Advanced study on country scale monitoring of agri-environmental sustainability. Technical Report

Audrey Bethinger, Jacques-Eric Bergez, Clément Rivière

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Introduction

In order to compare the agricultural sector across countries, Total Factor Productivity (TFP), the ratio between total market outputs and total markets inputs of the sector, and TFP growth are used to convey information about economic efficiency and productivity growth (Fuglie, 2012; Fuglie, 2015). Increases in TFP reduce the cost of producing agricultural commodities, and hence, the price of food. However, as a measure of sustainable intensification of agriculture, TFP is quite incomplete, since it is possible for TFP grow at the expense of nature (Fuglie *et al.*, 2016).

A more complete metric of sustainable intensification needs to take agriculture's effect on natural resources and ecosystem services (ES) into account, thereby addressing the sustainability of farm activities regarding social, economic, and environmental factors at farm scale and regional scale. Adoption of more sustainable agricultural practices entails defining sustainability, developing easily measured indicators of sustainability at multiple scales, moving towards integrated agricultural systems, and developing incentives or regulations and taxes to affect farmers' behavior (Dale *et al.*, 2013; Mouysset, 2015). So far, the implementation of sustainable intensification and the discussion of alternative approaches are not based on quantitative evidence of their simultaneous ecological and socioeconomic impacts (Garibaldi *et al.*, 2017).

OECD countries have made significant progress in developing agri-environmental indicators (AEI) to monitor these environmental impacts (Latruffe *et al.*, 2016). AEIs cover the following themes: Nitrogen balance, Phosphorus balance, Agriculture land area, Farm birds index, Soil erosion, Ammonia, NOx and SOx emissions, Greenhouse gas emissions, Water quality, Energy use and biofuel production, Pesticides sales and Water resources.

As well as providing valuable evidence of the state and trends in the environmental performance of agriculture, AEIs support analysis to explain the effects of different policies on the environment, and to assess whether budgets for policies are used effectively in terms of environmental outcomes and economic efficiency (OECD, 2018). However, in this approach, AEIs are only calculated at national scale, thereby neglecting regional variability and, hence, not showing in which regions agriculture is underperforming or unsustainable, even when the aggregate account shows agriculture is competitive. In contrast, defining national measures for a sustainable and resilient agriculture via scaling up allows understanding regional variability and the local constraints on ecosystem services and natural capital (Fuglie *et al.*, 2016).

Estimating and monitoring the societal benefits of agriculture towards climate, environment and rural development requires an improved monitoring of agricultural land by the use of Earth Observation data. In addition, new tools and technologies availability and the increased interoperability between different 'sub' systems, like open data, farm management and information systems, telemetry on farm machinery and local sensors provide additional incentives to modernize 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 and biodiversity. For example, a simple proxy for biodiversity is the amount, quality and connectivity of non-cropped land in agricultural landscapes, and it is already possible to map this remotely. This opens the possibility to use remote sensing to estimate natural capital stocks and ecosystem services flows, coupled with economic data from farms (Fuglie *et al.*, 2016).

As to make progress on environmental sustainability, TempAg has developed three pilot activities (PA) so far: PA1 focuses on multi-scale indicators of sustainable agriculture and life cycle assessment (LCA) studies; PA2 focuses on biodiversity and ecosystem services (ES), PA3 focuses on yield gaps (YG) and resource use efficiency. While each of these PAs has delivered useful evidence based results on temperate agriculture sustainability, they also have shown risks of discrepancies in conclusions when using one approach over the other.

Indeed a unified approach of environmental sustainability in agriculture is still lacking. Review of the literature shows that the number of agricultural LCA cases where land use impacts and ecosystem services were used instead of land areas is still limited (Tang *et al*., 2018). Though commonly used, LCA methodologies lack the spatial resolution and predictive ecological information to reveal key impacts on climate, water and biodiversity. Therefore, integrating spatially explicit modelling of land change and ecosystem services in LCAs could create some advances (Chaplin-Kramer *et al.*, 2017). Under current land use and land management, a range of ecosystem services benefiting both farmers (*e.g.* pollination, soil N mineralization) and the society at large (*e.g.* soil carbon sequestration, air quality) were simulated for agricultural land in France (Therond e*t al.*, 2017). This has shown the potential for scaling ecosystem services from field to country through modeling, an approach which could also allow for better inter-comparability with LCAs and multi-indicators approaches.

I. Purpose of the study

The present study aims to assess the environmental sustainability of agricultural systems across OECD countries, with operational implementation by the States in order to monitor the impact of their agricultural and environmental policies. Previous works conducted by TempAg within PA1, PA2 and PA3 are very relevant regarding the scope of the present study, which aims to synthetize their outcomes in order to propose a method for assessing the environmental sustainability of agriculture at the country level.

II. Human resources

1. Scientific experts panel

An international panel was put together, pairing French experts of each original framework (AEI, LCA, ES, YG) with experts from a diversity of European countries. A single expert on remote sensing completed this panel.

These scientific experts were identified from an analysis of the existing scientific literature, within the members of the TempAg network.

The experts' interests were examined at the beginning of the study by a commission chaired by INRAE's Ethics Commissioner to guard against the risks of conflicts of interest. No conflict of interest was reported. Beyond the risks of conflict, the analysis of the links of interest ensures the plurality and balance of interests at the level of the expert group. In concrete terms, each expert has completed a statement specifying the links he maintains whether they are institutional (member of board of directors or of scientific board, financial (contract of research, study or expertise, individually or collectively) and/or personal (member of an association, shareholder in a company. Below is a list by field of expertise:

AEI	
Christian Schader	Research Institute of Organic Agriculture (FIBL, CH) Department of Socio-Economic Sciences
Christian Bockstaller	French National Research Institute for Agriculture, Food and Environment (INRAE, FR) Department "Agronomy and environmental sciences for agroecosystems"
YG	
Pytrik Reidsman	Wageningen University (WUR, NL) Department of Plant Sciences
Nicolas Guilpart	AgroParisTech (FR)
LCA	
Christel Cederberg	Chalmers University of Technology (SE) Department of Space, Earth and Environment
Hayo van der Werf	French National Research Institute for Agriculture, Food and Environment (INRAE, FR) Department "Agronomy and environmental sciences for agroecosystems"
ES	
Felix Müeller Sabine Bicking	Christian-Albrechts-University (CAU, DE) Institute for Natural Resource Conservation
Olivier Thérond	French National Research Institute for Agriculture, Food and Environment (INRAE, FR) Department "Agronomy and environmental sciences for agroecosystems"
Remote sensing	
Eric Ceschia	Center for the Study of the Biosphere from Space (CESBIO, FR) Department "Ecology and biodiversity of forest, grassland and freshwater environments"

2. Project team

Jacques-Eric Bergez (INRAE, UMR AGIR, department « AgroEcoSystems»): scientific coordinator

Audrey Béthinger (INRAE, DEPE): project manager

Clément Rivière (INRAE, DEPE): project engineer in charge of the scientific literature reviews

3. Scientific and Technical Information team

Virginie Lelièvre and Sophie Le Perchec, INRAE, IST

III. Meetings

Plenary meetings:

- Project launching: January 28-29th 2020, INRAE Paris
- Online workshop: 2020, March 9th (0.5 day)
- Online workshop: 2020, June 9th (0.5 day)
- Online workshop: 2020, September 30th (0.5 day)
- Online workshop: 2020, November 10th (0.5 day)
- Online workshop: 2020, December 2nd (0.5 day)
- Online workshop: 2021, January 13th 2021 (0.5 day)
- Online workshop: 2021,March 29th (0.5 day)
- Online workshop: 2021,September 20th (0.5 day)

IV. Governance

Steering Committee: TempAg and OECD. Met only once during the course of the project.

V. Timeline

	Jan. 2020 (0)	March (2)	June (5)	July (6)	Sept. (8)	Nov. (10)	Dec. (11)	Jan. 2021 (12)	March (14)	Sept. (20)	Dec. (23)
Meetings	N°1	N°2	N°3		N°4	N°5	N°6	N°7	N°8	N°9	
Litterature review											
Pragmatic approach: Case study Framework											
Main article SLR article (case study)											
Technical report											
International workshop				Executive summary							

VI. Deliverables

1. Technical report

2. Public restitution

An executive summary (Appendix 1) was submitted for a potential communication at the 7th Symposium for Farming System Design initially planned in March 2021. However the Symposium was postponed to 2022 due to the Covid pandemic.

The general framework was presented to the Ministry of Agriculture in June 2021 as a base for a meta-analysis on conservation agriculture in the context of a project on the toxic effects of pesticides

3. Scientific articles

- Integrating Agri-Environmental Indicators, Ecosystem Services Assessment, Life Cycle Assessment and Yield Gap Analysis to assess the environmental sustainability of agriculture (Bergez et al., Ecological Indicators, under review) cf. Appendix 2
- A systematic literature review on the potential effects of cover crops on multiple environmental sustainability indicators (Rivière et al., Agronomy for Sustainable Development, under review) cf. Appendix 3

VII. Financing

Total budget is 70 k€ funded by TempAg:

- 44 162 €: salary for Clément Rivière from 04/15/2020 to 04/14/2021 (12 x 3 680,13 €)
- 3 k€ compensation for FIBL
- 3 k€ compensation for Chlamers University
- 3 k€ compensation for WUR
- 3 k€ compensation for Christian Albrecht University
- 13 838 € : study valorisation and functioning

