹ * yr ⁻¹	
[9] Precipitation – Evapotranspiration, calculated with InVEST model	1000 m ³	
[21] Annual average water yield	mm * yr ⁻¹	
[21] Annual sectoral water yield (e.g., domestic, agriculture and industry)	mm * yr ⁻¹	
[22] Annual total drainage	mm	
[10] Freshwater supply: values for land cover classes. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
[18] Water for drinking and non-drinking uses: expert based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class [km ²]	Index 1-5 * km ²	 ,  , 
[18] Water for drinking and non-drinking uses' value: expert based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class [km ²] and a literature-based monetary value of the ecosystem service	\$ * ha ⁻¹ * yr ⁻¹	 ,  , 
[3] Water purification and provision: NPP × (1–VCNPP) × ICs × Scf; where NPP: Net Primary Production calculated from NDVI-values and expressed on a relative scale set to (0 - 1000), VCNPP: coefficient of variation of NPP (0 - 1), ICs: soil	-	

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infiltration capacity (0 - 1), Scf: slope average correction factor of the study area (0 - 1)		
^[21] Leakage of nutrients	kg * ha ⁻¹ * yr ⁻¹	
^[21] Total dissolved solids	mg * l ⁻¹	
^[8] Designated drinking water protection areas	ha	
^[17] Runoff: renewable water supply. Values were normalized [0-1] using benchmark values where available and observed values otherwise	mm	
^[24] Freshwater recharge from the entire landscape	m ³ / (km ² * year)	

Table 4: Multinational Scale

Indicator	Unit	Indicator values from
^[13] Groundwater recharge: Corine land cover classes based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones	Index 0-5	
^[13] Freshwater: Corine land cover classes based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones	Index 0-5	

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^{29*} The impact area discussed on this factsheet is not a focus of the cited paper

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18	Huq N, Bruns A, Ribbe L (2019) Interactions between freshwater ecosystem services and land cover changes in southern Bangladesh: A perspective from short-term (seasonal) and long-term (1973-2014) scale. <i>Science of the Total Environment</i> 650: 132-143. DOI: 10.1016/j.scitotenv.2018.08.430
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21	Phama HV, Torresan S, Critto A, Marcomini A (2019) Alteration of freshwater ecosystem services under global change - A review focusing on the Po River basin (Italy) and the Red River basin (Vietnam). <i>Science of the Total Environment</i> 652: 1347-1365. DOI: 10.1016/j.scitotenv.2018.10.303

Appendix – Ecosystem Services

No.	Citation
22	Qiu JX, Carpenter SR, Booth EG, Motew M, Zipper SC, Kucharik CJ, Loheide SP, Turner AG (2018) Understanding relationships among ecosystem services across spatial scales and over time. <i>Environmental Research Letters</i> 13(5): 054020. DOI: 10.1088/1748-9326/aabb87
23*	Tang LL, Hayashi K, Kohyama K, Leon A (2018) Reconciling Life Cycle Environmental Impacts with Ecosystem Services: A Management Perspective on Agricultural Land Use. <i>Sustainability</i> 10(3): 630. DOI: 10.3390/su10030630
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Ecosystem Service	Groundwater for non-drinking purposes
CICES class name	Groundwater (and subsurface) used as a material (non-drinking purposes)
CICES Section	Provisioning (Abiotic)
CICES Class code	4.2.2.2

Brief Description

- Sub-surface water that humans use for things other than drinking
- Natural, ground water bodies or aquifers that provide water for that can be used as a material for cooling

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[23] Groundwater replenishment	$\text{m}^3 * \text{m}^{-2} * \text{yr}^{-1}$	
^[5, 22] Annual total drainage	$\text{mm} * \text{yr}^{-1}$	
^[6] Seepage rate: the amount of water that leaves the rooting zone toward the groundwater table	$\text{mm} * \text{yr}^{-1}$	
^[7] Seepage rate: the amount of water that leaves the rooting zone toward the groundwater table	$\text{mm} * \text{yr}^{-1}$	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[13] Aquifer recharge from irrigation channels: Four-level index based on the share of water lost through seepage in open channel irrigation [%]. The higher the value, the higher the recharge	poor-fair-good-excellent	

Appendix – Ecosystem Services

[13] Aquifer recharge from irrigation channels: Four-level index based on the share of unlined irrigation channels [%]. The higher the value, the higher the recharge	poor-fair-good-excellent	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[1] Groundwater recharge, calculated with the soil-water balance model (SWBM) by the U.S. Geological Survey	mm	
[14] Provisioning of water: Groundwater recharge rate calculated from water balance	mm	
[2] Groundwater recharge, calculated as: (Precipitation - Evapotranspiration) * (1 - Share of anthropogenic surface sealing) / (Discharge factor). Discharge factor [-] is determined based on distance from the surface to groundwater and slope	mm * yr ⁻¹	
[11] Groundwater recharge: mean annual infiltration rate	l * m ⁻²	
[19] Groundwater recharge: Share of precipitation not used by evapotranspiration or surface-runoff	%	
[4, 16] Freshwater supply: Annual groundwater recharge	cm * yr ⁻¹	
[21] Groundwater recharge rate	mm * ha ⁻¹ * yr ⁻¹	
[9] Groundwater recharge: values for land cover classes. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
[20] Water yield: calculated as annual precipitation - evapotranspiration	m ³ * area ⁻¹ * yr ⁻¹	
[8] Precipitation - Evapotranspiration calculated with InVEST model	1000 m ³	
[21] Annual average water yield	mm * yr ⁻¹	
[21] Annual sectoral water yield (e.g., domestic, agriculture and industry)	mm * yr ⁻¹	
[22] Annual total drainage	mm	
[9] Freshwater supply: values for land cover classes. The matrix defined by Burkhard et al., 2012 (DOI:10.1016/j.ecolind.2011.06.019) was adapted and used in this study.	Index 0-5	
[18] Water for drinking and non-drinking uses: expert-based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class [km ²]	Index 1-5 * km ²	 ,  , 

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[18] Water for drinking and non-drinking uses' value: expert-based index for ecosystem service supply by land cover class [1-5], multiplied by the area of the land cover class [km ²] and a literature-based monetary value of the ecosystem service	\$ * ha ⁻¹ * yr ⁻¹	
[3] Water purification and provision: $NPP \times (1 - VCNNP) \times ICs \times Scf$; where NPP: Net Primary Production calculated from NDVI-values and expressed on a relative scale set to (0 - 1000), VCNNP: coefficient of variation of NPP (0 - 1), ICs: soil infiltration capacity (0 - 1), Scf: slope average correction factor of the study area (0 - 1)	-	
[21] Leakage of nutrients	kg * ha ⁻¹ * yr ⁻¹	
[21] Total dissolved solids	mg * l ⁻¹	
[17] Runoff: renewable water supply. Values were normalized [0-1] using benchmark values where available and observed values otherwise	mm	
[24] Irrigated area	Not provided	
[24] Area irrigated using groundwater	Not provided	
[25] Freshwater recharge from the entire landscape	m ³ / (km ² * year)	

Table 4: National Scale

Indicator	Unit	Indicator values from
[15] Groundwater bodies	Not specified	
[15] Groundwater abstraction	Not specified	

Table 5: Multinational Scale

Indicator	Unit	Indicator values from
[12] Groundwater recharge: Corine land cover classes based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones	Index 0-5	
[12] Freshwater: Corine land cover classes based on values published by Burkhard et al. (2009; DOI: 10.3097/LO.200915) and modified for the context of riparian zones	Index 0-5	

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No.	Citation
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4	Qiu JX, Turner MG (2015) Importance of landscape heterogeneity in sustaining hydrologic ecosystem services in an agricultural watershed. Ecosphere 6(11): 229. DOI: 10.1890/es15-00312.1
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8	Zarandian A, Baral H, Stork NE, Ling MA, Yavari AR, Jafari HR, Amirnejad H (2017) Modeling of ecosystem services informs spatial planning in lands adjacent to the Sarvelat and Javaherdasht protected area in northern Iran. Land Use Policy 61: 487-500. DOI: 10.1016/j.landusepol.2016.12.003
9*	Zhang ZM, Gao JF, Fan XY, Lan Y, Zhao MS (2017) Response of ecosystem services to socioeconomic development in the Yangtze River Basin, China. Ecological Indicators 72: 481-493. DOI: 10.1016/j.ecolind.2016.08.035
11	Bastian O, Lupp G, Syrbe RU, Steinhäufel R (2013) Ecosystem services and energy crops - Spatial differentiation of risks. Ekologia Bratislava 32(1): 13-29. DOI: 10.2478/eko-2013-0002
12	Clerici N, Paracchini ML, Maes J (2014) Land-cover change dynamics and insights into ecosystem services in European stream riparian zones. Ecohydrology and Hydrobiology 14(2): 107-120. DOI: 10.1016/j.ecohyd.2014.01.002
13	Fleming WM, Rivera JA, Miller A, Piccarello M (2014) Ecosystem services of traditional irrigation systems in northern New Mexico, USA. International Journal of Biodiversity Science, Ecosystem Services and Management 10(4): 343-350. DOI: 10.1080/21513732.2014.977953
14	Kay S, Crous-Duran J, Ferreiro-Domínguez N, García de Jalón S, Graves A, Moreno G, Mosquera-Losada MR, Palma JHN, Rocas-Díaz JV, Santiago-Freijanes JJ, Szerencsits E, Weibel R, Herzog F (2018) Spatial similarities between European agroforestry systems and ecosystem services at the landscape scale. Agroforestry Systems 92(4): 1075-1089. DOI: 10.1007/s10457-017-0132-3
15	Maes J, Liqueste C, Teller A, Erhard M, Paracchini ML, Barredo JI, Grizzetti B, Cardoso A, Somma F, Petersen JE, Meiner A, Gelabert ER, Zal N, Kristensen P, Bastrup-Birk A, Biala K,

^{30*} The impact area discussed on this factsheet is not a focus of the cited paper

No.	Citation
	Piroddi C, Egoh B, Degeorges P, Fiorina C, Santos-Martín F, Naruševičius V, Verboven J, Pereira HM, Bengtsson J, Gocheva K, Marta-Pedroso C, Snäll T, Estreguil C, San-Miguel-Ayanz J, Pérez-Soba M, Grêt-Regamey A, Lillebø AI, Malak DA, Condé S, Moen J, Czucz B, Drakou EG, Zulian G, Lavalle C (2016) An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. <i>Ecosystem Services</i> 17: 14-23. DOI: 10.1016/j.ecoser.2015.10.023
16	Qiu J, Wardropper CB, Rissman AR, Turner MG (2017) Spatial fit between water quality policies and hydrologic ecosystem services in an urbanizing agricultural landscape. <i>Landscape Ecology</i> 32(1): 59-75. DOI: 10.1007/s10980-016-0428-0
17	Rodríguez-Loinaz G, Alday JG, Onaindia M (2014) Multiple ecosystem services landscape index: A tool for multifunctional landscapes conservation. <i>Journal of Environmental Management</i> 147: 152-163. DOI: 10.1016/j.jenvman.2014.09.001
18	Huq N, Bruns A, Ribbe L (2019) Interactions between freshwater ecosystem services and land cover changes in southern Bangladesh: A perspective from short-term (seasonal) and long-term (1973-2014) scale. <i>Science of the Total Environment</i> 650: 132-143. DOI: 10.1016/j.scitotenv.2018.08.430
19	Kay S, Crous-Duran J, García de Jalón S, Graves A, Palma JHN, Rocés-Díaz JV, Szerencsits E, Weibel R, Herzog F (2018) Landscape-scale modelling of agroforestry ecosystems services in Swiss orchards: a methodological approach. <i>Landscape Ecology</i> 33(9): 1633-1644. DOI: 10.1007/s10980-018-0691-3
20	Peng J, Tian L, Liu Y, Zhao M, Hu Y, Wu J (2017) Ecosystem services response to urbanization in metropolitan areas: Thresholds identification. <i>Science of the Total Environment</i> 607-608: 706-714. DOI: 10.1016/j.scitotenv.2017.06.218
21	Phama HV, Torresan S, Critto A, Marcomini A (2019) Alteration of freshwater ecosystem services under global change - A review focusing on the Po River basin (Italy) and the Red River basin (Vietnam). <i>Science of the Total Environment</i> 652: 1347-1365. DOI: 10.1016/j.scitotenv.2018.10.303
22	Qiu JX, Carpenter SR, Booth EG, Motew M, Zipper SC, Kucharik CJ, Loheide SP, Turner AG (2018) Understanding relationships among ecosystem services across spatial scales and over time. <i>Environmental Research Letters</i> 13(5): 054020. DOI: 10.1088/1748-9326/aabb87
23*	Tang LL, Hayashi K, Kohyama K, Leon A (2018) Reconciling Life Cycle Environmental Impacts with Ecosystem Services: A Management Perspective on Agricultural Land Use. <i>Sustainability</i> 10(3): 630. DOI: 10.3390/su10030630
24	Chatzinikolaou P, Viaggi D, Raggi M (2018) Using the Ecosystem Services Framework for Policy Impact Analysis: An Application to the Assessment of the Common Agricultural Policy 2014-2020 in the Province of Ferrara (Italy). <i>Sustainability</i> 10: 890. DOI: 10.3390/su10030890.
25	Gasparatos A, Romeu-Dalmau C, von Maltitz GP, Johnson FX, Shackleton C, Jarzebski MP, Jumbe C, Ochieng C, Mudombi S, Nyambane A, Willis K (2018) Mechanisms and indicators for assessing the impact of biofuel feedstock production on ecosystem services. <i>Biomass & Bioenergy</i> 114: 157-173. DOI: 10.1016/j.biombioe.2018.01.024

Ecosystem Service	Abiotic filtration, sequestration and storage of waste
CICES class name	Mediation by other chemical or physical means (e.g., via filtration, sequestration, storage or accumulation)
CICES Section	Regulation & Maintenance (Abiotic)
CICES Class code	5.1.1.3

Brief Description

- Natural processing of wastes by abiotic ecosystem elements
- Mediation of waste, toxic substances and other nuisances, by natural chemical and physical processes that can contribute to people's well-being

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 1: Regional Scale

Indicator	Unit	Indicator values from
^[3] Nitrate leaching	kg * ha ⁻¹ * yr ⁻¹	
^[2] Risk of nitrate leaching: exchange frequency of the soil water in the root layer. Infiltration rate divided by field capacity	%	
^[1] Mechanical filtration capacity: infiltration capacity, calculated as: $IC = Perm_{soil} * (1 - s)$ With: IC – infiltration capacity, Perm _{soil} – soil permeability [cm*d ⁻¹], s – share of anthropogenic surface sealing	cm * d ⁻¹	 , 
^[1] Physicochemical filtration capacity, calculated as: $IC_{physicochem} = CEC_{eff} * (1 - s)$	cmol(+) * kg dm ⁻¹	 , 

Appendix – Ecosystem Services

With: $IC_{\text{physicochem}}$ – physicochemical filtration capacity, CEC_{eff} – effective cation exchange capacity, s – share of anthropogenic surface sealing)		
[4] Volume of purified water	$\text{m}^3 / (\text{km}^2 \cdot \text{year})$	⊘
[4] Mass of a specific nutrient retained	$\text{ton} / (\text{km}^2 \cdot \text{year})$	⊘
[5] Area of undisturbed creek banks that serve as buffers to pesticide and fertilizer runoff	Not provided	⊘

