



Methods

A collection of field-based indicators for assessing ecosystem services in crop fields

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Abstract

The transition from intensive crop production to more sustainable practices, such as ecologically intensive cropping systems, requires precise, field-based assessments of Ecosystem Services (ES). These assessments depend on selecting appropriate indicators that can measure the supply of ES directly within crop fields. Despite the growing recognition of the ES role in sustainable agriculture, comprehensive lists of field-applicable indicators remain scarce. To address this gap, we present and discuss a collection of 128 indicators for assessing provisioning and regulating ES in cropping systems, specifically designed for *in situ*, empirical measurements. The collection aims to support researchers and practitioners in selecting context-specific indicators that enhance site-specific knowledge for developing sustainable cropping systems. It was derived from an exhaustive previously published list, which included 507 indicators applicable across various ecosystem types and linked to various data collection methods. We filtered that exhaustive list using three criteria: applicability to crop fields, level in the ES cascade model (including ecosystem property, ecosystem function and human benefit, but excluding value and adding and including a new level of dis-service) and method of data collection (including field observation and remote sensing, but excluding all indirect methods). In the resulting dataset, including 128 indicators, we analysed the distribution of indicators across the different ES, cascade levels and methods of data collection to identify potential gaps in indicator availability that could hinder comprehensive assessments of the ES provided in crop fields. This analysis highlighted

significant disparities in indicator distribution, notably concerning the levels of ES cascade quantifiability, as a vast majority of indicators for regulating ES quantify ecological properties or functions, while most indicators for provisioning ES quantify human benefits. We also identified a lack of indicators for air quality regulation, life cycle maintenance and water provision and, in contrast, a multiplicity of indicators employed for soil quality regulation and pollination. We discuss the reasons and consequences of these disparities and we underscore the importance of staying alert to emerging indicators driven by recent research trends and technological advancements, such as remote sensing.

Keywords

agroecosystem, ecosystem service cascade, biophysical method, in situ, ecologically intensive, provisioning ecosystem service, regulating ecosystem service

Introduction

During the 20th century, agricultural revolutions driven by productivity transformed farming systems worldwide. In industrial countries, crop yields primarily increased through the intensification of inorganic fertilisation, pesticide use, modern plant breeding and mechanical tillage (Hazell and Wood 2007). While this intensification of crop production led to an unprecedented abundance of food at low prices (Hazell and Wood 2007, Bommarco et al. 2013), it also imposed high environmental and socio-economical costs. The environmental costs include biodiversity loss, natural and semi-natural habitat loss, soil degradation, water eutrophication, amplified net greenhouse gas emissions from agriculture and increased exposure of living beings to toxic agrochemicals (Foley et al. 2005, Tschamtker et al. 2005, Hazell and Wood 2007, Kremen and Miles 2012, Duru et al. 2015b). Socio-economically, intensive crop production coupled with the global market for crop products has contributed to poverty and loss of land access for less productive, small-scale farmers (Hazell and Wood 2007, Kremen and Miles 2012). Additionally, the cropping systems resulting from this intensification are unsustainable in the long term. Firstly, the environmental impacts listed above degrade agricultural areas, threatening future crop productivity and stability (Hazell and Wood 2007, Bommarco et al. 2013). Secondly, intensive crop production heavily depends on off-farm inputs, many of which are depletable resources like phosphorus for fertilisation or fossil fuel, either used directly for tractors or as an energy source for synthesising inputs like mineral nitrogen (Lin et al. 2008, Woods et al. 2010, Duru et al. 2015a, Dardonville et al. 2022).

Ecosystem Services (ES) are often highlighted as a key for transitioning from intensive to sustainable crop production (Foley et al. 2005, Zhang et al. 2007, Power 2010, Bommarco et al. 2013, Duru et al. 2015b, Palomo-Campesino et al. 2018). Defined as “*the contributions that ecosystems make to human well-being*” (Haines-Young and Potschin 2018, page III), ES can be categorised into three sections: provisioning, regulating (as an abbreviation for regulation and maintenance) and cultural services

(Haines-Young and Potschin 2018). In agroecosystems, a crop field is a sub-unit that includes a cultivated plot and its surroundings, that humans manage and that simultaneously supplies ES and benefits from ES (Potschin-Young et al. 2018). In crop fields, provisioning ES include material and energy outputs useful to humans such as plants cultivated for food, fibre, genetic resources or biofuel synthesis. Regulating ES mediate or moderate the ambient environment affecting human health, safety or comfort. In crop fields, these latter can include climate regulation, soil quality regulation, pollination or biological pest control (Zhang et al. 2007, Potschin-Young et al. 2018). Cultural ES encompass non-material outputs that affect human physical and mental states. In crop fields, these latter can include artistic inspiration, recreation or education (Haines-Young and Potschin 2018). Conversely, ecosystems may generate dis-services, defined as “negative contributions to human well-being” or “undesired negative effects resulting from the generation of other ES” (Haines-Young and Potschin 2018). Pest damage to the crop and soil erosion are examples of dis-services in crop fields. In agroecosystems, the supply of ES and dis-services is shaped by both land-use management and pedoclimatic context (Duru et al. 2015b).

Calls to regenerate, maintain or enhance ES in agroecosystems gained momentum in the 2000s (Tscharntke et al. 2005, Dale and Polasky 2007, Power 2010) and are now central in agricultural and ecological studies (Palomo-Campesino et al. 2018). Various theoretical frameworks emphasise the importance of biodiversity and ecological processes for sustainable cropping systems, including “biodiversity-based agriculture”, “ecologically intensive agriculture”, “strong ecological modernisation of agriculture” (Duru et al. 2015b), “agroecology” (Wezel et al. 2013), “agroecological intensification” (Tscharntke et al. 2012), “biologically diversified farming systems” (Kremen and Miles 2012) and “ecological intensification” (Bommarco et al. 2013). While these approaches, which we will refer to as “ecologically intensive cropping systems” throughout this article, vary in their scopes, implementations and views on the future crop yield needed, they all share the goal of reducing reliance on off-farm inputs by utilising the natural functions of well-managed agroecosystems. By doing so, ecologically intensive cropping systems aim to replace non-renewable or energy-intensive inputs with ES and to reduce negative environmental externalities, offering a sustainable alternative to intensive crop production (Duru et al. 2015b).

The development of agroecosystem visualisations distinguishing between suppliers and beneficiaries of ES has supported the formalisation and promotion of ecologically intensive cropping systems. Zhang et al. (2007) proposed a framework that differentiates ES “to” and “from” the agroecosystem, later adapted as “input” and “output” ES by French researchers (Le Roux et al. 2008, Clermont-Dauphin et al. 2014, Duru et al. 2015b). This framework complements the three-section ES classification presented above (Haines-Young and Potschin 2018) by clarifying agroecosystem-specific dynamics. Input ES, provided by cultivated fields and their surroundings for the benefit of the farmer, support crop production through processes like pollination, soil retention, microclimate regulation and nutrient cycling, while input dis-services, such as pest damage and weed competition, impede it (Zhang et al. 2007). Farmers on one hand benefit from input ES as

they can replace off-farm inputs for crop production (Dardonville et al. 2022) and, on the other hand, are affected by input dis-services. Output ES, delivered from agroecosystems for the benefit of society, include provisioning ES like food and fibre production, regulation ES like water purification, climate change mitigation or wildlife habitat and cultural ES like aesthetic landscapes. Some output ES – mostly provisioning ES – generate a direct income for the farmer, while others – mostly regulation and cultural ES – do not (Zhang et al. 2007). Output dis-services, such as greenhouse gas emissions or nutrient runoff, come from agroecosystems and negatively impact society. Using this framework, ecologically intensive cropping systems can be described as systems aiming to substitute off-farm inputs with input ES, while maximising output ES and minimising dis-services (Duru et al. 2015b). Some ES can be categorised simultaneously as input and output ES, as the farmer and the society both benefit from their supply: for example, the ES of water regulation impacts the farmer through water availability for cultivated plants on one side and the neighbourhood through the flows of water leaving the crop field on the other side. This framework of input and output ES is comprehensible and engaging for farmers and other agroecosystem stakeholders, as it highlights the mutual benefits of well-managed agroecosystems for farmers and society.

