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## ▶ To cite this version:

Jacques-Eric J.-E. Bergez, Audrey Bethinger, Christian C. Bockstaller, C Cederberg, Eric Ceschia, et al.. Integrating agri-environmental indicators, ecosystem services assessment, life cycle assessment and yield gap analysis to assess the environmental sustainability of agriculture. Ecological Indicators, 2022, 141, 12p. ⟨10.1016/j.ecolind.2022.109107⟩. ⟨hal-03711131⟩

**HAL Id: hal-03711131**

**https://hal.inrae.fr/hal-03711131v1**

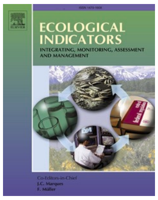
Submitted on 1 Jul 2022

Ecological Indicators 141 (2022) 109107

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind



# Integrating agri-environmental indicators, ecosystem services assessment, life cycle assessment and yield gap analysis to assess the environmental sustainability of agriculture

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## ARTICLE INFO

*Keywords:*
Multi-criteria assessment
Environmental issues
Environmental policies
Conceptual framework

## ABSTRACT

Agriculture's primary function is the production of food, feed, fibre and fuel for the fast-growing world population. However, it also affects human health and ecosystem integrity. Policymakers make policies in order to avoid harmful impacts. How to assess such policies is a challenge. In this paper, we propose a conceptual framework to help evaluate the impacts of agricultural policies on the environment. Our framework represents the global system as four subsystems and their interactions. These four components are the cells of a 2 by 2 matrix [Agriculture, Rest of the word]; [Socio-eco system, Ecological system]. We then developed a set of indicators for environmental issues and positioned these issues in the framework. To assess these issues, we used four well-known existing approaches: Life Cycle Assessment, Ecosystem Services Analysis, Yield Gap Analysis and Agro-Environmental Indicators. Using these four approaches together provided a more holistic view of the impacts of a given policy on the system. We then applied our framework on existing cover crop policies using an extensive literature survey and analysing the different environmental issues mobilised by the four assessment approaches. This demonstration case shows that our framework may be of help for a full systemic assessment. Despite their differences (aims, scales, standardization, data requirements, etc.), it is possible and profitable to use the four approaches together. This is a significant step forward, though more work is needed to produce a genuinely operational tool.

## 1. Introduction

Agriculture's primary function is the production of food, feed, fibre and fuel for the fast-growing world population (Huang et al., 2015). Although it delivers several additional services (e.g. carbon sequestration and landscape amenities), it is also an important driver of environmental impacts such as emissions of greenhouse gases (GHGs) due to $CH_4$ and $N_2O$ emissions, leading to climate change (between 11% and 23% of GHGs are from agriculture depending on how enteric emission and soil carbon sequestration are counted, IPCC, 2019). There is also biodiversity loss due to an increased use of pesticides (Dudley et al., 2017) and loss of habitat due to deforestation in the tropics and

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https://doi.org/10.1016/j.ecolind.2022.109107
Received 3 March 2022; Received in revised form 2 June 2022; Accepted 24 June 2022

intensification in Western world agriculture (IPBES, 2019). Furthermore, there is soil erosion due to poor soil management (García-Ruiz et al., 2015) and water depletion and shortage due to irrigation systems (Boretti and Rosa, 2019). Agriculture also affects human health as well as ecosystem integrity (IPPC, 2019; IPBES, 2019). In recent decades, many attempts have been made to reduce agriculture's environmental impacts by testing and implementing innovative and sustainable farming practices (Scherer et al., 2018), e.g. no-till practices, precision agriculture, pasture-based feeding, specific animal housing, through to the development of new agriculture models such as organic farming and conservation agriculture (Therond et al., 2017) and by applying policies to support environmentally friendly management (Pe'er et al., 2020).

Since the late 90 s, growing concern about environmental issues in agriculture has led to an 'indicator explosion', with a multiplication of initiatives and indicator developments, used at different levels, from field to national or even international scales (Soulé et al., 2021). These initiatives belong to four main approaches. First is the Agro-Environmental Indicators (AEI) approach, which indicates states and trends in the environmental impacts of agriculture (e.g. water pollution) and supports analysis to explain the effects of different policies on the environment (de Olde et al., 2016). The second is the Life Cycle Assessment (LCA) methodology, which has increasingly been used in research and industry to assess the environmental impacts of agri-food systems (van der Werf et al., 2020). LCA focuses on product chains (from upstream to downstream) and assesses impacts considering both resource use, pollutant emissions and land use. More recently, Ecosystem Services Assessment (ESA) has become a growing interdisciplinary research field that studies links between ecosystem structures, functions, ecosystem services and the associated benefits for humans (Porter et al., 2009; Häyhä and Franzese, 2014; Grunewald and Bastian, 2015). The fourth approach, Yield Gap Analysis (YGA), has been proposed to assess food production capacity per hectare of land (van Ittersum et al., 2013) and to guide the sustainable intensification of agriculture.

These four approaches (AEI, LCA, ESA, and YGA), foremost used independently, offer different views of agriculture's environmental sustainability (Soulé et al., 2021; Tibi and Therond, 2017) and represent a gradient of normative calculations to obtain assessment indicators. We hypothesize that these views are complementary to a certain extent, so that a unified framework combining these four approaches would provide a more holistic assessment of the environmental sustainability of agricultural systems. Such a unified framework would be useful to national governments or the European Union to improve their tracking of progress towards sustainable agricultural systems and policies, however such a framework is still lacking (ibid). To make progress in this area, TempAg, The International Sustainable Temperate Agriculture Network (www.tempag.net) has initiated an international consortium (the authors) to investigate the potential and initial development of such a unified framework.

This paper presents an analysis of challenges and possibilities when integrating the four assessment approaches into a unified framework to evaluate environmental issues relevant for European agricultural policies. We used a participatory approach by including experts from the four assessment approaches to design a first conceptual model of an integrated indicator framework that we tested on a demonstration case of implementing cover crops, which are increasingly used in the EU CAP policy. Based on this, we discuss the pros and cons of this integrated framework, how to go from a conceptual model as sketched here to a more operational framework and provide lessons for the individual approaches.

## 2. Method / strategies – approach

Our research strategy proceeded in five steps:

1. Creation of an international expert panel;
2. Short description of four assessment approaches;
3. Participatory approach to create the integrated framework;
4. Choice and structuring of the comprehensive indicator set;
5. Presentation of the demonstration case used to exemplify our unified framework.

### 2.1. *Creating an international expert panel*

The first step was to create an international expert panel. INRAE (as member of the TempAg consortium) created a four-person core group consisting of INRAE French experts of each of the four approaches. After an analysis of the different scientific productions for each of the four assessment approaches, each of these French experts invited one or two colleagues experts from other countries involved in the TempAg consortium in order to work on the unified framework (Table 1).

### 2.2. *Insights of the four assessment approaches*

Below is a short overview of the four approaches, including current drawbacks. To compare the approaches, we identified eight criteria: 1) general aim, 2) systems of application, 3) spatial scale, 4) system studied, 5) type of indicator, 6) indicators' reference (expressed per), 7) degree of standardisation and 8) data requirement (see further Table 2).

### 2.3. *Agri-environmental Indicators (AEI)*

AEI is a diversified group of indicators and associated calculation methods more or less structured according to a conceptual framework (Alkan Olsson et al., 2009). Work first started on AEI in the 1990s with the emerging awareness of the environmental impacts of intensive agriculture and the need to support the design of solutions using assessment tools (Soulé et al., 2021). AEI have a pragmatic approach due to the urgent need to develop operational assessment methods for target users to orient policy making, to help nations report on environmental issues or to support the design of innovative systems (prototyping). In this perspective, OECD countries have developed AEI to monitor impacts at a national scale (Latruffe et al., 2016). AEI cover a broad range of environmental themes in relation to farmers' management approaches such as pesticide use and nutrient balances or addressing environmental impacts such as soil erosion, air emissions of different particles, GHG emissions, water quality and resources, energy use and biofuel production, and farm bird diversity.