References

No.	Citation
1	Nordborg M, Sasu-Boakye Y, Cederberg C, Berndes G (2017) Challenges in developing regionalized characterization factors in land use impact assessment: impacts on ecosystem services in case studies of animal protein production in Sweden. <i>International Journal of Life Cycle Assessment</i> 22(3): 328-345. DOI: 10.1007/s11367-016-1158-x
2	Bastian O, Lupp G, Syrbe RU, Steinhäuser R (2013) Ecosystem services and energy crops - Spatial differentiation of risks. <i>Ekologia Bratislava</i> 32(1): 13-29. DOI: 10.2478/eko-2013-0002
3	Kay S, Crous-Duran J, Ferreira-Domínguez N, García de Jalón S, Graves A, Moreno G, Mosquera-Losada MR, Palma JHN, Rocas-Díaz JV, Santiago-Freijanes JJ, Szerencsits E, Weibel R, Herzog F (2018) Spatial similarities between European agroforestry systems and ecosystem services at the landscape scale. <i>Agroforestry Systems</i> 92(4): 1075-1089. DOI: 10.1007/s10457-017-0132-3
4	Gasparatos A, Romeu-Dalmau C, von Maltitz GP, Johnson FX, Shackleton C, Jarzebski MP, Jumbe C, Ochieng C, Mudombi S, Nyambane A, Willis K (2018) Mechanisms and indicators for assessing the impact of biofuel feedstock production on ecosystem services. <i>Biomass & Bioenergy</i> 114: 157-173. DOI: 10.1016/j.biombioe.2018.01.024
5	Groot JCJ, Yalew SG, Rossing WAH (2018) Exploring ecosystem services trade-offs in agricultural landscapes with a multi-objective programming approach. <i>Landscape and Urban Planning</i> 172: 29-36. DOI: 10.1016/j.landurbplan.2017.12.008

Short name	Recreational interactions with abiotic nature
CICES class name	Recreational interactions with abiotic nature
CICES Section	Cultural (biotic)
CICES Class code	6.1.1.1

Brief Description

- Abiotic elements in the physical environment (e.g. mountains, glaciers) that we can experience actively or passively for recreation
- Natural, abiotic characteristics of nature that enable active or passive physical and experiential interactions

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[1] Participatory mapping of outdoor activities: Respondents in an online survey mark on a map areas in their region where different cultural ES are provided. Then, the proportion of markings in each of the investigated land cover classes is calculated and multiplied with the area extent of the respective land cover classes in the sub region. Finally, the result for all land cover classes are summed up.	[ha]	

References

No.	Citation
1	Jaligot R, Chenal J, Bosch M, Hasler S (2019) Historical dynamics of ecosystem services and land management policies in Switzerland. Ecological Indicators 101: 81-90. DOI: 10.1016/j.ecolind.2019.01.007

Short name	Intellectual interactions with abiotic nature
CICES class name	Intellectual interactions with abiotic nature
CICES Section	Cultural (biotic)
CICES Class code	6.1.2.1

Brief Description

- Abiotic elements in the physical environment that we can study or think about
- Natural, abiotic characteristics of nature that enable intellectual activities

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[1] Participatory mapping of inspiration, spiritual and religious values: Respondents in an online survey mark on a map areas in their region where different cultural ES are provided. Then, the proportion of markings in each of the investigated land cover classes is calculated and multiplied with the area extent of the respective land cover classes in the sub region. Finally, the result for all land cover classes are summed up.	[ha]	

References

No.	Citation
1	Jaligot R, Chenal J, Bosch M, Hasler S (2019) Historical dynamics of ecosystem services and land management policies in Switzerland. Ecological Indicators 101: 81-90. DOI: 10.1016/j.ecolind.2019.01.007

Short name	Symbolic and spiritual meaning of abiotic nature
CICES class name	Symbolic and spiritual meaning of abiotic nature
CICES Section	Cultural (biotic)
CICES Class code	6.2.1.1

Brief Description

- Abiotic elements in the physical environment that are important as symbols
- Natural, abiotic characteristics of nature that have symbolic or spiritual importance

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[1] Participatory mapping of inspiration, spiritual and religious values: Respondents in an online survey mark on a map areas in their region where different cultural ES are provided. Then, the proportion of markings in each of the investigated land cover classes is calculated and multiplied with the area extent of the respective land cover classes in the sub region. Finally, the result for all land cover classes are summed up.	[ha]	

References

No.	Citation
1	Jaligot R, Chenal J, Bosch M, Hasler S (2019) Historical dynamics of ecosystem services and land management policies in Switzerland. Ecological Indicators 101: 81-90. DOI: 10.1016/j.ecolind.2019.01.007

Short name	Non-use value of abiotic nature
CICES class name	Non-use value of abiotic nature
CICES Section	Cultural (biotic)
CICES Class code	6.2.2.1

Brief Description

- Abiotic elements in the physical environment that we think are important to us, others and future generations

Sample Indicators

Indicator values from			
Experiment or direct measurement		Survey	
Expert assessment		Statistical- or census data	
Model or GIS		Literature values	
Stakeholder participation		Not provided	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[1] Participatory mapping of existence value: Respondents in an online survey mark on a map areas in their region where different cultural ES are provided. Then, the proportion of markings in each of the investigated land cover classes is calculated and multiplied with the area extent of the respective land cover classes in the sub region. Finally, the result for all land cover classes are summed up.	[ha]	

References

No.	Citation
1	Jaligot R, Chenal J, Bosch M, Hasler S (2019) Historical dynamics of ecosystem services and land management policies in Switzerland. Ecological Indicators 101: 81-90. DOI: 10.1016/j.ecolind.2019.01.007

C. Indicator Factsheets: Resource Use Efficiencies

Impact Area: **Benefits per Area**

Definition:
$$\frac{\text{Financial benefits}}{\text{Area of land}}$$

Description:

Benefit: This impact area assesses benefits via their appreciation by markets (Di Maio et al., 2017). It is sensitive to various socio-economic factors because commodity prices reflect demand and are also influenced by value systems and policies through effects of financial incentives and tax regulations.

Resource: Agricultural land is always a limited resource. The type of land can be specified to distinguish between different land qualities. Distinctions are often made, for example, between cropland and pasture, high nature value (HNV) farmland and other farmland, or based on soil fertility and yield potential. For this indicator, the temporal reference must always be specified. However, in case of the standard period of one year, this information is sometimes omitted in scientific publications.

Correlation with soil management:

[26] Organic farms recorded higher operating profit (operating profit + subsidies) per hectare of farmland than conventional farms

[55] Cooperatives have higher revenue per area of land than single farms

[133] The production in agriculture is associated with quality standards of lands, nature and conditions of their use

[149] Smaller farms are more efficient in land productivity

[162] Studies proved reduction of field crop yields from organic fields in comparison to conventional ones

[182] Improving the conditions of mineral nutrition by introducing balanced doses of fertilizers for all elements contributed to a sufficiently high yield

[207] Nitrogen utilization efficiency played a significant role in determining grain yield, while a negative and poor dependence of grain yield on Nitrogen uptake efficiency was observed

[241] Highest land use efficiencies (potato yield per hectare of area) were achieved in regions that produce potatoes under irrigation in summer where solar radiation is high and lowest land use efficiencies were reported for the predominantly dry land and partially dry land regions

[248] Small rice-producing farms ranging from 0.61 to 1.0 ha yielded higher energy ratios (4.14) than larger ones

Strength & weaknesses pertaining to measurement of this impact area

Financial Benefits: Financial indicators are well suited for integrating or comparing agricultural production processes with products for very different end uses. For calculating benefit-cost ratios (BCR), indicators that reflect revenue should be used. In most other cases, indicators that reflect net benefits (after deduction of charges, costs and expenses) provide a more realistic picture of benefits generated. Price volatilities make efficiency calculations valid only for a certain point in time and space.

Area of land: While area of land is a standard measure that is used as reference in most statistics and inventories, a weakness of this indicator is that other relevant information like soil type, soil fertility or management history is often not provided.

In short, one hectare of dry, sandy cropland soil is very different from one hectare of pasture on drained peat soils.

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: No Scale

Indicator	Unit	Indicator values from
^[55] Production output/Area of land	\$ * ha ⁻¹	

Table 2: Field Scale

Indicator	Unit	Indicator values from
^[207] Net income/Area of land	\$ * ha ⁻¹	

Table 3: Farm Scale

Appendix – Ecosystem Services

Indicator	Unit	Indicator values from
^[26] Operational efficiency (Operational profit/Area of land)	\$ * ha ⁻¹	
^[26] Operational efficiency (including subsidies)(Operational profit + subsidies/Area of land)	\$ * ha ⁻¹	
^[26] Accounting profit/Area of land	\$ * ha ⁻¹	
^[62] Total gross margin/Area of land	\$ * ha ⁻¹	
^[149] Land productivity (Total income generated from farming during a year/Cultivated area of land)	\$ * Not specified ⁻¹	
^[162] Additional income from fertilization (Additional yields from fertilization*price of products)/Area of land	\$ * ha ⁻¹	
^[162] Additional profit from fertilization/Area of land	\$ * ha ⁻¹	
^[162] Residual effect of fertilization-additional profit/Area of land	\$ * ha ⁻¹	
^[175] Average price (Gross income/Area of land)	\$ * ha ⁻¹	
^[175] Operating margin (Gross margin/Area of land)	\$ * ha ⁻¹	
^[176] Value of gross product/Fodder area	\$ * ha ⁻¹	 , 
^[176] Net agricultural income (Prices of inputs or sold products)/Fodder area	\$ * ha ⁻¹	 , 

Table 4: Regional Scale

Indicator	Unit	Indicator values from
^[1] Value of yields (including subsidies)/Agricultural land	\$ * ha ⁻¹	
^[1] Added value/Agricultural land	\$ * ha ⁻¹	
^[100] Agricultural profitability (Profit contribution (revenue - costs)/Area of land)	\$ * ha ⁻¹	
^[133] Land productivity (Value of yields/Area of land)	\$ * ha ⁻¹	
^[182] Gross value of winter wheat/Area of land	\$ * ha ⁻¹	
^[241] Gross profit/Area of land	\$ * ha ⁻¹	
^[248] Net Economic gain [Monetary unit]/Area of land	\$ * ha ⁻¹	 , 

References

Appendix – Resource Use Efficiencies

ID	Citation	¹ Soil type/ texture
1	Adamisin, P., et al. (2015). "Natural climatic conditions as a determinant of productivity and economic efficiency of agricultural entities." <i>Agricultural Economics-Zemедelska Ekonomika</i> 61(6): 265-274.	n/a
26	Brožová, I. and J. Vanek (2013). "Assessment of economic efficiency of conventional and organic agricultural enterprises in a chosen region." <i>Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis</i> 61(2): 297-307.	n/a
62*	Dhehibi, B., et al. (2015). "Impacts of soil salinity on the productivity of Al-Musayyeb small farms in Iraq: An examination of technical, economic and allocative efficiency." <i>Agricultural Economics Review</i> 16(2): 42-55.	Mainly silty loams or loamy silts
100*	Hagen, Z. (2012). "A basic design for a multicriteria approach to efficient bioenergy production at regional level." <i>Energy, Sustainability and Society</i> 2(1): 1-17.	n/a
149*	Li, G., et al. (2013). "Re-examining the inverse relationship between farm size and efficiency: The empirical evidence in China." <i>China Agricultural Economic Review</i> 5(4): 473-488.	n/a
162	Manolova, V., et al. (2015). "Economic efficiency of fertilization and its residual-effect during conversion period to organic field crop production." <i>Bulgarian Journal of Agricultural Science</i> 21(5): 1022-1026.	n/a
175	Moore, A. D., et al. (2011). "Evaluation of the water use efficiency of alternative farm practices at a range of spatial and temporal scales: A conceptual framework and a modelling approach." <i>Agricultural Systems</i> 104(2): 162-174.	Black vertosol soil
176	Moreau, P., et al. (2012). "Reconciling technical, economic and environmental efficiency of farming systems in vulnerable areas." <i>Agriculture Ecosystems & Environment</i> 147: 89-99.	Deep loamy and shallow brown soils
207	Rehman, A., et al. (2011). "Grain quality, nutrient use efficiency, and bioeconomics of maize under different sowing methods and NPK levels." <i>Chilean Journal of Agricultural Research</i> 71(4): 586-593.	Sandy clay loam
241	Steyn, J. M., et al. (2016). "Resource use efficiencies as indicators of ecological sustainability in potato production: A South African case study." <i>Field Crops Research</i> 199: 136-149.	Loam, sandy-loam, sand
248	Talukder, B., et al. (2019). "Energy efficiency of agricultural systems in the southwest coastal zone of Bangladesh." <i>Ecological Indicators</i> 98: 641-648.	n/a

¹**Soil type/ texture:** If provided, what are type and texture of the soils studied in the paper?

*The impact area discussed on this factsheet is not a focus of the cited paper

Impact Area: Biomass per Area

Definition:
$$\frac{\text{Aboveground Biomass}}{\text{Area of land}}$$

Description:

Benefit: This impact area refers to the total weight of all aboveground, harvestable parts of cultivated plants. It is suitable, where production is to be used for energy and other non-food purposes that can utilize the whole plant. Woody crops and forage crops will show high efficiencies in this impact area.

Resource: Agricultural land is always a limited resource. The type of land can be specified to distinguish between different land qualities. Distinctions are often made, for example, between cropland and pasture, high nature value (HNV) farmland and other farmland, or based on soil fertility and yield potential. For this indicator, the temporal reference must always be specified. However, in case of the standard period of one year, this information is sometimes omitted in scientific publications.

Correlation with soil management:

[157] For sustainable agricultural systems is required to improve the efficiency of crop nitrogen recovery and to reduce gaseous and leaching losses. #Poultry manure, rice hulls and mineral fertilizer combination may represent a good soil amendment to obtain a high yield with a lower environmental impact, at least in the short-term.

[253] Use of mulch helps to retain soil moisture, it can provide room for farmers to reduce the frequency and amount of irrigation.

[268] Nitrogen (N) efficient maize (*Zea mays* L.) varieties capable of producing higher maize grain yields under conditions of low soil N supply and infertile soils condition.

[274] Result suggests that in the presence of superabsorbent polymer, maize leaf and grain carbon isotope discrimination could be good indicators for evaluating maize water use efficiency during periods of low rainfall.

Strength & weaknesses pertaining to measurement of this impact area:

Biomass: Total amount aboveground biomass (production is generally easy to measure.

However, the informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Area of Land: While area of land is a standard measure that is used as reference in most statistics and inventories, a weakness of this indicator is that other relevant information like soil type, soil fertility or management history is often not provided.

In short, one hectare of dry, sandy cropland soil is very different from one hectare of pasture on drained peat soils.

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[253] Weed biomass during wet (W) and dry (D) seasons for lowland (IR-841) rice varieties/Area of land	Mg mulch * ha ⁻¹	
^[253] Weed biomass during wet (W) and dry (D) seasons for upland (Nerica-4) rice varieties/Area of land	Mg mulch * ha ⁻¹	
^[268] Non-reproductive aboveground biomass accumulated from flowering to harvest/Area of land	Mg * ha ⁻¹	
^[268] Aboveground biomass at flowering/Area of land	Mg * ha ⁻¹	
^[274] Above-ground biomass/Area of land	g * ha ⁻¹	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[157] Total plant biomass/Area of land	kg * m ⁻²	

Reference

ID	Citation	¹ Soil type & texture
157	Machado, D., et al. (2010). "The use of organic substrates with contrasting C/N ratio in the regulation of nitrogen use efficiency and losses in a potato agroecosystem." <u>Nutrient Cycling in Agroecosystems</u> 88(3): 411-427.	Sandy-loam texture
253	Totin, E., et al. (2013). "Mulching upland rice for efficient water management: A collaborative approach in Benin." <u>Agricultural Water Management</u> 125: 71-80.	n/a
268	Worku, M., et al. (2012). "Nitrogen efficiency as related to dry matter partitioning and root system size in tropical mid-altitude maize hybrids under different levels of nitrogen stress." <u>Field Crops Research</u> 130: 57-67.	Eutric Fluvisol ; Reddish brown clay soil (Nitosol, FAO soil classification)
274	Yang, W. and P. F. Li (2018). "Association of carbon isotope discrimination with leaf gas exchange and water use efficiency in maize following soil amendment with superabsorbent hydrogel." <u>Plant, Soil and Environment</u> 64(10): 484-490.	Sandy loam

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Impact Area: Energy per Area

Definition:
$$\frac{\text{Embodied Energy}}{\text{Area of land}}$$

Description:

Benefit: Energy content can be used for an integrated evaluation of crops. Generally, the type of energy should be specified to distinguish between use as fuel or use as food and feed. For use as animal feed, further definitions are required to determine if lignocellulosic crops qualify. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: Agricultural land is always a limited resource. The type of land can be specified to distinguish between different land qualities. Distinctions are often made, for example, between cropland and pasture, high nature value (HNV) farmland and other farmland, or based on soil fertility and yield potential. For this indicator, the temporal reference must always be specified. However, in case of the standard period of one year, this information is sometimes omitted in scientific publications.