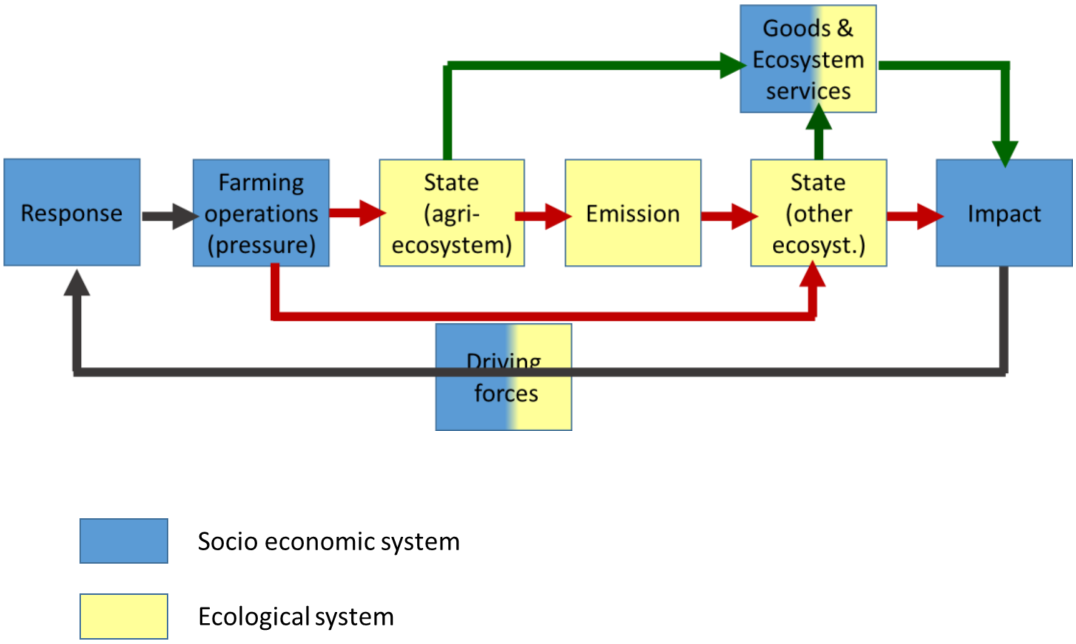
VIII. Methodological approach

1. Redaction of the study's Terms of Reference and its validation by the TempAg Board.
2. Test of the assumption with a French panel of experts
3. Recruitment of the international experts on the different original frameworks (LCA, AEI, ES, YG)
4. In parallel, state of the art conducted by the STI team on both the existing environmental sustainability assessment methods: AEI, LCA, ES, YG (based on TempAg Pilot Activities) and the data fueling of indicators (remote sensing, modeling, hybrid methods, etc.)
5. First meeting using pragmatic and participatory approach based on collective brainstorming and codesign, to map a conceptual framework. This framework was put to test in a case study: the implementation of catch crops in the context of the Nitrates directive 91/676/EEC. We used a list of 41 indicators taking from the four original frameworks (LCA, AEI, ES, YG) and checked how they fitted in our unified framework and verify that it was comprehensive.
6. Systematic literature review to determine the effects of catch crops on the environmental sustainability using this list of indicators chosen in step 5.
7. Loop of interactions between the different experts to deepen the framework and put it in action based on the literature review
8. Co-writing of the paper describing the integrated framework

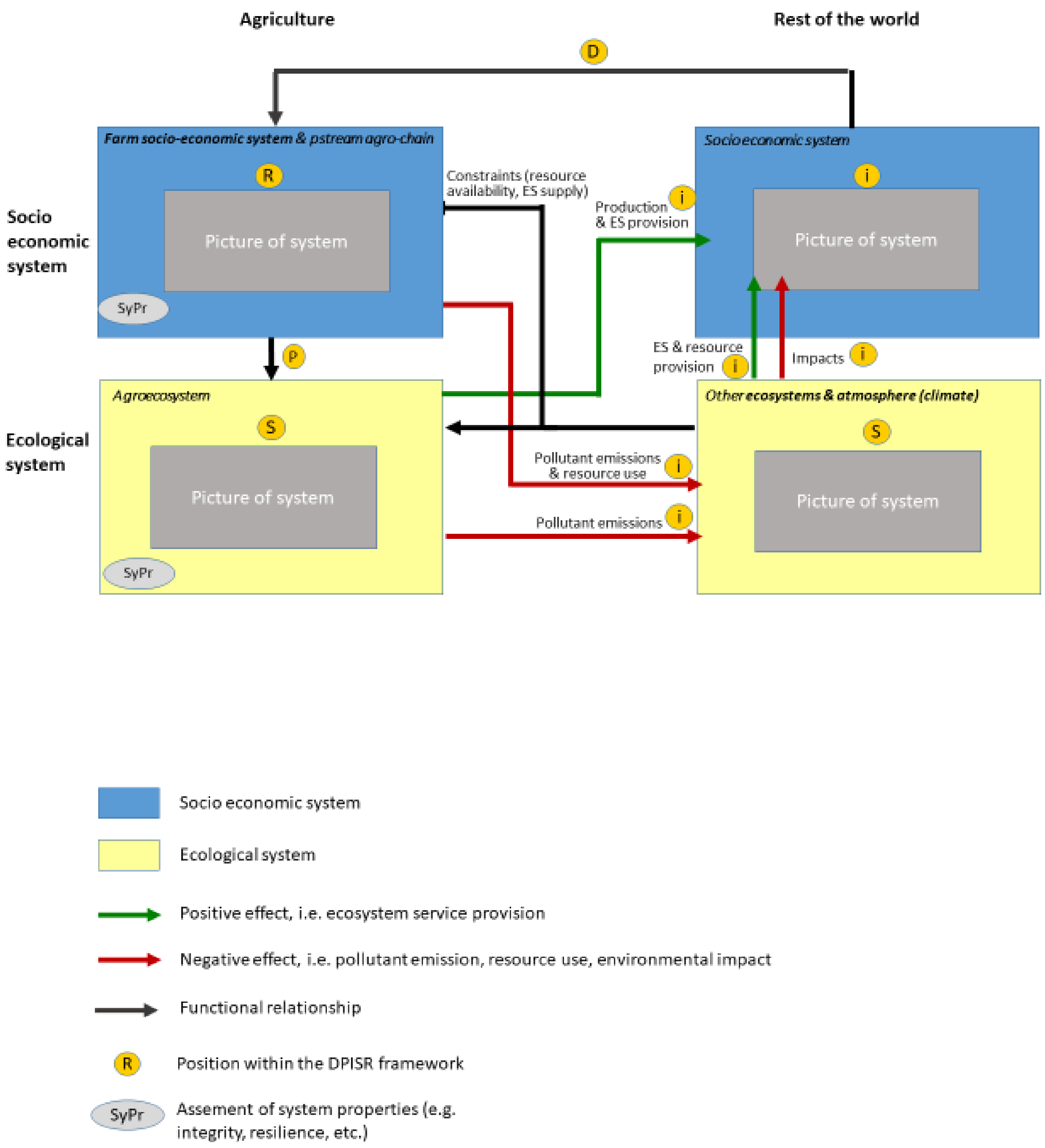
IX. Building the unique framework

We built the unique framework in three steps by combining all the four original approaches (LCA, AEI, ES, YG)