Based on their positioning on the causal chain and structure (see DPSIR in the section *Participatory approach to create an integrated framework*), AEI fall into three generic classes (Bockstaller et al., 2015):

i. *Causal indicators* based on a single variable (e.g. rate of nitrogen fertilisation in kg/ha) or a simple combination of variables (e.g. farm gate nitrogen balance).
ii. *Predictive effect indicators* based on outputs from operational models developed specifically for the assessment (e.g. the

**Table 1**
International panel consisting of experts of the four approaches: agri-environmental indicators (AEI), life cycle assessment (LCA), ecosystem services assessment (ESA) and yield gap analysis (YGA).

| Approach | French core expert group | Invited experts |
|---|---|---|
| AEI | Christian Bockstaller (INRAE) | Christian Schader (FiBL, Switzerland) |
| LCA | Hayo van der Werf (INRAE) | Christel Cederberg (U. Chalmers, Sweden) |
| ESA | Olivier Therond (INRAE) | Felix Müller (CAU Kiel, Germany) and Sabine Lange (CAU Kiel, Germany) |
| YGA | Nicolas Guilpart (INRAE/ AgroParisTech) | Pytrik Reidsma (WUR, Netherlands) |

**Table 2**

Key characteristics of the four approaches: agri-environmental indicators (AEI), life cycle assessment (LCA), ecosystem services assessment (ESA) and yield gap analysis (YGA).

| | AEI | LCA | ESA | YGA |
|---|---|---|---|---|
| Aim | Assessment of environmental Drivers, Pressures, States, Impacts | Assessment of products and services environmental impacts and resource usage | Assessment of ecosystem services delivered | Assessment of yield gaps |
| Systems of application | Agriculture | Any economic systems | Terrestrial and aquatic ecosystems | Agriculture |
| Spatial scale | Field, farm, regional, national | Field, farm, regional, national | Field, landscape, regional, national | Field, farm, regional, national |
| System studied | Agricultural production system, sometimes upstream processes | Agricultural and non-agricultural production systems, up- and downstream processes | Agricultural and non-agricultural land | Agricultural land |
| Types of indicators | Qualitative and quantitative | Quantitative | Qualitative and quantitative | Quantitative |
| Indicators´ reference | Surface unit | Product unit (or surface unit) | Surface unit | Surface unit |
| Degree of standardisation | Low | High | Intermediate | Intermediate to high |
| Data requirement | Low to intermediate | High to intermediate | Intermediate | Intermediate |

nitrogen indicator of the INDIGO method, Avadí et al., 2022) or complex indicators without considering the number and availability of input data (e.g. output of the nitrate leaching model in the SEAMLESS project (Alkan Olsson et al., 2009).

iii. *Measured effect indicators* (e.g. soil mineral nitrogen before winter, earthworm abundance).

While *causal indicators* are positioned at the beginning of a causal chain, *predictive effect indicators* can address emissions, states of the systems or impacts (Payraudeau and van der Werf, 2005; Bockstaller et al., 2008). There is an increasing gradient in terms of application difficulty from *causal* to *measured effect indicators* (*causal indicators* are easiest to calculate) and an inverse gradient in predictive quality (*measured effect indicators* may deliver the most reliable information). Therefore *predictive effect indicators* may appear as a compromise regarding feasibility and predictive quality, while allowing for the tracing of cause-effect relations. Most AEI assess on-site effects at the field, farm and national levels. However, some AEI include off-site effects associated with the production of inputs (e.g. fertilizers) for calculating energy use or GHG emissions (Bockstaller et al., 2015).

## 2.4. *Life Cycle Assessment (LCA)*

LCA has its origin in the early 1970s with the publication of the *Limits to growth* study (Meadows et al., 1972) and the 1973 energy crisis. This generated interest in product energy balances that considered whole product life cycles from the extraction of raw materials via the use phase through to the end-of-life phase. The Coca-Cola Company performed the first LCAs when it investigated the consequences of switching from glass bottles to plastic bottles. In the 1990s, the application of LCA to agricultural systems began.

LCA is a standardized conceptual and methodological approach (ISO 14040, 2006; ISO 14044, 2006) for the multi-criteria environmental assessment of products and services. Its basic principle is to follow a product through its life cycle, defining a boundary between its ‘product system’ (the ‘technosphere’) and the surrounding environment. Energy and material flows crossing this boundary relate to the system’s inputs (e.g. resources) and outputs (e.g. emissions to water and air). Resources consumption and pollutant emissions are then aggregated into impact indicators and this allows for the identification of burden shifting from one impact or life cycle phase to another. LCA defines the function of the studied system using a ‘functional unit’, which should be a precise measure of what the system delivers. Impacts are quantified using a set of indicators often reported using a functional unit of product (e.g. kg of milk or wheat), and thus quantify eco-efficiency. Expressing the impacts of agricultural systems not only per unit of product, but also per unit of land occupied offers a complementary view on the land management function of these systems.

From 1992 to 2018, the number of peer-reviewed English-language articles using LCA to assess agri-food systems increased from 1 to 1,040 per year (van der Werf et al., 2020). LCA has been used to compare agricultural production systems, to assess agricultural input efficiency and to guide food choice (Clark and Tilman, 2017; Poore and Nemecek, 2018). Today, LCA is the core method in the EÚs development of a harmonized methodology for calculating the environmental footprints of products, including several food groups (Zampori and Pant, 2019). For policy purposes, LCA methodology has mostly been used for quantifying greenhouse gas emissions (GHGs) from agriculture, e.g. in a large study by Weiss and Leip (2012) presenting product-based net GHG emissions of the main animal products at a national level for the whole EU. Current LCA methodology and studies tend to favour high-input intensive agricultural systems and misrepresent less intensive agroecological systems such as organic agriculture. This is due partly to LCA’s product-based approach, which focuses on the production of biomass, without considering the other ecosystem services provided by agricultural systems. This is also partly because LCA rarely considers key environmental issues that agroecology aims to improve (soil health, biodiversity status, pesticide use impacts), due to a lack of operational and satisfactory indicators for these issues. The current practice of limiting the consideration of indirect effects in LCA studies to indirect land use change, by using economic models that ignore drivers of societal change and the effects of policy instruments, further favours intensive agricultural systems (van der Werf et al., 2020).

## 2.5. *Ecosystem services assessment (ESA)*

Ecosystem services (ES) are contributions that ecosystems provide to human wellbeing (Costanza et al., 1997; Daily et al., 1997). The concept strongly developed with the Millennium Ecosystems Assessment (Millennium Ecosystem Assessment, 2005) to support the conservation of biodiversity and ecosystems. According to Fisher et al. (2009), ecosystem services are the “aspects [structures or processes] of ecosystems utilized (actively or passively) to produce human well-being”. The capacity of ecosystems to provide ecosystem services depends on the properties and conditions of the respective ecosystem (Müller and Kroll, 2011; Müller and Burkhard 2012; Syrbe and Grunewald, 2017) also referred to by the natural capital concept (Dardonville et al., 2022).

ES are classically divided into three categories; provisioning, regulating and cultural ES (Burkhard et al., 2014; Sohel et al., 2015; Stoll et al., 2015; Haines-Young and Potschin, 2017; Schneiders and Müller, 2017). Provisioning ES refer to the material goods ecosystems provide for humans (de Groot et al., 2010; Haines-Young and Potschin-Young, 2010; Haines-Young and Potschin, 2017). Regulating ES correspond to the benefits people obtain from the ecosystem’s regulation of natural processes, e.g. global climate, erosion or flooding regulation (Kandziora et al., 2013; Haines-Young and Potschin, 2017). Cultural ES refer to non-material, intangible benefits humans obtain from ecosystems, such as recreation or inspirational experiences (de Groot et al., 2010; Haines-Young and Potschin, 2017).