Correlation with soil management:

[58] Systems based on sugarcane, sweet sorghum and oil palm performed best when comparing net energy per area of land.

[182] Improving the conditions of mineral nutrition by introducing balanced doses of fertilizers for all elements contributed to a sufficiently high yield.

[214] In Brazil, biodiesel addition into diesel is mandatory and soybean oil is its main source. Energy balance showed linearity with yield, whereas for EROI, the increases in input and yield were not affected.

[248] Small rice-producing farms ranging from 0.61 to 1.0 ha yielded higher energy ratios (4.14) than larger ones

[270] Energy consumption from irrigation process is converted to electricity, thus the corresponding GHG emission caused by irrigation is included into that of electricity

Strength & weaknesses pertaining to measurement of this impact area

Embodied Energy: Indicators for embodied energy are generally easy to measure and allow integration of or comparison between benefits from very different crops. However, their information value for questions of nutrition is limited because the provision of amino-acids and vitamins is not considered.

Area of land: While area of land is a standard measure that is used as reference in most statistics and inventories, a weakness of this indicator is that other relevant information like soil type, soil fertility or management history is often not provided.

In short, one hectare of dry, sandy cropland soil is very different from one hectare of pasture on drained peat soils.

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Region Scale

Indicator	Unit	Indicator values from
^[182] Aggregate energy output+ increment of energy (grain tillage crop rotation+ grain grass tillage rotation)/Area of land	GJ * ha ⁻¹	
^[214] Output energy flow (potential oil in the grains)/Area of land	MJ * ha ⁻¹	 , 
^[248] Land use efficiency (Output energy/Area of land)	MJ * ha ⁻¹	 , 
^[248] Net energy gain/Area of land	MJ * ha ⁻¹	 , 
^[270] Net energy gain/Area of land	GJ * ha ⁻¹	 , 

Table 2: Global Scale

Appendix – Ecosystem Services

Indicator	Unit	Indicator values from
[58] Net energy (Net energy yield (Energy content of biofuel and its coproducts – energy used for production, transportation and conversion)/Area of land)	GJ * ha ⁻¹	

Table 3: National Scale

Indicator	Unit	Indicator values from
[270] Net energy gain [GJ]/Area of land [ha]	GJ * ha ⁻¹	 , 

References

ID	Citation	¹ Soil type/ texture
58	de Vries, S. C., et al. (2010). "Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques." <i>Biomass and Bioenergy</i> 34 (5): 588-601.	n/a
182	Neshchadim, N. N., et al. (2018). "Bioenergetic assessment and economic efficiency of predecessors and fertilizer systems in the cultivation of winter wheat." <i>International Journal of Engineering and Technology(UAE)</i> 7 (4.38 Special Issue 38): 685-689.	Ordinary chernozem with low content of humus (4.5-5.5%)
214	Romanelli, T. L., et al. (2012). "Material embodiment and energy flows as efficiency indicators of soybean (Glycine max) production in Brazil." <i>Eng. Agric., Jaboticabal</i> 32 (2): 261-270.	n/a
248	Talukder, B., et al. (2019). "Energy efficiency of agricultural systems in the southwest coastal zone of Bangladesh." <i>Ecological Indicators</i> 98 : 641-648.	n/a
270	Wu, H., et al. (2017). "Temporal trends and spatial patterns of energy use efficiency and greenhouse gas emissions in crop production of Anhui Province, China." <i>Energy</i> 133 : 955-968.	n/a

Impact Area: Nitrogen per Area

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Definition:
$$\frac{\textit{Embodied Nitrogen}}{\textit{Area of land}}$$

Description:

Benefit: Refers to the total amount of nitrogen in the harvested product. The indicator is relevant for the assessment of food or feed quality as nitrogen content is indicative of the amount of proteins. Furthermore, high protein concentrations are essential for some uses in bio-refineries. Protein rich crops will show high efficiencies in this impact area.

Resource: Agricultural land is always a limited resource. The type of land can be specified to distinguish between different land qualities. Distinctions are often made, for example, between cropland and pasture, high nature value (HNV) farmland and other farmland, or based on soil fertility and yield potential. For this indicator, the temporal reference must always be specified. However, in case of the standard period of one year, this information is sometimes omitted in scientific publications.

Correlation with soil management:

[245] Higher nitrogen fertilizer rates applied to spring wheat results in an increase of grain and aboveground biomass N and in a decrease of the N effectiveness indicators

[261] Paper showed as regards fertilizer treatments, higher yields were obtained in wet years than in dry ones

Strength & weaknesses pertaining to measurement of this impact area

Embodied Nitrogen: can be used to calculate nitrogen use efficiencies (NUE) (e.g., the share of nitrogen recovered by plants relative to the amount of nitrogen fertilizer applied). However, efficiency measures are less suited to assess risks of environmental contamination by nitrogen fertilizer than nitrogen budgets (i.e. amount recovered – amount applied).

Area of land: While area of land is a standard measure that is used as reference in most statistics and inventories, a weakness of this indicator is that other relevant information like soil type, soil fertility or management history is often not provided.

In short, one hectare of dry, sandy cropland soil is very different from one hectare of pasture on drained peat soils.

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[206] Nitrogen content of the shoots/Area of land	kg * ha ⁻¹	
^[245] N content of grain yield/Area of land	kg * ha ⁻¹	
^[245] N content of aboveground biomass/Area of land	kg * ha ⁻¹	
^[246] Content of mineral nitrogen (Nmin)/Area of land	kg * ha ⁻¹	
^[246, 247] Nitrogen uptake by fertilized plants/Area of land	kg * ha ⁻¹	
^[246] Nitrogen uptake by control plants (unfertilized)/Area of land	kg * ha ⁻¹	
^[247] Nitrogen uptake by plants/Control (unfertilized) plot	kg * ha ⁻¹	
^[261] Amount of N of fertilization on maize yield/Area of land	kg N * ha ⁻¹	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[176] Nitrogen uptake by crops or fodder grass/ Fodder area	kg N * ha ⁻¹	 , 

References

ID	Citation	¹ Soil type/ texture

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Appendix – Resource Use Efficiencies

176	Moreau, P., et al. (2012). "Reconciling technical, economic and environmental efficiency of farming systems in vulnerable areas." <u>Agriculture Ecosystems & Environment</u> 147 : 89-99.	Deep loamy and shallow brown soils
206	Ratjen, A. M. and H. Kage (2016). "Nitrogen-limited light use efficiency in wheat crop simulators: Comparing three model approaches." <u>Journal of Agricultural Science</u> 154 (6): 1090-1101.	Pseudogleyic luvisol; Sandy loam to clayey loam
245	Szmigiel, A., et al. (2016). "Efficiency of nitrogen fertilization in spring wheat." <u>International Journal of Plant Production</u> 10 (4): 447-456.	Luvic Chernozem
246	Szulc, P., et al. (2018). "The size of the nminsoil pool as a factor impacting nitrogenutilization efficiency in maize (Zea mays L.)." <u>Pakistan Journal of Botany</u> 50 (1): 189-198.	Deer soil; Clay lightweight sand, shallow defaulting on light clay
247	Szulc, P., et al. (2016). "Efficiency of nitrogen fertilization based on the fertilizer application method and type of maize cultivar (Zea mays L.)." <u>Plant Soil and Environment</u> 62 (3): 135-142.	Luvisol; Granulometric composition of shallow, light clay sand on light clay, belonging to the good rye soil class
261	Vig, R., et al. (2012). "The efficiency of natural foliar fertilizers." <u>Idojaras</u> 116 (1): 53-64.	Calcareous chernozem; Mid-heavy adobe

Impact Area: Yield per Area

Definition:
$$\frac{\text{Grain/Fruit/ Tuber yield}}{\text{Area of land}}$$

Description:

Benefit: This impact area refers to the weight of harvested parts of plants that possess economic value. It is suitable, where production is to be used for food or feed purposes or as a non-energetic production factor in bio-refineries. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: Agricultural land is always a limited resource. The type of land can be specified to distinguish between different land qualities. Distinctions are often made, for example, between cropland and pasture, high nature value (HNV) farmland and other farmland, or based on soil fertility and yield potential. For this indicator, the temporal reference must always be specified. However, in case of the standard period of one year, this information is sometimes omitted in scientific publications.

Correlation with soil management:

[38] Controlled traffic system showed lower value in winter wheat production, but higher value in summer maize production

[67] Application of hydrogel, on sandy soils improves water holding capacity, availability of the nutrients, leading to higher productivity. The higher the application rate of the hydrogel, the higher the productivity

[157] For sustainable agricultural systems it is required to improve the efficiency of crop nitrogen recovery and to reduce gaseous and leaching losses. Poultry manure, rice hulls and mineral fertilizer combination may represent a good soil amendment to obtain a high yield with a lower environmental impact, at least in the short-term

[162] Studies proved reduction of field crop yields from organic fields in comparison to conventional ones

[177] Extensive farming produces lower yield and requires more land than intensive farming

[182] Improving the conditions of mineral nutrition by introducing balanced doses of fertilizers for all elements contributed to a sufficiently high yield

[207] Nitrogen utilization efficiency played a significant role in determining grain yield, while a negative and poor dependence of grain yield on Nitrogen uptake efficiency was observed

[214] In Brazil, biodiesel addition into diesel is mandatory and soybean oil is its main source. Energy balance showed linearity with yield, whereas for EROI, the increases in input and yield were not affected

[241] Highest land use efficiencies (potato yield per hectare of area) were achieved in regions that produce potatoes under irrigation in summer where solar radiation is high and lowest land use efficiencies were reported for the predominantly dry land and partially dry land regions

[242] Water-saving irrigation and high nitrogen use efficiency are becoming more and more important in rice production aimed at high and stable yield due to the shortage of water resources and the spread of non-point source pollution caused by irrational fertilization

[245] Higher nitrogen fertilizer rates applied to spring wheat results in an increase of grain and aboveground biomass N and in a decrease of the N effectiveness indicators

[248] Small rice-producing farms ranging from 0.61 to 1.0 ha yielded higher energy ratios (4.14) than larger ones

[250] Paper anticipates that the development and implementation of an integrated modeling platform across world's regions could build capabilities in understanding the agriculture-centered food,

energy and water (FEW) nexus and guiding policy and land management decision making for a sustainable future

[252] In the case of crop rotations, increasing resource-use efficiency while reducing yield gaps can be addressed by suitable agricultural management practices

[260] Inoculation of rice with dark septate endophytic (DSE) fungi represents a strategy to improve green manure-N recovery, grain yield per plant, and grain quality in terms of micronutrients contents in cropping systems with a low N input

[266] Alternate partial root-zone irrigation usually resulted in a higher water use efficiency improvement with no significant difference in yield but 33.3% less irrigation water

[268] Nitrogen (N) efficient maize (*Zea mays* L.) varieties capable of producing higher maize grain yields under conditions of low soil N supply and infertile soils condition

[274] Result suggests that in the presence of superabsorbent polymer, maize leaf and grain carbon isotope discrimination could be good indicators for evaluating maize water use efficiency during periods of low rainfall

[281] Paper indicates the importance of Arbuscular mycorrhizal fungi (AMF) inoculation in improving P efficiency of rice production

[284] System of rice intensification methods was beneficial for improving soil fertility because of effects on soil microbial biomass. Results also suggest that there is a substantial potential to raise rice yields by changing field management and cultivation methods rather than depending on genetic modifications or increases in agrochemical inputs

Strength & weaknesses pertaining to measurement of this impact area

Yield: Yield values are generally easy to measure and readily available at farm level or in the form of national inventories.

Appendix – Ecosystem Services

However, their informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Area of land: While area of land is a standard measure that is used as reference in most statistics and inventories, a weakness of this indicator is that other relevant information like soil type, soil fertility or management history is often not provided.

In short, one hectare of dry, sandy cropland soil is very different from one hectare of pasture on drained peat soils.

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: No Scale

Indicator	Unit	Indicator values from
^[250] Crop yield/Area of land	ton * ha ⁻¹	

Table 2: Field Scale

Indicator	Unit	Indicator values from
^[67] Marketable yield(Squash) /Area of land (feddan = arabic unit of area)	mg * feddan ⁻¹	
^[207] Grain yield/Area of land	ton * ha ⁻¹	
^[242] Grain yield/Area of land	kg * hm ⁻²	
^[245,260,274] Grain yield/Area of land	kg * ha ⁻¹	

Appendix – Resource Use Efficiencies

^[246] Grain yield/Plot	kg * ha ⁻¹	
^[247] Grain yield/Field	ton * ha ⁻¹	
^[266] Fresh yield /Area of land	g * ha ⁻¹	
^[266] Dry yield/Area of land	g * ha ⁻¹	
^[268] Mean grain yield/Area of land	Mg * ha ⁻¹	
^[281] Biological yield/Area of land	kg * ha ⁻¹	
^[281] Economic yield/Area of land	kg * ha ⁻¹	
^[284] Yield/Area of land	ton * ha ⁻¹	

Table 3: Farm Scale

Indicator	Unit	Indicator values from
^[157] Tuber yield/Area of land	kg * m ⁻²	
^[162] Additional yield from fertilization/Area of land	kg * ha ⁻¹	
^[162] Additional yield from fertilization in the previous year/Area of land	kg * ha ⁻¹	
^[175, 252] Grain yield/Area of land	kg * ha ⁻¹	
^[175] Fodder conservation rate (Fodder conserved/Area of land)	kg * ha ⁻¹	
^[176] Annual Gross Product (Average yield/ Fodder area)	kg * ha ⁻¹	 , 

Table 4: Regional Scale

Indicator	Unit	Indicator values from
^[38] Crop productivity (Yield/Area of land)	kg * ha ⁻¹	
^[110] Average yield (Yield/Area of land)	ton * ha ⁻¹	
^[182] Grain yield/Area of land	ton * ha ⁻¹	
^[185] Extension Yield (Yield of main crop (s)/Area of land)	Not provided* ha ⁻¹	 , 

Appendix – Ecosystem Services

[190] Grain yield/Area of land	kg * ha ⁻¹	 , 
[202] Gross yield (weight of all harvested fruits) /Area of land	mg * ha ⁻¹	
[202] Fresh marketable yield (gross yield minus the fruit discarded as a result of fruit rot or small size, or fruit used for processed products) /Area of land	mg * ha ⁻¹	
[214] Yield (obtained product) /Area of land	kg * ha ⁻¹	 , 
[241] Land use efficiency (Potato yield /Area of land)	ton * ha ⁻¹	
[248] Rice yield/Area of land	kg * ha ⁻¹	 , 

Table 5: National Scale

Indicator	Unit	Indicator values from
[177] Marginal yield (yield at the level of fertilization where the curves: "yield per fertilizer unit" and "groundwater nitrate content per fertilizer unit" intersect/Area of land	ton* ha ⁻¹	 , 
[202] Gross yield (weight of all harvested fruits) /Area of land	mg * ha ⁻¹	
[202] Fresh marketable yield (gross yield minus the fruit discarded as a result of fruit rot or small size, or fruit used for processed products) /Area of land	mg * ha ⁻¹	