A growing body of literature supports the transition from intensive to ecologically intensive crop production (Duru et al. 2015b, Boeraeve et al. 2020). Agroecology terminology and objectives, as well as the concept of leveraging ES through agricultural management, are increasingly included in public policies (Dardonville et al. 2022, Van Ruymbeke et al. 2023). While agroecology extends far beyond ecologically intensive crop production – encompassing ecological, economic and social dimensions across entire food systems (Wezel et al. 2011) – its growing political recognition can support ecologically intensive agriculture. Specifically, two principles of agroecology at the agroecosystem level closely align with ecological intensification: (1) minimising exogenous, non-renewable inputs and (2) promoting key ecological processes and services (Altieri 1995). Furthermore, a substantial scientific groundwork has been built, with fundamental knowledge about ecological processes in agroecosystems and numerous theories on ecologically intensive cropping systems (Power 2010, Duru et al. 2015a, Duru et al. 2015b). Authors also agree on global principles for designing agroecosystems that enhance input ES, such as increasing plant diversity and soil cover, minimising mechanical and chemical soil disturbances and organising natural, semi-natural and cultivated areas to promote biological regulation (Duru et al. 2015b).

However, in industrial countries, farmers have not widely adopted ecologically intensive cropping systems (Palomo-Campesino et al. 2018). According to several authors, their practical implementation is notably hindered by the complexity and uncertainty involved in translating theoretical principles into site-specific cultivation decisions (Duru et al. 2015a, Palomo-Campesino et al. 2018). While many relationships between agricultural practices and ES are well understood at a general level, this knowledge is not always sufficient to anticipate the impact of a cropping system – and the various practices it comprises – on ES delivery in a given agroecosystem with its specific pedoclimatic conditions, erosion potential, soil fertility and pests and weeds communities (Palomo-

Campesino et al. 2018). For example, while an increasing use of cover crops consistently has positive effects on the supply of pollination and erosion control across cropping systems and local conditions, its impact on crop production or climate regulation through carbon sequestration varies significantly in both magnitude and direction depending on studies (Palomo-Campesino et al. 2018, Van Ruymbeke et al. 2023). This illustrates the shift in innovation needed when moving from intensive to ecologically intensive cropping systems: more than before, general agronomic knowledge must be complemented by applied, local knowledge to support the informed adoption of context-specific agricultural practices (Duru et al. 2015b). Beyond knowledge-related challenges, a range of economic, organisational and structural barriers also contribute to the limited adoption of ecologically intensive systems – such as the cost of transition, access to adapted equipment, regulatory constraints and food chain organisation (Le Roux et al. 2008, Palomo-Campesino et al. 2018). These aspects, though beyond the scope of this paper, are important to acknowledge. Here, we focus on addressing knowledge gaps as a foundational step towards wider implementation.

Generating precise, site-specific knowledge requires carrying out field-based ES assessments that: (1) are strategically located to represent precise bio-physical conditions for soil, climate and environment (Palm et al. 2014, Duru et al. 2015a, Duru et al. 2015b); (2) consider multiple ES simultaneously to account for synergies and trade-offs between ecological processes (Power 2010, Seppelt et al. 2011, Bommarco et al. 2013, Deng et al. 2016); (3) integrate entire cropping systems rather than single cultivation practices (Kremen and Miles 2012, Palm et al. 2014, Boeraeve et al. 2020); and (4) are based on collaboration amongst scientists and stakeholders to ensure that findings are practical, applicable and support decision-making processes (Seppelt et al. 2011, Duru et al. 2015b). Assessments combining all these characteristics are emerging in industrial countries (Boeraeve et al. 2020, Chabert and Sarthou 2020).

In situ ES assessments are based on measurement methods that quantify ES supply through indicators, i.e. quantifiable biotic or abiotic variables measuring an ecosystem's capacity to provide ES (van Oudenhoven et al. 2012, Duru et al. 2015b, Vihervaara et al. 2018). Indicators vary in how closely they estimate a final ES, as conceptualised in the cascade model (Haines-Young and Potschin 2013a). In this model, the supply of ES is represented by a “cascade flow” including five levels: upstream, within the ecological system, (1) “ecosystem properties” influence (2) “ecosystem functions”, which in turn influence (3) the central level of “final ES” (TEEB 2010, van Oudenhoven et al. 2012, Potschin and Haines-Young 2016). Properties are biophysical structures of the ecosystem (Boerema et al. 2016) and functions are biological, chemical or physical changes or reactions of the ecosystem (TEEB 2010). In the centre of the cascade, “final ES” are the contributions that ecosystems make to the well-being of humans (TEEB 2010). Downstream, within the socio-economic system, (4) “benefits” and (5) “values” derive from ES supply. Benefits are the positive changes in human well-being coming from the fulfilment of needs and wants by ES and values are the economic worth of said benefits (TEEB 2010). The cascade model provides measurable entities for assessing ES (Boerema et al. 2016) and allows comprehensive and objective assessments by

including both ecological and socio-economic indicators (van Oudenhoven et al. 2012, Kandziora et al. 2013).

A wide range of indicators has been used to assess ES in agroecosystems (Boerema et al. 2016, Vidaller and Dutoit 2022), several methodologies for choosing those indicators have been built (Dale and Polasky 2007, Seppelt et al. 2011, van Oudenhoven et al. 2012) and pre-made indicators sets, specific to certain agroecosystems, have been proposed (Dale and Polasky 2007, Ritz et al. 2009, Quinn et al. 2012, Dominati et al. 2014, Meyer et al. 2015, Thoumazeau et al. 2019, Tzivilakis et al. 2019). Nonetheless, comprehensive lists of indicators applicable specifically to agroecosystems remain scarce (but see Boerema et al. (2016), Paul et al. (2022), Vidaller and Dutoit (2022)) and, to our knowledge, no existing compilation focuses on indicators based on empirical data from direct crop field measurements. Yet, field-based assessments at the crop field scale are essential to understand how cultivation practices affect ES (Dale and Polasky 2007), which is necessary for advancing ecologically intensive cropping systems. Given the context-specific nature of those assessments (Duru et al. 2015b), researchers need access to an exhaustive collection of available indicators to select those most suitable for their studied agroecosystems.

This study aims to build, from a global literature review about ES indicators (Boerema et al. 2016), a clear and accessible collection of field-based indicators for assessing ES in crop fields with empirical measurements. Beyond compiling this collection, we also examine how the indicators are distributed across ES types, cascade levels and measurement methods, as well as their application in past research. Specifically, we address the following research questions:

1. In ES research, which provisioning and regulating ES are covered by field-based indicators at the crop-field scale?
2. How are these indicators distributed across the levels of the ES cascade model?
3. How have ES studies applied these indicators, particularly regarding the number of ES assessed and the integration of multiple levels of the ES cascade?

By answering these questions, we aim to provide a clearer picture of the possibilities and limitations of field-based ES assessments in crop fields, thereby supporting the development and implementation of ecologically intensive cropping systems through empirical ES studies.

Methods

Source of indicators

Our study builds upon the systematic literature review conducted by Boerema et al. (2016), which identified the methods used by scientists for quantifying ES in various ecosystems throughout the world. Their review included 16 ES within the provisioning and regulation sections, whose names were chosen by compiling the ES names found in 19 prior key reviews of ES indicators. To ensure traceability, we retained these ES names

for our indicator selection process, but linked them to two widely-used classifications (Table 1): The Economics of Ecosystems and Biodiversity (TEEB) classification and the Common International Classification of Ecosystem Services (CICES) V.5.1 at the group level (TEEB 2010, Haines-Young and Potschin 2018). These classifications, respectively developed by the United Nations and by the European Agency for Environment, enhance the usability of our indicator collection across contexts as they are extensively recognised in scientific and policy communities, particularly in Europe (European Union 2020). We identified correspondences between ES names across classifications using a web-based tool from the HUGIN OpenNESS project (Haines-Young and Potschin 2013b). One ES name in Boerema et al. (2016) may correspond to multiple names in other classifications, as CICES and TEEB do not align perfectly. To reflect that agroecosystems both benefit from and provide ES, we also linked the 16 ES names from Boerema et al. (2016) with the framework of input and output ES for agriculture (Table 1, Zhang et al. (2007), Le Roux et al. (2008)).

Table 1.

Ecosystem services (ES) considered in the review of Boerema et al. (2016) for the provisioning and regulation sections. The first column presents the ES sections (Haines-Young and Potschin 2018). The second column presents the ES names included in the review of Boerema et al. (2016). The third and fourth columns respectively represent the potential corresponding ES from the Common International Classification of Ecosystem Services V.5.1 (CICES) and The Economics of Ecosystems and Biodiversity (TEEB) classification (TEEB 2010, Haines-Young and Potschin 2018). If more than one ES correspond, they are separated by “;”. If no ES corresponds, it is precised by “(No equivalent)”. The last column categorises ES depending on their main beneficiary in an agroecosystem (Le Roux et al. 2008). If two beneficiaries are identified, the ES is included in two categories.