When dealing with agriculture, both services to agriculture (farmers) and to society should be considered (Duru et al., 2015; Tibi and Therond, 2017; Therond et al., 2017). ES to agriculture correspond to "processes that support the production of consumable goods (e.g. food and timber)" (Nelson and Daily, 2010). Bommarco et al. (2013), Garbach et al. (2014) and Duru et al. (2015) clarified that regulation services that determine soil fertility (soil structure and water and nutrient cycling) and biological regulations (pest control and pollination) are the key ES provided by ecosystems to agriculture. Duru et al. (2015) clearly established the link between the yield gap (van Ittersum and Rabbinge, 1997) and the theory of ES provided to agriculture. They highlighted that ES to agriculture and exogenous inputs (e.g. fertilizers), are two types of production factors that can substitute one for the other to reduce limiting and growth-reducing factors and, in turn, the yield gap. Developing ecosystems that provide a high level of these ES can enable farmers to decrease significantly their use of exogenous inputs and their associated negative impacts. The concentration towards one service in an area, such as plant production, often leads to a reduction of many other potential ES, e.g. concerning regulation or cultural aspects. Therefore, provisioning, regulating and cultural services should be evaluated as a comprehensive bundle.

### 2.6. *Yield gap analysis (YGA)*

The difference between actual and potential crop yields, i.e. the yield gap, has been of interest to agronomists and farmers for a long time. However, rigorous formalization of the conceptual framework underlying yield gap analysis started in the 1990s with the work of Evans (1993) and van Ittersum and Rabbinge (1997). This early work took place in the context of slowing rates of yield gain in major crops such as wheat in Europe (Grassini et al., 2013), and growing interest in increasing input-use efficiency (e.g. water and nitrogen) because of concerns about their negative effects on the environment. A renewed interest in yield gap analysis appeared after the global food crisis of 2007–2008 (Lobell et al., 2009; van Ittersum et al., 2013). Indeed, to meet the increasing food demand from a burgeoning population it is argued that yield gap reduction is needed to avoid cropland expansion with attendant biodiversity loss and GHG emissions (Foley et al., 2011; van Ittersum et al., 2016; van Loon et al., 2019). Standard protocols for estimating yield gaps from local to global scales have been proposed (Grassini et al., 2015; van Bussel et al., 2015) and several projects aiming to quantify yield gaps at the global scale have been developed, such as the Global Yield Gap and Water Productivity Atlas (www.yieldgap.org) and EarthStat (http://www.earthstat.org/).

Yield gap analysis seeks to evaluate the scope to increase crop production by estimating potential and water-limited yield levels as benchmarks under, respectively, irrigated and rainfed conditions. The differences between these theoretical yield levels and farmers' actual yields define the yield gaps (van Ittersum and Rabbinge, 1997). Recent work has shown that yield gaps can be broken down into efficiency, resource and technology yield gaps (Silva et al., 2017a,b; van Dijk et al., 2017). This makes it possible to identify management options that can maintain or increase crop yields while reducing environmental impacts (Silva et al., 2017b; Chukalla et al., 2020; Van Dijk et al., 2020). Yield gap analysis is, therefore, used to guide sustainable intensification at local (Hochman et al., 2020) to global scales (Mueller et al., 2012; van Oort et al., 2017).

While yield gap analysis has proved to be useful for addressing a number of food security related questions, some drawbacks of the approach have also been highlighted (Cunningham et al., 2013). First, yield gap analysis focuses on yield as a central evaluation metric at the expense of the environmental and social performances of agricultural systems and the ecosystem services they provide. Second, closing the yield gap may fail to prevent further cropland expansion because of the so-called Jevon's paradox, or "rebound effect" (Hamant, 2020). This paradox occurs "if an increase in the productivity of one factor (here cropland) leads to its increased utilization, in a form of spillover where adoption of intensifying practices increases agricultural profitability and stimulates land-use expansion" (García et al., 2020). Third, management options for closing the yield gap may increase the negative impacts of agricultural systems on the environment. This may happen when increased input use, such as nitrogen and pesticides at the field scale, result in larger emissions of these inputs or their metabolites to adjacent ecosystems. As cited above, recent work has partly addressed these points, e.g. by distinguishing efficiency and resource yield gaps (Silva et al., 2017a), and by assessing impacts of yield gap closure on GHG emissions (van Loon et al., 2019), but yield remains the central focus. Finally, the possibility of reducing both yield gap and input use through the development of ecosystem services to agriculture is not really considered.

In order to compare the four approaches, we developed a table of eight criteria explaining: 1) general aim, 2) systems of application, 3) spatial scale, 4) system studied, 5) type of indicator, 6) indicators' reference (expressed per), 7) degree of standardisation and 8) data requirement.

### 2.7. *Participatory approach to create an integrated framework*

In order to share the general idea of our study and start developing a conceptual integrated framework, we organised a two-day workshop to draft a first sketch of the desired framework. This helped to conceptualise the system at hand, i.e. the agricultural system as part of a more general socio-environmental and socio-economic system (see Fig. 1A).

### 2.8. *Choice and structuring of the comprehensive indicator set*

The fourth step was to group environmental indicators stemming from the four approaches in a single set to evaluate the impacts of different agricultural policies on the different elements of the system. In order to represent the results in a comprehensive manner, we structured the indicator dataset following the Driver-Pressure-State-Impact-Response (DPSIR) framework. The DPSIR framework is a conceptual tool for analysing all the cause-effect relationships of a system between human activity and the environment. It can be used to select and organise indicators (Alkan Olsson et al., 2009). According to Gabrielsen and Bosch (2003), a *Driver* is a change in lifestyle, overall level of consumption and production pattern, or the motivation for specific land use strategies. These drivers exert some *Pressure* on the environment, via the emission of substances, physical and biological agents or even technical tools, and the use of resources by human activities. These pressures alter the *State* of the environment, which refers to the quantifiable and qualitative physical, biological and chemical conditions in a defined area. These chain reaction flows *Impact* the environment and the provision of ecosystem benefits and the socioeconomic system. Finally, this leads to a societal and political *Response*, which refers to the actions carried out by society and governments in order to minimise the negative effects on the environment, feeding back to the driving forces or pressures due to anthropogenic developments. After completing the indicator database, we reported the different environmental issues on the conceptual integrated framework.

We identified environmental indicators from the four approaches to create a comprehensive set of indicators for environmental issues. Thirty-one AEI indicators were identified according to expert knowledge, the ReCiPe2016 method (Huijbregts et al., 2017) supplied 16 LCA indicators, Müller et al. (2020) supplied 38 ESA indicators, 19 YGA indicators were identified based on expert knowledge (also considering the variables that explain yield gaps). This yielded a list of 72 indicators, classified as Driver (5), Pressure (12), State (15), Impact (35) and Response (5). The set was then condensed by merging identical or similar indicators, and by excluding response indicators, yielding a set of 41 indicators of environmental issues, classified as Driver (3), Pressure (8), State (8), Impact (12 ecosystem services, 10 environmental impacts), see Table 3. After completing the indicator set, we distributed the 41 indicators into the conceptual integrated framework (see Fig. 1B). After completing the indicator set, we distributed the 41 indicators into the conceptual integrated framework (see Fig. 1B).

### *2.9. Demonstration case*

The fifth and last step was to test our framework on an example of a policy action in agriculture to analyse its potential utility. For this, we used a demonstration case of implementing cover crops during the autumn and winter, which is one of the main European public policies and measures implemented for promoting more sustainable agriculture.

Rivière et al. (under review, see appendix 1 for the query equation) performed an extensive literature review (51 papers) on the effects of cover crops on environmental sustainability indicators. These papers were randomly assigned to two experts in the group of experts who checked for the presence of the 41 environmental issues and the assessment approach used. When inconsistencies between experts appeared, a third expert was involved for discussions and to reach a general agreement. This gave an overview of how the environmental issues were represented in the reviewed papers (Table 4).

## 3. Results

### *3.1. Comparison of the four approaches*

The development of the integrated framework started by a comprehensive comparison of the features, overlaps and missing parts of each approach (Table 2). The comparative representation is based on the references given in the M&M section and on the judgement of participating experts.