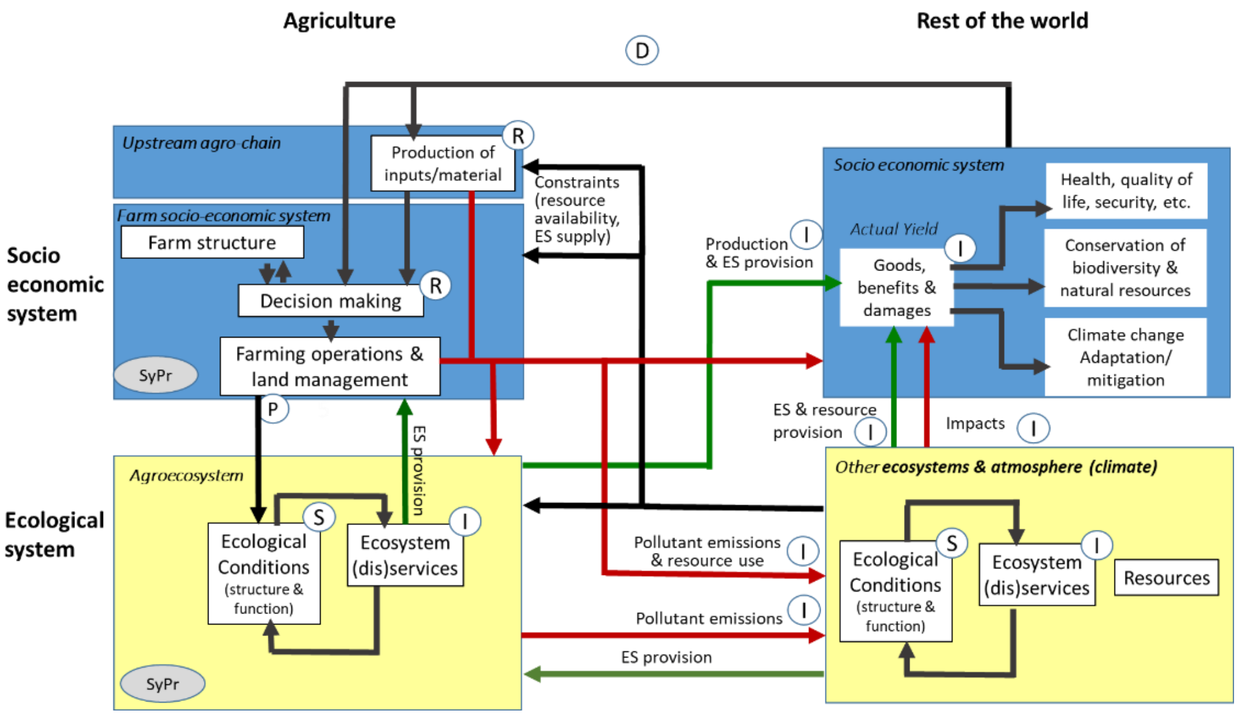
1. First step



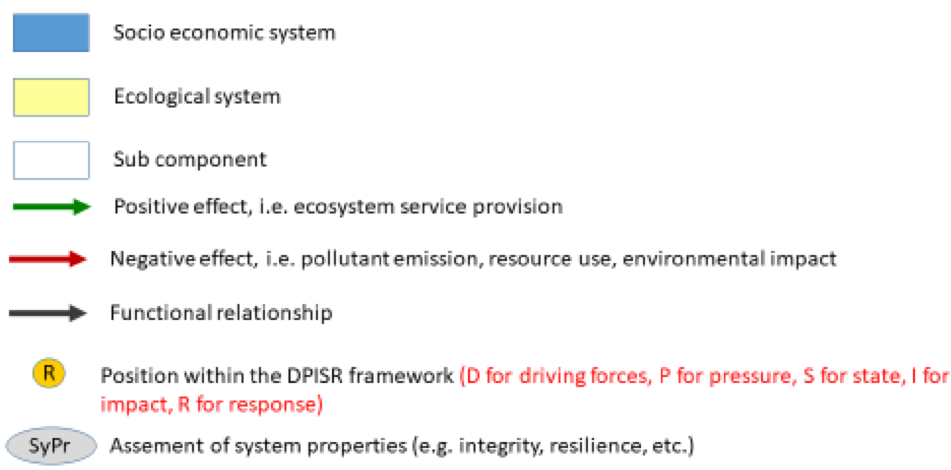
2. Second step



3. Third step



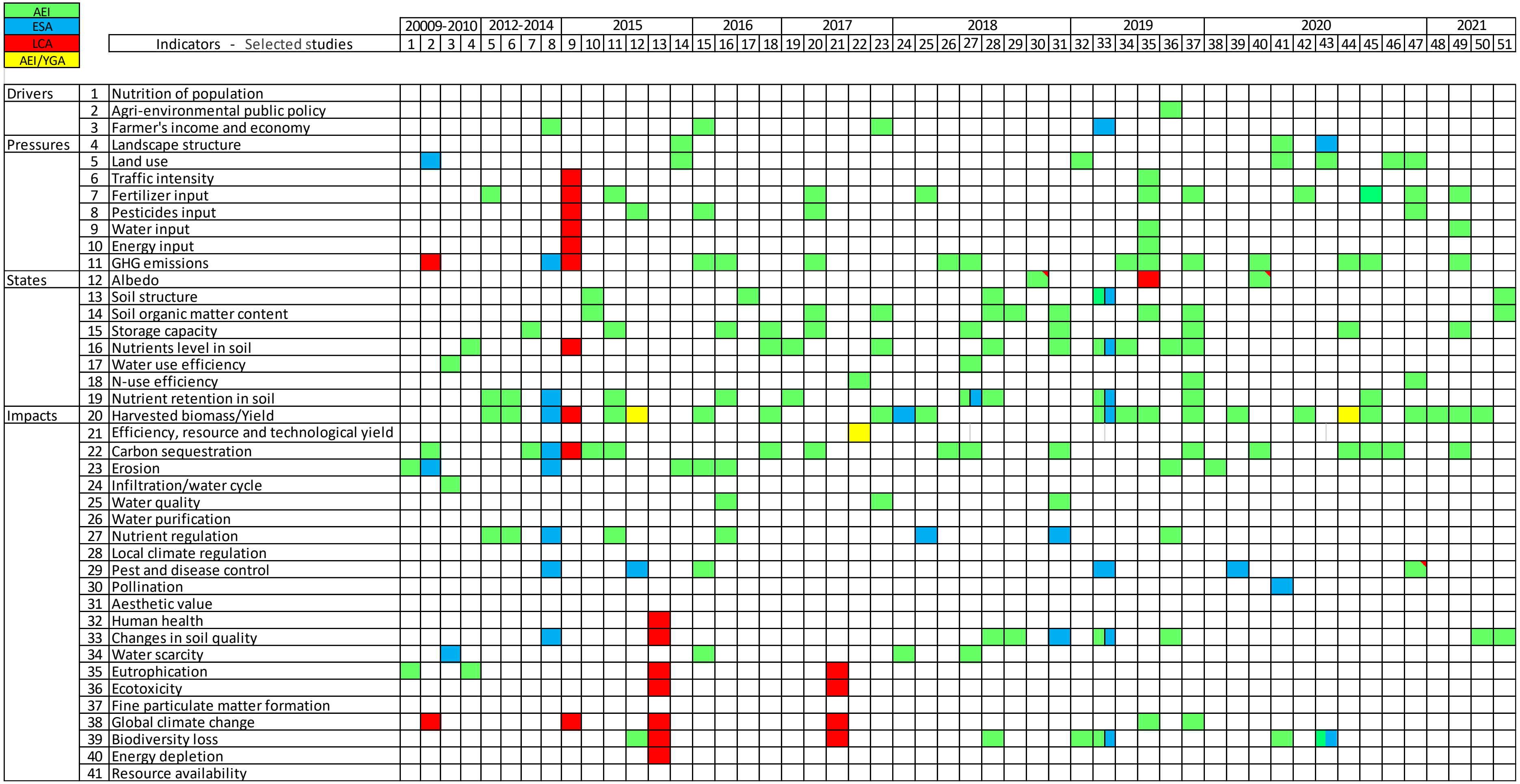
Framework centred on the agricultural system and therefore not exhaustive
Farming operation = crop, livestock and landscape management
Agroecosystem = managed agricultural land + soil (root depth) + atmosphere above canopy + farm's semi-natural elements



X. A case study: cover crops

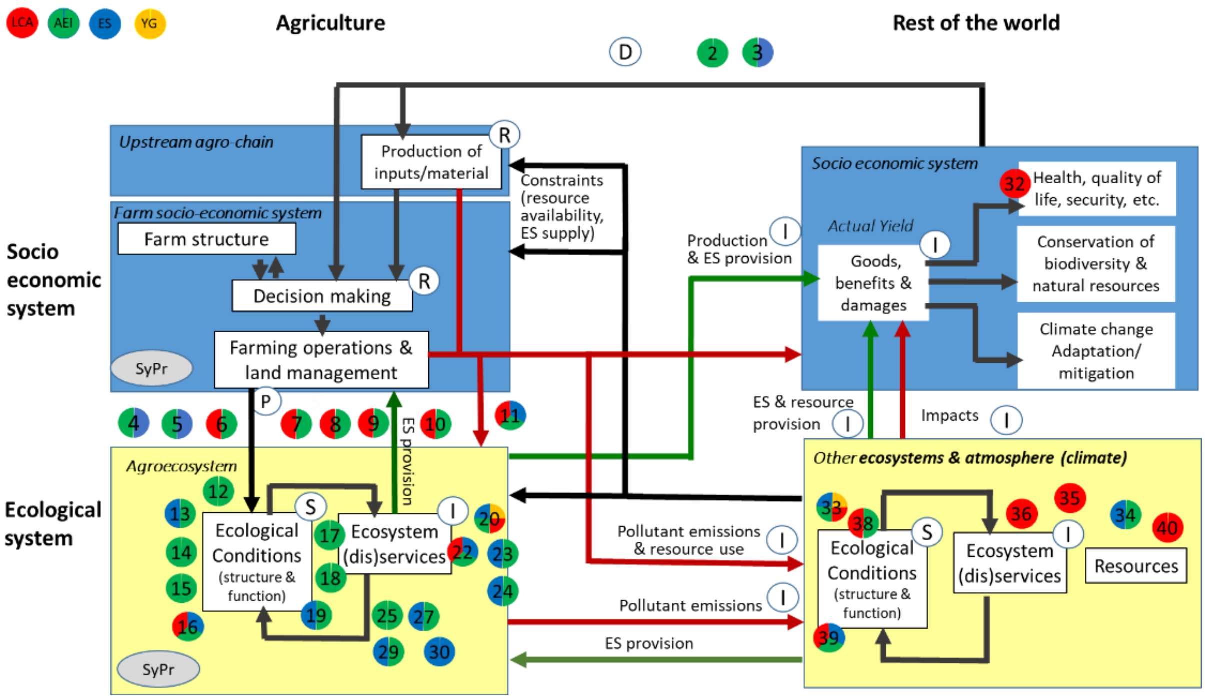
We then tested our original framework using a cover crop systematic literature review (Rivière et al., under review).

The table below gives an overview of how the 41 chosen environmental issues were represented in the 51 reviewed papers (numbered in chronological order from 2009-2020) that analyse environmental issues concerning cover crops.



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

We later represented these results in our framework (see figure below). 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; some others are assessed by the four approaches, while others are assessed only by one or two approaches. Therefore, for some of the environmental issues, the use of the four methodological approaches was needed to embrace the different dimensions of these issues.



XI. Conclusion

This project was the first international advanced study carried on by the Direction for Collective Scientific Assessment, Foresight and Advanced Studies (DEPE).

Pairing experts by fields of expertise was very effective. Indeed the French INRAE experts were easy to recruit as part of the INRAE work force then they were able to offer names of European experts they sometimes had collaborated with in the past, which made for good work dynamics.

On the other hand, it was a bit more difficult to appeal to the international experts. A financial incentive towards their lab helped secure their full cooperation.

The first workshop was organized in Paris and offered an opportunity for the experts to create bonds and work as a tight group throughout the project.

The sanitary situation would not permit for other presential interactions and the work dynamics would probably have suffered had not it been for this first workshop in Paris.

A rigorous collective work was key to building the conceptual framework and the COVID situation nonetheless slowed that part of the project, not sparing enough time to work on a tier 2 level (quantitative application of said framework) as initially planned.

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Appendix 1

A holistic framework to assess environmental sustainability of agricultural policies

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Introduction

Agriculture is an important driver of environmental changes and contributes to urgent global challenges such as land degradation, biodiversity loss, and emission of greenhouse gases (Diaz et al., 2019). Several frameworks and methods for assessing agriculture´s environmental performances exist, but a unified framework for environmental sustainability in agriculture is still lacking. Such a framework should consider agriculture's effects on natural resources and ecosystem services (Sukhdev et al., 2016). Since the late 1990s, the growing concern for environmental issues in agriculture has led to an "indicator explosion", with a multiplication of initiatives for and publications on agri-environmental indicators at different scales, from field to country (Bockstaller et al., 2015). To progress in this area, TempAg, the International Sustainable Temperate Agriculture Network (www.tempag.net), has initiated a project to develop a framework to unify four major environmental sustainability approaches: agri-environmental indicators (AEI), ecosystem services assessment (ESA), life cycle assessment (LCA) and yield gap analysis (YGA). This study presents the unified conceptual framework that merges these assessment approaches.

Materials and Methods

Four assessment approaches were considered to develop our unified framework (Table 1).

Table 1. Key features of the four environmental sustainability assessment approaches.