References

ID	Citation	¹ Soil type/ texture
38	Chen, H., et al. (2016). "Effect of controlled traffic on energy use efficiency in wheat-maize production in North China Plain." <u>Journal of Computational and Theoretical Nanoscience</u> 13 (4): 2634-2638.	Silt loam; Porous and homogenous
67	C.Y. El-dewiny et al. (2011) "Water and fertilizer use efficiency by squash grown under stress on sandy soil treated with acrylamide hydrogels." <u>Journal of Applied Sciences Research</u> 7 (12): 1828-1833.	Sandy soil
110	Homolka, J. and R. Mydlar (2011). "Efficiency evaluation in intensive growing of winter rape." <u>Agricultural Economics-ZemедelskaEkonomika</u> 57 (5): 247-257.	Pararendzina on terraced broken stones and gravel sands from the acid material
157	Machado, D., et al. (2010). "The use of organic substrates with contrasting C/N ratio in the regulation of nitrogen use efficiency and losses in a potato agroecosystem." <u>Nutrient Cycling in Agroecosystems</u> 88 (3): 411-427.	Sandy-loam texture
162	Manolova, V., et al. (2015). "Economic efficiency of fertilization and its residual-effect during conversion period to organic field crop production." <u>Bulgarian Journal of Agricultural Science</u> 21 (5): 1022-1026.	n/a
175	Moore, A. D., et al. (2011). "Evaluation of the water use efficiency of alternative farm practices at a range of spatial and temporal scales: A conceptual framework and a modelling approach." <u>Agricultural Systems</u> 104 (2): 162-174.	Black vertosol soil
176	Moreau, P., et al. (2012). "Reconciling technical, economic and environmental efficiency of farming systems in vulnerable areas." <u>Agriculture Ecosystems & Environment</u> 147 : 89-99.	Deep loamy and shallow brown soils
177	Mozner, Z., et al. (2012). "Modifying the yield factor based on more efficient use of fertilizer-The environmental impacts of intensive and extensive agricultural practices." <u>Ecological Indicators</u> 16 : 58-66.	n/a
182	Neshchadim, N. N., et al. (2018). "Bioenergetic assessment and economic efficiency of predecessors and fertilizer systems in the cultivation of winter wheat." <u>International Journal of Engineering and Technology(UAE)</u> 7 (4.38 Special Issue 38): 685-689.	Ordinary chernozem with low content of humus (4.5-5.5%)
185	Oladele, O. I. (2013). "Towards Developing a set of Indices to assess the Effectiveness and Efficiency of Agricultural Extension Policy." <u>Life Science Journal-Acta Zhengzhou University Overseas Edition</u> 10 (1): 3309-3314.	n/a
190	Pan, G., et al. (2009). "Using QuickBird imagery and a production efficiency model to improve crop yield estimation in the semi-arid hilly Loess Plateau, China." <u>Environmental Modelling & Software</u> 24 (4): 510-516.	n/a
202	Plénet, D., et al. (2009). "Using on-field data to develop the	n/a

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Appendix – Ecosystem Services

	EFI© information system to characterise agronomic productivity and labour efficiency in peach (<i>Prunus persica</i> L. Batsch) orchards in France." <u>Agricultural Systems</u> 100 (1-3): 1-10.	
207	Rehman, A., et al. (2011). "Grain quality, nutrient use efficiency, and bioeconomics of maize under different sowing methods and NPK levels." <u>Chilean Journal of Agricultural Research</u> 71 (4): 586-593.	Sandy clay loam
214	Romanelli, T. L., et al. (2012). "Material embodiment and energy flows as efficiency indicators of soybean (<i>Glycine max</i>) production in Brazil." <u>Engenharia Agricola</u> 32 (2): 261-270.	n/a
241	Steyn, J. M., et al. (2016). "Resource use efficiencies as indicators of ecological sustainability in potato production: A South African case study." <u>Field Crops Research</u> 199 : 136-149.	Loam, sandy-loam, sand
242	Sun, Y., et al. (2012). "The effects of different water and nitrogen managements on yield and nitrogen use efficiency in hybrid rice of China." <u>Field Crops Research</u> 127 : 85-98.	Sandy loam
245	Szmigiel, A., et al. (2016). "Efficiency of nitrogen fertilization in spring wheat." <u>International Journal of Plant Production</u> 10 (4): 447-456.	Luvic Chernozem
246	Szulc, P., et al. (2018). "The size of the nminsoil pool as a factor impacting nitrogen utilization efficiency in maize (<i>Zea mays</i> L.)." <u>Pakistan Journal of Botany</u> 50 (1): 189-198.	Clay lightweight sand, shallow defaulting on light clay; Deer soil
247	Szulc, P., et al. (2016). "Efficiency of nitrogen fertilization based on the fertilizer application method and type of maize cultivar (<i>Zea mays</i> L.)." <u>Plant Soil and Environment</u> 62 (3): 135-142.	Granulometric composition of shallow, light clay sand on light clay, belonging to the good rye soil class; Luvisol
248	Talukder, B., et al. (2019). "Energy efficiency of agricultural systems in the southwest coastal zone of Bangladesh." <u>Ecological Indicators</u> 98 : 641-648.	n/a
250	Tian, H., et al. (2018). "Optimizing resource use efficiencies in the food–energy–water nexus for sustainable agriculture: from conceptual model to decision support system." <u>Current Opinion in Environmental Sustainability</u> 33 : 104-113.	n/a
252	Tomaz, A., et al. (2018). "Efficient use of water and nutrients in irrigated cropping systems in the Alqueva region." <u>Spanish Journal of Soil Science</u> 8 (1): 12-23.	Silt loam; Chromic Cambisols (Bc)
260	Vergara, C., et al. (2018). "Dark Septate Endophytic Fungi Increase Green Manure-N-15 Recovery Efficiency, N Contents, and Micronutrients in Rice Grains." <u>Frontiers in Plant Science</u> 9 : 613.	Sandy soil (3% clay, 5% silt, and 92% sandy); Haplic Planosol
266	Wei, Z. H., et al. (2016). "Carbon isotope discrimination shows a higher water use efficiency under alternate partial root-zone irrigation of field-grown tomato." <u>Agricultural Water Management</u> 165 : 33-43.	Sandy loam; Arid
268	Worku, M., et al. (2012). "Nitrogen efficiency as related to dry matter partitioning and root system size in tropical mid-altitude maize hybrids under different levels of nitrogen stress." <u>Field Crops Research</u> 130 : 57-67.	Reddish brown clay soil (Nitosol, FAO soil classification); Eutric Fluvisol

Impact Area & Indicator Factsheet: **Resource Use Efficiency**

274	Yang, W. and P. F. Li (2018). "Association of carbon isotope discrimination with leaf gas exchange and water use efficiency in maize following soil amendment with superabsorbent hydrogel." <u>Plant, Soil and Environment</u> 64 (10): 484-490.	Sandy loam
281	Zhang, S., et al. (2016). "Arbuscularmycorrhiza improved phosphorus efficiency in paddy fields." <u>Ecological Engineering</u> 95 : 64-72.	n/a
284	Zhao, L., et al. (2010). "Comparisons of yield, water use efficiency, and soil microbial biomass as affected by the system of rice intensification." <u>Communications in Soil Science and Plant Analysis</u> 41 (1): 1-12.	n/a

Impact Area: Benefits per Water

Definition:
$$\frac{\text{Financial benefits}}{\text{Water}}$$

Description:

Benefit: This impact area assesses benefits via their appreciation by markets (Di Maio et al., 2017). It is sensitive to various socio-economic factors because commodity prices reflect demand and are also influenced by value systems and policies through effects of financial incentives and tax regulations.

Resource: Even in rainfed agriculture, water can constitute a stressed resource, impacting for example on farmers' decisions whether or not to plant cover crops. Irrigation water is always a stressed resource. In cases of seasonal water shortages, the use of water can also be specified as use during critical time periods.

Correlation with soil management:

[156] Technology and water management can improve water use efficiency

[249] Result indicates perception of water scarcity, irrigation infrastructure, water price and income increase irrigation water efficiency while time spent on farming and fragmentation decreases it

Strength & weaknesses pertaining to measurement of this impact area

Financial Benefits: Financial indicators are well suited for integrating or comparing agricultural production processes with products for very different end uses. For calculating benefit-cost ratios (BCR), indicators that reflect revenue should be used. In most other cases, indicators that reflect net benefits (after deduction of charges, costs and expenses) provide a more realistic picture of benefits generated. Price volatilities make efficiency calculations valid only for a certain point in time and space.

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	

Impact Area & Indicator Factsheet: Resource Use Efficiency

Stakeholder participation		Not provided	

Table 1: Farm Scale

Indicator	Unit	Indicator values from
[175] Gross margin use efficiency (Total gross margin (Sum of gross income from grain, conserved fodder, and animal products)/Total rainfall)	\$ * mm ⁻¹	
[249] Irrigation water use efficiency (Optimal cost (when all inputs are technically and allocatively efficient)/Amount of irrigation water)	\$ * m ⁻³	

Table 2: Regional Scale

Indicator	Unit	Indicator values from
[142] Water use efficiency (Economic output of crop yield/Amount of irrigation water)	\$ * m ⁻³	
[156] Water use efficiency index (Value of agricultural output /Total agricultural water use (irrigation and precipitation))	\$ * m ⁻³	
[233] Maximum revenue /Unit of Irrigation Water per ton of product	\$ * m ⁻³	

Table 3: National Scale

Indicator	Unit	Indicator values from
[81] Irrigated agriculture water use efficiency (Gross value added by the portion of the agricultural sector that uses irrigation/Input of irrigation water)	\$ * m ⁻³	

References

ID	Citation	¹ Soil type/ texture
81	Giupponi, C., et al. (2018). "Spatial assessment of water use efficiency (SDG Indicator 6.4.1) for regional policy support." <u>Frontiers in Environmental Science</u> 6 (NOV).	n/a
142	Latinopoulos, D. (2009). "Multicriteria decision-making for efficient water and land resources allocation in irrigated agriculture." <u>Environment, Development and Sustainability</u> 11 (2): 329-343.	n/a
156	Long, K. S. and B. C. Pijanowski (2017). "Is there a relationship between water scarcity and water use efficiency in China? A national decadal assessment across spatial scales." <u>Land Use Policy</u> 69 : 502-511.	n/a
175	Moore, A. D., et al. (2011). "Evaluation of the water use efficiency of alternative farm practices at a range of spatial and temporal scales: A conceptual framework and a modelling approach." <u>Agricultural Systems</u> 104 (2): 162-174.	Black vertosol soil
233	Soliman, N. Y. and R. M. Barghash (2016). "The economic efficiency of water irrigation usage and restructuring cultivation of agricultural crops." <u>International Journal of ChemTech Research</u> 9 (10): 62-71.	n/a
249	Tang, J. and H. Folmer (2016). "Latent vs. Observed Variables: Analysis of Irrigation Water Efficiency Using SEM and SUR." <u>Journal of Agricultural Economics</u> 67 (1): 173-185.	n/a

¹**Soil type/ texture:** If provided, what are type and texture of the soils studied in the paper?

Impact Area: **Biomass per Water**

Definition:
$$\frac{\text{Aboveground Biomass}}{\text{Water}}$$

Description:

Benefit: This impact area refers to the total weight of all aboveground, harvestable parts of cultivated plants. It is suitable, where production is to be used for energy and other non-food purposes that can utilize the whole plant. Woody crops and forage crops will show high efficiencies in this impact area.

Resource: Even in rainfed agriculture, water can constitute a stressed resource, impacting for example on farmers' decisions whether or not to plant cover crops. Irrigation water is always a stressed resource. In cases of seasonal water shortages, the use of water can also be specified as use during critical time periods.

Correlation with soil management:

[57] Treatment with constant groundwater table showed higher water use efficiency than crops in irrigated field, irrespective of planting density

[195] Results showed a positive and additive effect of water and nitrogen application on Water Use Efficiency, reflected by yield enhancement

Strength & weaknesses pertaining to measurement of this impact area

Biomass: Total amount aboveground biomass (production is generally easy to measure.

However, the informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[57] Water use efficiency of total biomass (Total dry matter of bean plants/Amount of evapotranspiration)	$\text{g} * \text{mm}^{-1}$	
[275] Accumulation of biomass/Soil water content	$\text{g} * \%^{-1}$	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[175] Shoot biomass transpiration efficiency (Shoot biomass production (Above-ground net primary productivity of plants that contribute to the production of grain, grazed forage or conserved fodder) /Total rainfall)	$\text{kg} * \text{mm}^{-1}$	

Table 3: Global Scale

Indicator	Unit	Indicator values from
[195] Normalized Water productivity of biomass (Biomass produced/Irrigation water applied + effective rainfall/evapotranspiration)	$\text{kg} * \text{mm}^{-1}$	

References

ID	Citation	¹ Soil type/ texture
57	de Medeiros, G. A., et al. (2014). "Water use efficiency as an indicator of environmental impact of irrigated crops under subtropical conditions." 181 : 455-466.	Red Latosol (Oxisoil); Clay texture (61% clay)
175	Moore, A. D., et al. (2011). "Evaluation of the water use efficiency of alternative farm practices at a range of spatial and temporal scales: A conceptual framework and a modelling approach." <i>Agricultural Systems</i> 104 (2): 162-174.	Black vertosol soil

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Impact Area & Indicator Factsheet: **Resource Use Efficiency**

195	Pascual, M., et al. (2016). "Water use efficiency in peach trees over a four-years experiment on the effects of irrigation and nitrogen application." <u>Agricultural Water Management</u> 164 : 253-266.	Petrocalcic calcixerept (Petrocalcic Calcisol); Loamy textured (20% clay and 40% sand) and pH (1:2.5) is basic(8.3)
275	Yang, Z., et al. (2016). "Leveraging abscisic acid receptors for efficient water use in Arabidopsis." <u>Proceedings of the National Academy of Sciences of the United States of America</u> 113 (24): 6791-6796.	n/a

Impact Area: Yield per Water

Definition:
$$\frac{\text{Grain/Fruit/ Tuber yield}}{\text{Water}}$$

Description:

Benefit: This impact area refers to the weight of harvested parts of plants that possess economic value. It is suitable, where production is to be used for food or feed purposes or as a non-energetic production factor in bio-refineries. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: Even in rainfed agriculture, water can constitute a stressed resource, impacting for example on farmers' decisions whether or not to plant cover crops. Irrigation water is always a stressed resource. In cases of seasonal water shortages, the use of water can also be specified as use during critical time periods.

Correlation with soil management:

[57] Treatment with constant groundwater table showed higher water use efficiency than crops in irrigated field, irrespective of planting density

[67] Application of hydrogel, on sandy soils improves water holding capacity and availability of the nutrients. The higher the amount of hydrogel the higher the water use efficiency

[73] Water is clearly a key resource in potato production that affects the use efficiency of other resources

[98] Limiting irrigation or changing irrigation patterns in areas with high water pressure, as well as expanding irrigation in areas with abundant water resources increases water use efficiency. Improving irrigation efficiency and reducing irrigation water per unit area are methods to increase regional water use efficiency. Enhancing crop varieties and crop yield can contribute to increase regional water use efficiency

[130] The treatments with alternate furrow and surge flow irrigation had higher crop yield and water use efficiency of all treatments

[135] Water use efficiency of the treatment with micro irrigation was higher than with check basin irrigation for both crops

[195] Results showed a positive and additive effect of water and nitrogen application on Water Use Efficiency, reflected by yield enhancement

[241] Highest land use efficiencies (potato yield per hectare of area) were achieved in regions that produce potatoes under irrigation in summer where solar radiation is high and lowest

land use efficiencies were reported for the predominantly dryland and partially dryland regions

[242] Water-saving irrigation and high nitrogen use efficiency are becoming more and more important in rice production aimed at high and stable yield due to the shortage of water resources and the spread of non-point source pollution caused by irrational fertilization

[252] In the case of crop rotations, increasing resource-use efficiency while reducing yield gaps can be addressed by suitable agricultural management practices

[266] Alternate partial root-zone irrigation usually resulted in a higher water use efficiency improvement with no significant difference in yield but 33.3% less irrigation water

[274] Result suggests that in the presence of superabsorbent polymer, maize leaf and grain carbon isotope discrimination could be good indicators for evaluating maize water use efficiency during periods of low rainfall

[284] System of rice intensification methods were beneficial for improving soil fertility because of effects on soil microbial biomass. Results also suggest that there is a substantial potential to raise rice yields by changing field management and cultivation methods rather than depending on genetic modifications or increases in agrochemical inputs

[286] AquaCrop model has been widely used and calibrated to simulate yield for a number of crops under diverse environments and types of water management

Strength & weaknesses pertaining to measurement of this impact area

Yield: Yield values are generally easy to measure and readily available at farm level or in the form of national inventories.