*Aim:* AEI aim to assess environmental drivers, pressures, states or impacts of agricultural systems, focusing most often on production systems (cropping and/or farming systems), whereas LCA seeks to assess potential environmental impacts and resource use during the whole life cycle of an agricultural product. ESA aims to assess ecosystem services, while YGA assesses the gap between actual and potential crop yields. The four approaches are therefore clearly complementary in their aims, even if AEI and LCA can present some overlap in terms of environmental impacts of the production system.

*Systems of application*: By definition, AEI and YGA are dedicated to the assessment of agricultural production systems, whereas LCA are developed and used to assess production systems across all economic sectors. ESA can be used to assess services provided by any terrestrial and aquatic ecosystems.

*Spatial scale:* AEI, LCA and YGA are applied at a wide range of spatial scales, from the field to the national scale, whereas ESA is generally applied at an intermediate landscape scale but increasingly studies are carried out at the field and regional to national scale (e.g. National Ecosystem Assessment).

*System studied:* AEI and YGA focus on agricultural production systems, with AEI considering some upstream processes (i.e., the production of inputs) for some environmental issues (e.g. non-renewable energy use, climate change). In their review of 262 environmental sustainability assessment methods based mainly on AEI, Soulé et al. (2021) found that about 25% of the methods included at least one indicator that assesses upstream processes. LCA can be distinguished from the other approaches as it often has a product supply chain perspective including all phases (e.g. agriculture, processing industry, transport and packaging) in a food product's life cycle. However, concerning agriculture, it is often used with a narrower system boundary corresponding to the agricultural production system and the upstream processes (e.g. inputs and other materials required for production systems). ESA can consider all land and waterbodies present in the studied landscape, irrespective of their productive (i.e., agricultural) function. Concerning agriculture, many studies focus on agricultural ecosystems. Focusing on the ecosystem, ESA does not consider up- or downstream processes.

*Indicator type and reference unit:* AEI may be qualitative (e.g. the DEXiPM approaches, Angevin et al., 2017), semi-quantitative expressed as a score or quantitative (Bockstaller et al., 2008). Either qualitative or quantitative indicators support ESA where LCA and YGA only use quantitative indicators. AEI, ESA and YGA express indicators per surface unit, whereas LCA expresses impacts by default per unit product. Some LCA studies of agricultural products also express impacts per unit of land occupied, reflecting the land management function of agriculture.

*Degree of standardisation:* AEI designate a diverse grouping of indicators and assessment methods, which is not formally defined and has a low degree of standardisation (Soulé et al., 2021). LCA is highly standardised; it is formally defined by international standards, guidelines and handbooks, developed by international bodies (ISO14040, ISO14044, EC-JRC-IES 2010). ESA also presents a low level of standardisation, with a wide range of assessment methods used, though CICES is attempting to become a conceptual and methodological standard (Haines-Young and Potschin, 2018). YGA has standardised protocols to assess yield gaps (Grassini et al., 2015; van Bussel et al., 2015; www.yieldgap.org), but different approaches still exist (e.g. Mueller et al., 2012; https://www.earthstat.org). Frameworks to explain yield gaps have been proposed (Silva et al., 2017a; van Dijk et al., 2020), but the methods applied differ depending on data availability (Beza et al., 2017).

*Input data*: Input data required to implement the approaches vary. The data requirement is variable for AEI, depending on the specific characteristics of the indicators or method implemented. For causal indicators the data requirement is low, while for predictive effect indicators it may be intermediate. When an indicator is measured (e.g. soil nitrogen in soil), the data collection cost is also important. For ESA, the data requirement can be relatively low when qualitative methods based on expert knowledge are used. However, when quantitative methods using simulation models are used, the data requirement can be (very) high. YGA has an intermediate level of data requirement, as different options for yield gap assessment are suggested depending on the data available. The method for yield gap analysis can be adapted to data availability, but data on various biophysical, socio-economic and management variables from a large number of fields or farms are needed when explaining yield gaps. For LCA, the data requirement is very high, as a wide range of environmental impacts is assessed for a wide range of processes along the product's life cycle. This requires data on farmers' practices, soil and weather as well as data on input types and quantities used. However, comprehensive databases containing data on inputs are available, and can be used to assess long, complex food supply chains, e. g. for average cropping systems at the national scale.

This comparison show that the four approaches are complementary in terms of their aims and conceptual scopes. Some of the data they require are largely similar and could support the development of an integrated framework, as explained below. Using the DPSIR framework to represent the different environmental issues, the experts positioned their approaches as suitable to evaluate each given issue (Table 3).

### *3.2. Agriculture in the global system*

Considering the characteristics of the four assessment approaches investigated, the TempAg consortium developed an integrated assessment framework by iteratively developing a graphical representation of the system and subsystems at hand and their key properties to consider when dealing with agriculture's environmental sustainability (Fig. 1A). The global system can be represented as four subsystems and their interactions.

*Agriculture* is a part of the *Socio-Economic system* (blue boxes). It is presented separately here since this representation focuses on agriculture's environmental sustainability. *Agriculture* is also part of the *Ecological system* (yellow boxes), as its land use in a landscape is the foundation for production. *Agroecosystems* correspond to a farm or a farming region, including both productive and semi-natural areas, such as hedgerows, buffer strips, field margins, woods, streams and ponds. Humans create *Socio-economic systems* and have responsibility for their