Framework	Spatial scale	System definition	Expressed per	Degree of standardisation	Economic sectors of application	Data requirements	Reference value
AEI[1]	Field, farm, small region, nation	Agroecosystem, (upstream processes)	Area unit	Low	Agriculture	Low to medium	Absolute (relative)

LCA[2]	Field, farm, small region, nation	Product chain	Product unit	High	Most/all	High	Relative (absolute)
A[3]	Field, landscape	Agroecosystem	Area unit	Intermediate	Agriculture and other land- or waterbased sectors	Intermediate to high	None or relative
YGA[4]	Field, farm, small region, nation, global scale	Agricultural system	Area unit	Intermediate to high	Agriculture	Intermediate to high	Relative or absolute

1. Agri-environmental indicators (AEIs) have been developed by OECD countries to monitor impacts of agriculture at the national scale (Latruffe et al., 2016). AEIs cover the themes Agricultural land area, Farm bird diversity, Soil erosion, Air emissions, Greenhouse gas emissions, Water quality and resources, Energy use and biofuel production, Pesticide sales and Nutrient balances. AEIs indicate states and trends in the environmental performance of agriculture and support analysis to explain effects of different policies on the environment.
2. Life cycle assessment (LCA) is the methodology used most widely in research and industry to estimate environmental impacts of agri-food products and systems (van der Werf et al., 2020). LCA assesses environmental and health impacts as well as resource depletion issues considering both on-site and off-site resource use, pollutant emissions and land use.
3. Ecosystem services assessment (ESA) is a growing interdisciplinary research field that seeks to develop methods and tools to assess a wide range of provisioning, regulation and cultural ecosystem services. The scale of assessing ecosystem services ranges from the field to landscape depending on the ecological processes involved (Zhang et al., 2007);
4. Yield gap analysis (YGA) was developed to assess the food production capacity per ha of land (Van Ittersum et al., 2013) in order to guide sustainable intensification of agriculture. Differences between theoretical yields and farmers' actual yields define the yield gaps.

We characterize the components of our framework according to a DPSIR perspective (Niemeijer and de Groot, 2008).

Results and discussion

Our framework considers the agroecosystem as a *Social-ecological system* in relation with the overall *Ecological system* and *Other ecosystems and the atmosphere* at local and global scales. Driving forces, i.e. environmental forces (e.g. climate) and policies and human requirements (Ecosystem Services gap and Yield gap), influence S*ocial agricultural system* changes. Farmers (general term) make decisions that lead to technical actions (e.g. land use, farming operations). To implement these decisions, inputs are required (e.g. pesticides, fertilizers, machines) whose production requires resources (natural or industrial) and generates emissions. Farming operations create pressure on the *Agricultural ecosystem* (field scale) embedded in the *Landscape* (ecosystem mosaic). These operations modify ecological conditions (state) of the *Agricultural ecosystem and landscape*. Conditions of the agricultural ecosystem determine the potential yield (based on pedoclimatic conditions and farmers' strategies) and potential ecosystem services levels (based on the actual abiotic and biotic components, landscape matrix, etc). *Production* of the *actual yield of goods* and level of *benefits/damages* derived from ecosystem (dis)services depend on farming practices and human demand. Farming operations also deplete resources and generate emissions that modify ecological conditions of *Other ecosystems and the atmosphere* and, in turn, the related ecosystem (dis)services. These modifications of *Other ecosystems and the atmosphere* impact outputs of the system (goods, benefits and damages). The outputs lead to modification of human well-being components and ecosystem quality (or integrity) and natural resource availability.

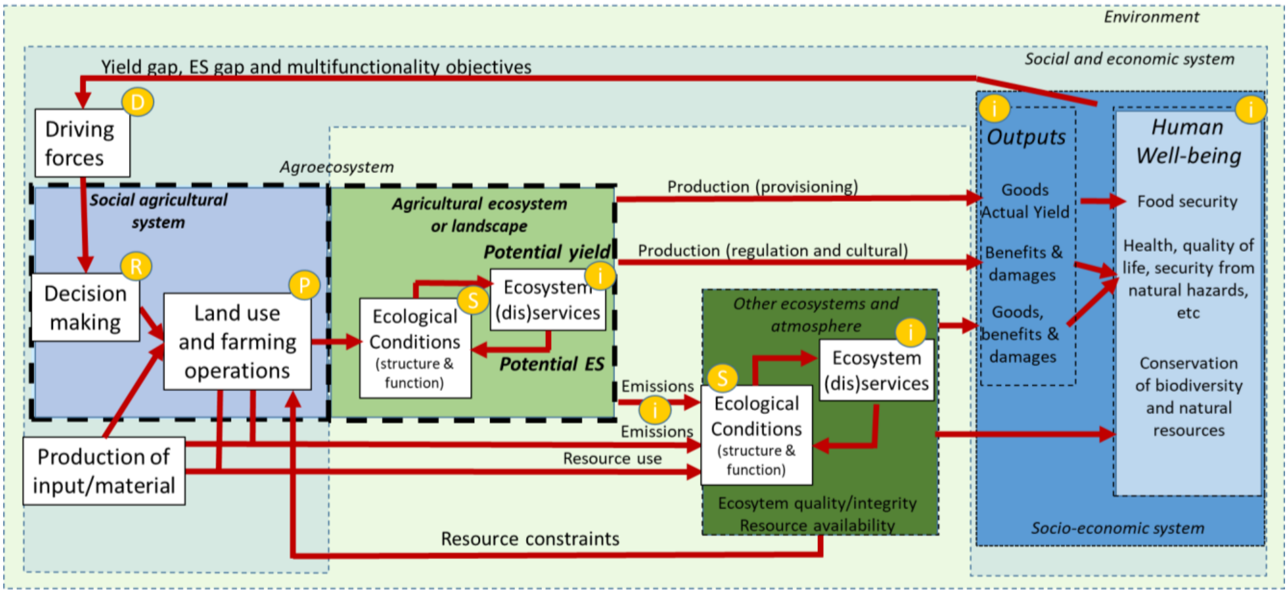

Figure 1. The unified framework. Letters in the yellow circles are related to the DPSIR framework: D: driving forces, P: pressure, S: State, I: impact, R: response

This unified framework presents a holistic view of the causal chain and feedbacks that connect agricultural policies, farmer behaviour, ecosystem states, impacts, outputs and human well-being. Elements of the individual frameworks can be identified that serve either as inputs to another framework or as a complementary point of view.

Conclusion

This conceptual framework is appealing, as it integrates the strengths and complementarities of four major approaches for assessing the environmental sustainability of farming systems. Operational indicators now need to be developed to test this conceptual framework in a real situation: our next challenge!

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Appendix 2

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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ARTICLEINFO

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.

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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

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 (Soule 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; Hayh¨ a 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 (Soul´e 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.

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.

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).

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).

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

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 (Soul´e 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 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).

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).

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.

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.

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).

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).

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.

Riviere 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).

Results

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, Soul´e 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 (Soul´e 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).

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 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.

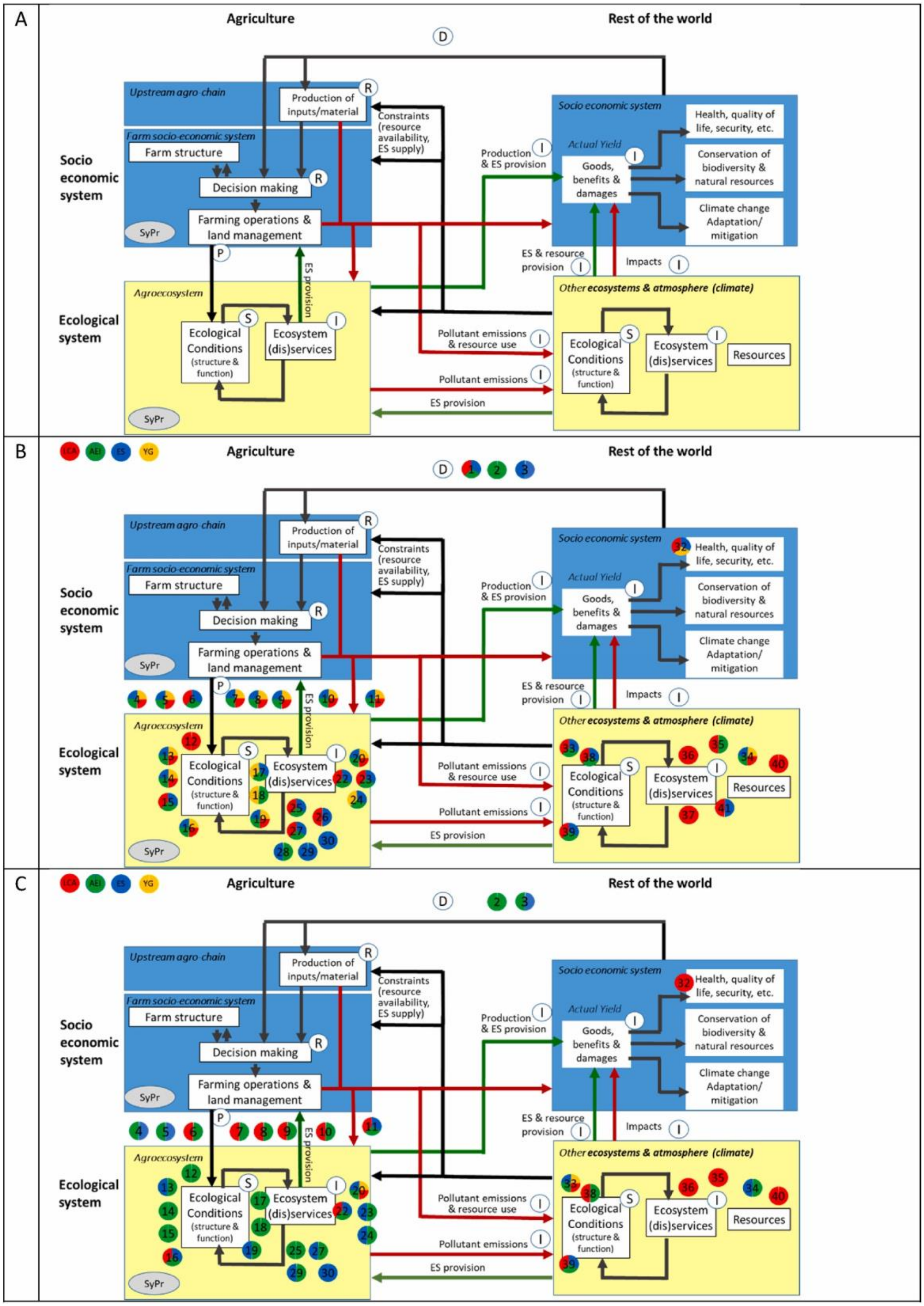

Fig. 1. A) Global systems view showing relations between the Socioeconomic system (blue) and the Ecological system (yellow). Agriculture (left side) is distinguished from the Rest of the world (right side). Black arrows indicate functional relationships, green arrows indicate provision of ecosystem services, 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.)