ES section (Haines-Young and Potschin 2018)	ES names in the review of interest (Boerema et al. 2016)	Potential corresponding ES at the group level of the CICES V. 5.1 classification (Haines-Young and Potschin 2018)	Potential corresponding ES in the TEEB classification (TEEB 2010)	Category of ES in the framework of input and output ES for agroecosystems (Zhang et al. 2007, Le Roux et al. 2008)
Provisioning	Energy and fuel	Cultivated terrestrial plants for nutrition, materials or energy; Wild animals (terrestrial and aquatic) for nutrition, materials or energy; Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Raw materials and medicinal resources	Output with direct income

ES section (Haines-Young and Potschin 2018)	ES names in the review of interest (Boerema et al. 2016)	Potential corresponding ES at the group level of the CICES V. 5.1 classification (Haines-Young and Potschin 2018)	Potential corresponding ES in the TEEB classification (TEEB 2010)	Category of ES in the framework of input and output ES for agroecosystems (Zhang et al. 2007, Le Roux et al. 2008)
	Food production	Cultivated terrestrial plants for nutrition, materials or energy; Wild animals (terrestrial and aquatic) for nutrition, materials or energy; Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Food	Output with direct income
	Genetic resources	Genetic material from animals; Genetic material from organisms; Genetic material from plants, algae or fungi	Genetic materials	Output without direct income
	Materials and fibre	Cultivated terrestrial plants for nutrition, materials or energy; Wild animals (terrestrial and aquatic) for nutrition, materials or energy; Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Raw materials and medicinal resources	Output with direct income
	Medicinal resources	Cultivated terrestrial plants for nutrition, materials or energy; Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Raw materials and medicinal resources	Output with direct income
	Ornamental resources	Cultivated terrestrial plants for nutrition, materials or energy; Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Raw materials and medicinal resources	Output with direct income
	Water provision	Groundwater used for nutrition, materials or energy; Surface water used for nutrition, materials or energy	Water	Output without direct income

ES section (Haines-Young and Potschin 2018)	ES names in the review of interest (Boerema et al. 2016)	Potential corresponding ES at the group level of the CICES V. 5.1 classification (Haines-Young and Potschin 2018)	Potential corresponding ES in the TEEB classification (TEEB 2010)	Category of ES in the framework of input and output ES for agroecosystems (Zhang et al. 2007, Le Roux et al. 2008)
Regulation and maintenance	Air quality regulation	Mediation of nuisances of anthropogenic origin; Mediation of waste, toxics and other nuisances by non-living processes; Mediation of wastes or toxic substances of anthropogenic origin by living processes; Regulation of baseline flows and extreme events; Regulation of chemical composition of atmosphere and oceans	Air quality regulation	Output without direct income
	Biological control	Pest and disease control	Biological control	Input
	Climate regulation	Atmospheric composition and conditions	Climate regulation	Input (for micro-climate); Output without direct income (for regional and global climate)
	Life cycle maintenance	Life cycle maintenance, habitat and gene pool protection	(no equivalent)	Output without direct income
	Pollination	Life cycle maintenance, habitat and gene pool protection	Pollination	Input
	Soil quality regulation	Regulation of soil quality	Maintenance of soil fertility	Input
	Soil retention	Regulation of baseline flows and extreme events	Erosion prevention	Input (for crop production); without direct income (for neighbours)
	Water purification	Mediation of nuisances of anthropogenic origin; Mediation of waste, toxics and other nuisances by non-living processes; Mediation of wastes or toxic substances of anthropogenic origin by living processes; Water conditions	Waste treatment (water purification)	Output without direct income

ES section (Haines-Young and Potschin 2018)	ES names in the review of interest (Boerema et al. 2016)	Potential corresponding ES at the group level of the CICES V. 5.1 classification (Haines-Young and Potschin 2018)	Potential corresponding ES in the TEEB classification (TEEB 2010)	Category of ES in the framework of input and output ES for agroecosystems (Zhang et al. 2007, Le Roux et al. 2008)
	Water regulation	Regulation of baseline flows and extreme events	Regulation of water flows and regulation of extreme events	Input (for crop production); Output without direct income (for neighbours)

To identify indicators used by researchers for quantifying these 16 ES, Boerema et al. (2016) performed a systematic search in the Science Direct database, covering publications up to April 2014. For each ES, they applied search strings combining "ecosystem service" and a list of the different names under which the ES could be labelled (see Table 1 in Boerema et al. (2016)), targeting abstracts, titles and keywords. They excluded grey literature, books, as well as papers not explicitly measuring ES. The resulting corpus consisted of 405 peer-reviewed research papers, from which they compiled a list of 507 ES indicators covering a wide range of ecosystem types (see Appendix S1 in Boerema et al. (2016)).

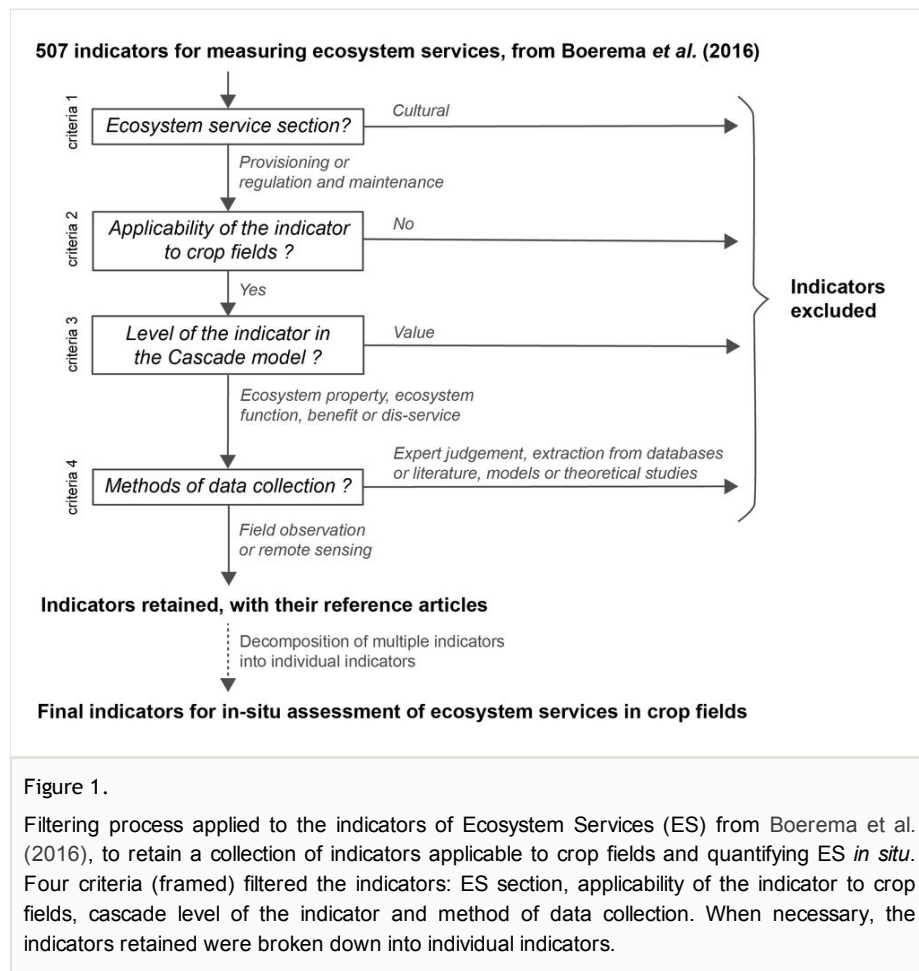
Boerema et al. (2016) classified the 507 indicators into five cascade levels – ecosystem property, ecosystem function, final ES, human benefit and value – based on the definitions from TEEB (2010) and van Oudenhoven et al. (2012), which we presented in the Introduction. For each ES, they also included indicators of ecosystem dis-services as a special sixth level "outside the cascade", to represent the negative impacts occurring when the ES is not adequately provided. Notably, while the "final ES" level is conceptually central in the cascade model, Boerema et al. (2016) found that none of the reviewed indicators aligned uniquely with this level. Instead, each indicator that could have been "final ES" corresponded more closely to either "ecosystem function" or "human benefit". Consequently, they did not treat "final ES" as a distinct level for indicator classification, but rather considered it as a global concept encompassing both the ecosystem function and human benefit levels (Boerema et al. 2016). We adopted the same approach when filtering and classifying indicators in our study.

Finally, for each indicator, Boerema et al. (2016) also identified all existing methods of data collection amongst field observation, mapping, modelling, remote sensing, theoretical study, extraction from a database, extraction from the literature or expert judgement.

Filtering and structuring

From the 507 indicators identified by Boerema et al. (2016), we only kept indicators suited for *in situ* biophysical assessments of ES in crop fields, using four filtering criteria: ES section, applicability to crop fields, cascade level and data collection methods (Fig. 1).