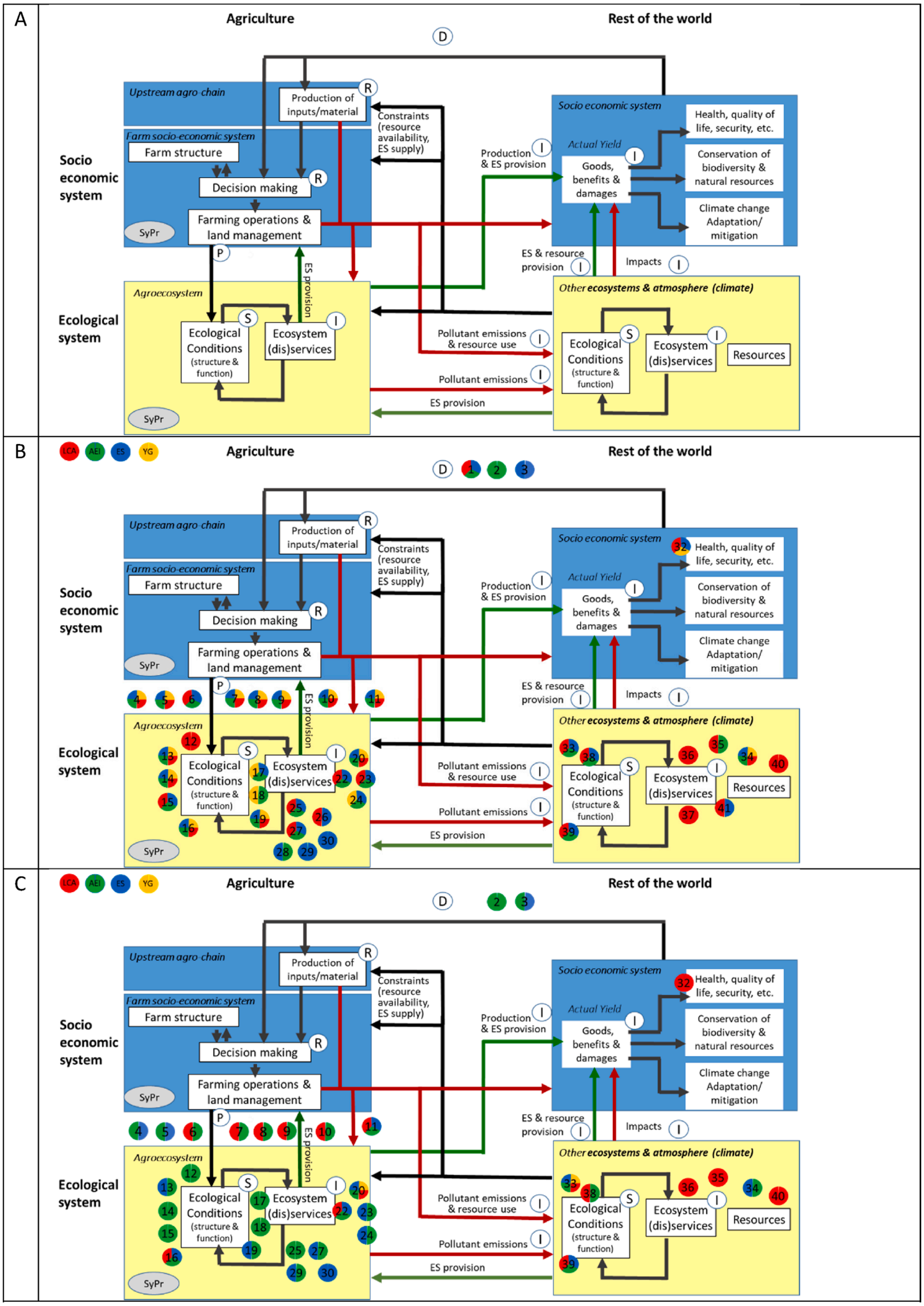

**Fig. 1.** A) Global systems view showing relations between the Socioeconomic system (blue) and the Ecological system (yellow). Agriculture (left side) is distinguished from the Rest of the world (right side). Black arrows indicate functional relationships, green arrows indicate provision of ecosystem services, red arrows indicate environmental impacts. Letters in yellow circles indicate position in the DPISR framework: D: driver, P: pressure, S: state, I: impact, R: response. SyPr indicates assessment of system properties such as integrity, resilience. B) Positioning of environmental issues from Table 2. C) Environmental issues found in the literature review. In B) and C) each colour indicates a specific assessment approach: red for LCA, green for AEI, yellow for YG and blue for ESA. Multiple coloured circles indicate that the environmental issue is assessed by different approaches. Numbers in circles refers to the environmental issue number from Table 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

environmental sustainability. Consequently, human activities should not exceed the carrying capacity of nature, i.e. *ecological systems*. For simplicity, the *Social-economic* and *Ecological systems* appear here side by side, while in reality the former is embedded in the latter. In addition, other land- or water-based production systems such as forestry and aquaculture are not shown.

The socio-economic part of *Agriculture* is composed of an *Upstream agro-chain*, which produces manufactured inputs, such as fertilizers, pesticides and machines for the *Farm socio-economic system*. It is also composed of a farm system. Farm *Decision making* and *Input production* respond to demand from other *Socio-economic systems*. *Production of inputs* and *Farming operations & land management* cause pollutant emissions and resource use, and thus impacts on ecosystems and human health. *Farming operations & land management* also affect the ecological conditions of the *Agroecosystem* which supplies ecosystem services. In the long run, the provision of ecosystem services will, in turn, affect ecological conditions. Ecosystem services such as pollination and pest regulation benefit the *Agroecosystem* itself, while ecosystems services such as the provision of crop products and carbon sequestration benefit *the Socio-economic system*.

*Other socio-economic systems* correspond to all socio-economic systems other than the agricultural ones. These benefit from ecosystem services (including agricultural products) supplied by the *Agroecosystem* and the *Other ecosystems and atmosphere*. The latter are also affected by environmental impacts of the *Farm socio-economic system* and the *Agroecosystem*.

The boundaries separating *Agroecosystems* and *Other ecosystems and atmosphere* are not defined in local details, for instance, a forest bordering agricultural land may be considered part of the *Agroecosystem* or *Other ecosystems*, depending on its size. *Other ecosystems* are impacted by pollutant emissions and resource use from the *Upstream agro-chain*, the *Farm socio-economic system* and the *Agroecosystem*. In turn, all three are constrained by resources (e.g. water, minerals, genes) and ecosystem services (e.g. climate regulation) supplied by the *Other ecosystems*. Pollutant emissions affect the ecological conditions of *Other ecosystems*, which supply ecosystem services that benefit both the *Socio-economic system (green arrow)* and the *Agroecosystem*. Resource use affects resource availability in *Other ecosystems*.

AEI, LCA and YGA focus on assessing the functioning of the *Farm socio-economic system* while AEI and LCA also consider its environmental sustainability and have developed a number of indicators to this end. However, the provision of agricultural products relies not only on manufactured inputs but must be seen in the larger *Agroecosystem* context, including other ecosystem services. The more the agroecosystem is biodiversity-based, the larger the relative contribution of ecosystem service bundles (Duru et al., 2015). ESA allows the ecological functioning of the *Agroecosystem* assessment, most often at the landscape scale, which is outside the scope of AEI, LCA and YGA. Increasing the proportion of semi-natural areas favours ecosystem services and biodiversity. Furthermore, crop heterogeneity, in terms of field size and diversity of crop types, has a strong effect on biodiversity, in particular when the proportion of semi-natural area is low in an agricultural landscape (Sirami et al., 2019). ESA captures these effects well. For example, Power (2010) outlines how on-farm management practices can enhance the provision of ecosystem services such as pollination, pest control and soil fertility.

Positioning indicators from Table 3 in the figure representing the global system (Fig. 1B) shows that the Driver indicators [#1–3] in Table 3 represent the relation of *Rest of the world* and *Agriculture* within the socio-economic system. Pressure indicators [#4–11] represent pressures from the *Farm socio-economic system* on the *Agroecosystem* and *Other ecosystems and atmosphere*. State indicators [#12–19] reflect the state of the *Agroecosystem*. Ecosystem services impact indicators [#20–31] correspond to ecosystem services delivered by the *Agroecosystem*. Environmental impact indicators correspond to impacts on the *Socio-economic system* [#32, #37], the *Agroecosystem* [#33] and *Other ecosystems and atmosphere* [#34–36, #38–41]. Some parts of the system are very strongly assessed with a large panel of indicators and the use of the four approaches (*Agroecosystem*) while others are covered by fewer indicators (*Farm socio-economic system*).

The experts then represented the 41 environmental issues in the conceptual framework (Fig. 1B). Due to the aim of the integrated framework to assess the environmental impacts of European policy, the *Agroecosystem* was assessed by many indicators. As already seen in Table 3, some environmental issues are present in different assessment approaches or are specific to some of them.

### *3.3. Application of the framework to the cover crops policy*

We then tested our framework using a cover crop systematic literature review (Rivière et al., under review). Table 4 gives an overview of how the 41 chosen environmental issues were represented in the 51 reviewed papers (numbered in chronological order from 2009 to 2020). A representation of these results in our framework is given in Fig. 1C. Indicators that we classified as AEI are dominant and we interpret this as an effect of this framework's lower degree of standardization, which allows for a more arbitrary choice of indicators than in the LCA, ESA and YGA approaches. Issues placed under the category ‘Impact ecosystems service’ [#20; #31] have been indicated foremost with AEI and to some degree with ESA, and there is a clear trend where these impacts are increasingly quantified and reported in the latter half of the period. However, despite an increasing trend for reporting these issues, it is still obvious that some crucial ecosystem services for agricultural production, e.g. pollination, water infiltration, and local climate regulation, were hardly quantified and barely indicated at all in this review of cover crops.

Due to the differences in assessment approaches, using a combination of the four assessment approaches provides a better picture of the environmental impacts of this given policy. Some indicators are not assessed at all because they are part of the drivers and not of the impacts (e.g. nutrition of population [#1], Agri-environmental public policy [#2]), some are assessed by the four approaches (e.g. Harvest biomass [#20]), while others are assessed only by one (e.g. Storage capacity [#15]) or two approaches (e.g. Fertilizer input [#7]). Using multiple approaches thus allows to address a wider set of indicators, but also to compare results for specific indicators to improve understanding of the impacts.

Rivière et al. (submitted) shown that when comparing the effects of using CC on the environmental issue “Water scarcity” [#34] using an ESA approach concluded to a positive effect of CC while AEI concluded to both a variable and controversial effect. Regarding the effects on “Energy Input” [#10] using LCA resulted in a positive assessment while the AEI approach concluded to a variable effect. Considering the effects on “Albedo” [#12], the AEI approach described positive effects while the LCA approach described variable effects. As different approaches use different methods to estimate the impacts on indicators, using and comparing multiple approaches allows to embrace all dimensions of environmental sustainability.