However, their informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	

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Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[57] Water use efficiency of seed yield (Yield (bean seeds)/Amount of evapotranspiration)	$g * mm^{-1}$	
[67,130,242] Water use efficiency (Yield/Amount of irrigation water)	$kg * m^{-3}$	
[73] Water use efficiency (Potato yield/Irrigation water)	$g * l^{-1}$	 , 
[135] Water use efficiency (Grain yield (pea and bean)/ Amount of irrigation water)	$kg * mm^{-1}$	
[266] Water use efficiency at fresh yield scale (Fruit fresh yield/Crop evapotranspiration over the growth period)	$gm^{-2} * mm^{-1}$	
[266] Water use efficiency at dry yield scale (Fruit dry yield/Crop evapotranspiration over the growth period)	$gm^{-2} * mm^{-1}$	
[274] Water use efficiency at the yield level (Grain yield [kg]/Evapotranspiration [mmol m ⁻² s ⁻¹])	$kg * mmol^{-1} * m^2 * s$	
[284] Water use efficiency (Grain yield/Water consumed for system of rice intensification)	$ton ha^{-1} * mm^{-1}$	
[284] Irrigation water use efficiency (Grain yield/Irrigation water)	$ton ha^{-1} * mm^{-1}$	
[286] Water use efficiency (Crop yield/Evapotranspiration)	$ton * mm^{-1}$	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[175] Rainfall use efficiency for grain (Total grain yield/ Total rainfall)	$kg * ha^{-1} * mm^{-1}$	
[252] Water use efficiency (Grain yield/Crop evapotranspiration)	$kg * m^{-3}$	
[252] Irrigation water use efficiency (Grain yield/Seasonal irrigation water applied)	$kg * m^{-3}$	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
[98] Marginal water productivity (Grain or tuber yield/Amount of irrigation water)	$kg * m^{-3}$	
[233] Yield/Unit of Irrigation Water	$ton * m^{-3}$	
[241] Water use efficiency (Tuber yield/Total amount of rainfall + irrigation water applied)	$kg * m^{-3}$	

Table 4: Global Scale

Indicator	Unit	Indicator values from
[195] Water productivity of irrigation (Fruit yield/Irrigation water)	kg * mm ⁻¹	
[195] Normalized Water productivity of yield (Fruit yield/Irrigation water applied + effective rainfall/evapotranspiration)	kg * mm ⁻¹	

References

ID	Citation	¹ Soil type/ texture
57	de Medeiros, G. A., et al. (2014). "Water use efficiency as an indicator of environmental impact of irrigated crops under subtropical conditions." 181 : 455-466.	Red Latosol (Oxisol); Clay texture (61% clay)
67	C.Y. El-dewiny (2011) "Water and fertilizer use efficiency by squash grown under stress on sandy soil treated with acrylamide hydrogels." <u>Journal of Applied Sciences Research</u> 7 (12): 1828-1833.	Sandy soil
73	Franke, A. C., et al. (2018). "Resource use efficiencies in potato production." <u>Water Wheel</u> 17 (2): 18-21.	Sandy soil
98	Guo, X., et al. (2018). "Spatial-temporal distribution and impact factors of irrigation water use efficiency in the grain production of China." <u>International Journal of Agricultural and Biological Engineering</u> 11 (5): 131-138.	n/a
130	Kifle, M., et al. (2017). "Effect of surge flow and alternate irrigation on the irrigation efficiency and water productivity of onion in the semi-arid areas of North Ethiopia." <u>Agricultural Water Management</u> 187 : 69-76.	Clay texture
135	Kumar, M., et al. (2009). "Integrating water harvesting and gravity-fed micro-irrigation system for efficient water management in terraced land for growing vegetables." <u>Biosystems Engineering</u> 102 (1): 106-113.	n/a
175	Moore, A. D., et al. (2011). "Evaluation of the water use efficiency of alternative farm practices at a range of spatial and temporal scales: A conceptual framework and a modelling approach." <u>Agricultural Systems</u> 104 (2): 162-174.	Black vertosol soil
195	Pascual, M., et al. (2016). "Water use efficiency in peach trees over a four-years experiment on the effects of irrigation and nitrogen application." <u>Agricultural Water Management</u> 164 : 253-266.	Petrocalcic calcixerept (Petrocalcic Calcisol); Loamy textured (20% clay and 40% sand) and pH (1:2.5) is basic(8.3)
233	Soliman, N. Y. and R. M. Barghash (2016). "The economic efficiency of water irrigation usage and restructuring	n/a

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

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	cultivation of agricultural crops." <u>International Journal of ChemTech Research</u> 9 (10): 62-71.	
241	Steyn, J. M., et al. (2016). "Resource use efficiencies as indicators of ecological sustainability in potato production: A South African case study." <u>Field Crops Research</u> 199 : 136-149.	Loam, sandy-loam, sand
242	Sun, Y., et al. (2012). "The effects of different water and nitrogen managements on yield and nitrogen use efficiency in hybrid rice of China." <u>Field Crops Research</u> 127 : 85-98.	Sandy loam
252	Tomaz, A., et al. (2018). "Efficient use of water and nutrients in irrigated cropping systems in the Alqueva region." <u>Spanish Journal of Soil Science</u> 8 (1): 12-23.	Chromic Cambisols (Bc); Silt loam
266	Wei, Z. H., et al. (2016). "Carbon isotope discrimination shows a higher water use efficiency under alternate partial root-zone irrigation of field-grown tomato." <u>Plant, Soil and Environment</u> 64 (10): 484-490.	Arid; Sandy loam
274	Yang, W. and P. F. Li (2018). "Association of carbon isotope discrimination with leaf gas exchange and water use efficiency in maize following soil amendment with superabsorbent hydrogel." <u>Plant, Soil and Environment</u> 64 (10): 484-490.	Sandy loam
284	Zhao, L., et al. (2010). "Comparisons of yield, water use efficiency, and soil microbial biomass as affected by the system of rice intensification." <u>Communications in Soil Science and Plant Analysis</u> 41 (1): 1-12.	n/a
286	Zhuo, L. and A. Y. Hoekstra (2017). "The effect of different agricultural management practices on irrigation efficiency, water use efficiency and green and blue water footprint." <u>Frontiers of Agricultural Science and Engineering</u> 4 (2): 185-194.	n/a

Impact Area: Biomass per Nitrogen fertilizer

Definition:
$$\frac{\text{Aboveground Biomass}}{\text{Nitrogen fertilizer}}$$

Description:

Benefit: This impact area refers to the total weight of all aboveground, harvestable parts of cultivated plants. It is suitable, where production is to be used for energy and other non-food purposes that can utilize the whole plant. Woody crops and forage crops will show high efficiencies in this impact area.

Resource: Nitrogen fertilizer is considered a stressed resource for several reasons. While the supply of nitrogen is effectively unlimited, its production is highly energy intensive and its application results in emissions of ammonium and nitrous oxide, creating a conflict between nitrogen fertilizer application and climate change mitigation targets.

Depending on the application rate and type of nitrogen fertilizer (in combination with site specific conditions), diffuse pollution and contamination of water resources is also relevant. Diffuse nitrogen pollution may also strongly affect nutrient poor natural ecosystems and alter species composition.

Finally, fertilizer application is a relevant factor in farmers' cost calculations.

Correlation with soil management:

^[260] Inoculation of rice with dark septate endophytic (DSE) fungi represents a strategy to improve green manure-N recovery, grain yield per plant, and grain quality in terms of micronutrients contents in cropping systems with a low N input

Strength & weaknesses pertaining to measurement of this impact area:

Biomass: Total amount aboveground biomass (production is generally easy to measure.

However, the informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Can be measured as:

Biomass:

- yield, fresh weight [t]
- yield, dry matter weight [t]

Nitrogen fertilizer:

- total nitrogen fertilizer application [kg N]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
^[260] Nutrient concentration (%) (Dry matter/N content)	mg plant ⁻¹ * (mg plant ⁻¹) ⁻¹	

References

ID	Citation	¹ Soil type & texture
260	Vergara, C., et al. (2018). "Dark Septate Endophytic Fungi Increase Green Manure-N-15 Recovery Efficiency, N Contents, and Micronutrients in Rice Grains." <u>Frontiers in Plant Science</u> 9 .	Haplic Planosol; Sandy soil (3% clay, 5% silt, and 92% sandy)

¹**Soil type & texture:** If provided, what are type and texture of the soils studied in the paper?

Impact Area: Energy per Nitrogen fertilizer

Definition:
$$\frac{\text{Embodied Energy}}{\text{Nitrogen fertilizer}}$$

Description:

Benefit: Energy content can be used for an integrated evaluation of crops. Generally, the type of energy should be specified to distinguish between use as fuel or use as food and feed. For use as animal feed, further definitions are required to determine if lignocellulosic crops qualify. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: Nitrogen fertilizer is considered a stressed resource for several reasons. While the supply of nitrogen is effectively unlimited, its production is highly energy intensive and its application results in emissions of ammonium and nitrous oxide, creating a conflict between nitrogen fertilizer application and climate change mitigation targets.

Depending on the application rate and type of nitrogen fertilizer (in combination with site specific conditions), diffuse pollution and contamination of water resources is also relevant. Diffuse nitrogen pollution may also strongly affect nutrient poor natural ecosystems and alter species composition.

Finally, fertilizer application is a relevant factor in farmers' cost calculations.

Correlation with soil management:

[45] Precision farming (applying nutrients and pesticides match temporally and spatially crop requirements) increases fertilizer use efficiency. Locating food production in areas with the suitable climate and soil conditions for a crop can increase agricultural input efficiency (the amount of food produced per input of fertilizer or feed)

[58] Soybean performed well on nitrogen use efficiency (ability to fix nitrogen)

Strength & weaknesses pertaining to measurement of this impact area:

Embodied Energy: Indicators for embodied energy are generally easy to measure and allow integration of or comparison between benefits from very different crops. However, their information value for questions of nutrition is limited because the provision of amino-acids and vitamins is not considered.

Can be measured as:

Embodied Energy:

- nutritional value (humans) [J]
- nutritional value (non-grazing livestock) [J]
- nutritional value (grazing livestock) [J]
- heating value [J]

Nitrogen fertilizer:

- total nitrogen fertilizer application [kg N]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: No Scale

Indicator	Unit	Indicator values from
^[58] Nitrogen use efficiency (Net energy yield (Energy content of biofuel and its coproducts – energy used for production, transportation and conversion)/Nitrogen input)	GJ * kg ⁻¹	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[45] Nitrogen use efficiency (Digestible calories in grain yield/Nitrogen fertilizer)	Kcal * g ⁻¹	

References

ID	Citation	¹Soil type/ texture
45*	Clark, M. and D. Tilman (2017). "Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice." <u>Environmental Research Letters</u> 12 (6).	n/a
58	de Vries, S. C., et al. (2010). "Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques." <u>Biomass and Bioenergy</u> 34 (5): 588-601.	n/a

¹**Soil type/ texture:** If provided, what are type and texture of the soils studied in the paper?

*The impact area discussed on this factsheet is not a focus of the cited paper

Impact Area: Nitrogen per Nitrogen fertilizer

Definition: *Embodied Nitrogen*
Nitrogen fertilizer

Description:

Benefit: Refers to the total amount of nitrogen in the harvested product. The indicator is relevant for the assessment of food or feed quality as nitrogen content is indicative of the amount of proteins. Furthermore, high protein concentrations are essential for some uses in bio-refineries.

Protein rich crops will show high efficiencies in this impact area.

Resource: Nitrogen fertilizer is considered a stressed resource for several reasons. While the supply of nitrogen is effectively unlimited, its production is highly energy intensive and its application results in emissions of ammonium and nitrous oxide, creating a conflict between nitrogen fertilizer application and climate change mitigation targets.

Depending on the application rate and type of nitrogen fertilizer (in combination with site specific conditions), diffuse pollution and contamination of water resources is also relevant. Diffuse nitrogen pollution may also strongly affect nutrient poor natural ecosystems and alter species composition.

Finally, fertilizer application is a relevant factor in farmers' cost calculations.

Correlation with soil management:

[27] Strategies to improve N use efficiency on Irish dairy farms: Optimization of application of N fertilizers and organic manures (timing, rate, form, method of application). Incorporation of N fixing forage legumes into grass swards. Improved grazing management and grass utilization (offsetting concentrate feed import) and better soiled water management

[68] Agricultural systems can reduce fertilizer use and can achieve higher nitrogen use efficiency by facilitating biological nitrogen fixation

[91] Increasing farm size and new technologies for fertilizer application could increase nitrogen use efficiency in Chinese cropland

[157] For sustainable agricultural systems is required to improve the efficiency of crop nitrogen recovery and to reduce gaseous and leaching losses. Poultry manure, rice hulls and mineral fertilizer combination may represent a good soil amendment to obtain a high yield with a lower environmental impact, at least in the short-term

[259] Effectiveness of fertilization strategies using bio-digestion waste derivatives as compared to conventional practices using animal manure and chemical fertilizer

[260] Inoculation of rice with dark septate endophytic (DSE) fungi represents a strategy to improve green manure-N recovery, grain yield per plant, and grain quality in terms of micronutrients contents in cropping systems with a low N input

Correlation with soil functions:

[27] Land with more free draining soils was related to higher nitrogen use efficiency

[82] Change in soil N stock influences system N efficiency

Strength & weaknesses pertaining to measurement of this impact area

Embodied Nitrogen: can be used to calculate nitrogen use efficiencies (NUE) (e.g., the share of nitrogen recovered by plants relative to the amount of nitrogen fertilizer applied). However, efficiency measures are less suited to assess risks of environmental contamination by nitrogen fertilizer than nitrogen budgets (i.e. amount recovered – amount applied).