This process aimed to retain indicators supporting the creation of empirical, site-specific knowledge useful for ecologically intensive crop production. For the first criterion – section of ES – the review of Boerema et al. (2016) contained sufficient information for determining whether an indicator should be retained in our collection. The second, third and fourth criterion – applicability to crop field, cascade level and data collection method – required consulting source papers as the review was too synthetic. During this paper consultation, indicators were directly excluded if they failed to meet any criterion.



In the first step of indicator selection, we excluded cultural ES because their provision depends on the broad landscape of a crop field to an extent that can overshadow the effects of local crop cultivation practices. Cultural ES requiring direct human interaction often rely on the crop field accessibility (Ridding et al. 2018), hence on landscape-level factors like the proximity to hiking trails or the presence of nearby schools. Additionally, these ES often arise from a configuration of multiple land covers rather than a single ecosystem (Aalders and Stanik 2019). Thus, the field scale – targeted by our collection –

is not optimal for assessing cultural ES, which are typically evaluated at the landscape scale in agroecosystems (Vidaller and Dutoit 2022).

In the second step, we only retained indicators applicable to agroecosystems, specifically targeting crop fields as both an ecosystem type and a spatial scale for assessment. We focused on the crop field as it is critical for studying how agricultural practices affect ES, which is essential for creating site-specific knowledge to support ecologically intensive crop production. A crop field was defined as a cultivated plot and its immediate semi-natural surroundings, both of which influence ES provision. Concerning ecosystem type, this criterion excluded indicators irrelevant to crop fields, such as "Fish catch" for the ES of food production, which applies only to aquatic ecosystems. Within crop fields, we included indicators suitable for arable crops, permanent crops and temporary, non-grazed grasslands, without restricting to specific cultivation practices or regions, thereby ensuring broad applicability. Concerning spatial scale, we excluded indicators that could not be attributed to a single crop field. For example, we excluded "Groundwater availability" for the ES of water provision, as it depends on hydrological processes at the watershed scale and cannot be linked to individual fields. We mainly kept indicators measured within one crop field and its direct surroundings. However, we also retained indicators based on broader spatial observations if they supported the assessment of ES delivery for a specific field. For example, "Edge density of potential pest-controlling species habitat in the landscape" was retained as it refers to the landscape, but provides information for the biological control potential *within* the crop field, hence supporting field-level decision-making.

In the third step, we retained indicators for biophysical assessments and excluded those for monetary valuation. Biophysical indicators quantify ecosystem structures and functions, offering consistent, comparable data about the ecosystem's current state for assessments (Vihervaara et al. 2018). In contrast, monetary indicators reflect ES value within specific economic contexts, limiting comparability and reuse. For instance, a rising demand for a product can increase its perceived value and hence the monetary value of the ES providing it (van Oudenhoven et al. 2012). Consequently, we excluded indicators related to the value level of the cascade model and retained those related to the ecosystem property, ecosystem function, final ES (but there was none, as explained in "Sources of indicators") and human benefit levels, as well as dis-service indicators derived from biophysical measures. To aid future selections of indicators from our collection, each indicator's cascade level was explicitly noted. Following Boerema et al. (2016), we categorised dis-services as distinct indicators linked to specific ES, rather than a separate, negative equivalent of an ES (as done by Zhang et al. (2007) or Power (2010)). We represented them as a special cascade level corresponding to the negative side of the benefit level (Fig. 2).

In the fourth step, we excluded indicators relying solely on non-direct data, such as modelling, expert judgement, theoretical study or data extraction. Non-direct data are useful for exploratory purposes, such as comparing ES across cropping system scenarios (Vihervaara et al. 2018). However, the lack of site-specific knowledge about how cropping systems affect ES limits their applicability. We prioritised field-based indicators

that rely on empirical data, as these are essential for accurately quantifying ES and building this foundational knowledge. Hence, we retained indicators linked to methods collecting empirical data from the field via remote sensing or field observation - *in situ* analysis or sampling with *ex situ* analysis (Vidaller and Dutoit 2022).

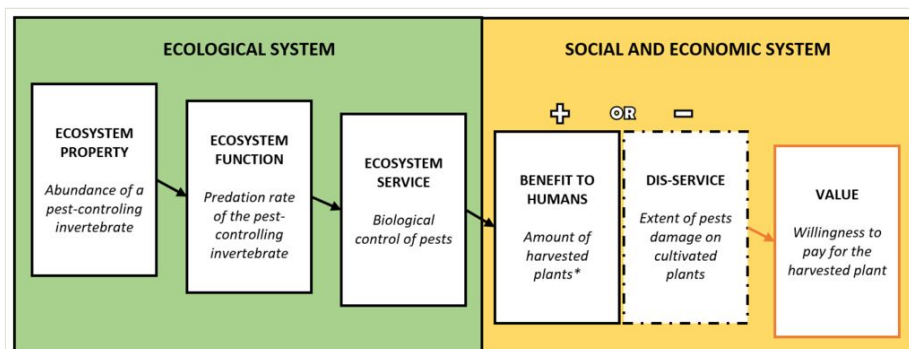


Figure 2.

Model of Ecosystem Services (ES) cascade (Haines-Young and Potschin 2013a) used to characterise the indicators of our collection. Each box represents an indicator level, in bold capital letters, with an illustrative indicator for the ES of biological control in agroecosystems, in italics. All illustrative examples come from our indicator collection, except for the “benefit to humans” level (*), as the filtration process did not retain any indicator at that level for biological control. Each upstream level, from ecosystem properties to ecosystem functions in the ecological system, directly influences the supply of ES, which, in turn, affects the downstream levels of benefits, dis-services and values within the socio-economic system. Compared to the original figure (Haines-Young and Potschin 2013a) that includes the boxes with plain lines, we added a dashed-lines box for the “dis-service level”, as a negative counterpart to the “Benefits to human” level. The black or orange outlines of the boxes respectively correspond to indicator levels retained or eliminated during our filtration process.

After the filtering process, we simplified the retained indicators’ names from Boerema et al. (2016), synthesising them for clarity. For example, for biological control, “Vegetation - indicator: percentage of cover of weed species” from Boerema et al. (2016) was renamed “Weed species cover”. We simultaneously stored descriptions of the protocols and units used to obtain indicators in each reference paper to avoid losing information through the name simplification. We also identified and decomposed assemblies of multiple indicators, presented as single indicators, by consulting the original protocols. These assemblies, often composite indicators summarising ES supply, were individualised, as presenting individual indicators allows researchers to select those most relevant to their study context. For instance, “Multiple soil properties: Once-off measurement: chemical properties: SOM, P, N, C, Al, base cations” from Boerema et al. (2016) was split into six indicators, one per soil component. Then, we eliminated redundancies amongst the newly-created individual indicators and the rest of the retained list.

We summarised this final indicator collection in a dataset detailing for each indicator the ES section, ES category in the framework “input and output ES”, ES name in Boerema

classification, ES group, class and code in the CICES V.5.1, indicator level in the cascade model, original and simplified indicator name, DOI of reference paper(s) and main authors of reference paper(s). For each combination of ES indicator and reference paper, we also included the method of data collection, the unit of the indicator and a brief description of the protocol.

Analysis of the final collection

To address our three research questions, we analysed the final collection of indicators along three main dimensions.

First, to determine which provisioning and regulating ES were covered by field-based indicators at the crop-field scale, we calculated the number of indicators associated with each ES. We also compared the distribution of indicators between input and output ES categories and between the two ES sections (provisioning and regulating). These comparisons help identify potential imbalances on how different types of ES are measurable and represented in empirical ES assessments.

Second, to assess how indicators were distributed across the ES cascade model, we counted the number of indicators assigned to each cascade level for every ES. This distribution reflects the range of assessment possibilities offered by the indicator collection – based on the presence or absence of indicators at each level – and highlights the relative emphasis placed on ecological versus socio-economic dimensions. It also provides information on the variety of indicators used within each level for a given ES, hence on the underlying complexity of that ES and on the existence or absence of a scientific consensus on how to best quantify it for each cascade level.

Third, to examine how the reference articles that originally reported the indicators used them in practice, we recorded for each article the number of ES assessed, the sections of ES assessed and the cascade levels represented for each ES. This enabled us to evaluate how comprehensive each study was in terms of both ES diversity and cascade integration and, specifically, to explore how frequently studies incorporated both ecological and socio-economic perspectives in field-based ES assessments. Finally, we summarised the method(s) of data collection used by each study to obtain each indicator.

All the summary statistics were obtained from the variables characterising ES indicators that are available in our complete dataset (Leveau 2025), using the *dplyr* package (Wickham et al. 2023) in R (version 4.3.0).