## 4. Discussion

### *4.1. Conceptual framework, added value of hybridising approaches and demonstration case study analysis*

The sustainable development of agricultural landscapes and production systems is a target of recent agricultural and environmental policies all around the world. To identify optimal sustainable land use strategies, decision makers at all levels need comprehensive qualitative and quantitative information on the actual states and possible future conditions of agricultural landscapes and production. Sustainability is a strong interdisciplinary human-environmental concept meaning that ecological, technological, social and economic dimensions have to be

**Table 3**
Set of environmental issues used to assess the environmental impacts of agricultural policies (from Müller et al., 2020) classified according to the Driver, Pressure, State, Impact, Response (DPSIR) framework. Black squares indicate approaches that consider a given issue. AEI: agri-environmental indicators, LCA: life cycle assessment, ESA: ecosystem services assessment, YGA: yield gap analysis.

| DPSIR class | Environmental issues | # | Approaches | | | |
|---|---|---|---|---|---|---|
| | | | AEI | LCA | ESA | YGA |
| Drivers (1) | Nutrition of population | 1 | | ■ | ■ | ■ |
| | Agri-environmental public policy | 2 | ■ | | | |
| | Farmer's income and economy | 3 | | | ■ | |
| Pressures (2) | Landscape structure | 4 | ■ | ■ | ■ | ■ |
| | Land use | 5 | ■ | ■ | ■ | ■ |
| | Traffic intensity | 6 | ■ | ■ | ■ | |
| | Fertilizer input | 7 | ■ | ■ | ■ | ■ |
| | Pesticide input | 8 | ■ | ■ | ■ | ■ |
| | Water input (irrigation) | 9 | ■ | ■ | ■ | ■ |
| | Energy input | 10 | ■ | ■ | ■ | ■ |
| | GHG emissions | 11 | ■ | ■ | ■ | ■ |
| States (3) - Specific agroecological criteria | Albedo | 12 | | ■ | | |
| | Soil structure | 13 | ■ | ■ | ■ | ■ |
| | Soil organic matter content | 14 | ■ | ■ | ■ | ■ |
| | Storage capacity (soil organic carbon) | 15 | ■ | ■ | ■ | |
| | Nutrient level in soil (nitrogen, phosphate) | 16 | ■ | ■ | ■ | ■ |
| | Water use efficiency | 17 | ■ | | ■ | ■ |
| | N-use efficiency | 18 | ■ | | | ■ |
| | Nutrient retention in soil | 19 | ■ | ■ | ■ | ■ |
| Impacts (4A) - Ecosystem services | Harvested biomass/yield | 20 | ■ | ■ | ■ | ■ |
| | Efficiency, resource and technological yield gap | 21 | | | | ■ |
| | Carbon storage, sequestration | 22 | ■ | ■ | ■ | |
| | Erosion, particulate matter | 23 | ■ | ■ | ■ | |
| | Infiltration (groundwater recharge, water flow) | 24 | ■ | | ■ | ■ |
| | Drinking water | 25 | ■ | ■ | ■ | |
| | Water purification | 26 | | ■ | ■ | |
| | Nutrient regulation (e.g. N, P) | 27 | ■ | ■ | ■ | |
| | Local climate regulation (wind, precipitation, temperature, radiation) | 28 | ■ | | ■ | |
| | Pest and disease control (e.g. weed pressure) | 29 | | | ■ | |
| | Pollination | 30 | | | ■ | |
| | Aesthetic value | 31 | | ■ | ■ | |
| Impacts (4B) - Environmental impacts | Human health | 32 | | ■ | ■ | ■ |
| | Changes in soil quality | 33 | ■ | ■ | ■ | |
| | Water use (scarcity) | 34 | ■ | ■ | ■ | ■ |
| | Eutrophication | 35 | ■ | ■ | | |
| | Ecotoxicity (aquatic, terrestrial) | 36 | | ■ | | |
| | Fine particulate matter formation (aerosol) | 37 | | ■ | | |
| | Global climate change | 38 | ■ | ■ | ■ | |
| | Biodiversity loss | 39 | ■ | ■ | ■ | |
| | Energy depletion | 40 | | ■ | | |
| | Resource availability (competition for water and nutrients) | 41 | | ■ | ■ | |

**Table 4**

Analysis of the environmental issues covered by the four assessment approaches in the review study of environmental assessments of cover crops from 2000 to 2020. In columns, the 51 papers reviewed in chronological order, in rows the different environmental issues (Table 2) sorted using the DPSIR model. Colours represent the different assessment approaches used in the different papers.