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[259] Nitrogen use efficiency (Plant N uptake/Amount of N applied in fertilization)	$\text{kg ha}^{-1} * (\text{kg ha}^{-1})^{-1}$	
[260] N recovery efficiency (10%) (Amount of N in the plants derived from C. ensiformis-15 N/Amount of applied N as 15N-labeled green manure (NGM))	$\text{mg plant}^{-1} * (\text{mg plant}^{-1})^{-1}$	
[260] Fraction of N in the plant derived from finely ground C. ensiformis N (N in excess in rice plant/N in excess in green manure)	$\text{mg plant}^{-1} * (\text{mg plant}^{-1})^{-1}$	

Appendix – Ecosystem Services

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[27] Nitrogen use efficiency (Total nitrogen output (N milk + N crop + N livestock)/Total N input (fertilizer + concentrates + forage feeds + livestock imports))	kg * kg ⁻¹	
[82] System nitrogen efficiency (Net N output (Animals + milk + high protein crops + low protein crops + manure)/Net N input (Fertilizer + biological N fixation + seed input + high protein feed + low protein feed + manure) + net indirect losses (occurring during production and transport of inputs) + change in soil N))	kg * kg ⁻¹	 , 
[82] Nitrogen use efficiency (N output (Animals + milk + high protein crops + low protein crops + manure)/N input (Fertilizer + biological N fixation + seed input + high protein feed + low protein feed + manure))	kg * kg ⁻¹	
[157] Nitrogen use efficiency (Nitrogen measured in plant biomass at harvest – amount of Nitrogen coming from the initial soil/Total amount of applied Nitrogen (MF: mineral fertilizer; P + F: poultry manure and mineral fertilizer; R + F: rice hulls and mineral fertilizer and P + R + F: poultry manure, rice hulls and mineral fertilizer))	g * g ⁻¹	

Table 3: National Scale

Indicator	Unit	Indicator values from
[68] Full-Chain nitrogen use efficiency (Embodied Nitrogen in Food/Total nitrogen input (fertilizer + biological nitrogen fixation + atmospheric deposition + net N import of food and feed) + changes in N stock (annual net balance of national imports and exports of food and feed))	Kton * Kton ⁻¹	
[83] System nitrogen efficiency (Net N output (Animal products + crops + manure)/Net N input (fertilizer + biological N fixation + atmospheric N deposition + manure + crops + animals) + net N indirect losses (occurring during production and transport of inputs) + change in soil N))	kg * kg ⁻¹	
[83] Nitrogen use efficiency (N output (Animal products + crops + manure)/Net N input (Fertilizer + biological N fixation + atmospheric N deposition + manure + crops + animals))	kg * kg ⁻¹	
[91] Nitrogen use efficiency in the cropland (Total N in the crop (including seed and straw)/Total N input (fertilizer, manure, biological nitrogen fixation, atmospheric deposition, straw recycled, irrigation))	Tg * Tg ⁻¹	 , 



References

ID	Citation	¹ Soil type/ texture
27	Buckley, C., et al. (2016). "Farm gate level nitrogen balance and use efficiency changes post implementation of the EU Nitrates Directive." <u>Nutrient Cycling in Agroecosystems</u> 104 (1): 1-13.	n/a
68	Erisman, J. W., et al. (2018). "An Integrated Approach to a Nitrogen Use Efficiency (NUE) Indicator for the Food Production-Consumption Chain." <u>Sustainability</u> 10 (4).	n/a
82	Godinot, O., et al. (2014). "SyNE: An improved indicator to assess nitrogen efficiency of farming systems." <u>Agricultural Systems</u> 127 : 41-52.	n/a
83*	Godinot, O., et al. (2016). "Indicators to evaluate agricultural nitrogen efficiency of the 27 member states of the European Union." <u>Ecological Indicators</u> 66 : 612-622.	n/a
91	Gu, B., et al. (2017). "Nitrogen use efficiencies in Chinese agricultural systems and implications for food security and environmental protection." <u>Regional Environmental Change</u> 17 (4): 1217-1227.	n/a
157	Machado, D., et al. (2010). "The use of organic substrates with contrasting C/N ratio in the regulation of nitrogen use efficiency and losses in a potato agroecosystem." <u>Nutrient Cycling in Agroecosystems</u> 88 (3): 411-427.	Sandy-loam texture
259	Vaneeckhaute, C., et al. (2014). Assessing nutrient use efficiency and environmental pressure of macronutrients in biobased mineral fertilizers: A review of recent advances and best practices at field scale. <u>Advances in Agronomy</u> . 128 : 137-180.	Sandy loam
260	Vergara, C., et al. (2018). "Dark Septate Endophytic Fungi Increase Green Manure-N-15 Recovery Efficiency, N Contents, and Micronutrients in Rice Grains." <u>Frontiers in Plant Science</u> 9 .	Haplic Planosol; Sandy soil (3% clay, 5% silt, and 92% sandy)

¹**Soil type/ texture:** If provided, what are type and texture of the soils studied in the paper?

*The impact area discussed on this factsheet is not a focus of the cited paper

Impact Area: **Yield per Nitrogen fertilizer**

Definition:
$$\frac{\text{Grain/Fruit/ Tuber yield}}{\text{Nitrogen fertilizer}}$$

Description:

Benefit: This impact area refers to the weight of harvested parts of plants that possess economic value. It is suitable, where production is to be used for food or feed purposes or as a non-energetic production factor in bio-refineries. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: Nitrogen fertilizer is considered a stressed resource for several reasons. While the supply of nitrogen is effectively unlimited, its production is highly energy intensive and its application results in emissions of ammonium and nitrous oxide, creating a conflict between nitrogen fertilizer application and climate change mitigation targets.

Depending on the application rate and type of nitrogen fertilizer (in combination with site specific conditions), diffuse pollution and contamination of water resources is also relevant. Diffuse nitrogen pollution may also strongly affect nutrient poor natural ecosystems and alter species composition.

Finally, fertilizer application is a relevant factor in farmers' cost calculations.

Correlation with soil management:

^[67] Application of hydrogel, on sandy soils improves water holding capacity and availability of the nutrients. Higher amount of hydrogel improves fertilizer use efficiency

^[92] Integrated management could increase grain yield and nitrogen use efficiency: increasing planting density and tillage depth, improving water management and applying organic fertilizer

^[252] In the case of crop rotations, increasing resource-use efficiency while reducing yield gaps can be addressed by suitable agricultural management practices

Strength & weaknesses pertaining to measurement of this impact area

Yield: Yield values are generally easy to measure and readily available at farm level or in the form of national inventories.

However, their informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies

Appendix – Ecosystem Services

of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[67] Fertilizer use efficiency (Squash yield/Amount of N fertilizer)	kg * kg ⁻¹	
[92] Nitrogen partial factor productivity (Grain yield/Total N input (fertilizer + manure + biological N ₂ fixation + atmospheric deposition + straw recycled + irrigation))	kg * kg ⁻¹	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
[252] Nitrogen use efficiency (Grain yield/Available N)	kg * kg ⁻¹	

References

ID	Citation	¹ Soil type/ texture
67	C.Y. El-dewiny (2011). "Water and fertilizer use efficiency by squash grown under stress on sandy soil treated with acrylamide hydrogels." <u>Journal of Applied Sciences Research</u> 7 (12): 1828-1833.	Sandy soil
92	Gu, J., et al. (2017). "Canopy light and nitrogen distributions are related to grain yield and nitrogen use efficiency in rice." <u>Field Crops Research</u> 206 : 74-85.	Typic Fluvaquent; Sandy loam
252	Tomaz, A., et al. (2018). "Efficient use of water and nutrients in irrigated cropping systems in the Alqueva region." <u>Spanish Journal of Soil Science</u> 8 (1): 12-23.	Chromic Cambisols (Bc); Silt loam

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Impact Area: **Benefits per Energy**

Definition:
$$\frac{\text{Financial benefits}}{\text{Energy}}$$

Description:

Benefit: This impact area assesses benefits via their appreciation by markets (Di Maio et al., 2017). It is sensitive to various socio-economic factors because commodity prices reflect demand and are also influenced by value systems and policies through effects of financial incentives and tax regulations.

Resource: The use of energy usually refers to inputs of fuel or electricity. Solar irradiation is not considered because it is not a stressed resource, but also because the amount of this natural input would dwarf out all other energy inputs. Furthermore, energy from human or animal labour is usually not considered, although some studies explicitly include it (Arodudu et al., 2017).

Correlation with soil management:

^[255] Paper anticipated that in long-term agricultural activity would gradually contract in currently better developed countries and energy intensity in agricultural sector should gradually diminish

Strength & weaknesses pertaining to measurement of this impact area

Financial Benefits: Financial indicators are well suited for integrating or comparing agricultural production processes with products for very different end uses. For calculating benefit-cost ratios (BCR), indicators that reflect revenue should be used. In most other cases, indicators that reflect net benefits (after deduction of charges, costs and expenses) provide a more realistic picture of benefits generated. Price volatilities make efficiency calculations valid only for a certain point in time and space.

Energy: For this indicator, a number of standard values for agricultural management are readily available. LCA inventories even provide standard values for energy used in precursory processes.

If the (fossil) energy input is used as a proxy for greenhouse gas emission, it is necessary to also consider the share of non-energy related GHG emission sources like drained soils or nitrous oxide from fertilizers.

Can be measured as:

Financial Benefits:

- revenue [\$]
- gross profit [\$]
- farmers' net income [\$]

Energy:

- total energy use [J]
- energy use from non-renewable sources [J]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Global Scale

Indicator	Unit	Indicator values from
[255] Energy intensity (One European Euro/Amount of energy used)	\$ * ton ⁻¹	

References

ID	Citation	¹ Soil type/ texture
255	Tvaronavičiene, M., et al. (2017). "Energy security and long-term energy efficiency: Case of selected countries." <u>Journal of Security and Sustainability Issues</u> 7(2): 349-357.	n/a

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Impact Area: **Biomass per Energy**

Definition:
$$\frac{\text{Aboveground Biomass}}{\text{Energy}}$$

Description:

Benefit: This impact area refers to the total weight of all aboveground, harvestable parts of cultivated plants. It is suitable, where production is to be used for energy and other non-food purposes that can utilize the whole plant. Woody crops and forage crops will show high efficiencies in this impact area.

Resource: The use of energy usually refers to inputs of fuel or electricity. Solar irradiation is not considered because it is not a stressed resource, but also because the amount of this natural input would dwarf out all other energy inputs. Furthermore, energy from human or animal labour is usually not considered, although some studies explicitly include it (Arodudu et al., 2017).

Strength & weaknesses pertaining to measurement of this impact area

Biomass: Total amount aboveground biomass (production is generally easy to measure.

However, the informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Energy: For this indicator, a number of standard values for agricultural management are readily available. LCA inventories even provide standard values for energy used in precursory processes.

If the (fossil) energy input is used as a proxy for greenhouse gas emission, it is necessary to also consider the share of non-energy related GHG emission sources like drained soils or nitrous oxide from fertilizers.

Can be measured as:

Biomass:

- yield, fresh weight [t]
- yield, dry matter weight [t]

Energy:

- total energy use [J]
- energy use from non-renewable sources [J]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[275] Biomass/Energy	g * MJ ⁻¹	

Table 2: Regional Scale

Indicator	Unit	Indicator values from
[190] Aboveground biomass/Absorbed photosynthetic active radiation	g * MJ ⁻¹	 , 

References

ID	Citation	¹ Soil type/ texture
190	Pan, G., et al. (2009). "Using QuickBird imagery and a production efficiency model to improve crop yield estimation in the semi-arid hilly Loess Plateau, China." <u>Environmental Modelling & Software</u> 24 (4): 510-516.	n/a

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?



275	Yang, Z., et al. (2016). "Leveraging abscisic acid receptors for efficient water use in Arabidopsis." <u>Proceedings of the National Academy of Sciences of the United States of America</u> 113 (24): 6791-6796.	n/a

Impact Area: Energy in (harvested) Biomass per Energy

Definition:
$$\frac{\text{Energy in (harvested) Biomass}}{\text{Energy}}$$

Description:

Benefit:

Resource: The use of energy usually refers to inputs of fuel or electricity. Solar irradiation is not considered because it is not a stressed resource, but also because the amount of this natural input would dwarf out all other energy inputs. Furthermore, energy from human or animal labour is usually not considered, although some studies explicitly include it (Arodudu et al., 2017).

Correlation with soil management:

[5] Integrated farming techniques (balancing N fertilization and adopting minimum tillage) improves energy use efficiency of a maize based rotation system compared to conventional farming

[10] Lower tractor implementation, as well as human and animal labor, surface irrigation and reduced tillage improve the energy efficiency of biofuel production systems

[17] Reduced tillage improves energy use efficiency

[38] Controlled traffic system showed lower value in winter wheat production, but higher value in summer maize production

[58] Biofuel production from sugarcane, sweet sorghum and oil palm is efficient (highest energy yield per hectare). Reduced tillage could reduce energy use and increase energy efficiency. For cereals, planting legumes in rotation, may increase energy efficiency. Energy ratios can be improved by using crop residues as fuel

[125] Conservation management (including the use of organic compost, cover crops, and reduced level of tillage) are more energy efficient than conventional systems

[152] Mixed organic farming produce food with high energy-use efficiency. Improved farm management and technologies can increase resource-use efficiency and maintain high yield performance. Energy use efficiency of agro-forestry systems was higher than for arable farming in both the organic and conventional systems

[186] to improve energy efficiency, several technological and organizational procedures may be applied, e.g. reducing distances between fields, reducing the amounts of transported goods by preliminary treatment, efficient machinery for tillage operations

[199] Results showed a positive and additive effect of water and nitrogen application on Water Use Efficiency, reflected by yield enhancement

[214] In Brazil, biodiesel addition into diesel is mandatory and soybean oil is its main source. Energy balance showed linearity with yield, whereas for EROI, the increases in input and yield were not affected

[248] Small rice-producing farms ranging from 0.61 to 1.0 ha yielded higher energy ratios (4.14) than larger ones

[270] Energy consumption from irrigation process is converted to electricity, thus the corresponding GHG emission caused by irrigation is included into that of electricity

Correlation with soil functions:

[152] Organic mixed farming improved soil fertility and soil structure. Grass cover alfalfa of organic arable farming and organic agro-forestry systems is used to increase soil structure, soil fertility, and humus content

Strength & weaknesses pertaining to measurement of this impact area

Energy: For this indicator, a number of standard values for agricultural management are readily available. LCA inventories even provide standard values for energy used in precursory processes.

If the (fissile) energy input is used as a proxy for greenhouse gas emission, it is necessary to also consider the share of non-energy related GHG emission sources like drained soils or nitrous oxide from fertilizers.

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: No Scale

Indicator	Unit	Indicator values from

Appendix – Ecosystem Services

[58] Energy ratio (Bioenergy output (including co-products)/Fossil energy (used in agriculture, transport and processing))	MJ * MJ ⁻¹	
[85] Energy in harvested fruits/Energy input (farmyard manure energy + chemical fertilizers + machinery and diesel fuel energy)	MJ * MJ ⁻¹	

Table 2: Field Scale

Indicator	Unit	Indicator values from
[5] Energy use efficiency (EUE) (Energy in harvested grains/Total energy inputs until field gate (Mechanization + fertilization + irrigation + crop propagation + herbicides))	GJ * GJ ⁻¹	
[5] Environmental Efficiency of Support Energy (EESE) (Energy in harvested grains + soil organic matter/Total energy inputs (Mechanization + fertilization + irrigation + crop propagation + herbicides))	GJ * GJ ⁻¹	
[17] Energy use efficiency (Energy content of sunflower grain yield/Total energy input (human labor, machinery, chemical fertilizers, diesel fuel, irrigation, seeds))	MJ * MJ ⁻¹	
[125] Energy use efficiency (Energy in harvested potato/Total Energy input (direct energy (diesel fuel, lubricants) + indirect energy (manufacturing of machinery, fertilizer, pesticides)))	GJ * GJ ⁻¹	
[152] Energy use efficiency (Energy in harvested biomass – energy in the seed/Total energy input (Direct energy (diesel) + indirect energy (Seed + mineral and organic fertilizers + pesticides + machines))	GJ * GJ ⁻¹	

Table 3: Farm Scale

Indicator	Unit	Indicator values from
[152] Energy use efficiency (Energy in harvested biomass – energy in the seed/Total energy input (Direct energy (diesel) + indirect energy (Seed + mineral and organic fertilizers + pesticides + machines))	GJ * GJ ⁻¹	
[186] Partial energetic efficiency (Energy content of biofuel after processing/Energy used for transportations of products, machines or tools)	MJ * MJ ⁻¹	 , 
[186] Partial energetic efficiency (Energy content of biofuel after processing/Energy used after tillage operations)	MJ * MJ ⁻¹	 , 
[276] Energy use efficiency (Output energy/Input energy)	MJha ⁻¹ * (MJha ⁻¹) ⁻¹	

Table 4: Regional Scale

Indicator	Unit	Indicator values from



[38] Energy use efficiency (Energy output (wheat grain + maize grain + straw)/Energy input (machine + diesel fuel + labor + seed + nitrogen + P2O5 + K2O + herbicides + electricity))	MJ * MJ ⁻¹	
[199] Energy Return on Investment (EROI) (Energy output/Energy input)	MJ * MJ ⁻¹	,
[214] Energy return over investment (EROI) (Energy output flow - energy input flow/Energy input flow (grain yield))	MJ * MJ ⁻¹	,
[248] Energy efficiency (Output energy/Input energy)	MJha ⁻¹ * (MJha ⁻¹) ⁻¹	,
[248] Non-renewable energy ratio (Output energy/Non-renewable energy input)	MJha ⁻¹ * (MJha ⁻¹) ⁻¹	,
[270] Energy output/Energy input	GJha ⁻¹ * (GJha ⁻¹) ⁻¹	,
[271] Energy output/Energy input	J * J ⁻¹	
[283] Thermal efficiency (Released energy (energy released by the fuel and ignition material)/Useful energy (energy used by the water temperature rising + water evaporating + energy absorbed by the pot))	kJ * kJ ⁻¹	