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 (Rivi`ere 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.

Rivi`ere 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.

Discussion

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 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.

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 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.

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 (green)
ESA (blue)
LCA (red)
AEI/YGA (yellow)

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

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.

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.

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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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Review

Appendix 3
The Effects of Cover Crops on Multiple Environmental Sustainability Indicators—A Review

Clément Rivière [1], Audrey Béthinger [1] and Jacques-Eric Bergez [2,*]

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Abstract: Cover crops have been introduced in European agricultural systems due to their multiple agro-ecological services and environmental benefits, which do not necessarily affect profitability. Our paper follows a systematic literature review approach to highlight the results of 51 studies on the effects of adopting cover crops. We used a list of 41 agri-environmental sustainability indicators to present the different impacts of cover crops in European pedoclimatic situations. Herein, we review the positive effects of cover crops on agri-environmental sustainability (e.g., reduced soil erosion and nitrate leaching, higher carbon sequestration and soil quality, biodiversity enhancement, and reduced mineral fertilizer requirement), but also the more variable effects associated with the use of cover crops (e.g., management and interest for farm economics, nutrient and water competition with cash crops, and improved GHG balance, even if N20 emissions are slightly increased). Our review highlights these synergies among the sustainability indicators. More research data are needed on the multiple effects of cover crops in the context of diverse site-specific conditions and farm-management practices, especially between the traditional positive effects of cover crops (i.e., soil C sequestration and fertilizer savings) and their effects on climate change (i.e., GHG net balance and potential effects on global warming).

1. Introduction

Over recent decades, EU member states have shown a willingness to improve the environmental and socio-economic sustainability of their agricultural systems. As part of the European Nitrate Directive, the generalization of permanent soil cover using cover crops (CC) during the fall and winter periods is one of the main European public policies introduced to promote more sustainable agriculture [1]. This soil coverage using CC concerns all fallow periods (i.e., bare soil between the harvest of a main crop and the sowing of the next main crop) that precede a spring-summer crop. There are four main classes of CC [2]: legumes (e.g., alfalfa, vetches, and clovers), non-legumes (e.g., spinach, canola, and flax), grasses (e.g., ryegrass and cereals such as barley), and brassicas (e.g., rapeseed, mustard, radish, and turnip). The use of CC still represents a small percentage of cropland in Europe compared to bare soil. However, it grew from 6.5 to 8.9% of the EU-28 arable land between 2010 and 2016 [3]. Their adoption by farmers is progressing due to an encouragement by agronomists for their multi-ecosystem and agro-ecological services [4,5] and due to policies in some areas of the EU's agricultural land through the Common Agricultural Policy.

The scientific literature on CC's effects on European farming systems mainly deals with environmental sustainability criteria (e.g., the soil erosion rate, soil structure, nitrate leaching, nutrient and organic matter supply, weeds, pest and disease control, soil quality, and greenhouse gas balance) but also with socio-economic criteria (e.g., crop yield and economic returns). Several reviews and meta-analyses have already shown that the

Keywords: cover crops; European countries; sustainability indicators; multicriteria assessment

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adoption of CC in temperate regions can provide multiple benefits to both famers and society [2,4,6–12]. Two reports from the French National Research Institute for Agriculture, Food, and Environment (INRAE, France) have provided a comprehensive bibliographic analysis on the agronomic and environmental effects of introducing CC in cropping systems [1,13]. A recent meta-analysis has shown that CC generate an increase in organic matter, carbon and nitrogen in the soil, better soil erosion control, a decrease in nitrate leaching, and an increase in biodiversity [14]. Besides these positive effects, the literature also highlights the fact that the use of CC can have variable effects. For example, CC increased N_2O emissions but the GHG balance was generally improved when carbon sequestration was considered (e.g., [1,15]). A possible resource (nutrient and water) competition with cash crops may occur, as well as an uncertain economic benefit with lower yields of cash crops in the short-term [6,14]. Despite the numerous papers and reviews on CC's effects on agri-environmental criteria, few have attempted to consider a wide range of sustainability indicators to assess their multiple effects. A study with such an attempt is the recent paper [4]. In this regard, a review of the existing literature about potential CC benefits and disadvantages is needed to better understand the effects of CC on agri-environmental sustainability criteria.

In this paper, we aimed to answer two questions: (i) What are the environmental and socio-economic effects of cover crops' introduction on sustainability indicators across regions in Europe? (ii) How have the effects been assessed and what analytical frameworks have been used? We used the word 'effect' rather than 'impact', as the latter could have a negative connotation while 'effect' is more neutral. The main purpose of this work is to review the effects of introducing CC on the environmental sustainability of agroecosystems by reviewing the literature while considering a wide range of sustainability indicators. This paper describes the empirical material of the conceptual companion paper written by [16].

2. Constitution of a Corpus and Data Analysis

Our study is based on a systematic literature review protocol. According to the Cochrane definition [17], a systematic literature review uses systematic and explicit methods to identify, select, critically appraise, extract, and analyze data from relevant research studies. It is a methodological, rigorous, and reproducible synthesis of the results from scientific papers, undertaken in response to a research question [17]. We used the *rapid review* type that is a form of knowledge synthesis in which components of the systematic literature review process are simplified or omitted to produce information in a timely manner [18]. Such a review follows the following protocol: (i) the literature is searched on more than one database (limited to published sources); (ii) the search is limited by both date and language; (iii) the source screening is performed by a single reviewer; (iv) the data abstraction is performed by one person while another person verifies it; (v) lastly, one person assesses the risk of bias while another person verifies it [18]. Based on this protocol, our systematic literature review is qualitative and provides a synthesis from previous study results, which is different from the quantitative analysis known as meta-analysis.

2.1. From a Research Question to Query Building

We used the PICO (Population, Intervention, Comparator, and Outcome) method for defining the general scope of our review and formulating our questions of interest [17]. The PICO framework helps to outline the keywords for query construction and to set the limits of inclusion and exclusion in the selection process (Table 1).

Population: Refers to the terms related to European countries/regions, i.e., the EU 27 countries plus the United Kingdom and Switzerland, and Common Agricultural Policy.

Intervention: Refers to the presence of CC. We defined a CC as sown plants growing between cash crops and during a fallow period between the harvest and planting of regular crops. From this broad definition, we included cover crops as well as catch crops (known as nitrogen-fixing crops), green manures, and crop residues such as mulch. All these words were entered in our query plus the terms intermediate crop, intercropping, and undersown crop.

Table 1. PICO method and process for query building.

Questions	1. What are the environmental and socio-economic effects of cover crops' introduction on sustainability indicators across regions in Europe? 2. How have the effects been assessed and what analytical frameworks have been used?		
Key concept	Countries of the European Union	Introduction of cover crops (CC)	Assessment of CC's effects and environmental sustainability approaches
Population	- The 27 countries of the European Union (EU) - Plus, the United Kingdom and Switzerland		
Intervention	Presence of CC in the targeted countries		
Comparator	- Farm-management practices with and without CC - Farm systems before and after the use of CC		
Outcome	- CC's effects on multiple sustainability indicators: environmental criteria (e.g., nitrate leaching, erosion, and biodiversity) and socioeconomic criteria (e.g., productivity, crop yields, and climate change) - Sustainability assessment methods: agri-environmental indicators (AEI), ecosystem services assessment (ESA), life cycle assessment (LCA), and yield gap analysis (YGA). - Spatio-temporal monitoring: scientific models and tools used for CC monitoring (e.g., model approaches, remote sensing, and hybrid methods)		
Example of keywords	Europe*, EU*, names of the countries	Catch crop*, cover crop*, crop residue, mulch, intermediate crop	Environment* indicator,sustainability indicator, ecosystem service*, life cycle*, yield gap*, multi-scale

Comparator: Indicates which comparative factors should be considered. We focused this work on studies that reported their results by comparing with/without or before/after the introduction of cover crops.

Outcome: Terms related to the main methods used for assessing environmental sustainability; synonymous terms of sustainability indicators, environmental-effect assessment, or multi-criteria analysis; and generic terms associated with spatial scales for monitoring (cf. Appendix A).

2.2. Literature Research Strategy

We used the Web of Science Core Collection (WoS) and Scopus databases in July 2020. We searched for all types of documents (articles, books, book chapters, reviews, and proceeding papers) with no search limits placed on the citation indexes; a timespan limitation of 2000–2020 of was set, and only English documents were curated. We searched the topic terms related to our PICO key concepts in the title, the abstract, the keywords, and the authors' keywords.

2.3. Study Selection Process and Eligibility Criteria

The detailed study-selection process (Figure 1) was based on the PRISMA diagram [19]. The following criteria were applied to assess the eligibility of the studies and to decide on their inclusion or exclusion in this systematic literature review:

- Studies assessing CC's effects in European countries. We excluded sources from other countries and regions of the world, except for two studies in the USA.
- Studies with a minimum aggregation analysis at the farm and field levels, if available at regional and national scales.
- Studies with a temporal frame of at least three years.
- Studies comparing situations with and without CC, but also studies that deal with other farm-management practices (e.g., reduced fertilization, reduced tillage, or no-till farming) whether in organic, conventional, or both systems.
- Studies reporting at least one of the three outcome types of the PICO framework.

- Document types—articles only (no books, book chapters, reviews, nor proceeding papers). Only primary studies are included in the results of this paper, and other reviews on the subject are only mentioned or discussed.
- Timespan limited to 2000–2020, but we included four studies from 2021.
- Language—English.