🟩 AEI
🟦 ESA
🟥 LCA
🟨 AEI/YGA

| | | | 20009-2010 | | | | 2012-2014 | | | | 2015 | | | | | | 2016 | | | | 2017 | | | | | 2018 | | | | | | | | 2019 | | | | | | 2020 | | | | | | | | | | 2021 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Indicators - Selected studies | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 |
| Drivers | 1 | Nutrition of population | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 2 | Agri-environmental public policy | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | | | | | | | | | | | |
| | 3 | Farmer's income and economy | | | | | | | | 🟩 | | | | | | | 🟩 | | | | | | | | 🟩 | | | | | | | | | | 🟦 | | | | | | | | | | | | | | | | | | |
| Pressures | 4 | Landscape structure | | | | | | | | | | | | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | 🟦 | | | | | | | | |
| | 5 | Land use | | 🟦 | | | | | | | | | | | | 🟩 | | | | | | | | | | | | | | | | | | 🟩 | | | | | | | | | 🟩 | | 🟩 | | | 🟩 | 🟩 | | | | |
| | 6 | Traffic intensity | | | | | | | | | 🟥 | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | | | | | | | | | | | | |
| | 7 | Fertilizer input | | | | | 🟩 | | | | 🟥 | | 🟩 | | | | | | | | | 🟩 | | | | | 🟩 | | | | | | | | | | 🟩 | | 🟩 | | | | | 🟩 | | | 🟩 | | 🟩 | | 🟩 | | |
| | 8 | Pesticides input | | | | | | | | | 🟥 | | | 🟩 | | | 🟩 | | | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | |
| | 9 | Water input | | | | | | | | | 🟥 | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | | | | | | | | | | 🟩 | | |
| | 10 | Energy input | | | | | | | | | 🟥 | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | | | | | | | | | | | | |
| | 11 | GHG emissions | | 🟥 | | | | | | 🟦 | 🟥 | | | | | | 🟩 | 🟩 | | | | 🟩 | | | | | | 🟩 | 🟩 | | | | | | | 🟩 | 🟩 | | 🟩 | | | 🟩 | | | | 🟩 | 🟩 | | | | 🟩 | | |
| States | 12 | Albedo | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟩🟥 | | | | | 🟥 | | | | | 🟩🟥 | | | | | | | | | | | |
| | 13 | Soil structure | | | | | | | | | | 🟩 | | | | | | | 🟩 | | | | | | | | | | | 🟩 | | | | | 🟩🟦 | | | | | | | | | | | | | | | | | | 🟩 |
| | 14 | Soil organic matter content | | | | | | | | | | 🟩 | | | | | | | | | | 🟩 | | | 🟩 | | | | | 🟩 | 🟩 | | 🟩 | | | | 🟩 | | 🟩 | | | | | | | | | | | | | | 🟩 |
| | 15 | Storage capacity | | | | | | | 🟩 | | | | 🟩 | | | | | 🟩 | | 🟩 | | 🟩 | | | | | | | 🟩 | | | | 🟩 | | | | | | 🟩 | | | | | | | 🟩 | | | | | 🟩 | | |
| | 16 | Nutrients level in soil | | | | 🟩 | | | | | 🟥 | | | | | | | | | 🟩 | 🟩 | | | | 🟩 | | | | | 🟩 | | | 🟩 | | 🟩🟦 | 🟩 | | 🟩 | 🟩 | | | | | | | | | | | | | | |
| | 17 | Water use efficiency | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | |
| | 18 | N-use efficiency | | | | | | | | | | | | | | | | | | | | | | 🟩 | | | | | | | | | | | | | | | 🟩 | | | | | | | | | | 🟩 | | | | |
| | 19 | Nutrient retention in soil | | | | | 🟩 | 🟩 | | 🟦 | | | 🟩 | | | | | 🟩 | | | 🟩 | | | | | | | | 🟩🟦 | 🟩 | | | | | 🟩🟦 | | | | 🟩 | | | | | | | | 🟩 | | | | | | |
| Impacts | 20 | Harvested biomass/Yield | | | | | 🟩 | 🟩 | | 🟦 | 🟥 | | 🟩 | 🟨 | | | 🟩 | | | 🟩 | | | | | 🟩 | 🟦 | 🟩 | | | | | | | | 🟩🟦 | 🟩 | 🟩 | | 🟩 | | 🟩 | | | 🟩 | | 🟨 | 🟩 | | 🟩 | 🟩 | 🟩 | 🟩 | |
| | 21 | Efficiency, resource and technological yield | | | | | | | | | | | | | | | | | | | | | | 🟨 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 22 | Carbon sequestration | | 🟩 | | | | | 🟩 | 🟦 | 🟥 | 🟩 | 🟩 | | | | | | | 🟩 | | 🟩 | | | | | | 🟩 | 🟩 | | | | 🟩 | | | | | | 🟩 | | | 🟩 | | | | 🟩 | 🟩 | 🟩 | | | 🟩 | | |
| | 23 | Erosion | 🟩 | 🟦 | | | | | | 🟦 | | | | | | 🟩 | 🟩 | 🟩 | | | | | | | | | | | | | | | | | | | | 🟩 | | 🟩 | | | | | | | | | | | | | |
| | 24 | Infiltration/water cycle | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 25 | Water quality | | | | | | | | | | | | | | | | 🟩 | | | | | | | 🟩 | | | | | | | | 🟩 | | | | | | | | | | | | | | | | | | | | |
| | 26 | Water purification | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 27 | Nutrient regulation | | | | | 🟩 | 🟩 | | 🟦 | | | 🟩 | | | | | 🟩 | | | | | | | | | 🟦 | | | | | | 🟦 | | | | | 🟩 | | | | | | | | | | | | | | | |
| | 28 | Local climate regulation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 29 | Pest and disease control | | | | | | | | 🟦 | | | | 🟦 | | | 🟩 | | | | | | | | | | | | | | | | | | 🟦 | | | | | | 🟦 | | | | | | | | 🟩🟥 | | | | |
| | 30 | Pollination | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | 🟦 | | | | | | | | | | |
| | 31 | Aesthetic value | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 32 | Human health | | | | | | | | | | | | | 🟥 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 33 | Changes in soil quality | | | | | | | | 🟦 | | | | | 🟥 | | | | | | | | | | | | | | | 🟩 | 🟩 | | 🟦 | | 🟩🟦 | | | 🟩 | | | | | | | | | | | | | | 🟩 | 🟩 |
| | 34 | Water scarcity | | | 🟦 | | | | | | | | | | | | 🟩 | | | | | | | | | 🟩 | | | 🟩 | | | | | | | | | | | | | | | | | | | | | | | | |
| | 35 | Eutrophication | 🟩 | | | 🟩 | | | | | | | | | 🟥 | | | | | | | | 🟥 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 36 | Ecotoxicity | | | | | | | | | | | | | 🟥 | | | | | | | | 🟥 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 37 | Fine particulate matter formation | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 38 | Global climate change | | 🟥 | | | | | | | 🟥 | | | | 🟥 | | | | | | | | 🟥 | | | | | | | | | | | | | | 🟩 | | 🟩 | | | | | | | | | | | | | | |
| | 39 | Biodiversity loss | | | | | | | | | | | | 🟩 | 🟥 | | | | | | | | 🟥 | | | | | | | 🟩 | | | | 🟩 | 🟩🟦 | | | | | | | | 🟩 | | 🟩🟦 | | | | | | | | |
| | 40 | Energy depletion | | | | | | | | | | | | | 🟥 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| | 41 | Resource availability | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

considered. Our current goal is to develop a comprehensive framework for environmental assessment of agriculture which considers its environmental impacts and effects on natural resources, climate and ecosystem services, thereby addressing the conditions of farm activities regarding social, economic, and environmental issues (Pe‘er et al., 2020).

After expert analyses and brainstorming it became obvious that the anticipated integration was possible and could provide added value for each assessment approach, as demonstrated in the case study. Conceptual modelling turned out to be an appropriate tool for understanding and demonstrating issues, their interactions, distributing significance and for translating facts and attitudes between the disciplines and viewpoints involved. The resulting conceptual model makes it possible to position the agricultural domain as part of the socio-economic and ecological system. The interactions existing between these two components and the rest of the world were well depicted.

Different sets of indicators exist coming from different research communities: e.g. CICES (2018) and Müller et al. (2020). In spite of some ambiguities and its simplified linear representation (Bockstaller et al., 2008), the initial use of the DPSIR approach on the set of indicators proposed by Müller et al. (2020) turned out to be a straightforward idea to bring a functional order into the enormous number of potential indicators. Here, the four approaches (AEI, LCA, ESA and YGA) have been characterised to evaluate their complementarity. They all have distinct targets and disciplinary backgrounds in terms of the systems and properties considered. The resulting indicator framework is a first step towards a unified, holistic framework to provide information for management activities with respect to the response function (R) of the DPSIR scheme applied to agricultural items.

In spite of their origins, some indicators and thematic similarities were found. For instance, in Table 2 the environmental issues GHG emissions [#11], nutrient levels/cycling in soil [#16] and harvested biomass [#20] were considered in each approach. However, differences also existed, e.g. for ecotoxicity [#36], energy depletion [#40] and pollination [#30] which were used in a single approach only. The comparison also showed that the four approaches were complementary in terms of aims and conceptual scopes. Nevertheless, in spite of different interpretations, the data they required were largely similar, which could facilitate the implementation of our integrated approach.

The analysis of the cover crop demonstration case required a lot of working and discussion time for the experts. Nevertheless, it allows us to demonstrate that the proposed framework and the list of related environmental issues to quantify the impact was a good start to performing the systemic assessment of a policy. More than 50 relevant papers were analysed and have been assigned to the four approaches making it possible to highlight differences in the chronological use of indicators and the utility of mixing the four approaches. It also makes it possible to show that some environmental issues are assessed by all approaches while only one assesses others. This is an important output of the demonstration case. Another interesting point is the comparison between Fig. 1B and 1C. It makes it possible to stress that some approaches did not analyse cover crop impacts on the environment for some issues even though these issues might have been analysed. Take the environmental issue #17 (Water use efficiency). From our literature review, we found that only AEI explicitly tackled this issue. However, from Table 2, YGA and ESA may have provided some insights on this issue.

### 4.2. *From conceptual framework to an operational tool*

We have presented a conceptual framework for an integrated and holistic environmental assessment of the impact of agricultural policies on the environment. There is interesting potential for further integration. Our paper represents the ‘tier 1′ level of this integration with the conceptualisation of the problem at hand, including the identification of redundancies and complementarities of the approaches. In order to create an operational tool for policymakers, further steps should focus on:

Reference values and reference situations. The reference situation is often used in LCA when assessing impacts on biodiversity and (some) ecosystem services, and is defined as the natural, pristine state of nature (before human intervention). The concept of setting a benchmark value also exists in the other approaches but rather differently. In AEI, most indicators are expressed per unit area (ha), in LCA the default functional unit is the amount of product, reflecting the primary function of agriculture as a producer of market goods (Basset-Mens and van der Werf, 2005). However, with the growing awareness that agriculture also plays a major role as a producer of non-market goods (e.g. environmental services) the functional unit of area of land occupied is increasingly used. This has led to debate on the choice of functional units, because the former tends to favour intensive system whereas the latter favours extensive systems (Salou et al., 2017).