Data resources

The indicator collection underpinning the analysis reported in this paper is available in different formats:

- A unique table including the whole dataset, with one line by combination of ES indicator and reference paper, deposited as an Excel file on the Zenodo repository (Leveau 2025, <https://doi.org/10.5281/zenodo.15234008>);
- A relational dataset that can be explored interactively through a Shiny application, accessible either online (https://plantmodelling.shinyapps.io/crop_field_es_indicators) or via local deployment on the R software of the scripts available on [GitHub](#) and Zenodo (Lobet and Leveau 2025);
- A unique table that is a simplified version of the dataset, excluding original indicator names, ES group, DOI of reference papers and descriptions of the protocols, available as Supplementary material (Suppl. material 1). An extract from this table, including only the "food production" ES, is presented in the Results section to illustrate the data collected on the indicators.

Results

Out of the 507 indicators from Boerema et al. (2016), our filtering process yielded a collection of 59 indicators for field-based assessments of ES in crop fields. The first filtering step excluded 104 cultural ES indicators, while the subsequent steps – evaluating applicability to crop fields, cascade level and methods of data collection – excluded together an additional 344 indicators.

Out of the 59 retained indicators, 20 assemblies of multiple indicators were disaggregated, primarily in the ES of soil quality regulation, climate regulation and pollination (details in Leveau (2025)). After disaggregation and removal of redundancies, the final collection comprised 128 single indicators (Table 2).

Out of the 128 indicators, 121 were unique to one ES, while seven appeared in two ES. All duplicates were ecosystem property or ecosystem function indicators that related to soil quality regulation and either soil retention, water purification or climate regulation (Suppl. material 1). For example, soil available phosphorus concentration and soil nitrogen mineralisation rate appeared in both soil quality regulation and water purification. Interestingly, all the duplicates appeared after the disaggregation of multiple indicators into single ones, so they were not apparent in the original indicator list of Boerema et al. (2016). The existence of duplicates in ES indicators shows that the same properties or functions of an agroecosystem can influence the supply of different ES, which is well documented in agricultural ES research (Tibi and Therond 2024).

The 128 indicators in our collection showed an uneven distribution, whether across ES sections (provisioning or regulating), input and output ES categories, specific ES, cascade levels (Fig. 3) or methods of data collection (Suppl. material 1).

In terms of sections, 8% of the indicators related to provisioning ES, while 92% related to regulating ES. This disparity cannot be solely attributed to the number of ES in each section, as provisioning ES accounted for 44% (seven ES) of the total, compared to 56% (nine ES) for regulating ES.

Table 2.
Extract of the collection of 128 ES indicators usable for *in situ*, biophysical quantification of ES in crop fields, selected from the Boerema et al. (2016) review. The full table is available as a pdf in the supplementary material (Suppl. material 1) and the complete dataset, including original indicators names, brief protocol description, CICES groups and reference papers DOI, is available as an Excel file on Zenodo (Leveau 2025). This shortened version only includes the ES of "food provision". The first column lists the ES sections (Haines-Young and Potschin 2018), while the second specifies the ES name used in Boerema et al. (2016) and categorises ES within the "output and input ES" framework : I = Input ES; O+i = Output ES with direct farmer income; O-i = Output ES without direct farmer income (Zhang et al. 2007, Le Roux et al. 2008). The third column classifies each indicator to one or multiple CICES (V.5.1) classes (Haines-Young and Potschin 2018). The fourth column specifies the cascade level each indicator quantifies: P : ecosystem property; F = ecosystem function ; B = benefit to human ; D = dis-service (Potschin and Haines-Young 2016). The fifth column lists the 128 indicators of our collection. The last column summarises the unit(s) used to quantify the indicator and specifies the reference papers using each unit in brackets. Units corresponding to measures via field observations are in regular text, while those corresponding to remote sensing are in *italics* and marked with an asterisk (*). Multiple units in the same cell are separated by semi-colons.

ES section	ES name from Boerema	Class and code in CICES V.5.1	Cascade level	Name of the indicator	Units used for the indicator (corresponding references)
Provisioning	Food production (O+i)	1.1.1.1 Cultivated terrestrial plants (including fungi algae) grown for nutritional purposes	P	Land-use area for crop	<i>Surface area percentage*</i> (Maes et al. 2012)
			B	Food or fodder provision as number of fruits per plant	Number of fruits per plant (Holzschuh et al. 2012)
			B	Food or fodder provision as protein yield of harvested product	Mass of protein from harvested product by hectare and harvest (Snapp et al. 2010)
			B	Food or fodder provision as weight of harvested product (fresh or dry)	Fresh or dry mass of harvested product by surface unit and harvest (DuPont et al. 2009, Kahiluoto et al. 2009, Smukler et al. 2010, Snapp et al. 2010, van Eekeren et al. 2010, Ferris et al. 2012, Williams and Hedlund 2013, Meyer and Priess 2014, Syswerda and Robertson 2014)

In terms of input and output ES categories, the range of indicators per ES varies notably. Output ES providing direct income to farmers were represented by 1 - 4 indicators, while

output ES not providing direct income were represented by 0 (for three ES) to 12 indicators. Input ES exhibited the widest range, as they were represented by 5 - 56 indicators.

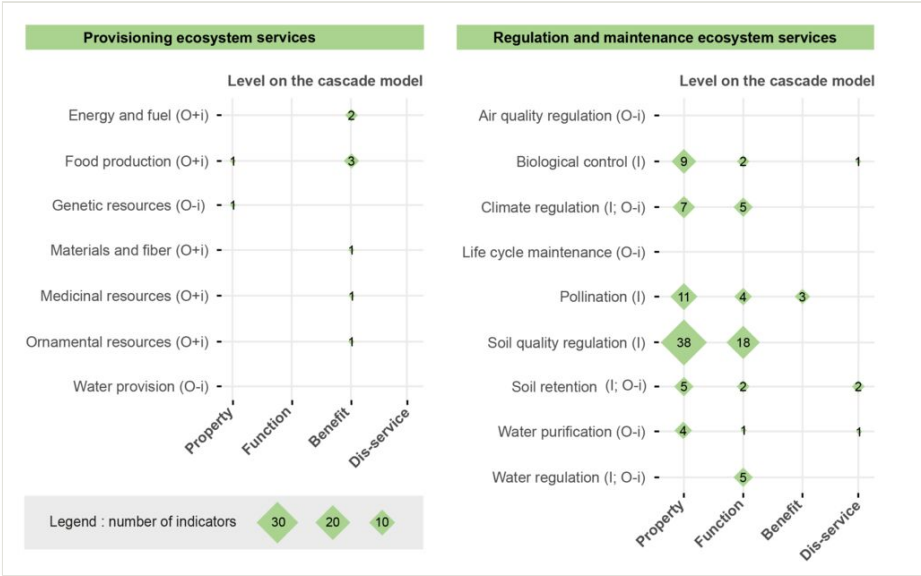


Figure 3. Distribution of the 128 Ecosystem Services (ES) indicators retained from Boerema et al. (2016) after our filtering process. The left and right plots respectively display indicators from the sections of provisioning ES and regulation and maintenance ES. In each plot, ES are presented on the y-axis while the cascade level to which each indicator belongs is presented on the x-axis. For each ES, its category in the framework “input and output ES” is specified in parentheses: (I) = Input ES; (O+) = Output ES with direct income for the farmer; (O-) = Output ES without direct income for the farmer. The “value” level of the cascade is not represented on the x-axis, as it was filtered out during our selection process. For each combination of ES and cascade level, a green diamond represents the number of indicators available, indicated by its size and central number.

The number of indicators per ES ranged from 0 - 56, with soil quality regulation (56) and pollination (18) having the most. Notably, no indicator met our filtering criteria for three ES – water provision, air quality regulation and life cycle maintenance – indicating that these ES have not been assessed empirically in crop fields in the studies reviewed by Boerema et al. (2016). Interestingly, all three are output ES without direct income for the farmer (Zhang et al. 2007, Le Roux et al. 2008).

The distribution of indicators across cascade levels varied considerably by ES section. In the provisioning section, only 20% of the indicators were related to ecosystem properties, while 80% were related to human benefits. Only two provisioning ES – food production and genetic resources – were measurable with indicators from the ecological system (e.g. properties and functions), whereas others only included indicators from the social

and economic system (e.g. benefits and dis-services). This pattern was reversed for the regulation section, where 63% of indicators related to properties, 31% to functions and only 6% to human benefits or dis-services. Out of nine regulating ES, only four – biological control, pollination, soil retention and water purification – included indicators from the social and economic system. Besides, pollination was the only one including benefit indicators.