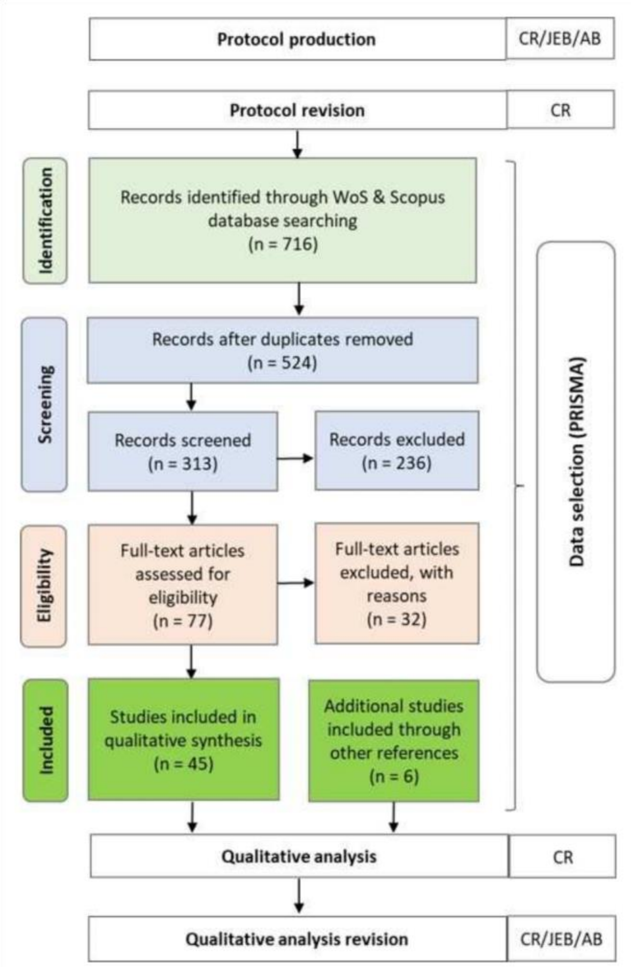

Figure 1. Data selection process—protocol based on PRISMA figure. Initials in the right column indicate the person(s) who performed the given step.

2.4. Data Collection and Qualitative Analysis

In order to help represent the effects of CC, we used the 'Driver-Pressure-State-ImpactResponse' (DPSIR) general framework. The DPSIR framework is a conceptual tool for analyzing all the cause-effect relationships of a system between human activity and the environment. According to the DPSIR definition [20], social demographic and economic developments in societies act as a *Driver* (e.g., changes in lifestyles, consumption and production patterns, or land use strategies). These drivers exert some *Pressure* on the environment by releasing pollutant substances (e.g., emissions), physical and biological agents, and use resources for 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 those of the socioeconomic system, which leads to a societal and political *Response* that refers to the actions carried out by society and governments in order to minimize the negative effects on the environment due to anthropogenic developments. To represent this cause-effect chain for the use of CC on the environment, we used the analytical framework developed by [16], who developed a set of 41 environmental issues sorted in a DPSIR manner:

(i) *Driver*, three indicators: nutrition of human population, agri-environmental public policy, and farmers' income-economy.

(ii) *Pressure*, eight indicators: landscape structure, land use, traffic intensity (labor input, soil compaction, number of machineries in use, etc.), fertilizer inputs, pesticide inputs, water inputs (irrigation), energy inputs, and GHG emissions.

(iii) *State*, eight indicators: albedo, soil structure, soil organic matter content, soil-storage capacity, nutrient levels in soil (availability of N, P, and K), water-use efficiency, N-use efficiency, and sensitivity to nutrient losses (i.e., nitrate leaching).

(iv) *Impact,* 21 indicators for assessing CC's effects on provisional, regulatory, and cultural ecosystem services (i.e., harvested biomass or yield, yield gap, carbon storage or sequestration, erosion control rate, infiltration rate, drinking water, water purification, nutrient regulation, local climate regulation, pest and disease control, pollination, and aesthetic value), but also on society and the environment (i.e., human health, changes in soil quality, water use and scarcity, eutrophication, aquatic or terrestrial ecotoxicity, fine particulate matter formation, global climate change, biodiversity loss, energy depletion, and natural resource availability).

3. Results

We gathered the conclusions of the 51 papers obtained by the PRISMA approach that assessed either the positive, negative, or variable effects of CC on the environmental sustainability of different agroecosystems (cf. Table A1). As the rapid SLR is mainly a qualitative approach, we present the results by summing the different papers per environmental indicator depending on the observed impact: positive (in green), negative (in red), and variable (in grey) (Figure 2).

Some indicators, as presented in Section 2.4, have been studied to various degrees. For some indicators, there are many papers (e.g., 'GHG emissions' and 'Harvested biomass/Yield') while for some others no papers have been established (e.g., 'Nutrition of population', 'Water purification', 'Local climate regulation', 'Aesthetic value', and 'Fine particulate matter formation').

For quite a large number of indicators, the different papers report only positive effects of the cover crop (15/41—36.6%), and occasionally along with a variable effect (6/41— 14.6%), as it may depend on the experimental context. This is mainly the case for the "state indicators". For five indicators, positive and negative effects are reported. This is mainly the case for the agronomical inputs ('Water input', 'Fertilization input', and 'Pesticides input'). However, for some indicators, more controversial effects have been reported (5/41—12.2%). Let us focus on the two indicators that have the highest number of studies in more detail:

- 'GHG emission' as part of the 'Pressure indicators'. Since the year 2000, the effects of cover crops on GHG emissions have been largely studied (see Appendix B). On the one hand, different authors have measured a positive effect of CC on GHG emission, often with a focus on N_2O emissions and sometimes CO_2:

  - Ref. [21] used an LCA approach in a Mediterranean organic-fruit-orchard system, which showed the potential of CC to reduce GHG emissions. Their results also suggested that the increase in N_2O emissions due to the extra N inputs from the legume CC was much lower than the effect on soil carbon in terms of climate change mitigation.
  - Over a 10-year experiment in Spain, Ref. [22] simulated the effects of the establishment of CC (vetch and barley), compared to the traditional fall-winter fallow, on the environmental pressures in terms of Global Warming Potential (GWP) and the total CO_2-eq emissions balance. They showed that higher GHG emission mitigation was obtained with legume CC, but both legume and cereal CC reduced N_2O emissions. Their study also highlighted that the management of synthetic N fertilization is crucial for GWP mitigation, particularly through the adjustment of N inputs to crop needs, which allows for N-synthetic inputs to be reduced with CC treatments.
  - Compared to bare soil, Ref. [15] showed—via simulating scenarios—that CC could improve the mean direct GHG balance by 315 kg CO_2-eq·ha^{-1}·year^{-1} from 2007 to 2052 in rainfed and irrigated cropping systems of southern France. This decrease in CO_2-eq (CO_2 + N_2O) emitted in cropping systems represented a decrease from 4.5% to 9% of annual GHG emissions from French agriculture.

◦ Ref. [23] have assessed the effects of management practices on GHG emissions for 15 European cropland sites and showed that when maize was combined with CC, compared to sites where no CC was grown, organic carbon fertilization inputs increased, while GHG emissions from fertilizer operations were mitigated.

◦ Using a model approach combined with remote sensing, Ref. [24] assessed the mitigatory potential of CC on GHG fluxes (CO_2 and N_2O) and albedo. The authors found that CC could reduce CO_2 emissions without affecting N_2O emissions by the year 2050.

◦ Ref. [25] showed that CC increased CO_2 emissions by 44% from 2007 to 2013 in the soils of Veneto (Italy) with the highest soil organic carbon content, but overall, CC management reduced GHG emissions by mitigating N_2O (by more than 50%) and CH_4 emissions, mainly due to their positive effect of an increased fertilization efficiency.

◦ Ref. [26], across all arable land in France, highlighted that the CC scenario slightly increased N_2O emissions but decreased indirect emissions and had the highest mitigation potential (9.1 Mt CO_2-eq·yr^{-1}) compared to the baseline scenario.

On the other hand, the negative effects of CC on the GHG emissions indicator were reported:

◦ Ref. [27] showed that the introduction of a legume CC increased N levels in the soil through additional biological fixation in almost all the simulated locations across the EU. Despite the strong reduction of mineral N fertilizers, using leguminous CC continuously led to a soil N surplus in the mid-term that increased gaseous N emissions and induced an increase in the cumulative soil GHG flux of 31 Mg CO_2-eq·ha^{-1} for EU countries by 2100.

◦ Ref. [28] studied a 19-year experiment in Northern France and reported that legume CC and green manures provided the highest organic N inputs from symbiotic fixation but also high rates of N_2O emissions due to the absence of tillage and the presence of living mulch compared to its incorporation in soil. These high N_2O emissions resulted in a slightly positive GHG balance.

◦ Ref. [29] showed through long-term field experiments in Europe that CC could lead to substantial N_2O emissions after their incorporation in soil and decomposition, particularly for legume CC with high N content.

◦ Ref. [30], using an LCA approach, reported that CC led to a higher global warming potential in Switzerland (especially the legume CC treatment, followed by a nonlegume and a mixed treatment) when compared to the use of bare soil during the fallow period by increasing GHG emissions in the field (i.e., additional N_2O emissions from crop residues) and the additional energy demand for seeding/mulching (i.e., the additional CO_2 emissions from the increased number of machines necessary for the cultivation of CC).

◦ The French experiment of [31] highlighted that conventional intensive tillage systems with the introduction of CC presented greater onsite GHG emissions compared to the use of fallow between cash crops, again due to the energy demand of the machinery use necessary for the CC's establishment (i.e., pre-sowing-soil tillage, sowing, and CC incorporation to the soil) and termination. On the other hand, legume CC significantly decreased external GHG emissions due to lower requirements for N fertilizers.

◦ In the Veneto region, Ref. [32] simulated different treatments from 2010 to 2014 and their results indicated that the no-tillage requirements associated with CC practices reduced CO_2 emissions due to the reduced use of mechanization and yield-drying requirements. However, this reduction in CO_2 emissions was largely offset by higher emissions from pesticides and planting operations.

◦ Ref. [33] simulated the long-term (1991–2013) effect of manure and composting practices on all the cropland soils of Switzerland with reduced tillage and winter CC compared to conventionally managed soils. The maximum reduction in net GHG emissions was predicted for each crop under the organic compost practice when combined with reduced tillage and winter CC (e.g., −4.17 Mg CO_2-eq·ha^{-1}·yr^{-1} for maize). However, the additional organic matter together with the manure practice alone or combined with winter CC tended to increase soil N_2O emissions.