More demonstration cases. We developed our framework on the existing catch crop demonstration case. This is an *ex-post* use of the framework. Using our conceptual framework on more case studies may be necessary to meet the expectations of policymakers better. Developing a participatory approach with experts for *ex-ante* use of the framework would help demonstrate its expressive power and utility.

Clarifying temporal and geographical scales. All frameworks are used to deal with a wide range of spatial scales (Table 1). However, LCA provides an addition, because the approach includes production chains, direct and indirect effects and upstream and downstream situations, with the latter not being considered in many agricultural studies. ESA and AEI often have a territorial perspective, i.e. a defined landscape and/or an agroecosystem, while LCA is increasingly used to analyse food product chains involving agroecosystems in different landscapes and even different world regions. The wide range of scales the four approaches operate on presents different methodological challenges, not least regarding data availability. Consequently, a combination of approaches is neither always suitable nor possible. It is then necessary to define suitable spatio-temporal scales for measurements/applications. Yield gap estimates are made at several spatial scales, from specific locations within important crop production regions (i.e. points at locations with a high-density harvested crop area and an associated buffer zone), to climate zones (CZs – defined by growing degree-days, temperature seasonality and aridity index), to large administrative units within a country (province/state), to a national average. For relatively large countries, only crops with a total national harvested area of >100,000 ha are evaluated in the Global Yield Gap Atlas (https://www.yieldgap.org). For smaller countries, crops with <100,000 ha are evaluated in the atlas. The underpinning principle is to select CZs and specific locations (points) and associated buffer zones within these CZs that best represent how a given crop is produced in terms of weather, soils and cropping system.

Ecosystem services are classically quantified at the landscape scale but new approaches at field or farm level were recently developed (e.g. Dardonville et al. 2022). Under current land use and land management, a range of ecosystem services benefiting both farmers (e.g. pollination, soil N mineralization) and society at large (e.g. soil carbon sequestration, air quality) were simulated for agricultural land in France (Therond et al., 2017). This has shown the potential for up-scaling ecosystem services from field to country through modelling, an approach that could also allow for better inter-comparability with LCAs and multi-indicator approaches. Furthermore, several other scaling mismatches can be avoided by similar scaling procedures.

Data and datasets required. Estimating and monitoring the societal benefits of agriculture with regards to climate, environment and rural development requires improved monitoring of agricultural land by the use of Earth Observation data. In addition, the availability of new tools and technologies and the increased interoperability between different 'sub' systems, such as open data, farm management and information systems, telemetry on farm machinery and local sensors, provide additional incentives to modernise the evidence base of agricultural sustainability assessments. Significant advances are being made in using remote sensing (airborne and satellite) for wide-area mapping of, for example, soil quality, soil moisture, water quality, pests and diseases, non-cropped vegetation, GHG emissions and biodiversity. This provides the possibility of using remote sensing to estimate natural capital stocks and ecosystem service flows, coupled with economic data from farms (Fuglie et al., 2016). As part of the data, an inventory of open access datasets (including official agricultural statistics, remote sensing products etc.) that could be used to calculate indicators would also be helpful for identifying datasets that can be used without any extra data collection efforts.

Developing an understandable dashboard. Our work has proposed a first core set of shared environmental issues. This set should evolve with progress in scientific knowledge and the evolution of stakeholder demands (Rasmussen et al., 2017). It will then be necessary to ensure an homogeneous directionality of the indicators (more positive -> higher values) in order to produce consequent spider diagrams, indicator fact sheets with clear methodological advice and some sort of dashboard (a red-green light dashboard) to help policymakers rapidly evaluate policies in this multidimensional assessment exercise. However, end-users may have preference for some type of representation (Albo et al., 2016).

Estimating the time required to work with the framework. The more complex or larger a framework is, the more time is needed to integrate all the data. Getting all the data to obtain (or calculate) the 40 issues requires quite a lot of time. Even if some approaches have published standard protocols (e.g. Global Yield Gap Atlas for the yield gap approach), which even include some tiered approaches to select data according to quality preferences, other issues are less normalised. For example, performing a yield gap analysis for a crop in a country (e.g. wheat in Canada) might require six months of full-time work for one person. We therefore need to make sure the time needed to calculate all the indicators in the unified framework is not too excessive.

Plan efficient workflow. Data, references, dashboard etc., all these items require setting up an efficient workflow approach making it possible to produce a robust assessment.

## 5. Conclusion

Developing operational tools to evaluate the impacts of various agricultural policies on the environment is a challenge. We propose a first conceptual framework to encompass the large complexity of the agroecosystem and the different dimensions requiring evaluation. We hybridized four assessment approaches showing the advantages of such an approach. It makes possible a broader assessment of environmental issues, providing for example more insights of the functioning of agroecosystems. Improving the set of indicators based upon experiences gained through additional case studies, getting reference values and developing workflows and a simplified dashboard for policymakers are the next steps. Given the changes in ecosystems and their impacts on climate change and the requirement for policies to mitigate the effect of the agricultural sector on the environment, this is actually quite an urgent research field.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgement

This study was funded by INRAE with a grant from Tempag (OECD). The authors wish to thank the INRAE librarians (S. Le-Perchec and V. Lelièvre) who helped in starting the project by a general literature query and A. Lewer for the English editing.

## Appendix 1: Details of the query for the WoS and Scopus database – July 2020

Set 1:TS=(europe* OR "EU" OR "european union*" OR "european community" OR "EU countr*" OR "EU state*" OR "EU member state*" OR "EU region*" OR "southern europe" OR "northern europe" OR "western europe" OR "eastern europe" OR austria* OR belgi* OR bulgaria* OR croatia* OR cyprus OR cypriot OR "czech republic" OR czechia OR denmark OR danmark OR danish OR estonia* OR finland OR finnish OR france OR french OR german* OR greece OR greek OR hungary OR hungarian OR ireland OR irish OR italy OR italian OR latvia* OR lithuania* OR luxembourg OR malta OR maltese OR netherlands OR dutch OR holland OR poland OR polish OR portugal OR portuguese OR romania* OR slovakia* OR slovenia* OR spain* OR sweden OR swedish OR switzerland OR swiss OR “united kingdom” OR “UK” OR “great britain” OR britain OR england OR “common agricultur* polic*” OR “CAP”)

Set 2:TS=(“catch crop*” OR “cover crop*” OR “crop residue*” OR “intermediate crop*” OR “living mulch*” OR “dead mulch*” OR “mulch of residue*” OR “green manur*” OR “intermediate plant*” OR “inter crop*” OR “undersown crop*”)

Set 3:#1 AND #2

Set 4:TS=(“ecosystem* service*” OR “ecosystem* approach*” OR “ecosystem* analysis” OR “ecosystem* service* assessment$” OR “ecosystem* service* analysis” OR “ecosystem* service* approach*” OR “LCA” OR “life cycle assessment*” OR “life cycle analysis” OR “life cycle approach*” OR “yield* gap*” OR “yield* gap* analysis” OR “yield* gap* assessment$” OR “yield* gap* approach*” OR “AEI*” OR “agri* environment* indicator$” OR “agro environment* indicator$” OR “environment* indicator$” OR “sustainability indicator$” OR “pressure indicator$” OR “impact* indicator$” OR “agri* environment* assessment*” OR “agri* environment* monitor*” OR “agri* environment* analysis” OR “agri* environment* evaluat*” OR “environment* assessment*” OR “environment* evaluat*” OR “environment* impact$” OR “environment* effect$” OR “impact* assessment*” OR “impact* evaluation*” OR “effect* assessment*” OR “effect* evaluation*” OR “benefit* analysis” OR “multicriteria*” OR “multi criteria*” OR “model* approach*” OR “model* scale$” OR “large scale$” OR “cross scale$” OR “multi scale*” OR “multilevel” OR “multi level” OR “regional level” OR “regional scale” OR “national level” OR “national scale” OR “national monitor*”)

Query used:(#3 AND #4)

Language: English

Document types: All types of documents

Custom year range: 2000 to 2020

Web of Science Core Collection: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC

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