Table 5: National Scale

Indicator	Unit	Indicator values from
[270] Energy output/Energy input	GJha ⁻¹ * (GJha ⁻¹) ⁻¹	,

Table 6: Global Scale

Indicator	Unit	Indicator values from
[10] Energy return on energy invested (EROI) (Bio energy output (including co-products)/Energy input (direct energy (farm operation + energy for conversion of biomass to energy) + indirect energy (production of chemicals)))	MJ * MJ ⁻¹	

References

ID	Citation	¹ Soil type/ texture
5	Alluvione, F., et al. (2011). "EUE (energy use efficiency) of cropping systems for a sustainable agriculture." <i>Energy</i> 36 (7): 4468-4481.	Coarse-loamy mixed non-acid mesic Typic Hapludalf; Loamy sand

¹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

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10	Arodudu, O. T., et al. (2017). "Integrating agronomic factors into energy efficiency assessment of agro-bioenergy production – A case study of ethanol and biogas production from maize feedstock." <i>Applied Energy</i> 198: 426-439.	n/a
17	Baran, M. F. and O. Gokdogan (2016). "COMPARISON OF ENERGY USE EFFICIENCY OF DIFFERENT TILLAGE METHODS ON THE SECONDARY CROP CORN SILAGE PRODUCTION." <i>Fresenius Environmental Bulletin</i> 25(9): 3808-3814.	Clayey and loamy soil
38	Chen, H., et al. (2016). "Effect of controlled traffic on energy use efficiency in wheat-maize production in North China Plain." <i>Journal of Computational and Theoretical Nanoscience</i> 13(4): 2634-2638.	Porous and homogenous; Silt loam
58	de Vries, S. C., et al. (2010). "Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques." <i>Biomass and Bioenergy</i> 34(5): 588-601.	n/a
85	Gökdoğan, O., et al. (2018). "Studies of Energy Use Efficiency on Fruit Production." <i>Erwerbs-Obstbau</i> : 1-5.	n/a
125	Khakbazan, M., et al. (2017). "Energy Use Efficiency of Conventional versus Conservation Management Practices for Irrigated Potato Production in Southern Alberta." <i>American Journal of Potato Research</i> 94(2): 105-119.	Mainly orthic brown Chernozemic soils
152	Lin, H. C., et al. (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." <i>European Journal of Agronomy</i> 82: 242-253.	Cambisol; Loamy to sandy soil
186	Orynych, O. and A. Swic (2018). "The Effects of Material's Transport on Various Steps of Production System on Energetic Efficiency of Biodiesel Production." <i>Sustainability</i> 10(8).	n/a
199	Peter, C., et al. (2017). "Impact of Energy Crop Rotation Design on Multiple Aspects of Resource Efficiency." <i>Chemical Engineering and Technology</i> 40(2): 323-332.	Stagnic Cambisol, Chernosem, Luvisol, Regosol, Planosol, Albeluvisol, Gleyic Cambisol, Stagnic Cambisol; Fine, medium and coarse
214	Romanelli, T. L., et al. (2012). "Material embodiment and energy flows as efficiency indicators of soybean (Glycine max) production in Brazil." <i>Engenharia Agricola</i> 32(2): 261-270.	n/a
248	Talukder, B., et al. (2019). "Energy efficiency of agricultural systems in the southwest coastal zone of Bangladesh." <i>Ecological Indicators</i> 98: 641-648.	n/a
270	Wu, H., et al. (2017). "Temporal trends and spatial patterns of energy use efficiency and greenhouse gas emissions in crop production of Anhui Province, China." <i>Energy</i> 133: 955-968.	n/a
271	Wu, Z. N., et al. (2017). "Water efficiency evaluation of a regional water scheme - Zhengzhou, China, using a water ecological-economic system (WEES) and based on emergy theory." <i>Water Science and Technology-Water Supply</i> 17(3): 674-687.	n/a



276	Yousefi, M. and A. Mohammadi (2011). "Economical analysis and energy use efficiency in alfalfa production systems in Iran." <u>Scientific Research and Essays</u> 6 (11): 2332-2336.	n/a
283	Zhang, Y., et al. (2018). "Assessment of pollutant emissions and energy efficiency of four commercialized charcoal stoves with modified Chinese cooking stove protocol." <u>International Journal of Agricultural and Biological Engineering</u> 11 (2): 202-207.	n/a

Impact Area: Yield per Energy

Definition:
$$\frac{\text{Grain/Fruit/Tuber yield}}{\text{Energy}}$$

Description:

Benefit: This impact area refers to the weight of harvested parts of plants that possess economic value. It is suitable, where production is to be used for food or feed purposes or as a non-energetic production factor in bio-refineries. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: The use of energy usually refers to inputs of fuel or electricity. Solar irradiation is not considered because it is not a stressed resource, but also because the amount of this natural input would dwarf out all other energy inputs. Furthermore, energy from human or animal labour is usually not considered, although some studies explicitly include it (Arodudu et al., 2017).

Correlation with soil management:

- [5] Maize had the most efficient biomass production per fossil energy. Low-input cropping and integrated farming were more efficient in biomass production than conventional management
- [17] Reduced tillage improves energy use efficiency
- [125] Conservation management (including the use of organic compost, cover crops, and reduced level of tillage) increased potato yield per unit of energy input
- [248] Small rice-producing farms ranging from 0.61 to 1.0 ha yielded higher energy ratios (4.14) than larger ones

Strength & weaknesses pertaining to measurement of this impact area

Yield: Yield values are generally easy to measure and readily available at farm level or in the form of national inventories.

However, their informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Energy: For this indicator, a number of standard values for agricultural management are readily available. LCA inventories even provide standard values for energy used in precursory processes.

If the (fossil) energy input is used as a proxy for greenhouse gas emission, it is necessary to also consider the share of non-energy related GHG emission sources like drained soils or nitrous oxide from fertilizers.

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: No Scale

Indicator	Unit	Indicator values from
^[85] Energy productivity (Fruit yield/Energy input (farmyard manure energy + chemical fertilizers + machinery and diesel fuel energy))	kg * MJ ⁻¹	

Table 2: Field Scale

Indicator	Unit	Indicator values from
^[5] Energy Intensity (EI) (Grain yield/Fossil energy used in farm operations and production of inputs and machinery)	kg * MJ ⁻¹	
^[17] Energy productivity (Sunflower grain yield/Total energy input (human labor, machinery, chemical fertilizers, diesel fuel, irrigation, seeds))	kg * MJ ⁻¹	
^[125] Potato yield/Total Energy input (direct energy (diesel fuel, lubricants) + indirect energy (manufacturing of machinery, fertilizer, pesticides))	kg * GJ ⁻¹	

Table 3: Farm Scale

Indicator	Unit	Indicator values from
^[276] Energy productivity (Forage yield/Input energy)	kg * MJ ⁻¹	

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Table 4: Regional Scale

Indicator	Unit	Indicator values from
^[190] Light use efficiency (Net primary production (crop yield depending on the fraction of plant biomass that is harvested)/Absorbed photosynthetic active radiation)	g * MJ ⁻¹	 , 
^[248] Energy productivity (Crop yield/Input energy)	kg * MJ	 , 

References

ID	Citation	⁴⁶ Soil type/ texture
5	Alluvione, F., et al. (2011). "EUE (energy use efficiency) of cropping systems for a sustainable agriculture." <i>Energy</i> 36 (7): 4468-4481.	Coarse-loamy mixed non-acid mesic Typic Hapludalf; Loamy sand
17	Baran, M. F. and O. Gokdogan (2016). "COMPARISON OF ENERGY USE EFFICIENCY OF DIFFERENT TILLAGE METHODS ON THE SECONDARY CROP CORN SILAGE PRODUCTION." <i>Fresenius Environmental Bulletin</i> 25 (9): 3808-3814.	Clayey and loamy soil
85	Gökdoğan, O., et al. (2018). "Studies of Energy Use Efficiency on Fruit Production." <i>Erwerbs-Obstbau</i> : 1-5.	n/a
125	Khakbazan, M., et al. (2017). "Energy Use Efficiency of Conventional versus Conservation Management Practices for Irrigated Potato Production in Southern Alberta." <i>American Journal of Potato Research</i> 94 (2): 105-119.	Mainly orthic brown Chernozemic soils
190	Pan, G., et al. (2009). "Using QuickBird imagery and a production efficiency model to improve crop yield estimation in the semi-arid hilly Loess Plateau, China." <i>Environmental Modelling & Software</i> 24 (4): 510-516.	n/a
248	Talukder, B., et al. (2019). "Energy efficiency of agricultural systems in the southwest coastal zone of Bangladesh." <i>Ecological Indicators</i> 98 : 641-648.	n/a
276	Yousefi, M. and A. Mohammadi (2011). "Economical analysis and energy use efficiency in alfalfa production systems in Iran." <i>Scientific Research and Essays</i> 6 (11): 2332-2336.	n/a

⁴⁶**Soil type/ texture:** If provided, what are type and texture of the soils studied in the paper?

Impact Area: Energy per GHG emissions

Definition:
$$\frac{\text{Embodied Energy}}{\text{GHG emissions}}$$

Description:

Benefit: Energy content can be used for an integrated evaluation of crops. Generally, the type of energy should be specified to distinguish between use as fuel or use as food and feed. For use as animal feed, further definitions are required to determine if lignocellulosic crops qualify. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: Under current policy targets such as the 2015 Paris Agreement or the United Nations' Sustainable Development Goals (SDG), the total amount of greenhouse gases that can safely be emitted into the atmosphere is limited. Greenhouse gas emissions can therefore be treated as a limited resource.

For this indicator, emissions of different greenhouse gases are combined by calculating carbon dioxide equivalent emissions (CO₂ eq.), based on the 100-year global warming potential (GWP) of each gas. It is necessary to define both the spatial reference (e.g. emissions per hectare) and the temporal reference (e.g. emissions per year).

Correlation with soil management:

^[58] Biofuel from sweet sorghum, sugarcane, soybean and oil palm show highest reduction in GHG emission per unit of energy produced compared to fossil fuel

Strength & Weaknesses (pertaining to measurement of this impact area)

Embodied Energy: Indicators for embodied energy are generally easy to measure and allow integration of or comparison between benefits from very different crops. However, their information value for questions of nutrition is limited because the provision of amino-acids and vitamins is not considered.

GHG Emissions: For this indicator, a number of standard values and national inventories exist. The use of the 100-year GWP enables comparability between studies and between emissions of different greenhouse gases. However, for short lived gases such as methane, this standard underestimates the contribution to global warming in the short term and overestimates their contribution in the long term.

Can be measured as:

Embodied Energy:

- nutritional value (humans) [J]
- nutritional value (non-grazing livestock) [J]
- nutritional value (grazing livestock) [J]
- heating value [J]

GHG Emissions:

- total emissions [Mg CO₂ eq. ha⁻¹ yr⁻¹]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: No Scale

Indicator	Unit	Indicator values from
^[58] GHG emission indicator (Produced Energy in the biofuel and its coproducts/CO ₂ emission)	MJ * g ⁻¹	

References

ID	Citation	⁴⁷ Soil type/ texture
58	de Vries, S. C., et al. (2010). "Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques." <i>Biomass and Bioenergy</i> 34 (5): 588-601.	n/a

⁴⁷**Soil type/ texture:** If provided, what are type and texture of the soils studied in the paper?

Impact Area: Yield per GHG emissions

Definition:
$$\frac{\text{Grain/Fruit/ Tuber yield}}{\text{GHG emissions}}$$

Description:

Benefit: Yield refers to the weight of harvested parts of plants that possess economic value. It is suitable, where production is to be used for food or feed purposes or as a non-energetic production factor in bio-refineries. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: Under current policy targets such as the 2015 Paris Agreement or the United Nations' Sustainable Development Goals (SDG), the total amount of greenhouse gases that can safely be emitted into the atmosphere is limited. Greenhouse gas emissions can therefore be treated as a limited resource.

For this indicator, emissions of different greenhouse gases are combined by calculating carbon dioxide equivalent emissions (CO₂ eq.), based on the 100-year global warming potential (GWP) of each gas. It is necessary to define both the spatial reference (e.g. emissions per hectare) and the temporal reference (e.g. emissions per year).

Correlation with soil management:

^[125] Conservation management (including the use of organic compost, cover crops, and reduced level of tillage) management was more efficient in terms of yield per GHG emissions than conventional management

^[241] Highest land use efficiencies (potato yield per hectare of area) were achieved in regions that produce potatoes under irrigation in summer where solar radiation is high and lowest land use efficiencies were reported for the predominantly dryland and partially dryland regions.

Strength & weaknesses pertaining to measurement of this impact area

Yield: Yield values are generally easy to measure and readily available at farm level or in the form of national inventories.

However, their informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

GHG Emissions: For this indicator, a number of standard values and national inventories exist. The use of the 100-year GWP enables comparability between studies and between emissions of different greenhouse gasses. However, for short lived gasses such as methane, this standard underestimates the contribution to global warming in the short term and overestimates their contribution in the long term.

Can be measured as:

Yield:

- yield, fresh weight [t]
- yield, dry matter weight [t]

GHG Emissions:

- total emissions [Mg CO₂ eq. ha⁻¹ yr⁻¹]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[125] Potato yield/GHG emission	kg * kg ⁻¹	

Table 2: Regional Scale

Indicator	Unit	Indicator values from
[241] Energy use efficiency (Potato yield/Energy use (CO ₂ emissions) associated with irrigation, fertilizer and seed production)	ton * kg ⁻¹	

References

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ID	Citation	⁴⁸ Soil type/ texture
125	Khakbazan, M., et al. (2017). "Energy Use Efficiency of Conventional versus Conservation Management Practices for Irrigated Potato Production in Southern Alberta." <u>American Journal of Potato Research</u> 94 (2): 105-119.	Mainly orthic brown Chernozemic soils
241	Steyn, J. M., et al. (2016). "Resource use efficiencies as indicators of ecological sustainability in potato production: A South African case study." <u>Field Crops Research</u> 199 : 136-149.	Loam, sandy-loam, sand

⁴⁸**Soil type/ texture:** If provided, what are type and texture of the soils studied in the paper?

Impact Area: **Benefits per Labour**

Definition:
$$\frac{\text{Financial benefits}}{\text{Human labour}}$$

Description:

Benefit: This impact area assesses benefits via their appreciation by markets (Di Maio et al., 2017). It is sensitive to various socio-economic factors because commodity prices reflect demand and are also influenced by value systems and policies through effects of financial incentives and tax regulations.

Resource: The use of labour is closely connected with the provision of employment and therefore a reduction is not always positive. If the main benefit of a reduction in the use of labour is reducing factor costs, it is recommended to use monetary indicators instead. However, where reductions serve the purpose of reducing hard physical labour and thereby increasing human health, labour should be used as indicator.

Correlation with soil management:

[149] Labor productivity of larger farms is higher than of small farms

[288] Formation of a mixed economy in the agrarian sector

Strength & weaknesses pertaining to measurement of this impact area

Financial Benefits: Financial indicators are well suited for integrating or comparing agricultural production processes with products for very different end uses. For calculating benefit-cost ratios (BCR), indicators that reflect revenue should be used. In most other cases, indicators that reflect net benefits (after deduction of charges, costs and expenses) provide a more realistic picture of benefits generated. Price volatilities make efficiency calculations valid only for a certain point in time and space.