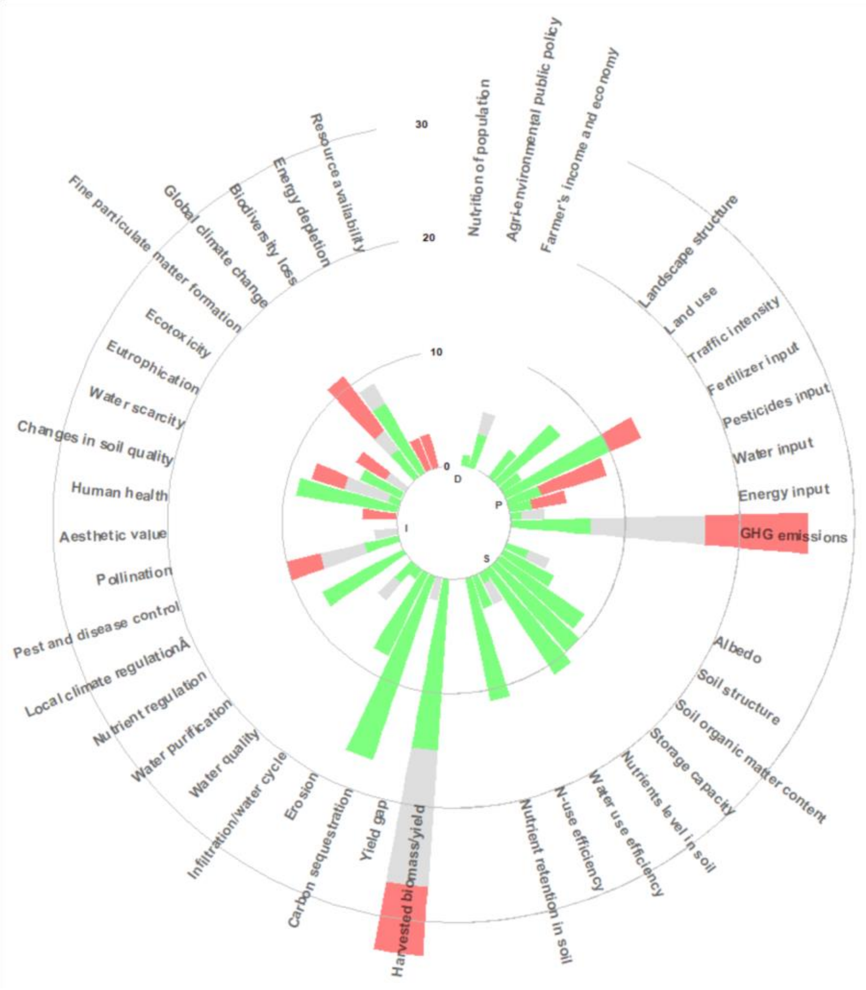

Figure 2. For each environmental sustainability indicator, the bar represents the number of papers showing a positive (green), a negative (red), or a variable effect (grey) on the environment. Indicators are sorted depending on the DPSIR framework (see [16]).

It is quite clear that for such a complex process (GHG emission), the results greatly differ depending on how it is calculated and on the system at hand.

- 'Harvested biomass/yield' as part of the 'Impact indicators'. Studies reported variable and potential negative effects of CC on "Harvested biomass/yield'.
  - Ref. [34], in a Mediterranean vineyard experiment, showed that yields decreased as the CC's soil coverage increased, especially in shallow soils. From this study, a CC soil coverage of 30% was recommended for balancing the trade-offs between Mediterranean winegrowers' yield objectives and soil-protection goals.
  - In northern French conservation agriculture systems with CC, Ref. [28] showed that yields were lower compared to other systems.
  - Ref. [35] showed that repeated catch crops can lead to positive effects on harvested biomass even if those effects do not always appear in the first few years, due to the effect of cover crops on the soil's N mineralization that takes several years to have an impact on yields.
  - Ref. [36] showed that CC cultivation led to a variable effect on main crop yields, but compared to the business-as-usual practices, CC slightly improved crop yields, particularly when CC were introduced between two winter cereals.
  - Ref. [26] observed that the use of CC had little effect on most crop yields in France, except for rapeseed (+8%) and silage maize (−7%).

4. Discussion and Conclusions

Compared to the study by [1] or even [4], in this review, we used a different approach by scanning a set of indicators involving flows and synergies between the results among the sustainability indicators. If one wants a more quantitative analysis on the impact of introducing CC on some specific indicators, another methodology such as a meta-analysis should be used. Following the presentation of these results, as expected, CC had positive effects on the selected sustainability indicators in most of the studies assessed. Cover crops increased the field-scale benefits and sustainability of agricultural production systems without seeking an economic return *a priori*, and their area increased in temperate countries such as the US [37] and those in Europe [3]. The economic interest in the introduction of cover crops compared to a bare soil is known and predictable but not always similar and therefore provides contrasts. For example, Ref. [5] performed a comprehensive economical analysis of the impacts of CC on the economic returns of the cropping system. In general, due to the implementation of a CC, the farmers could generally obtain good yields. More recently, a two-year maize-soybean rotation with an oat CC provided a 5% increase in the direct margin in a field experiment in southwest France. This experiment was conducted as part of the DiverIMPACTS project running from 2017 to 2022 and supported by the EU's HORIZON 2020 research program. However, the effect of CC towards a potential economic return for farmers involves a greater workload, which may hinder the CC's acceptance. For example, under 2% of US cash-crop-production farmland currently incorporates a cover crop [37]. In addition to this barrier, there is a new crucial problem directly related to climate change and the trend of more frequent dry summers, which is an increasing issue in successfully establishing a cover crop [38].

In general, the controversial and variable effects of CC [12] in the selected studies have shown the differences in the systems evaluated, the differences in the calculation methods used, and the synergies between the sustainability indicators (e.g., CC's effects on pesticide inputs or water inputs and pest and disease control or water scarcity). Indeed, the negative or variable effects of CC are mainly due to the variability within the key management factors, such as the sowing and destruction dates of the CC, the choice of species and their degree of mixing, and the adapted practices with respect to the specific conditions of the different agricultural sites (soils, climate, and cropping systems), where each context causes different problems [38]. For example, we know that non-leguminous species tend to increase a possible N-preemptive competition that is unfavorable for the succeeding cash crops, especially when they are destroyed late, whereas leguminous species that are destroyed earlier produce green manures that could be favorable to yields [1,6]. Taking another example, we know that one of the most important cover crop benefits is decreasing nitrate leaching by increasing the N retention in soils over winter [39]. In a DiverIMPACTS study case in the Netherlands—a field experiment that introduced CC (such as Italian rye-grass) sown under maize during the growing season or after the harvest—it was recommended that to prevent hydric stress for maize, CC should be removed under a month before sowing the cash crop, as already demonstrated (e.g., [12]). In terms of GHG emissions, CC have positive effects that can mitigate the global warming potential of agricultural fields [11], but the results of the studies are highly variable as this factor depends on explanatory elements such as the depth of the soil or the choice of species [15,28]. So, it is important to understand the different conditions and calculation methods in the selected studies, which may or may not include some trade-offs, to clarify the conclusions on GHG emissions and global climate change analyses. Another important point to consider is that the variability of the results, in general, is also due to differences between the short- and long-terms, and this review considers more short-term studies (3–5 years duration). For example, the uncertain economic benefit of CC through variable effects on the yields of subsequent cash crops is assessed in the short-term, whereas in the long-term (10–15 years at least) the effects of CC are generally positive, except on legumes [1,6].

From this systematic literature review, we can also conclude that there is quite a lot of variability between the selected studies; therefore, there is a need for more data on the effects of CC on environmental issues. The introduction of catch and cover crops must be based on site-specific agricultural management across EU countries and on their different environmental conditions, especially under climate change conditions. This would help to clarify the synergies among the indicators caused by the effects of cover crops, for example, on the indicator of global climate change that is mainly related to the GHG net balance (i.e., soil carbon sequestration and GHG emissions-exchange indicators), inputs savings (i.e., mostly fertilizer input indicator), and albedo indicators.

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Appendix A. Details of the Query for the WoS Database (Same Query for Scopus)—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

Appendix B

Table A1. Selected studies from the systematic literature review of the cover crops case study.

N ∘	Selected Author and Study Names by Chronological Order	Agri-Environmental Indicators Assessed	Location and Cash Crop Production	Sustainability Assessment Methods Used
1	[40]	Erosion	Spain (South) Olive orchard	Field trial; Agri-environmental indicators (AEI)
2	[23]	Land use; GHG emissions; Carbon sequestration; Erosion; Global climate change	Europe (climate gradient) Rapeseed, Winter wheat, Sunflower, Durum wheat, Peas, Sorghum, Rye, grass/maize, Fennel/maize, Spring barley, Maize, Winter barley, Sugar beet, Mustard/maize, Triticale, Potato seeds, Potato, Rice	Modelling; AEI, Ecosystem Services Assessment (ESA), Life Cycle Assessment (LCA)
3	[41]	Water use efficiency; Water cycle; Water scarcity	France (South) Vineyard	Modelling; AEI, ESA
4	[42]	Nutrient levels in soil; Eutrophication	Belgium (Walloon region) Typical Belgium crop rotations	Modelling; AEI
5	[35]	Fertilizer input; Nutrient retention in soil; Harvested biomass/yield; Nutrient regulation	France (North) Winter wheat, Spring barley, Spring pea, Silage maize, Sugar beet	Modelling; AEI
6	[36]	Nutrient retention in soil; Harvested biomass/yield; Nutrient regulation	Western Europe Fodder crop rotations: grass leys, legume leys, winter wheat, barley, maize	Modelling; AEI
7	[43]	Storage capacity; Carbon sequestration	European Union arable soils Main European cash crops	Modelling; AEI
8	[44]	Farmers' economy; GHG emissions; Nutrient retention in soil; Harvested biomass/yield; Carbon sequestration; Erosion; Nutrient regulation; Water cycle; Pest control; Changes in soil quality	USA (Mid-Atlantic climate) Soybean, Maize, Wheat	Modelling; AEI, ESA