The retained indicators were derived from 66 articles reviewed by Boerema et al. (2016), published between 2006 and 2014. Half of these articles were published in four journals: Agriculture, Ecosystem & Environment; Applied Soil Ecology; Biological Conservation; and Ecological Indicators. Analysing cascade levels in the 66 reference papers provided insight into the methodologies of *in situ* biophysical assessments of ES in crop fields. Most articles (64%) assessed one ES, 22% assessed two and 14% assessed three to six. Remarkably, only 14% measured both provisioning and regulating ES. Only four papers used both ecological and socio-economic indicators: one evaluated pollination (function and benefit), one assessed soil retention (function and dis-service) and two evaluated water purification (property and dis-service or property, function and dis-service). Additionally, 24 papers assessed climate regulation, pollination, soil retention or soil quality regulation using a combination of property and function indicators. Most studies focused on a single cascade level per ES.

Finally, in terms of methods for data collection, each indicator was either only obtained through field observation or through remote sensing, even when multiple reference papers measured it. Globally, 91% of indicators were based on field observation and 9% on remote sensing. Encouragingly, all ES, except water provision, air quality regulation and life cycle maintenance, could be quantified in crop fields through field observations, which globally covered all cascade levels. In contrast, remote sensing was only used for property indicators and was limited to food production, biological control, climate regulation, pollination and soil retention. Remote sensing data were either land-cover classes (arable crops, permanent crops, forests etc.), vegetation types combined with their spatial configurations or soil slope.

Discussion

This study aimed to identify field-based indicators for assessing ecosystem services (ES) in crop fields and to highlight gaps in their distribution across ES types and cascade levels. In this discussion, we first examine the causes of disparities in indicator availability between ES, considering both methodological filters and broader research dynamics. We then explore and discuss the theoretical possibilities and real applications of integrating multiple levels of the ES cascade – particularly ecological and socio-economic aspects – within an ES assessment.

Causes of disparities in indicators availability amongst Ecosystem Services

In our collection focused on biophysical, empirical assessments at the crop-field scale, great disparities exist in the availability of indicators across ES. The underlying reasons for the abundance or scarcity of indicators vary between ES.

A high number of indicators for a given ES is not inherently beneficial. For some ES, it is positive as it reflects thorough knowledge of the multiple components that need to be quantified to comprehensively assess the ES, as observed with climate regulation or pollination. For other ES, it rather signals inconsistencies across studies, often due to a lack of consensus on assessment methods (Seppelt et al. 2011, Boerema et al. 2016). In our collection, the abundance of indicators for soil quality regulation reflects both factors. Soil is a complex, multidimensional system, integrating abiotic and biotic elements and physical, biological and chemical processes, all well-studied, notably in agroecosystems (Lavelle and Alister 2003, Palm et al. 2014, Christel et al. 2021). However, soil quality, or health, remains a contested concept, with definitions and measures requiring further consensus across disciplines and practitioners (Bünemann et al. 2018, El Chami et al. 2020, Bagnall et al. 2023, European Commission 2024).

Similarly, a limited number of indicators for a given ES may also have multiple interpretations. On the one hand, it may reflect a broad consensus within the scientific community on the most effective *in situ* measurement method. For example, the benefit indicator “food or fodder provision as weight of harvested product” was used in ten of the twelve papers assessing food production in our collection. This widely recognised and comprehensive indicator has long been a cornerstone of agronomic research, even before the emergence of ES and ecologically intensive cropping systems frameworks (Power 2010). In such cases, a small number of indicators does not necessarily hinder accurate assessment. On the other hand, a limited number or absence of indicators may signal that the ES is either: (a) assessed in crop fields with other methodological approaches than those targeted by our collection or (b) not assessed in crop fields at all. These two cases are explored in the following sub-sections with illustrations from the results of our filtering process.

(a) Ecosystem Services assessed in crop fields with methods outside of our scope

A series of ES are often studied in crop fields, but with indicators and methods that were not retained during our filtration process centred on biophysical, direct measurements at the crop-field scale.

Firstly, we focused on assessments made at the crop field scale (Fig. 1, criteria 2), while many ES assessments of agroecosystems are conducted at scales broader than the crop field. For example, assessments of ES in conventional farming systems mainly focus on landscape, multi-farm and multi-plot scales, with the crop-field scale used in less than 10% of studies (Vidaller and Dutoit 2022). Different causes can explain the use of these broader scales. Some ES like climate regulation, water purification or water provision, are

not quite relevant to measure at the crop-field scale due to their substantial reliance on larger spatial processes (Liu et al. 2022). For instance, many indicators compiled by Boerema et al. (2016) for the ES of water provision, like groundwater storage, environmental flows or stream discharge, were excluded from our collection as they were designed for larger spatial scales than the crop field, such as river basins. It seems logical, since processes like the recharge rate of groundwater are strongly influenced by water flows, land uses and land covers at the watershed scale (Owuor et al. 2016, Ni et al. 2020). Conversely, ES like soil quality regulation, pollination or biological control mainly function at smaller scales and are more suitable for field-level assessments (Liu et al. 2022), which could explain why our collection include many indicators for these ES. Another reason for assessing ES at a larger spatial scale could be the study of agricultural practices operating at the said broader scale. For instance, agroecological practices at the landscape scale have significant impacts on biodiversity-related ES like pollination and biological control, while field-scale practices, such as crop rotations and residue retention, have more influence on soil quality regulation, food production and water regulation (Kremen and Miles 2012, Palomo-Campesino et al. 2018). However, ES are never influenced solely by landscape-level practices: for instance, pollination and biological control are also impacted by within-field practices like grass strips, crop rotation and cover crops (Zhang et al. 2007, Kremen and Miles 2012). Moreover, even when studying landscape-scale practices, ES measurements often occur at the crop-field level. For instance, studies on landscape complexity and pest predation usually measure predation rates within arable crops. This aligns with the abundance of biological control and pollination indicators in our collection, showing that ES influenced by landscape management are frequently assessed at the field scale if it is one of their main functioning scales.

Secondly, we only retained indicators linked to biophysical assessments (Fig. 1, criteria 3). It left aside studies using value indicators – for example, to assess economic trade-offs between practices, internalise external costs and benefits of crop production or highlight the socio-economic importance of ES (Faccioni et al. 2019, Zabala et al. 2021, Rath 2024). While this filtering criterion excluded a subset of studies, we do not believe it introduced bias towards particular ES, as all ecosystem services can hold indirect economic values and be relevant for monetary assessment (TEEB 2010).

Finally, we excluded all the indicators based on indirect data, such as literature or expert judgement (Fig. 1, criterion 4). The use of indirect data in a study can reflect two type of rationale: in some cases, it aligns with the study's objectives that do not rely on direct measurement, while in others, it reflects the practical challenges and resource constraints associated with collecting field-based data. For the first case, many biophysical ES assessments rely on expert opinions or previous literature, as they aim at supporting decision-making for future cultivation systems based on already available knowledge (Balbi et al. 2015, Sagie and Ramon 2015, Pokovai et al. 2020, Dardonville et al. 2022). For the second case, certain ES are too resource-intensive to evaluate through *in situ* measurements. For instance, assessing life cycle maintenance *in situ* requires significant time, expertise and materials to characterise species survival and reproduction. Similarly,

evaluating air quality or climate regulation involves costly methods for quantifying pollutants or greenhouse gases concentrations, emissions or removal rates by plants throughout the year (van Oudenhoven et al. 2012, Kandziara et al. 2013). Moreover, ES that mainly depend on and happen in the natural and semi-natural surroundings of arable crops, like life cycle maintenance, can be resource-intensive to assess. Indeed, measuring the impacts of different surroundings on ES *in situ* requires sampling crop fields with specific landscape features, which demands more time and workforce than comparing cultivation practices applied within arable crops. Researchers may favour modelling, mapping or other non-direct measures for such ES that are complex or resource-intensive to measure empirically, which could contribute to the lack of indicators for the said ES in our collection. For instance, many indicators for air quality regulation in Boerema et al. (2016) review were derived from modelling, such as air pollutants emissions, vegetation volume or vegetation cleaning capacity. While two theoretical studies proposed indicators for “air quality” and “air pollutant emissions” for agroecosystems, they lacked concrete data collection protocols, so our filtered collection contains no indicator for this ES.

Consequently, while many studies evaluate ES in crop fields, their methodologies often fall outside our collection focused on field-based, biophysical measures. This is not problematic, as diverse methodologies are needed to advance ES research. However, when indirect approaches are chosen due to resource constraints rather than suitability, it underscores the need for more accessible field-based indicators or increased support and resources for empirical data collection, especially for under-represented ES.

(b) Ecosystem Services rarely assessed in crop fields

Beyond the ES studied in crop fields with methods situated out of our filtering limits, some ES are globally less studied in agroecosystems because they are not perceived as critical for supporting agriculture compared to well-studied ES such as food production, pollination or biological control (Tancoigne et al. 2014, Liu et al. 2022). This likely leads to low prioritisation of the concerned ES and, consequently, to fewer indicators being developed for them in agronomic research.