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	

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Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: No Scale

Indicator	Unit	Indicator values from
^[288] Specific labor productivity (Gross output/Man-hour)	\$ * h ⁻¹	
^[288] Specific labor productivity (Gross output/Employee)	\$ * No ⁻¹	

Table 2: Farm Scale

Indicator	Unit	Indicator values from
^[149] Labor productivity (Total income generated from farming during a year/Total work days during a year)	\$ * day ⁻¹	
^[149] Labor productivity (Total income generated from farming during a year/Farm labor)	\$ * No ⁻¹	
^[176] Net agricultural income (Prices of inputs or sold products)/Family worker	\$ * No ⁻¹	

Table 3: Regional Scale

Indicator	Unit	Indicator values from
^[1] Value of yields (including subsidies)/Number of employees	\$ * No ⁻¹	
^[1] Added value/Number of employees	\$ * No ⁻¹	
^[142] Labor efficiency (Economic output of crop yield/Farming activities of labor)	\$ * labor time ⁻¹	

References

ID	Citation	⁴⁹ Soil type/ texture
1	Adamisin, P., et al. (2015). "Natural climatic conditions as a determinant of productivity and economic efficiency of agricultural entities." Agricultural Economics-Zemledelska Ekonomika 61(6): 265-274.	n/a
142*	Latinopoulos, D. (2009). "Multicriteria decision-making for efficient water and land resources allocation in irrigated	n/a

⁴⁹Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

*The impact area discussed on this factsheet is not a focus of the cited paper



	agriculture." <u>Environment, Development and Sustainability</u> 11 (2): 329-343.	
149*	Li, G., et al. (2013). "Re-examining the inverse relationship between farm size and efficiency: The empirical evidence in China." <u>China Agricultural Economic Review</u> 5 (4): 473-488.	n/a
176	Moreau, P., et al. (2012). "Reconciling technical, economic and environmental efficiency of farming systems in vulnerable areas." <u>Agriculture Ecosystems & Environment</u> 147 : 89-99.	Deep loamy and shallow brown soils
288	Zotov, V. P., et al. (2014). "The main labor-forming factors and the assessment of labor efficiency in agriculture (by the example of kemerovo oblast)." <u>Foods and Raw Materials</u> 2 (1): 91-97.	n/a

Impact Area: Yield per Labour

Definition:
$$\frac{\text{Grain/Fruit/ Tuber yield}}{\text{Human labour}}$$

Description:

Benefit: This impact area refers to the weight of harvested parts of plants that possess economic value. It is suitable, where production is to be used for food or feed purposes or as a non-energetic production factor in bio-refineries. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: The use of labour is closely connected with the provision of employment and therefore a reduction is not always positive. If the main benefit of a reduction in the use of labour is reducing factor costs, it is recommended to use monetary indicators instead. However, where reductions serve the purpose of reducing hard physical labour and thereby increasing human health, labour should be used as indicator.

Correlation with soil management:

^[182] Improving the conditions of mineral nutrition by introducing balanced doses of fertilizers for all elements contributed to a sufficiently high yield

Strength & weaknesses pertaining to measurement of this impact area

Yield: Yield values are generally easy to measure and readily available at farm level or in the form of national inventories.

However, their informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Sample Indicators

Indicator values from	Survey	

Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Regional Scale

Indicator	Unit	Indicator values from
[182] Yield of grain/Labor	kg * No ⁻¹	
[202] Gross yield (weight of all harvested fruits)/Working hours	Mg * h ⁻¹	
[202] Fresh marketable yield (gross yield minus the fruit discarded as a result of fruit rot or small size, or fruit used for processed products)/Working hours	Mg * h ⁻¹	

Table 2: National Scale

Indicator	Unit	Indicator values from
[202] Gross yield (weight of all harvested fruits)/Working hours	Mg * h ⁻¹	
[202] Fresh marketable yield (gross yield minus the fruit discarded as a result of fruit rot or small size, or fruit used for processed products)/Working hours	Mg * h ⁻¹	

References

ID	Citation	⁵⁰ Soil type/ texture
182	Neshchadim, N. N., et al. (2018). "Bioenergetic assessment and economic efficiency of predecessors and fertilizer systems in the cultivation of winter wheat." <u>International Journal of Engineering and Technology(UAE)</u> 7 (4.38 Special Issue 38): 685-689.	Ordinary chernozem with low content of humus (4.5-5.5%)
202	Plénet, D., et al. (2009). "Using on-field data to develop the EFI© information system to characterise agronomic productivity and labour efficiency in peach (<i>Prunus persica</i> L. Batsch) orchards in France." <u>Agricultural Systems</u> 100 (1-3): 1-10.	n/a

⁵⁰Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Impact Area: Yield per Phosphorus fertilizer

Definition:
$$\frac{\text{Grain/Fruit/ Tuber yield}}{\text{Phosphorus fertilizer}}$$

Description:

Benefit: This impact area refers to the weight of harvested parts of plants that possess economic value. It is suitable, where production is to be used for food or feed purposes or as a non-energetic production factor in bio-refineries. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: The primary source of inorganic phosphorous used in fertilizers is phosphate rock. As global reserves are limited and risk of contamination with heavy metals like uranium and costs of processing are expected to increase, there is a strong motivation to reduce the dependence on mineral phosphorous inputs.

Furthermore, phosphorous availability is a key limiting factor for aquatic ecosystems. High application rates of phosphorous fertilizer in agricultural management, in combination with runoff and erosion, can lead to phosphorous entering into waterways and thereby damaging aquatic ecosystems through eutrophication. Finally, fertilizer application is a relevant factor in farmers' cost calculations. It is therefore considered a stressed resource.

Correlation with soil management:

^[252] In the case of crop rotations, increasing resource-use efficiency while reducing yield gaps can be addressed by suitable agricultural management practices

Strength & weaknesses pertaining to measurement of this impact area

Yield: Yield values are generally easy to measure and readily available at farm level or in the form of national inventories.

However, their informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Can be measured as:

Yield:

- yield, fresh weight [t]
- yield, dry matter weight [t]

Phosphorus fertilizer:

- total phosphorous fertilizer application [kg P]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Farm Scale

Indicator	Unit	Indicator values from
^[252] Phosphorus use efficiency (Grain yield/Available phosphorus)	kg * kg ⁻¹	

References

ID	Citation	⁵¹ Soil type/ texture
252	Tomaz, A., et al. (2018). "Efficient use of water and nutrients in irrigated cropping systems in the Alqueva region." <u>Spanish Journal of Soil Science</u> 8 (1): 12-23.	Chromic Cambisols (Bc); Silt loam

⁵¹**Soil type/ texture:** If provided, what are type and texture of the soils studied in the paper?

Impact Area: **Energy per Pesticides**

Definition:
$$\frac{\text{Embodied Energy}}{\text{Pesticides}}$$

Description:

Benefit: Energy content can be used for an integrated evaluation of crops. Generally, the type of energy should be specified to distinguish between use as fuel or use as food and feed. For use as animal feed, further definitions are required to determine if lignocellulosic crops qualify. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: Pesticide application negatively affects biodiversity and is partly responsible for the continuing biodiversity decline of Europe's agricultural landscapes. For this reason, it conflicts with policy targets such as those included in the EU 2020 biodiversity strategy and can therefore be considered a stressed resource.

Production processes that provide the same benefits with lower use of pesticides are more efficient. For this indicator, the total amount of pesticides brought into the system should be considered, irrelevant of whether pesticides are applied externally, or produced by genetically modified plants themselves, as in the case of BT-maize.

Correlation with soil management:

^[58] Pesticide use efficiency was highest for sugarcane, sweet sorghum and oil palm

Strength & weaknesses pertaining to measurement of this impact area

Embodied Energy: Indicators for embodied energy are generally easy to measure and allow integration of or comparison between benefits from very different crops. However, their information value for questions of nutrition is limited because the provision of amino-acids and vitamins is not considered.

Pesticides: A weakness of this indicator is that the quantity of pesticides applied is insufficient to determine the associated environment problems. Effects on biodiversity will strongly depend on site characteristics and pesticide specific properties.

Can be measured as:

Embodied Energy:

- nutritional value (humans) [J]

- nutritional value (non-grazing livestock) [J]
- nutritional value (grazing livestock) [J]
- heating value [J]

Pesticides:

- total pesticide application [kg]
- total application of a specific pesticide (e.g. glyphosate) [kg]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: No Scale

Indicator	Unit	Indicator values from
[58] Pesticide use efficiency (Net energy yield (Energy content of biofuel and its coproducts – energy used for production, transportation and conversion)/Pesticide input)	GJ * kg ⁻¹	

References

ID	Citation	⁵² Soil type/ texture
58	de Vries, S. C., et al. (2010). "Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques." <i>Biomass and Bioenergy</i> 34 (5): 588-601.	n/a

⁵²Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Impact Area: Benefits per Money

Definition:
$$\frac{\text{Financial benefits}}{\text{Money}}$$

Description:

Benefit: This impact area assesses benefits via their appreciation by markets (Di Maio et al., 2017). It is sensitive to various socio-economic factors because commodity prices reflect demand and are also influenced by value systems and policies through effects of financial incentives and tax regulations.

Resource: Evaluation of costs is imperative for all agronomic planning and central to management decisions made by farmers. For this indicator, it is necessary to define whether investment costs are considered and what interest rates are applied.

Correlation with soil management:

[135] Micro irrigation treatment had higher benefit cost ratio than check basin irrigation

[149] including labor cost, profit ratio of smaller farms is much lower than of bigger farms

[162] Studies proved reduction of field crop yields from organic fields in comparison to conventional ones

[288] Formation of a mixed economy in the agrarian sector

Strength & weaknesses pertaining to measurement of this impact area

Financial Benefits: Financial indicators are well suited for integrating or comparing agricultural production processes with products for very different end uses. For calculating benefit-cost ratios (BCR), indicators that reflect revenue should be used. In most other cases, indicators that reflect net benefits (after deduction of charges, costs and expenses) provide a more realistic picture of benefits generated. Price volatilities make efficiency calculations valid only for a certain point in time and space.

Sample Indicators

Indicator values from	Survey	

Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: No Scale

Indicator	Unit	Indicator values from
[288] Overall labor productivity (Gross output/Current costs)	\$ * -	

Table 2: Field Scale

Indicator	Unit	Indicator values from
[135] Benefit cost ratio (Annual return of crops/Total costs (initial investment for irrigation system+ present worth value of annual cost))	\$ * \$ ⁻¹	

Table 3: Farm Scale

Indicator	Unit	Indicator values from
[149] Profit ratio (Economic benefit (total income – material costs – labor input costs) [Chinese yuan]/Total costs (Material costs (costs for machinery/animal operations + seed + chemical fertilizer + manure + agricultural plastic film + farm chemicals + irrigation + fuels and energy + small farm tools + total depreciation on the fixed asset) + labor input costs) [Chinese yuan])	\$ * \$ ⁻¹	
[149] Profit ratio (Economic benefit (total income – material costs)/Material costs)	\$ * \$ ⁻¹	
[162] Cost effectiveness of fertilization (Additional profit earned as a result of fertilization/Expenses on fertilization)	\$ * \$ ⁻¹	

Table 4: Regional Scale

Indicator	Unit	Indicator values from
[1] Value of yields (including subsidies)/Wage costs	\$ * \$ ⁻¹	
[1] Added value/Wage costs	\$ * \$ ⁻¹	

References

Appendix – Ecosystem Services

ID	Citation	⁵³ Soil type & texture
1	Adamisin, P., et al. (2015). "Natural climatic conditions as a determinant of productivity and economic efficiency of agricultural entities." <i>Agricultural Economics-Zemедelska Ekonomika</i> 61(6): 265-274.	n/a
135	Kumar, M., et al. (2009). "Integrating water harvesting and gravity-fed micro-irrigation system for efficient water management in terraced land for growing vegetables." <i>Biosystems Engineering</i> 102(1): 106-113.	n/a
149*	Li, G., et al. (2013). "Re-examining the inverse relationship between farm size and efficiency: The empirical evidence in China." <i>China Agricultural Economic Review</i> 5(4): 473-488.	n/a
162	Manolova, V., et al. (2015). "Economic efficiency of fertilization and its residual-effect during conversion period to organic field crop production." <i>Bulgarian Journal of Agricultural Science</i> 21(5): 1022-1026.	n/a
288	Zotov, V. P., et al. (2014). "The main labor-forming factors and the assessment of labor efficiency in agriculture (by the example of kemerovo oblast)." <i>Foods and Raw Materials</i> 2(1): 91-97.	n/a

⁵³**Soil type & texture:** If provided, what are type and texture of the soils studied in the paper?

*The impact area discussed on this factsheet is not a focus of the cited paper

Impact Area: **Carbon per Money**

Definition:
$$\frac{\textit{Sequestered Carbon}}{\textit{Money}}$$

Description:

Benefit: Carbon sequestered in soils or in long life products helps to achieve global climate change mitigation targets.

Resource: Evaluation of costs is imperative for all agronomic planning and central to management decisions made by farmers. For this indicator, it is necessary to define whether investment costs are considered and what interest rates are applied.

Correlation with soil management:

^[125]Conservation management (including the use of organic compost, cover crops, and reduced level of tillage) was more cost-effective (Mg of carbon retained/ cost) than conventional management

^[285]Analytical results provided evidence to guide agribusiness in improving their current performance toward sustainability under the BRI

Strength & weaknesses pertaining to measurement of this impact area:

Sequestered Carbon: For carbon sequestration, additionally and stability over time are usually relevant. Unfortunately, stability over time is very difficult to estimate. Depending on system boundaries and context, it may be appropriate to consider only a share of the sequestered carbon if external factors (like climate change, management change) are likely to result in emissions of previously sequestered carbon at a later point in time.

Can be measured as:**Sequestered Carbon:**

- carbon sequestered [t C]
- carbon sequestered until 2050 [t C]

Money:

- variable costs [\$]
- total costs [\$]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Field Scale

Indicator	Unit	Indicator values from
[125] Carbon retained in potatoes and aboveground residue/Production cost of potatoes	Mg * \$ ⁻¹	
[285] Carbon Emissions Per Product (Total Carbon Emissions (CO ₂ +diesel+recycled waste)/Total Amount of Products)	kg * \$ ⁻¹	 , 

References

ID	Citation	⁵⁴ Soil type & texture
125	Khakbazan, M., et al. (2017). "Energy Use Efficiency of Conventional versus Conservation Management Practices for Irrigated Potato Production in Southern Alberta." <u>American Journal of Potato Research</u> 94 (2): 105-119.	Mainly orthic brown Chernozemic soils
285	Zhao, R., et al. (2018). "Enhancing eco-efficiency of agro-products' closed-loop supply chain under the belt and road initiatives: A system dynamics approach." <u>Sustainability (Switzerland)</u> 10 (3).	n/a

⁵⁴Soil type/ texture: If provided, what are type and texture of the soils studied in the paper?

Impact Area: **Yield per Money**

Definition:
$$\frac{\textit{Grain/Fruit/ Tuber yield}}{\textit{Money}}$$

Description:

Benefit: This impact area refers to the weight of harvested parts of plants that possess economic value. It is suitable, where production is to be used food or feed purposes or as a non-energetic production factor in bio-refineries. Crops with high per hectare yield will show high efficiencies in this impact area.

Resource: Evaluation of costs is imperative for all agronomic planning and central to management decisions made by farmers. For this indicator, it is necessary to define whether investment costs are considered and what interest rates are applied.

Strength & weaknesses pertaining to measurement of this impact area:

Yield: Yield values are generally easy to measure and readily available at farm level or in the form of national inventories.

However, their informative value is limited where they do not account for qualitative differences between types of biomass and are not accompanied by information on site conditions such as local climate or soil fertility. Therefore, comparisons between efficiencies of different production processes with regard to yields should only be made where products and site conditions are similar. In some cases, it may be advisable to select alternative indicators where the type of benefit is more clearly defined (e.g., energetic value, financial benefit).

Can be measured as:**Yield:**

- yield, fresh weight [t]
- yield, dry matter weight [t]

Money:

- variable costs [\$]
- total costs [\$]

Sample Indicators

Indicator values from		Survey	
Experiment or direct measurement		Statistical- or census data	
Expert assessment		Literature values	
Model		Maps or GIS	
Stakeholder participation		Not provided	

Table 1: Farm Scale

Indicator	Unit	Indicator values from
^[276] Yield/Total production cost	kg * \$ ⁻¹	

References

ID	Citation	⁵⁵ Soil type & texture
276	Yousefi, M. and A. Mohammadi (2011). "Economical analysis and energy use efficiency in alfalfa production systems in Iran." <i>Scientific Research and Essays</i> 6(11): 2332-2336.	clay lightweight sand, shallow defaulting on light clay

⁵⁵Soil type & texture: If provided, what is the type & texture of the soil studied in the paper?