N∘	Selected Author and Study Names by Chronological Order	Agri-Environmental Indicators Assessed	Location and Cash Crop Production	Sustainability Assessment Methods Used
9	[21]	Traffic intensity; Fertilizer input; Pesticide input; Water input; Energy input; GHG emissions; Nutrient levels in soil; Harvested biomass/yield; Carbon sequestration; Global climate change	Spain Orchards	Modelling; LCA
10	[22]	Soil structure; Soil organic matter (SOM) content; Carbon sequestration	Spain (Southeast) Organic rainfed orchard	Experiment; AEI
11	[45]	Fertilizer input; Storage capacity; Nutrient retention in soil; Harvested biomass/yield; Carbon sequestration; Nutrient regulation	France (Brittany) Winter wheat, forage maize	Long-term experiment; AEI
12	[46]	Pesticide input; Harvested biomass/yield; Pest control; Biodiversity loss	France (Burgundy and Poitou-charente) 26 cropping systems	Modelling and simulation; AEI, AEI-Yield Gap Analysis (YGA)
13	[47]	Human health; Changes in soil quality; Eutrophication; Ecotoxicity; Global climate change; Biodiversity loss; Energy depletion	France (Burgundy, Moselle, Beauce) Oilseed rape, Rape seed, Winter wheat, Winter barley, Spring barley, Winter pea, Spring pea	Modelling; Life cycle assessment (LCA)
14	[48]	Landscape structure; Land use; Erosion	pan European sites Common wheat, Durum wheat, Rye, Barley, Grain maize, Rice, Dried pulses, Protein crop, Potatoes, Sugar beet, Oilseeds, Rape, Sunflower seed, Linseed, Soya, Cotton seed, Tobacco	Modelling; AEI
15	[49]	Farmers' economy; Pesticide input; GHG emissions; Harvested biomass/yield; Erosion; Pest control; Water scarcity;	France (Haute-Normandie, Champagne-Ardenne, Rhône-Alpes, Centre, Aquitaine, Franche-Comté) Alfalfa, Faba bean, Fescue, Hemp, Fiber flax, Grain maize, Silage maize, Oilseed rape, Sugar beet, Soybean, Spring pea, Sunflower, Triticale, Winter barley, Winter pea, Winter wheat	Modelling; AEI
N∘	Selected Author and Study Names by Chronological Order	Agri-Environmental Indicators Assessed	Location and Cash Crop Production	Sustainability Assessment Methods Used
16	[25]	GHG emissions; Storage capacity; Nutrient retention in soil; Erosion; Water quality; Nutrient regulation;	Italy (Veneto region) Maize, Wheat, Barley, Soybean, Sunflower, Rapeseed, Potato, Sugar beet, Pastures, and meadows	Modelling and simulation; AEI

N ◦	Selected Author and Study Names by Chronological Order	Agri-Environmental Indicators Assessed	Location and Cash Crop Production	Sustainability Assessment Methods Used
17	[50]	Soil structure	Germany (Lower Bavaria) Silage maize and sugar beet	Field trial; AEI
18	[51]	Storage capacity; Nutrient levels in soil; Harvested biomass/yield; Carbon sequestration	France (Southwest) Sorghum, Sunflower, Durum wheat, Winter pea, Soybean, Spring pea	Experiment; AEI
19	[52]	Nutrient levels in soil; Nutrient retention in soil	Belgium (Flanders) Cut grassland, Silage maize, Potatoes, Sugar beets, Winter wheat	Simulated scenarios; AEI
20	[32]	Fertilizer input; Pesticide input; GHG emissions; SOM content; Storage capacity; Carbon sequestration	Italy (Veneto region) Wheat, Maize, Soybean, Rapeseed	Farm scale measurements and modelling; AEI
21	[30]	Eutrophication; Ecotoxicity; Global climate change; Biodiversity loss	Switzerland (Zurich-Reckenholz) Winter wheat, Maize, Faba bean, Grass–clover ley	Field experiment; LCA
22	[53]	N-use efficiency; Harvested biomass/yield	Denmark (Southern Jutland, Central Jutland, Western Zealand) Spring barley, Winter wheat, Spring wheat, Winter rye, Winter triticale, Lupin, Faba bean, Pea, Spring barley, Potato, Grass-clover	Long-term field experiment; AEI, AEI-YGA
23	[54]	Farmers' economy; SOM content; Nutrient levels in soil; Harvested biomass/yield; Water quality	UK (Norfolk) Winter wheat, Winter barley, Spring barley, Spring beans	Field experiment; AEI
24	[34]	Harvested biomass/yield; Water scarcity	France (South) Vineyard	Modelling and simulation; AEI, ESA
25	[55]	Fertilizer input; Harvested biomass/yield; Nutrient regulation	Denmark (Foulum, Jyndevad) Maize, Sugar beet, Hemp, Winter triticale	Field experiment; AEI, ESA
26	[31]	GHG emissions; Carbon sequestration	France (Southwest) Sorghum, Sunflower, Durum wheat, Winter pea	Field experiment and model-simulation; AEI
27	[15]	GHG emissions; Storage capacity; Water use efficiency; Nutrient retention; Carbon sequestration; Water scarcity	France (Southwest) Maize, Wheat, Soybean, Sunflower, Pea, Sorghum	Field experiment and long-term simulating scenarios; AEI, AEI-ESA

28	[56]	Soil structure; SOM content; Nutrient levels in soil; Nutrient retention in soil; Changes in soil quality; Biodiversity loss	France (Brittany) Maize, Winter wheat, Winter barley, Silage maize	Farm surveys and modelling; AEI
29	[57]	SOM content; Changes in soil quality	France (North) Spring wheat, Green pea, Maize	Experiment; AEI
30	[58]	Albedo	Europe (pedoclimatic zones) No specific crops.	Satellite, meteorological and land cover data; AEI
31	[59]	SOM content; Storage capacity; Nutrient levels in soil; Carbon sequestration; Water quality; Nutrient regulation; Changes in soil quality	Italy (Veneto region) Winter wheat, Oilseed rape, Soybean, Maize	Field experiment and modelling; AEI, ESA
32	[60]	Land use; Biodiversity loss	Spain (Andalusia) Olive orchards	Field study and modelling; AEI
33	[61]	Farmers' economy; Soil structure; Nutrient levels in soil; Nutrient retention in soil; Harvested biomass/yield; Pest control; Changes in soil quality; Biodiversity loss	UK (Leicestershire) Wheat, Rapeseed	Field experiment; ESA, AEI-ESA
34	[29]	GHG emissions; Nutrient levels in soil; Harvested biomass/yield	Europe (Norway, Denmark, Poland, Switzerland, Italy, Spain) Crop depends on the site (mainly wheat and maize)	Field experiment and model simulation; AEI
35	[22]	Traffic intensity; Fertilizer input; Water input; Energy input; GHG emissions; Albedo; SOM content; Harvested biomass/yield; Global climate change	Spain (Madrid) Maize, Sunflower	Long term field experiment and modelling; AEI
36	[62]	Agri-environmental public policy; Nutrient levels in soil; Erosion, Nutrient regulation; Changes in soil quality	Baltic Sea region Variety of cash crops depending on the region	Analysis and synthesis; AEI
37	[28]	Fertilizer input; GHG emissions; SOM content; Storage capacity; Nutrient levels in soil; N-use efficiency; Nutrient retention; Harvested biomass/yield; Carbon sequestration; Global climate change	Switzerland (Therwil) and Denmark (Aarhus) Alfalfa, Beetroot, White cabbage, Clover-grass ley, Hemp, Lupin, Oat, Potato, Spring barley, Silage maize, Soybean, Spring pea, Spring wheat, Triticale, Winter barley, Winter wheat	Long-term experiment and modelling; AEI
38	[3]	Erosion	Europe Crop depends on the site	Modelling; AEI
39	[63]	Harvested biomass/yield; Pest and disease control	Switzerland (Changins) Maize	Field experiment; AEI

N ◦	Selected Author and Study Names by Chronological Order	Agri-Environmental Indicators Assessed	Location and Cash Crop Production	Sustainability Assessment Methods Used
40	[24]	GHG emissions; Albedo; Carbon sequestration	Europe Crop depends on the site	Modelling and remote sensing; AEI
41	[64]	Landscape structure; Land use; Pollination; Biodiversity loss	Europe Crop depends on the site	Modelling; AEI, ESA
42	[65]	Fertilizer input; Harvested biomass/yield	Europe (Belgium, France Germany, The Netherlands, Finland, Latvia, Norway, Sweden, Italy, Spain). Crop depends on countries	Data analysis; AEI
43	[66]	Landscape structure; Land use; Biodiversity loss	Europe (west-east European transect) Vineyards	Modelling; ESA, AEI, AEI-ESA
44	[33]	GHG emissions; Storage capacity; Harvested biomass/yield; Carbon sequestration	Switzerland Wheat, Maize, Barley, Rape, Beets, Potatoes, Spelt, Sunflower, Peas, Beans, Oats	Modelling; AEI, AEI-YGA
45	[27]	Fertilizer input; GHG emissions; Nutrient retention; Harvested biomass/yield; Carbon sequestration	Europe Crop depends on the site	Field scale and modelling; AEI
46	[67]	Land use; Carbon sequestration	Kazakhstan (Almaty), Finland (South), Italy (North) Spring barley, Maize	Experiment and modelling; AEI
47	[68]	Land use; Fertilizer input; Pesticide inputs; N-use efficiency; Harvested biomass/yield; Pest control	Switzerland (Tänikon) Winter wheat, Maize	Experiment and modelling; AEI
48	[69]	Harvested biomass/yield	Italy (central Italy) Maize, Durum wheat, Sunflower	Long term experiment and modelling; AEI
49	[26]	Fertilizer input; Water input; GHG emissions; Storage capacity; Harvested biomass/yield; Carbon sequestration	France (arable land) Grain and silage maize, Winter wheat, Rapeseed, Sugar beet, Sunflower, Winter and spring pea, Temporary grasslands	High-resolution modelling; AEI
50	[70]	Harvested biomass/yield; Changes in soil quality	North-south European gradient Crop depends on the site	Experimental sites and Modelling; AEI
51	[71]	Soil structure; SOM content; Changes in soil quality	USA (transect) Crop depends on the site	Farm scale experiment and modelling; AEI

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