In the same vein, intensive crop fields are not considered as “hotspots” or key ecosystems, for certain ES like genetic resources, life cycle maintenance air quality regulation or water purification (Foley et al. 2005). This can limit the interest for studying these ES in crop fields. For instance, the indicators of air quality regulation from Boerema et al. (2016) – all of which were excluded during our filtration process – were mainly designed for forest ecosystems, with some applicable to urban parks or roadside vegetation. These ecosystems share the common feature of dense perennial vegetation, which plays a key role in removing air pollutants (Diener and Mudu 2021).

Finally, some ES can be less frequently assessed, regardless of the ecosystem considered. For example, Boerema et al. (2016) identified only a few indicators for life cycle maintenance – and none that was applicable for agroecosystems. These indicators either concerned seed dispersal in urban parks or the maintenance of fish and plant

populations in aquatic ecosystems. This appears anecdotal when compared to the broader roles encompassed by life cycle maintenance through a wide range of ecosystems, which include wild plants seed dispersal, provision of habitats for wild plants and animals and pollination as defined in CICES V.5.1 (Haines-Young and Potschin 2018). However, it is important to note that Boerema et al. (2016) extracted pollination from life cycle maintenance and treated it as a different ES for which many indicators were collected. This separation can give the misleading impression that life cycle maintenance is rarely assessed in ES research, even though one of its classes, pollination, is in fact well represented.

Possibilities and realities of the integration of multiple cascade levels

Literature suggests that a comprehensive assessment of ES benefits from incorporating multiple levels of the cascade, particularly when both ecological and socio-economic indicators are included (van Oudenhoven et al. 2012, Kandziora et al. 2013, Boerema et al. 2016).

For the ecological aspect of the ES cascade, using function indicators compared to properties indicators makes the assessment more straightforward. Indeed, while ecosystem properties influence ES supply, their effects are indirect and interact with environmental processes, infrastructure and cultivation practices (Boerema et al. 2016). Relying solely on property indicators hence provides limited insights. For example, measuring soil organic carbon stocks once is not sufficient to assess net carbon sequestration and carabid abundance does not directly reflect their weed control contributions. Function indicators, in contrast, offer better predictions of ES supply over space and time (Boerema et al. 2016). Studies can create robust assessments by integrating property and function indicators or prioritising the latter, such as assessing pest control through aphid abundance (property) and predation rates (function) (Boeraeve et al. 2020) or soil retention through soil aggregate stability (function) rather than soil slope or morphology (property) (Chabert and Sarthou 2020). In our collection, most regulating ES include numerous properties and function indicators, especially biological control, climate regulation, pollination, soil quality regulation and water regulation, which is positive for designing comprehensive ES assessments. However, the theoretical possibility of creating ecological assessments including properties and functions does not translate well into practice. Indeed, out of 66 reference articles linked to our collection of indicators, only one-third used both property and function indicators to quantify the same ES. This limited use may partly reflect a deliberate effort by scientists to avoid double-counting in ecological ES assessments, which can occur if property and function indicators that are causally related are treated as separate, additive measures of ES supply. However, this risk is limited when causally related indicators are not treated as additive elements, but rather understood as complementary components within a single ecological process.

Concerning the integration of both the ecological and the socio-economic aspects of the cascade, our collection indicates that applying this recommendation is rarely feasible in

biophysical, *in situ* assessments of crop fields. Indeed, many ES only include indicators from either the ecological or the socio-economic side of the cascade (see Results). Furthermore, even for ES with indicators belonging to both sides of the cascade, very few studies consider these two sides simultaneously in our reference papers. The imbalance across cascade levels observed in our collection is consistent with the general findings from Boerema et al. (2016). They found that ecological indicators dominated regulation ES, with two-thirds related to ecosystem properties and functions. They also only found benefit indicators for the ES of pollination. In contrast, socio-economic aspects dominated for provisioning ES, with two-thirds of indicators related to human benefits or economic value. Studies assessing both ecological and socio-economic sides were rare and only 0.7% of the reference papers assessed more than two cascade levels. Thus, the patterns found in our collection reflect broader trends in ES indicators.

The framework of input and output agricultural ES offers an interesting perspective on this situation: output ES generating direct farmer income are, by definition, marketable, so their benefits can be quantified (Dale and Polasky 2007). In our collection, these ES are represented by one to three benefit indicators, all related to plant productivity via its harvested mass, protein content, energy content or number of fruits produced. While these indicators do not capture the full spectrum of nutritional or health-related benefits – such as vitamin and micronutrient content or the presence of contaminants like mycotoxins – they represent a core subset of benefits that are the primary metrics on which farmers are often paid for their production. With such concrete socio-economic indicators available, it is not surprising that *in situ* studies of the said ES rarely attempt to assess them through the various ecological properties and functions underpinning plant production. However, including ecological indicators could improve understanding of how cultivation practices influence the underlying processes that support these ES.

Output ES without direct farmer income, for their part, either include no indicator at all in our collection – for three indicators, all purely output ES – or include more property and function indicators than benefit and dis-service indicators – for five indicators, two purely output ES and three output and input ES. Interestingly, climate regulation and water purification are transitioning from non-marketed to marketed output ES for some farmers, through rewards for carbon sequestration (McDonald et al. 2021) and penalties for water pollution (OECD 2012). This new market potential could explain why these two output ES have a high total number of indicators in our collection: establishing a market for a regulating ES typically starts with empirical data gathering, which provides the foundation for developing models to estimate ES benefits – such as net greenhouse gas sequestration or nitrate pollution – at a scale broader than can be achieved through *in situ* measurements alone.

Finally, input ES are tangible inputs that support agricultural production and can substitute off-farm inputs. Given the current focus on sustainable, less input-dependent agriculture, it is unsurprising that these ES are assessed by numerous indicators in our collection. However, few input ES are associated with benefit indicators, likely because their primary benefit – plant production — is influenced by a multitude of ecological

processes and human interventions, making it unsuitable as a benefit indicator for any single input ES.

The lack of ecological indicators for marketed output ES and socio-economic indicators for input ES raises the idea that, in crop fields, input ES could represent the ecological side of the ecosystem and that their combined supplies could drive the delivery of output ES on the socio-economic side of the ecosystem. This idea resonates with Boerema et al. (2016), who noted that indicators for each ES tended to cluster either to the ecological or to the socio-economic side of the cascade and proposed that the functioning of certain ES underpins the delivery of others. This questions the opportunity of reclassifying input “ES” as property and function indicators of output ES, rather than as independent ES. However, beyond supporting plant production, input ES minimise reliance on off-farm inputs, with precise benefits that could be biophysically quantified as input substitution: human irrigation is replaced by water and micro-climate regulation, fertilisers and tillage by soil quality regulation, pesticides by biological control and so on. Our collection focusing on *in situ* assessments does not include this kind of benefit indicators – quantifying off-farm to ES input substitution for a given level of production. However, Dardonville et al. (2022) proposed a modelling assessment with a similar concept: indicators about “the actual use of ES by farmers as production factors”.

Limitations of our methodology and impacts for users of the collection

The methodology for constructing our indicator collection provided a good foundation for designing field-based ES assessments, but has its biases and is open to improvements. This section examines three key methodological choices and their implications for future users.

Firstly, incorporating dis-services indicators as a distinct level within the cascade, while unconventional (Zhang et al. 2007, Power 2010), proved relevant and useful for *in situ* assessments at the field scale. Indeed, all our dis-service indicators – such as pest damages or soil loss from water erosion – represent negative consequences that can be mitigated by the corresponding ES – such as biological control or soil retention. This framework may enhance stakeholder engagement by highlighting the benefits of an ES through the assessment of its corresponding dis-services.

Secondly, we retained all indicators applicable to *in situ*, biophysical assessments in crop fields without filtering for quality, ensuring a broad range of options for future users, as each assessment has specific objectives and resources. However, not all indicators are equally suitable for assessing ES in a given context. Several guidelines propose quality criteria for the design of ES assessments that can support indicator selection for agroecosystems (Dale and Polasky 2007, Seppelt et al. 2011, van Oudenhoven et al. 2012, Duru et al. 2015b, Meyer et al. 2015, Boerema et al. 2016, Maes et al. 2016). We encourage users of our collection to consult this literature when selecting indicators. Although we did not formally assess indicator quality, our selection process implicitly

addressed two quality criteria present in the literature: representativeness and comprehensiveness. The representativeness of an ES indicator is its capacity to accurately reflect the reality it approximates, by measuring states and processes that effectively translate into ES supply (Seppelt et al. 2011, Duru et al. 2015b, Boerema et al. 2016). Since ecosystem functions better reflect ES supply than ecosystem properties, the attribution of a cascade level to each indicator of our collection can help choose the most representative indicators for assessing the ecological aspects of an ES, for example, function indicators where available. Comprehensiveness, for its part, refers to the capacity of an indicator or, more frequently, a set of indicators, to represent all the key structural and compositional aspects of the ES under study (Dale and Polasky 2007, van Oudenhoven et al. 2012, Boerema et al. 2016). Once again, the presence of cascade levels in our dataset can help design assessments that integrate both the ecological aspects – via properties and function indicators – and the socio-economic aspects – via benefits and/or dis-services – of an ES. Such multidimensional assessments are more comprehensive than those focusing on one of the cascade aspects only (van Oudenhoven et al. 2012, Kandziora et al. 2013, Boerema et al. 2016).

Thirdly, our collection is inherently shaped by the methodology used by Boerema et al. (2016) to select reference papers and extract ES indicators. One key factor influencing our results is the specific list of ES categories and terminology they adopted. Some ES were deliberately excluded from their review because they were considered "supporting ES", a debated fourth ES section often omitted from assessments to avoid double counting. This concerns, for example, biodiversity, habitat and nutrient cycling. The argument of avoiding double counting appears justified when we consider that many indicators present in our collection would also fall under these excluded categories. For instance, all the indicators concerning auxiliaries habitats in pollination and biological control would be related to habitat and many indicators for water purification would be listed for nutrient cycling. Another bias of their ES terminology lies in the relatively narrow list of search terms used to identify reference papers for some ES. For example, biological control was only associated with "biological control" and "pest", whereas supplementary terms like "disease", "pathogen" and "regulation" could have expanded the reference corpus and resulted in a larger and more representative reference corpus and, thereby, in a more comprehensive list of indicators. The same limitation is, of course, applicable to our own corpus of 66 articles, as it is directly derived from the Boerema et al. (2016) review.

A second set of key factors of the Boerema et al. (2016) methodology that influences our results is that it limits references to literature published until 2014 and only includes papers explicitly stating that they measured an ES. We believe that the pronounced disparities in indicator distribution across ES and cascade levels are unlikely to change significantly with the inclusion of more recent studies – 2015 to 2025 – or broader literature – beyond explicit ES research. Many underlying causes – such as the scale of ES functioning, high costs of comprehensive field assessments, limited ES provision by crop fields and challenges in representing both ecological and socio-economic aspects – are not time- or discipline-dependent. Thus, while expanding the scope of this work to

include recent studies and adjacent disciplines might add a few more indicators due to constant knowledge and technologies improvements, the overall trends identified in our collection are expected to persist. We identify three exceptions that could cause major changes in our collection: rapid innovations for assessing ES that has newly gained interest, measures coming from recent remote sensing development and scientific disciplines systematically using indicators relevant for ES measurement without labelling it as ES research.

For example, over the past decade, research on climate regulation and soil health has grown substantially in agroecosystems, driven by the urgency of addressing climate change and sustainable agriculture (El Chami et al. 2020, Christel et al. 2021, van Wesemael et al. 2023). The new insights that resulted from it led to the development of new indicators, such as soil enzymes production (Gao et al. 2020) or the ratio between actual and expected soil organic carbon (Poeplau and Don 2023) and to the refinement of existing indicators by measurement standardisation or new reference ranges.

Besides, remote sensing technologies have advanced in recent years and are increasingly used to estimate ES in agricultural landscapes (Defourny et al. 2019, Masenyama et al. 2022, Paula et al. 2023). Several new empirical measures at the crop-field scale have emerged: tree stratum mappings and various vegetation status indexes were used as property indicators for ES of plant production and climate regulation. Starting dates of plant greening, wilting and drying served for their part as property indicators for the ES of water regulation (as above-ground carbon stock) (West et al. 2019, Weiss et al. 2020, Masenyama et al. 2022, Sharma et al. 2022, Paula et al. 2023, Pouladi et al. 2023, van Wesemael et al. 2023).

Finally, for some ES lacking indicators in our collection, well-established biophysical indicators from adjacent disciplines may exist, even if these studies do not explicitly frame their work within the ES context. For instance, pollutant emissions and air quality variables used in research on agricultural impacts (Borghi et al. 2023) could serve as property or dis-service indicators for air quality regulation. However, many of these indicators are likely already known to ES researchers, but are deemed "too resource-intensive" for use in ES assessments, as extensive measures would be required to ensure representativity.

Considering these three exceptions, we advise future users to:

- Explore new remote sensing applications, especially for plant production, water regulation and climate-related ES. More globally, explore emergent technologies that empirically assess ES;
- Engage with researchers studying agroecosystems via adjacent disciplines when indicators are lacking in our collection, as it is an opportunity to uncover innovative perspectives and methodologies for ES assessments.

In summary, while our methodology for constructing the indicator collection has its limitations, it offers a robust starting point for field-based ES assessments. By

acknowledging the potential biases and gaps in our approach, we encourage researchers to critically evaluate and complement our collection when necessary.

Conclusions

This study provides a comprehensive collection of field-based indicators for assessing ecosystem services (ES) in crop fields, derived through a rigorous filtering process applied to the global indicator list compiled by Boerema et al. (2016). By retaining only indicators linked to empirical, *in situ* data collection at the crop field scale – and focusing on ecosystem properties, functions, benefits and dis-services – we sought to bridge the gap between broad ES frameworks and the site-specific knowledge needed to implement ecologically intensive cropping systems.

Our final collection of 128 indicators, drawn from 66 peer-reviewed articles, supports assessments of both provisioning and regulating ES. However, it also reveals marked disparities in indicator availability across ES, cascade levels and data collection methods and gaps in current ES assessments. Regulating ES are well represented at the property and function levels, while provisioning ES are mostly associated with benefit and dis-service indicators. This imbalance highlights the ongoing challenge of integrating both ecological and socio-economic dimensions within comprehensive field-based assessments. The presence of property and function levels indicators for most input ES shows, however, that integration of levels within the ecological side of the ES cascade is theoretically feasible, although rarely applied in the studies we reviewed.

Moreover, some output ES without direct market value were absent from our collection. These gaps can reflect methodological constraints, practical challenges or limitations in the original review's scope. For water provision, the field scale appeared to be too small compared to the spatial scale at which water flows take place, which is rather the water basin in agricultural landscapes. For air quality regulation, crop fields are not considered as a hotspot for ES delivery, in contrast to ecosystems including perennial vegetation like forests or urban parks. Besides, carrying out empirical measures representative of a whole year or rotation of pollutants emissions and filtration is highly resource-intensive so modelling was often preferred to empirical assessments. Finally, the initial search terms used to obtain references for the ES of life cycle maintenance were probably too narrow to represent the real use of this ES in field-based assessments.

The findings of this research should encourage future users to not only rely on ES literature, but also to explore well-established indicators from adjacent biophysical disciplines. Such interdisciplinary exploration will likely yield additional insights into how cropping systems influence ES, ultimately enriching the framework for assessing and improving sustainable agricultural practices. Furthermore, it is important to remain vigilant for the emergence of new indicators in the ES literature, particularly in areas of growing research interest over the past decade, such as climate regulation or soil health. Advances in remote sensing technology, alongside increasing attention to ES like carbon sequestration and water regulation, may have led to the development of new indicators.

Although our collection is comprehensive within the constraints of its methodological scope, it remains open to future refinement as new indicators and methodologies emerge. By providing a flexible, yet robust set of indicators, we hope this work will serve as a valuable resource for researchers and practitioners aiming to enhance the ecological sustainability of cropping systems.

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Author contributions

L. Leveau : conceptualisation, data curation, formal analysis, investigation, methodology, project administration, resources, visualisation, writing - original draft, writing - review and editing ; N. Biot : writing - review and editing ; G. Lobet : data curation, software, visualisation ; P. Bertin : conceptualisation, funding acquisition, methodology, supervision, validation, writing - review and editing.

Conflicts of interest

The authors have declared that no competing interests exist.

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Supplementary material

Suppl. material 1: Collection of 128 ES indicators usable for in situ, biophysical quantification of ES in crop fields_ [doi](#)

Authors: Leveau Lola

Data type: Indicators

Brief description: Full version of Table 2 of the article. It details for each indicator the ES section, ES category in the framework "input and output ES", ES name in the Boerema classification, ES group, class and code in the CICES V.5.1, indicator level in the cascade model, simplified indicator name, DOI of reference paper(s) and main authors of reference paper(s). For each combination of ES indicator and reference paper, we also included the method of data collection, the unit of the indicator and a brief description of the protocol.

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